Assessment of Dynamic Maintenance Management

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(Abstract)

Today's technological systems are expected to perform at very high standards throughout their operational phase. The cost associated with unavailability of these systems is very high and especially with the defense systems or medical equipments which can directly affect human lives. The maintenance system plays an important role in achieving higher performance targets. In order to manage maintenance activities in more informed and rational manner, it is very important to understand the inherently complex and dynamic structure of the system. Traditionally maintenance policies are derived from reliability characteristics of individual components or sub-systems. This research makes an attempt to understand the system from the forest level and suggest better maintenance policies for achieving higher availability and lower system degradation. The leverage is gained from System Dynamics framework's ability to model complex systems and capture various feedback loops. The simulation results reveal that with the limited preventive maintenance capacity and within the given assumptions of the model, there exists and optimal preventive maintenance interval which is not the minimum. The simulation results also reflect that frequent preventive maintenance is required at higher load factors.

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1. Introduction

1.1 Introduction and context

The systems engineering field has identified maintainability and availability as important characteristics of any technological system. These parameters govern the cost and revenue components of the profit equation which directly or indirectly determines the usefulness of the system. Maintainability is a design parameter while availability is a result of implementing various systems management policies to the given technological system. The formulation and implementation of these policies is critical to achieve high system performance in terms of availability, reliability and total life cycle cost.

Today's technological systems, such as aircrafts, nuclear power plants, military systems and advanced medical equipment are characterized by a high level of complexity and total life cycle costs associated with these systems. The requirements of availability and reliability of such systems are very high (Smidt-Destombes, Heijden, Harten, 2003). These factors are also relevant for production systems as they determine throughput and quality of the product respectively (Davies, 1990).

In order to meet increasing performance standards, there is a growing emphasis on effectively utilizing the limited maintenance capacity to carry out preventive and corrective maintenance. Planning these activities beforehand and determining the resource requirements would help the managers reduce various delays associated with maintenance activities and hence reduce the overall life cycle costs. In order to plan and manage these maintenance activities, it is very important to understand the dynamics behind these activities and their impact on system performance.

Various models have been developed and policies have been proposed to improve systems' performance. These models were developed with the objective of improving system availability or improving system reliability or minimizing repair cost (Lam and Yeh, 1994, Yun and Bai, 1987, Menipaz, 1978) by varying the preventive maintenance interval (Chun, 1992, Dagpunar and Jack, 1994, Lie and Chun 1986) or by identifying the optimum replacement times (Nakagawa, 1984, Block, Langberg and Savits, 1993, Wang and Pham, 1999). These models implement various optimization and/or statistical models and are based on assumptions about the system structure (such as single unit or multiple unit, series or parallel), about maintenance effectiveness (such as perfect or imperfect (Makis and Jardane, 1991, 1993)), about the system failure distribution (such as weibull (Love and Guo (1996)), normal or exponential). The maintenance policies for single unit and multi unit defer because there exist economic dependence, failure dependence and structural dependence (Wang, 2002).

Perfect preventive maintenance means that the system is restored to good as new condition. Imperfect preventive maintenance restores the system to a condition that is between 'good as new' and 'bad as old'.

These models fail to account for the inherent system structure that generates particular failure pattern. For example in some cases it is assumed that the system failures are normally distributed. These failure distributions are usually determined based in the observation of failure pattern of the physical system. But it should be noted that while the system is in operations, some kind of maintenance policy is implemented which essentially generated the particular failure pattern. If the failure distribution is assumed based on the reliability characteristics of the component or a subsystem then there are some assumptions behind those calculations which are usually not accounted for while assuming the failure distribution for modeling purposes.

Van Der Duym Schouten (1996) pointed out that one of the reasons for lack of success in application of maintenance and replacement models is the simplicity of the models compared to the complex environment where the applications occur.

Also, most of the models that aim to determine the optimum preventive maintenance/replacement interval compare the different policies based on the time invested in preventive and corrective maintenance or based on the reliability characteristics of individual components or subsystems. They fail to identify the response of system to these policies and the impact of this response on the policy itself over the systems operational life cycle.

