# A CONCEPTUAL MODEL OF REAL SYSTEM AGE

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## Abstract

A major challenge for Department of Defense (DoD) decision makers is deciding when to retire a system. Often, engineered systems remain operational well beyond their planned retirement date. The B-52 bomber will continue to operate until 2045 for a total life of 90 years; whereas the DoD retired the F-117 stealth fighter after 25 years. So, the question becomes are there underlying attributes of engineered systems that affect the aging and if so, how can analysts model the real system age? Previous research found that attributes such as changeability, interoperability, robustness, and versatility are critical elements to this decision. This work drew inspiration from other research into the aging of biological systems, software systems, and human aging. However, the previous work did not capture a method to model and simulate the real system age over time to determine how potential policies impact the real system age. This paper begins to apply system dynamics as a method to model the real system age of an engineered system. It captures the causal relationships and presents an initial stock and flow model for some of the critical accumulations in the model to include the real system age, system errors, and capability performance.

## Key Words

System Engineering, System Aging, System Dynamics

## 1 Introduction

The concept of aging in engineered systems provides an excellent opportunity to apply system dynamics in order to model the dynamic nature of an engineered system's real system age. Aging in engineered systems is generally limited to the chronological age of systems and systems engineers only considered it as part of the lifecycle costing during the design of a system. However, the reality is that systems effectively age at different rates, which leads management to extend the life of some systems well beyond their intended life. This paper examines several areas outside of the traditional systems engineering literature, to include biological systems, software systems, and the medical field, to understand the concept of aging in these domains. One of the basic elements of aging in each of these fields is the accumulation of errors within the systems that eventually lead to system failure at some level. This aspect of accumulations within a system makes the modeling of an engineered system's real system age a prime candidate for system dynamics modeling.

Within the Department of Defense (DoD), the decision on when to retire a system is as complex decision that often results in systems being extended well beyond their planned service date. A prime example of this is the B-52 Stratofortress bomber that will be ninety years old in 2045 when the Air Force finally retires the aircraft. Likewise, the A-10 Thunderbolt II is another Air Force aircraft that the DoD continues to upgrade and improve in order to extend the life of the attack aircraft. A sharp contrast is the F-117 stealth fighter that the Air Force developed in the early 1980s and retired in 2008 after the planned twenty-five year lifespan. The concept of real system age takes the attributes of systems into account when determining the real system age of an engineered system that can be drastically different than the system's chronological age. The real system age takes into account the accumulation of errors to a system, from changes to the system design, as well as functional attributes of the system that can reduce or increase a system's real age.

This paper presents an initial, conceptual model of a system's real system age using casual loop diagrams to understand the feedback structure that affects real system age. It presents a brief review of the literature that includes a background on system dynamics and causal loop diagrams as well as a review of the relevant aging literature. The next section discusses the theory of real system age and the different components that contribute to the aging or in some cases rejuvenation of engineered systems. The main portion of the paper presents the conceptual model of real system age through a series of causal loop diagrams that capture the dynamic behavior of real system age. Finally, the paper proposes future work in this area to continue to expand and model the real system age of engineered systems with system dynamics.

# 2 Literature Review

The literature review section discusses several aspects of the literature for system dynamics, causal loop diagrams, and the modeling of aging that contribute to calculating and modeling real system age. System dynamics provides a means to model accumulations, flows, and the dynamic behavior of a system; an essential element of modeling a system's real system age. This paper focuses on establishing the causal relationships required for modeling the real system age and this section summarizes some of the literature on causal loop diagrams. Finally, the literature review relies on other aging literature, including biological systems, software systems, and the medical and healthcare fields, to provide a basis for the real system age.

## 2.1 System Dynamics

System dynamics is a methodology to understand the dynamic behavior of systems using accumulations, flows, and causal relationships within a system. It exposes the underlying structure of a system and models the behavior over time to adjust individuals' mental models of the system and test potential policy alternatives. Forrester's (1968) work describes a system as "a grouping of parts that operate together for a common purpose". He further classifies two types of systems: open systems, in which external variables affect the system, or closed systems where all variables are internal to the system (Forrester, 1961). In his book, World Dynamics, he presents an example system model of the world that described the interrelations between population, capital investment, geographical space, natural resources, pollution, and food production (Forrester, 1971). The behavior of a system over time is the dynamics of a system, which are often complex and non-linear in nature because of the system's underlying structure (Forrester, 1961). This complexity stems from feedback within the system, time delays between decisions and effects, and the learning process of the system (Sterman, 2000). These attributes of systems make them difficult to understand and identify the cause and effect relationships without an effective model of the system.

Within the management domain, Forrester (1961) described the potential for system dynamics to assist decision makers understand the implications of their policies and potentially identify and mitigate unintended consequences of their decisions. Applications of System Dynamics have provided insights across several domains; including corporate policy, infectious disease, commodity markets, and drug addiction, and commodity markets (Forrester, 1971). Companies and consultants have extensively used System Dynamics for managing large, complex projects with a great deal of success. One area where businesses utilize System Dynamics is in the development of corporate strategy and analysis of business decisions after a crisis or complex problem triggers these shifts in business strategy. System Dynamics assists in determining the root cause of the crisis and identifying potential consequences of alternative courses of action (Sterman, 2000). One of the main benefits of the system dynamics methodology is that it makes explicit causal relationships between variables to understand how the underlying structure and accumulations affect the behavior of the system over time.

## 2.2 Causal Loop Diagrams

A key component of system dynamics is the causal loop diagrams that represent the feedback structure within a system using signed diagrams. In closed systems, casual loops differ from discrete, event-oriented perspectives of individual causes and effects in that any cause is an effect on another variable (Richardson, 1991). In System Dynamics, the causal loop diagrams represent either physical or information flows that indicate how one variable influences. These diagrams describe the behavior of the system by talking through the loop to tell the story of the interactions within the system (Meadows, Randers, & Meadows, 2004). Causal loop diagrams provide value to modelers as a means to identify the feedback structure of a system and provide a basis for future modeling efforts.

There are two main types of individual feedback loops: reinforcing or positive loops and balancing or negative loops. Richardson (1991) describes a reinforcing feedback loop as a chain of cause and effect relationships that amplify a change in any one of the variables. A change to any variable in the loop in one direction propagates through the loop to change the original variable in the same direction. The positive loop designation does not necessarily indicate that the loop will have favorable results, quite often the opposite occurs. Additional when transferred to a stock and flow model, these loops have the potential to grow exponentially (Meadows, Randers, & Meadows, 2004). Balancing feedback loops work to diminish the effect of a change in a system and restore balance to a system (Richardson, 1991). In System Dynamics, balancing feedback loops bring a system back to a desired level or a level constrained by the system. Forrester (1968) provides a simple inventory control system an example of a first-order negative feedback loop; when inventories falls below a desired level, the order rate increases to increase inventories. In this type of loop, the decrease to a variable propagates through the loop to increase the original variable.

In natural and engineered systems delays, either information or material, often exist which increase the dynamic complexity of these systems. These delays are generally a key contributor to the dynamic behavior of systems and create problems, as they are difficult to capture in a mental model of the system. In material delays conservation of matter applies, so no units will be lost during the delay, but the delay will cause the inflow to differ from the outflow, thus resulting in an accumulation (Forrester, 1961). Whereas in information delays, the information may lose value over time, so the accumulation of information may diminish over time as people make decisions based on old information (Forrester, Industrial Dynamics, 1961). These delays can have dramatic effects on a system's behavior over time and may cause a system to overshoot is goal when the feedback signal is delayed. If the system overshoots its natural limit, the delay may result in the eventual collapse of the system if the delay allows the system to continue to grow to a point where it causes irreversible damage (Meadows, Randers, & Meadows, 2004).

## 2.3 Modeling of Aging

This section discusses various examples of the aging process in biological systems, software systems, and the medical and healthcare fields. Regardless of the field, the literature attributes the aging process to an accumulation of errors to a point where the errors begin to cause system level failures. In biological systems, the literature not only defines aging, but it also examines the modeling of aging in these biological systems to better understand the aging process. The literature for software systems describes the aging process in a similar manner and adds the concept of software rejuvenation to combat the effects of aging. Finally, in the medical and health care fields, the literature discusses the difference between a person's real age and their chronological age and methods to reduce the effects of aging.

The biological systems literature describes aging described as a gradual loss in function over time accompanied by an increase in mortality; however, systems age differently and in some cases not at all. An interesting aspect of the study of the biological systems literature is that biologists are exploring the application of systems thinking and mathematical modeling to biological systems. Biologists are beginning to apply mathematical and engineering tools and methods to better understand the aging process in biological systems and have begun to model elements of cellular function like the galactose utilization in yeast from historical data generated by past studies (Hood, 2003). West and Bergman (2009) identify two areas for aging research to include how aging manifests itself in molecular network and how mathematical modeling can be used in aging research. One effort to better understand aging applies network analysis to networks of genes, proteins and pathways within biological systems that relate to the aging process (Peysselon & Ricard-Blum, 2011). Computational systems biology relies on the systematic gathering of data and building models to identify systems and model the network behavior of these biological systems (Kriete, Sokhansanj, Coppock, & West, 2006).

Software aging is often a result of accumulations of errors over time, it is difficult to recreate the stress an operational environment can place on a software system, so some work in the software aging field focuses on detection in active software environments. In an operational setting, other efforts have applied fault management applications to monitor the health of operating systems by detecting faults that administrators can attribute to software aging in order to maintain functionality of the system (Garg, Moorsel, Vaidyanathan, & Trivedi, 1998). Given that most software aging is present in operational systems, non-intrusive methods to detect and mitigate software aging apply a variety of approaches, including machine learning, to identify and correct these errors without the need to shut down a system (Andrzejak & Silva, 2008). To counteract software aging, computer scientists have developed the concept of software rejuvenation to return the software code to its original operating state. At a very basic, yet extreme example, software rejuvenation method is the system reboot after a program or operating system has frozen. A major driver of efforts to understand software aging and rejuvenation is the high demand for system availability and reliability that requires software to operate without major faults (Trivedi, Vaidyanathan, & Goseva-Popstojanova, 2000). System administrators execute software rejuvenation by occasionally stopping the running software; cleaning its internal state by collecting garbage, flushing operations, and reinitializing internal data structures; and finally restarting the software (Castelli, et al., 2001).

In the medical field, the concept of real age estimates a patient's biological age in comparison to their calendar age as a means to evaluate the patient's health. Dr. Michael Roizen (1999) developed the concept of RealAge, later popularized by Dr. Oz on his television show, from a series of publications identifying increased mortality rates among smokers. Like in biological systems, several factors influence a person's RealAge to include diet, exercise, and other health habits. Diet is one of the key contributors to a reduction in biological age, not only in humans, but in other species as well and the literature that discusses these studies provides a basis for the calculation of RealAge. In some research on other species, specific reductions in certain macronutrients like glucose have shown to slow the aging process as they limit the production of destructive ROS in these biological systems (Ristow & Schmeisser, 2011). In humans, several studies based on regional diets, the Mediterranean being a popular example, demonstrate a linkage between a person's diet and their life expectancy (Willcox, Scapagnini, & Willcox, 2014). Another key contributor to aging in humans is exercise and a portion of the literature describes the importance of beginning an daily exercise routine to reduce the rate at which humans age (Roizen, 2006). Both diet and exercise focus on reducing obesity in humans as obesity is linked to several health problems to include cardiovascular diseases, cancer, and diabetes. By reducing a person's body fat percentage, they can reduce these adverse effects and actually reverse the biological aging process in their body (Roizen, 2015).