It is very important to account for these feedbacks in order to design a sound maintenance program.

1.2 Research Objective

The systems engineering discipline believes in the principle that system structure generates system behavior. Barry Richmond (1997) calls this phenomenon as 'System-as-Cause' thinking. This motivates us to model the structure of the system under consideration and identify the interrelationships among the various system components that generate the specific behavior over time. Systems engineering also fundamentally agrees that any problem can be modeled or viewed as the behavior manifested by the system over time.

The System Dynamics framework is an approach that is primarily used for system analysis and policy design. It is also sometimes called as the management laboratory. It enables us to model system structure and map non-linear causal interrelationships among the key elements and subsystems that comprise those elements. System Dynamics modeling also allows us to capture feedback structures that are inherent in the system.

The primary objective of this research is to model the maintenance system of a generic technology and to map the causal and non-linear relationships among the key variables in order to analyze the impact of various maintenance policies on systems' behavior. The resulting validated and verified model will provide us important insights into the system behavior and its causes. We would also attempt to analyze different policies by varying the controllable variables to study the system's response. This approach can help us understand the dynamics associated with maintenance functions and formulate the best possible policy for maintenance management of a technological system and simulate it in the virtual world to approximate the policy's response in the real world.

1.3 Problem Definition

It is observed and documented that over the operational phase of the life cycle, the technological system's performance deteriorates, costing more and more to manage the system. One of the reasons for system degradation deterioration might be the ineffective maintenance policies which might result from the lack of understanding of the underlying complex structure of the maintenance system.

This research focuses on accomplishing the following objectives –

- To study and analyze the dynamic behavior and the causal effects of various elements of maintenance policy on the system's economic and technical performance.
- To formulate, analyze and compare various policies to determine optimum level of maintenance parameters for improved system performance.

1.4 Research Motivation

Primary motivation for this research initiative is to understand the dynamic complexity of the maintenance functions and their impact of system performance. Identifying the factors that contribute to this complexity and analyzing the interactions among them can possibly help us make better decisions and save what is paid due to the poor management of technology. The outcome of this research can directly be used by decision makers to formulate various policies in the light of assumptions and constraints of the model. This research focuses only on maintenance system which is not a stand alone system. The sub-systems such as procurement management, material management, human resources and budgeting along with maintenance system form an integrated system or an enterprise. There exists a potential opportunity to analyze the impact of the structure of these sub-systems on the overall systems performance.

Many researchers have tried to address the issue of reliability degradation by mathematically modeling preventive maintenance schedule and replacement policies (Wang, 2002). But hardly any efforts have been made to analyze this issue from a systems perspective. Most of the mathematical models fail to capture the feedback structures that are undoubtedly inherent in any kind of system and have considerable impact on the performance of the system.

1.5 Contribution to the literature

This research basically integrates two different areas – System Dynamics and Maintenance Management. Efforts have been made to gain leverage from the ability of System Dynamics to model complex and dynamic systems, to model the maintenance management function by identifying and understanding the relationships between various performance governing factors like preventive maintenance, corrective maintenance, system degradation, cumulative system availability and maintenance cost.

This research would contribute to the System Dynamics knowledgebase by illustrating the use of System Dynamics modeling and simulation framework for the planning and management of preventive and corrective maintenance activities. The insights obtained from this research in the field of maintenance management would help in identifying the fundamental causal and feedback relationships that could be used for further research in this field for improving the system's performance dynamically. This research could also serve as a foundation for developing a detailed model that would help the acquisition community in planning new technology procurement.

1.6 Impact statement

In the real world, the decisions are made based on the decision maker's perception of how the system works. Understanding the underlying structure of the system and interactions that generate the complex behavior can facilitate decision makers in taking effective and proactive decisions in short time and at lower cost.