# 3 Theory of Real System Age

This section presents a background on real system age to include a discussion on the accumulation of errors in an engineered system, the functional factors that contribute to the real system age, and provides an example of theoretical calculations for real system age over time (Enos, 2018). The accumulation of errors over time results in the aging of both biological and software systems as these errors begin to degrade basic system functionality. The accumulation of errors in an engineered system, based on changes to that system, will results in errors that can eventually affect the performance of that system and is a critical piece of the real system age. Additionally, several functional factors, to include interoperability, robustness, and versatility, influence the real system age of an engineered system and have a profound impact on the retirement of the system. A model of real system age must take into account these two aspects of the real system age and capture how both internal and environmental changes impact the real system age. This section also presents previous work that calculated the real system age for a few example DoD systems that could provide a baseline for future modeling efforts.

## 3.1 Accumulation of Errors

Both the literature for biological and software systems attribute the aging process to the accumulation of errors to the point that system functionality begins to fail. Real system age incorporates the accumulation of system errors into the model of real system age engineering changes to the system over time will have less of an impact on the real system age. Eventually, changes to a system may reach a point where the change has a negative effect on the system's real age as the accumulation of errors begins to affect the performance of the system. Several assumptions influence this aspect of the theoretical real system age to include the assumption that a change to the system will introduce errors into the system. Additionally, it assumes that engineers will only detect a portion of these errors and only be able to correct a percentage of these detected errors. A stock and flow model must account for both the unidentified and identified, but uncorrected, errors to determine the overall number of errors within the system. Finally, it assumes that the undetected and uncorrectable errors will accumulate over time to the point of system failure.

### 3.2 Functional Factors

The other factors that affect the real system age are the functional factors of interoperability, robustness, and versatility. These functional factors are an interesting aspect of real system age in that they not only capture the effect of changes to the system, but also environmental changes that affect the performance of an engineered system. Previous identified these as critical attributes of DoD system that are extended beyond their planned retirement date and it is likely that these attributes of a DoD system directly influence real system age (Enos & Nilchiani, 2017).

Each of these factors draw upon systems engineering literature for attributes of systems often referred to as the ilities. Interoperability is “the ability to effectively interact with other systems” (de Weck, Ross, & Rhodes, 2012). In order for a legacy system to continue to provide value to the DoD, it must be able to operate alongside other legacy systems as well as new capabilities that the services introduce over time. McManus et al. (2009) describe robustness as “the ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal forces”. Given the unique operational environment for DoD systems, robustness includes both the attributes of survivability and lethality and is often influenced by environmental factors such as changes to adversary capabilities. Versatility is “the ability of a system to satisfy diverse expectations on the system without the need for changing form” (McManus, Richards, Ross, & Hastings, 2009). In some cases, the DoD achieves versatility without the need for system changes, like the A-10 assuming the forward air controller role (U.S. Air Force, 2015). Other cases, such as the Abram tank operating in urban environments, require changes to the systems, in the case of the Abrams the addition of the Tank Urban Survivability Kit (TUSK) allowed for the tank to operate in the cities of Iraq by mitigating the threat of IEDs (Roblin, 2016).

The functional factors of the real system age provide a means to capture how changes to the system may influence the performance of that system and reduce the real system age. However, in some cases, environmental changes may affect these functional factors and have a negative effect on the performance of a system, thus increasing its real system age. It is likely that these attributes of an engineered system will directly influence the real system age and a system dynamics model of these performance factors should include the behavior over time of these attributes.

### 3.3 Example Real System Age Calculations

This section presents an application of the real system age to a set of DoD systems that includes both extended, operational DoD systems as well as systems the DoD has retired to determine if there are observable trends for these two data sets. First, it presents a general mathematical representation of the real system age to account for the different factors that influence the real system age of an engineered system in the DoD. Then it presents an example application of the real system age to four DoD systems that provides a baseline real system age to demonstrate the dynamic behavior of real system age.

Figure 1 presents an example of the real system age over time for four DoD systems to include the B-52, A-10, F-117, and U-2 that previous work used as example systems. The intent of this section is to provide examples of the application of real system age to present the behavior over time of the real system age as a potential means to calibrate the model. From the initial graph, two initial observations are present. First, it appears that extended systems (B-52 and A-10) have a flat slope over time for their real system age; whereas, retired systems (F-117 and U-2) have increased slopes. Second, the systems that the DoD retires have real systems ages that approach the twenty-five year threshold, a generally accepted retirement age for DoD systems. Both groups do display some oscillation around the trend line for real system age as in reality changes are binary events in a system's lifecycle that influence the performance and real system age similar to a step function in system dynamics.

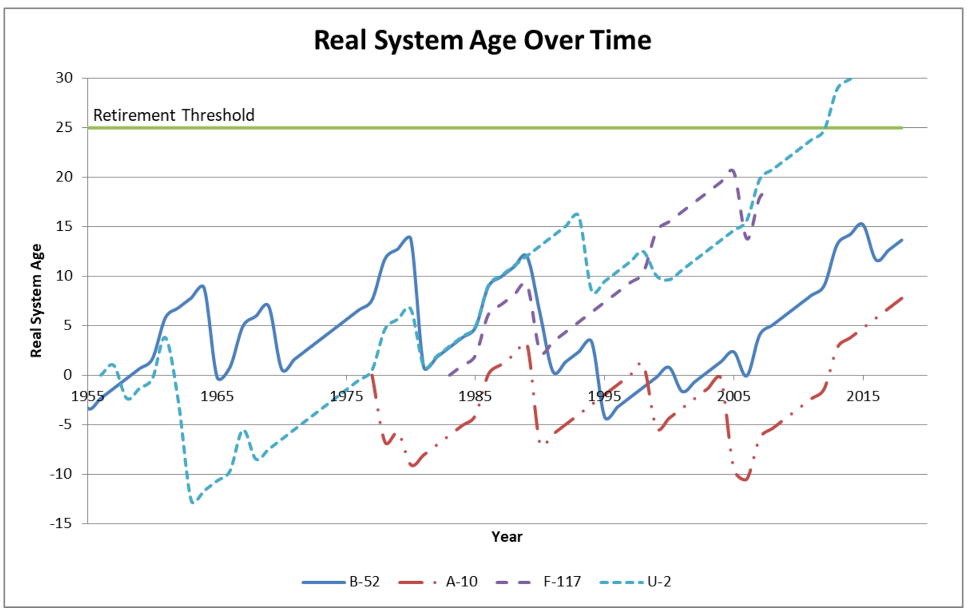


**Figure 1: Example Real System Age Over Time for DoD Systems (Enos, 2018)**

Mathematically, the real system age ($A_R$) is a function of the calendar age of a system ($A_c$), the number of changes to the system ($x$), and the functional elements of the real system age to include the interoperability ($I$), robustness($R$), and versatility ($R$) of the system (Enos, 2018). The calendar age represents the number of years since the DoD deployed the system and is often considered the main component of system aging. The changes to the system also affect the real system age as they can introduce errors into the system and as these errors accumulate, negatively impact the system real age. The functional components of real system age take into account the effect of both environmental and system changes over time that impact the performance of the system. This basic representation of the real system age provides the concept for developing a more detailed system dynamics model of real system age.

$$A_R = f(A_C, x, I, R, V)$$

## 4 Causal Structure of Real System Age

This section discusses the casual structure of the real system age of an engineered system in a causal loop diagram. Figure 2 presents the overall causal loop diagram for a system's real system age that includes two reinforcing feedback loops and three major balancing loops that create the dynamic behavior of real system age. The remainder of the section discusses aspects of the overall causal loop diagram in greater detail to better understand the structure of real system age. It presents a discussion on the basic structure of the capability gap, functional changes to a system, and environmental impacts to the real system age. Finally, it also presents basic stock and flow diagrams for the important accumulations in the model.

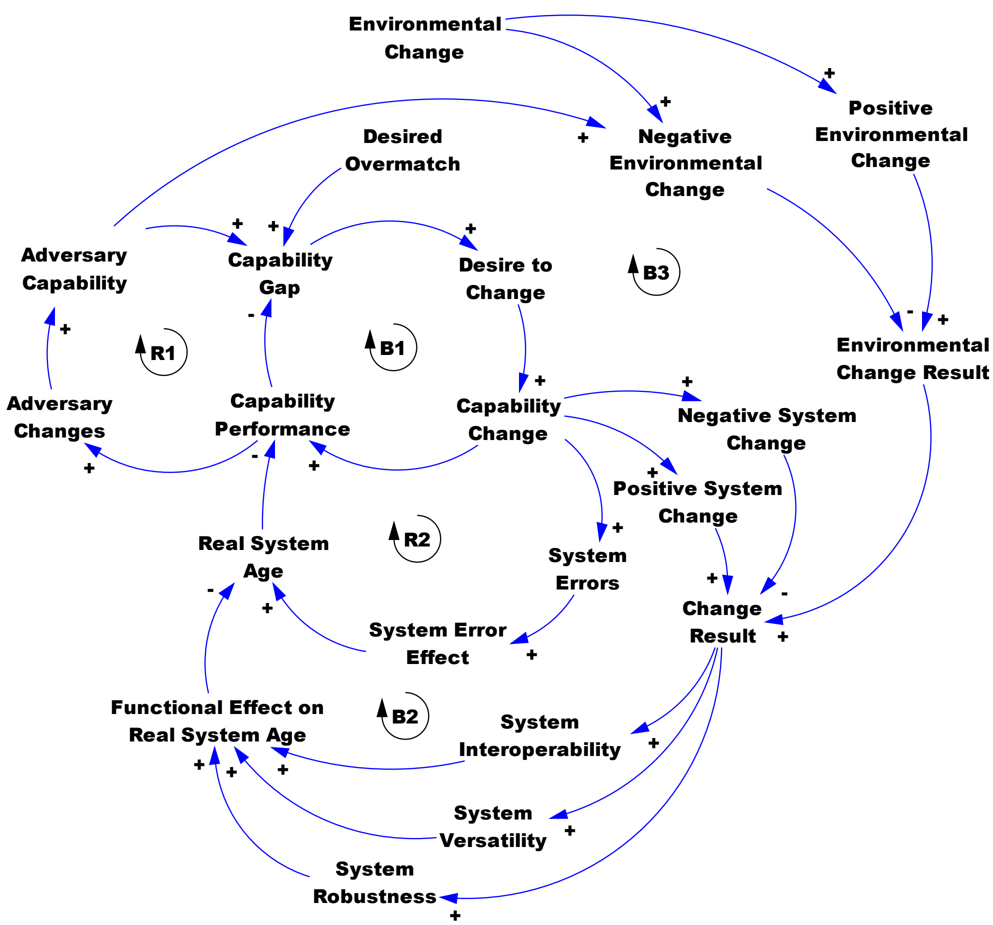


Figure 2: Real System Age CLD

## 4.1 Basic Structure

The DoD manages systems with the Joint Capability Integration and Development System that focuses on identifying capability gaps and developing capabilities to mitigate these gaps (Joint Chiefs of Staff, 2015). Figure 2 presents a causal loop diagram that represents this process through a balancing loop to meet a desired overmatch and reinforcing loop as adversary capabilities also improve over time. In this causal loop diagram, the *Adversary Capability* and the *Capability Performance* influence a *Capability Gap* based on an exogenous *Desired Overmatch*. In this manner, the DoD compares a system's current performance to the adversary's systems to determine if a true capability gap exists. On the DoD side, this results in balancing loop one as the *Capability Gap* increases the *Desire to Change* a system, which increases the actual *Capability Change*. These changes increase the *Capability Performance* of a system that decreases the *Capability Gap* until the DoD achieves the *Desired Overmatch*. However, the adversary also plays a role in this causal loop diagram as an increase in *Capability Performance* also increases the *Adversary Changes*, which increase the *Adversary Capability* and widen the *Capability Gap*. This type of feedback often results in the "arms race" affect where two countries compete against each other and consistently try to develop capabilities to surpass the other.