The model such as in this research can be used as a tool with which the decision variables that the decision maker has control over such as the preventive maintenance interval, maintenance capacity and load factor, could be varied to observe in simulation world how the system would potentially behave in real world. This is the faster and more economic method to test the policy without disturbing the actual physical system. The use of this model would also help the planners and decision makers to achieve top management's confidence and buy-in in their policies.

The technology procurement community can also be benefited from this research. This model can be used in the conceptual design phase while specifying the maintainability criterion based on the anticipated resource availability during operations phase.

1.7 Overview of System Dynamics Modeling Methodology

The systems dynamics field provides a framework for modeling complex and dynamic systems. Considering the complexity and dynamics associated with the problem that has been dealt in this research, System Dynamics was considered to be an appropriate tool for modeling the system structure.

Modeling, as a part of the learning process, is iterative and continual process of formulating hypothesis, testing, and revision of both formal and mental models (Sterman, 2000).

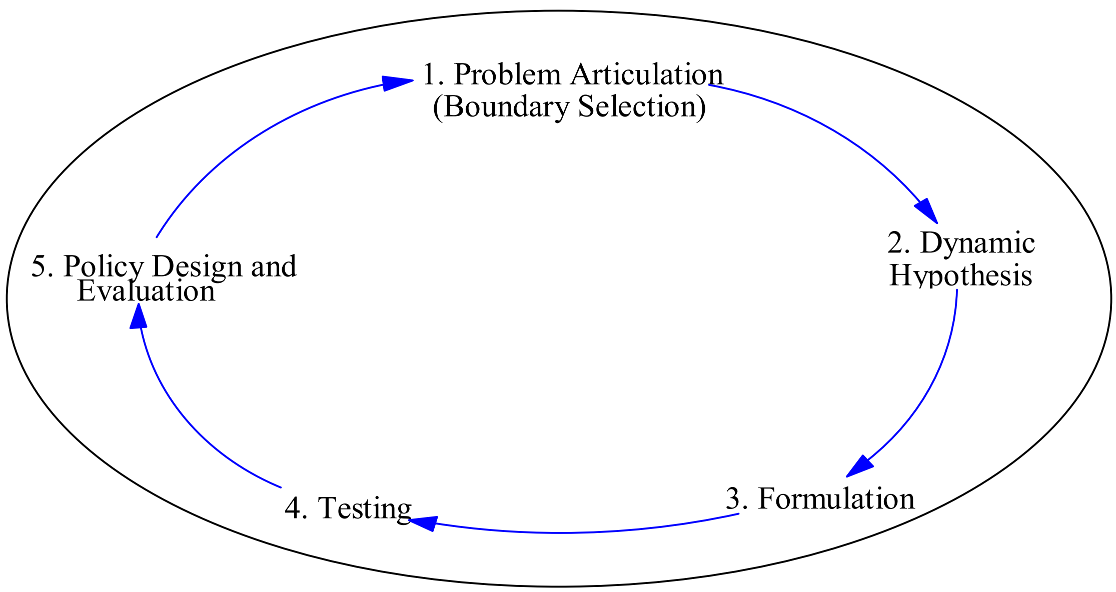


Figure 1-1: The Iterative Modeling Process

Problem Articulation

This is the most important step in modeling process. In this phase, the problem is identified, defined and clearly stated. In order to characterize the problem dynamically, behavior of the key variables is plotted over time to illustrate how the problem arose over time and how it might evolve in future. Also the time horizon for the problem under study is defined so that the cause and effects that are distant in time and space are not missed.

Formulation of Dynamic Hypothesis

A dynamic hypothesis is a working theory of how the problem arose. The hypothesis is called dynamic because it must characterize the problem in terms of the underlying feedback and stock and flows structures of the system and it must manifest itself over time. An endogenous explanation should be provided to explain the dynamics of the system. Endogenous means that the dynamics is generated within the system as a result of interactions and feedback among various system elements. To manage the model and prevent the modeling team from losing the focus on the problem, the model boundary diagram or subsystem diagram should be build. This helps in defining the boundaries of our model and mapping the model based on the subsystem considerations. Next, causal loop diagrams and stock and flows structures are developed to map the causal links among the variables.