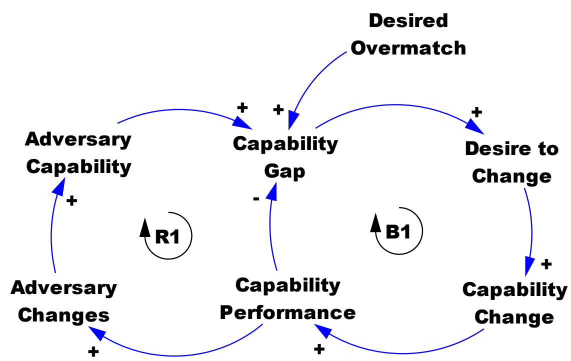


**Figure 3: Basic Structure of Capability Gap CLD**

The next portion of the causal loop diagram focuses on the accumulation of errors that can influence the real system age and over time will actually decrease the capability performance. The literature of other systems, biological, software, and medical, attribute aging to an accumulation of errors within the system that eventually result in functional failures within the system. It is likely that this phenomenon also exists in engineered systems as changes to the system can introduce errors that eventually lead to the failure of a system. The second reinforcing feedback loop accounts for this aspect of the real system age and introduces the variable of *Real System Age* to capture the real age of an engineered system in comparison to its chronological age. Figure 4 presents the causal loop diagram that depicts how errors affect a system's real system age and performance. A *Capability Change* to a system increases the number of *System Errors* that accumulate over time and have a *System Error Effect* on the *Real System Age*. This could potentially cause the system to age at a faster rate than its chronological aging and the *Real System Age* has a negative effect on the *Capability Performance*. This effect creates even more problems as the decrease in *Capability Performance* increases the *Capability Gap* and triggers additional changes to the system and more errors.

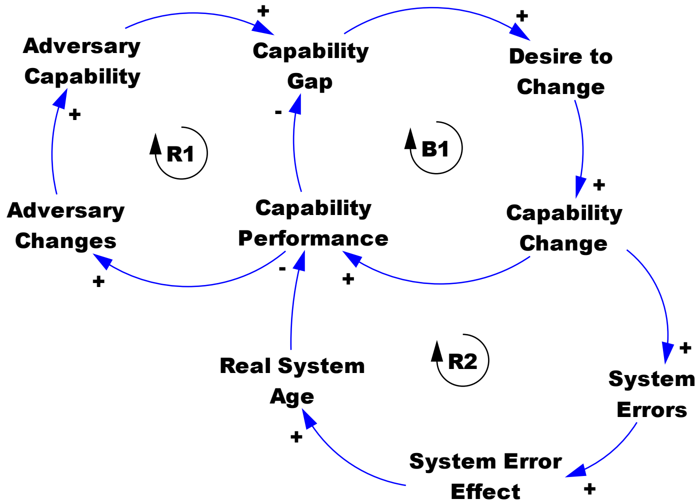


Figure 4: System Errors Effect on Real System Age

## 4.2 Functional Changes to a System

The second balancing loop in the causal loop diagram captures the effect a change to a system has on the real system age. Figure 5 presents this portion of the causal loop diagram that expands from the *Capability Change* variable to represent the effect of these changes. One would assume that a *Capability Change* would only have a *Positive System Change*; however, it is also possible that a *Capability Change* would negatively affect part of the *System Functionality*. This requires both a *Negative System Change* and a *Positive System Change* variable that influence the *Change Result*. From this point, a positive *Change Result* increases *System Functionality*, which in-turn increases the *Functional Effect on Real System Age*. The *Functional Effect on Real System Age* then decrease the *System Real Age*, potentially offsetting the *System Error Effect*, and results in an increase in *Capability Performance*. This feedback loop balances the *Capability Gap*, not shown here, in an effort to achieve the DoD's *Desired Overmatch*.

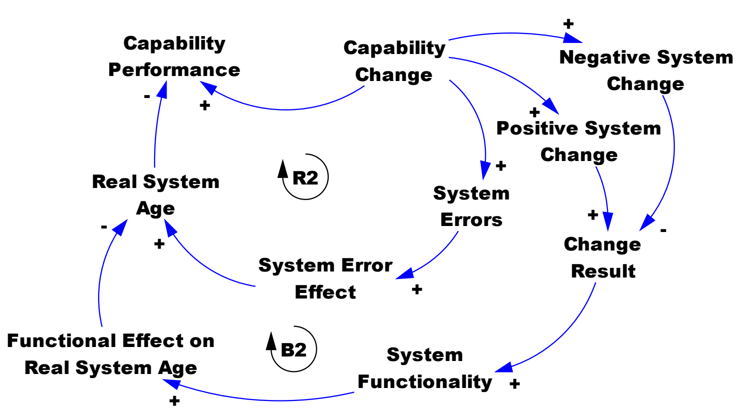


Figure 5: Functional Change to a System CLD

The literature has identified several critical non-functional attributes of systems that can affect the real system age of a DoD system and influence the decision to retire that system (Enos & Nilchiani, A Tale of Two Aircraft: How Non-Functional Attributes Impact a System's Lifecycle, 2017). This portion of the causal loop diagram decomposes system functionality into three components: *System Interoperability*, *System Versatility*, and *System Robustness*. A Change Result, whether positive or negative, has a positive relationship with each of these variables. In turn, these factors influence the *Functional Effect on Real System Age* in a similar manner; so an increase in *Change Result*, increase the *System Interoperability* and the *Functional Effect on Real System Age*. It is important to separate these three functional factors because each may have a slightly different effect on the real system age.

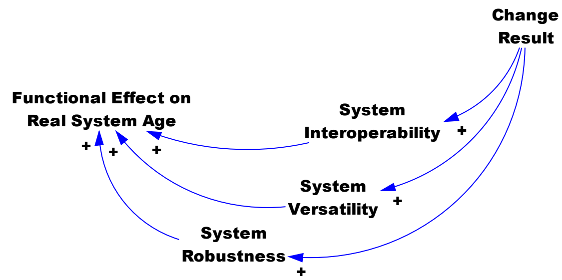


Figure 6: Functional Factors Effect CLD

## 4.3 Environmental Changes to a System

The final portion of the causal loop diagram captures both endogenous and exogenous aspects of environmental changes to the model. Figure 7 presents this portion of the casual loop diagram and shows how the environment also affects the *Change Result* and *System Real Age*. The endogenous portion of the feedback loop focuses on the *Adversary Changes* that increase *Adversary Capability*. An increase in *Adversary Capability* results in a *Negative Environmental Change* the decreases the *Environmental Change Results*. Although not preferred, exogenous variables also influence the model through the *Environmental Change* variable that can have either a *Positive Environmental Change* or a *Negative Environmental Change* that influence the *Environmental Change Results*. This result eventually affects the System Real Age of an engineered system.

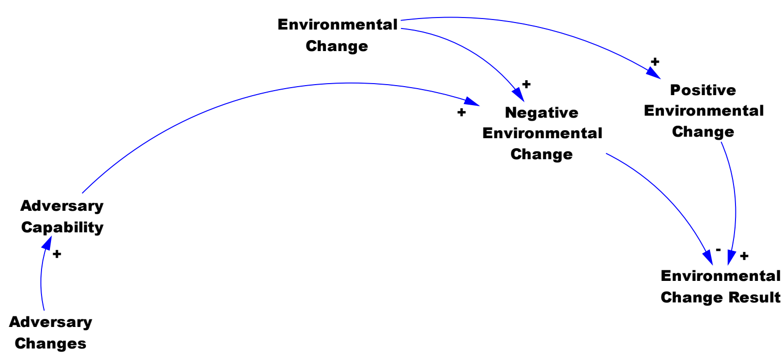


Figure 7: Environmental Factors CLD

## 4.4 Key Accumulations in the Model

The causal loop diagram provides a basis for a more detailed stock and flow diagram to capture the accumulations within the real system age model and eventually simulate the real system age for a system. This section presents three stock and flow diagrams for the key accumulations in the model to include the *Capability Performance*, *Real System Age*, and *System Errors* variables in the model. A limitation of this paper is that it does not present a functioning model of real system age; however, future work presents the opportunity to model, calibrate, and simulate the real system age of an engineered system over time. The future functioning model provides a means to analyze different policies for system upgrades and impacts of changes to the environmental factors that influence a system's real system age.

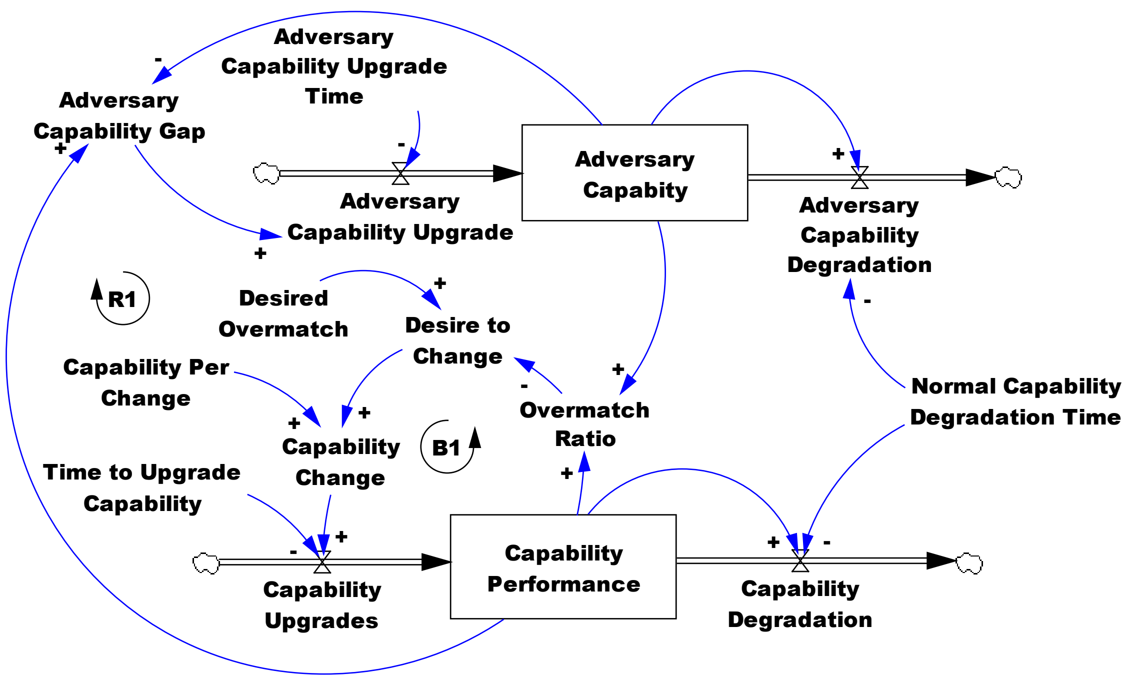


**Figure 8: Stock and Flow for Capability Performance**

Figure 8 presents the stock and flow model for the capability performance sub-model that depicts the structure behind the dynamic behavior of capability improvements. The two stocks for this portion of the model are *Capability Performance* and *Adversary Capability* that interact to determine the *Capability Gap*. On the DoD side of the model, the *Capability Gap* generates a *Desire to Change* and Results in *Capability Change*. A *Time to Upgrade Capability* variable provides the ability to calculate a flow, *Capability Upgrades* that increase the stock of *Capability Performance*. Over time, capabilities will normally decrease, and the *Capability Degradation* variable captures this aspect of performance. An important aspect of this portion of the model is the reliance on adversary capabilities to drive the need for upgrades to DoD capabilities. Like the DoD capabilities, *Adversary Capability* also has an inflow for

*Adversary Capability Upgrade* and outflow for *Adversary Capability Degradation*. To ensure this portion of the model remains endogenous, the DoD Capability Performance influences the *Adversary Capability Change* in a reinforcing feedback mechanism that generates the "arms race" behavior over time.

The next stock and flow diagram captures the real system age for an engineered system and the changes, both inflows and outflows from the stock that affect the real system age level. Additional analysis could include a comparison of the chronological age, that increases linearly as time goes on, and the real system age to determine if a system was nearing retirement. Figure 8 presents the stock and flow diagram for the *Real System Age* variable and the single flow of *Change to Real System Age*. As changes to the system could increase or decrease the real system age, the flow indicates that units of real system age can move in either direction. The *Normal System Aging Rate*, which represents the normal chronological aging of a system, affects the *Change to Real System Age*. Additionally, the real system age of an engineered system can be increased or decreased by the *Functional Effect on Real System Age*, with a negative relationship, or the *System Error Effect on Real System Age* with a positive relationship. So, an increase in the functional effect decreases the *Real System Age* while an increase in the system error effect increases the *Real System Age*.

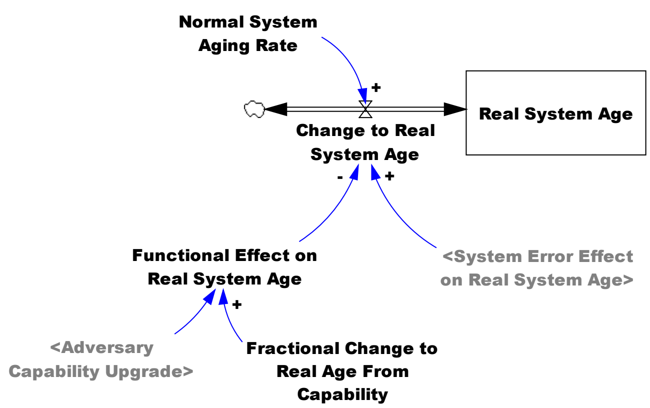


Figure 9: Stock and Flow for Real System Age

The next stock and flow diagram models the accumulation of errors in the system that results in an adverse effect on the real system age of an engineered system. First, the model captures the Error Introduction Rate that increases the *Unidentified System Error* in the system as a result of *Capability Change* to the system. System engineers will be able to identify a portion of these error, the *Identified System Errors*, over time and correct a smaller portion of these errors. The sum of the two classifications of errors, unidentified and identified, results in the total *System Error*, which can affect the system's performance. As the *System Error* variable increases beyond the *System Error Threshold,* it will begin to have an effect on the real system age.

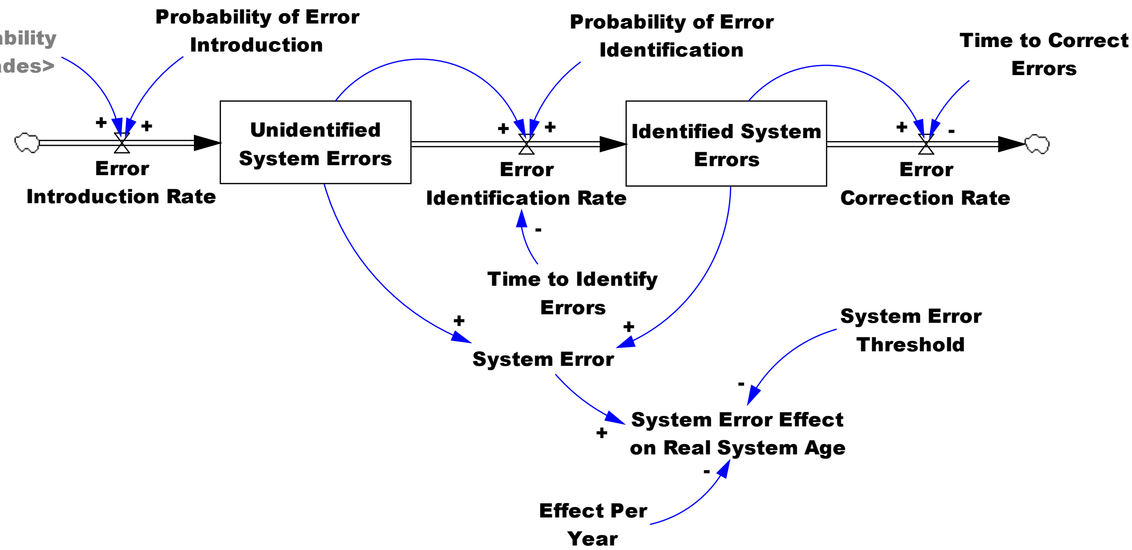


Figure 10: Stock and Flow for System Errors

The stock and flow models this paper present are the beginning of a modeling effort to capture the dynamic behavior of the real system age for engineered systems. Additional variables will be required for model completion and expanding the current model to include the environmental factors that affect the real system age of an engineered system. Upon completion of a functional model, the calibration effort can identify calibration variables and match the model output with historical data from DoD systems. With a calibrated model, further analysis can examine the potential approaches to managing the changes to DoD systems to determine what approach is best to mitigate the effect of aging on engineered systems.

## 4.5 Initial Model Output

The model simulated the capability performance of a DoD system over an extended life cycle to determine if system dynamics could provide a means to model the real system age over time. The model took two approaches to managing the capabilities over time. First, it examined a re-active approach by decreasing the *Desired Overmatch*. This meant that the DoD would be less likely to improve capabilities until an adversary greatly improved their own capabilities to a point that it threatened the DoD capability. The second approach took a more proactive approach to managing capabilities by increasing the *Desired Overmat*ch which would trigger more frequent *Capability Upgrades*. Figure 11 presents the output of the model for the *Capability Performance* and as expected, the proactive approach greatly improves the performance when compared to the reactive approach. However, this comes at a potential cost to the real system age as it has the potential to introduce errors into the system and increase the aging rate. Figure 12 presents the *System Errors* over time and there is a large increase between the two approaches. So, it appears that a pro-active approach improves performance, but comes at a cost.

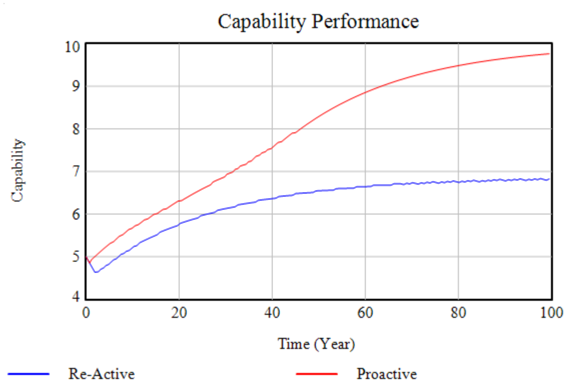


**Figure 11: Capability Performance over time**

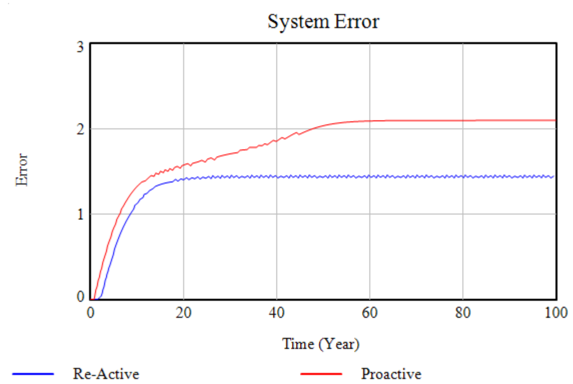


**Figure 12: System Errors over time**

The other variable to examine is the actual Real System Age for the system over time and the impact the two approaches have over time. Figure 13 presents the real system age over time for a reactive and proactive approach to managing the capability. Initially, these two approaches are almost the same; however, later in life, the proactive strategy decrease the real system age and would potentially prevent the retirement of the system. This is similar to the case of the B-52, in which several upgrades throughout its lifecycle have keep it flying well beyond its initial design life.

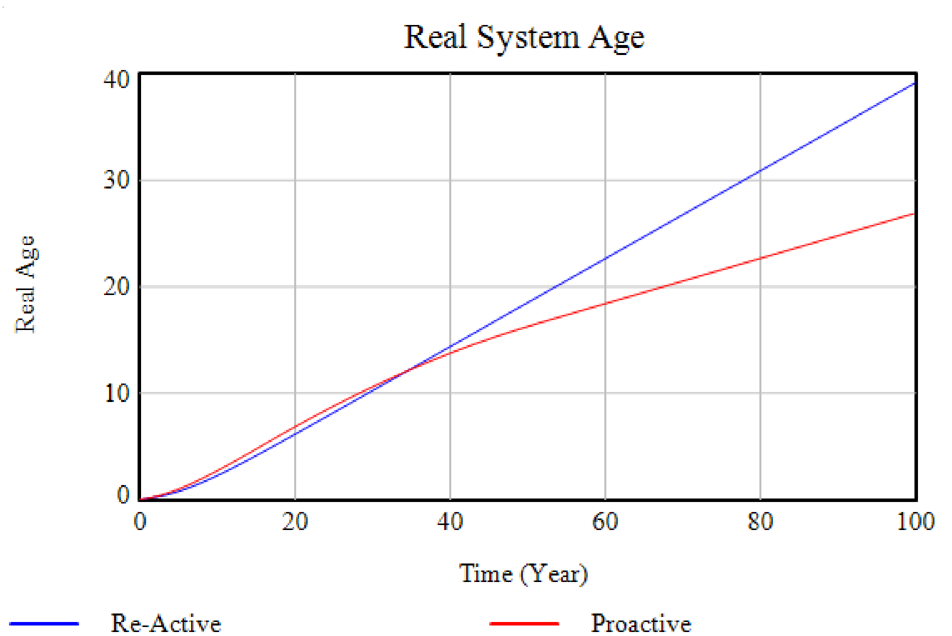


**Figure 13: Real System Age over time**

# 5 Conclusion and Future Work

The purpose of this paper is to present a basic model of the system structure behind the dynamic behavior of the real system age of an engineered system. The theory behind real system age indicates that system attributes and changes to a system can influence the real system age and affect the decision to retire a system. The paper summarizes the literature for system dynamics as well as a review of aging literature from biological systems, software systems, and the medical and healthcare fields. This literature provides a basis for understanding how the accumulation of errors in these systems leads to aging and the eventual degradation of system performance. The real system age takes the accumulation of errors into account through a stock and flow model of errors that eventually increase the aging rate of an engineered system. The paper also presents a causal loop diagram for the real system age and provides details on the various reinforcing and balancing feedback loops responsible for the behavior over time. In the final part of the paper, it presents several stock and flow diagrams that will be part of a functioning model to simulate the behavior over time.

The future work for this effort should focus on the modeling and simulation of a system's real system age over time. The first part of the future work should construct a functioning model of the real system age in order to simulate the behavior over time. The causal loop diagram in this paper provides the basis for this model and captures a majority of the variables that contribute to the real system age. Historical examples of DoD systems provide the a baseline real system age for engineered systems and contain the data required for model calibration. A functioning, calibrated model of real system age enables the analysis of possible policy alternatives for the DoD when managing the life of an engineered system. Additionally, a system dynamics model could provide the means to evaluate future changes to the system to determine how they affect the performance and the real system age of a DoD system.

The power of system dynamic models is in the ability of these models to evaluate future policies to identify the best alternative and prevent unintended consequences from delays and feedback in the system. A system dynamics model of the real system age enables the evaluation of several different approaches to managing the lifecycle of DoD systems. First, the model could evaluate an aggressive capability development policy in which the DoD focuses on maintaining a high level of overmatch over its adversaries. Second, it could vary the overmatch variable to determine if a less aggressive approach yields more longevity for engineered systems within the DoD. The model could also evaluate a more passive approach to capability management in which upgrades are only executed when absolutely necessary. Finally, it could examine how drastic environmental changes, both good and bad, impact the performance and real system age of DoD systems.

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