Formulation of Simulation Model

Our inability to infer correctly the dynamics of the complex system requires us to formulate the conceptual model that we have developed and simulate it using the software tools. Formalization helps us to recognize the vague concepts and resolve contradictions that were overseen during the conceptual phase. This also helps us improve our understanding of the system. Formulation can be based on the data collected from the field and the inputs provide by the subject matter experts. Various tests can be performed during the formulation phase to identify the flaws in the proposed equations.

Testing

Every variable must correspond to a meaningful concept of the real world. Testing partially involves the comparison of the model output with the real world behavior of the system. Models must also be tested for the extreme conditions that might not even occur in the real world. Extreme condition tests along with few other tests are critical tools to uncover the flaws in the model.

Policy Design and Evaluation

The tested model can be used for policy design and evaluation. One of the ways to design and test the policy is to change the values of some of the variables and see if the system performance improves. Most of the times, the high leverage policies involve changing some of the feedback structures or time delays or the stock and flow structures. The robustness of the policies and their sensitivity to uncertainties in model parameters and structure must be assessed under a wide range of alternative scenarios. The interactions of different policies must also be considered: because the real systems are highly non-linear, the impact of combination policies is usually not the sum of their impacts alone. These policies interact with each other may reinforce one another or have an opposite effect.

1.8 Organization of thesis

This thesis is organized in five chapters, including the first chapter, which basically talks about the motivation behind this research endeavor and the contribution of this research. Chapter 2 provides the overview of the research work that has already been documented in the field of system dynamics, and maintenance and reliability. In this chapter the basic concepts of system dynamics such as various fundamental modes of behavior and derived modes are discussed. The modeling process and evolution of the model are described in Chapter 3. Chapter 4 presents the results obtained from the simulation, testing, validation and verification, and sensitivity analysis. And the last chapter concludes with the overview of the results, policy suggestions and evaluation and a discussion on the challenges for the future.

2. Literature Review

2.1 Introduction

A system is defined as any set of interrelated components working together towards some common objective (Blanchard and Fabrycky, 1998). A System is also defined as a group of interrelated, interacting, or interdependent constituents forming a complex whole (Webster's II, new Riverside, 1988). With increasing complexity of the systems, the importance of systems engineering and management field is highly embraced. Forrester (1961) defines systems engineering as the formal awareness of the interactions between the parts or components of a system.

Traditionally the systems engineering concepts have been applied to engineering problems and systems. But with increasing complexity of management systems, the interactions and interdependence of the management system components are becoming important considerations in decision making process. A framework developed by Forrester in 1961 called Industrial Dynamics facilitates the integration of various functional areas of management such as marketing, production, accounting, research and development, and capital investment. Basically Industrial Dynamics addresses the dynamically complex behavior of the industrial organizations (Forrester, 1961).

2.2 System Dynamics Concepts

Jay W Forrester, who was associated with MIT Sloan School of Management in 1956, pioneered the field of Industrial Dynamics. It was initially used to study industrial management problems and was gradually embraced by other disciplines such as urban planning, economics, sociology, traffic engineering and medicine. As the field matured through research and applications it evolved into System Dynamics.

With the increasing complexities of the systems, we require more than technical tools to create, test, validate and verify the mathematical models and its usefulness. System dynamics is based on the theory of non-linear dynamics and feedback control developed in mathematics, physics and engineering. It provides us a framework to model complex systems and embedded feedback structures between various elements. Thus System Dynamics can be used to simulate real world systems, obviously with some assumptions, to enhance our understanding of the complex systems, the dynamic complexity and the sources of policy resistance in order to design highly effective policies.

2.2.1 Counter intuitive behavior and policy resistance

> *"And it all fall out as in a complication of diseases, that by applying a remedy to one sore, you will provoke another; and that which removes the one ill symptom produces another....."*
>
> \- Sir Thomas More

This is a very commonly observed phenomenon that when a decision is taken based on our understanding of the system, anticipating a favorable outcome, the system might react in the unexpected fashion resulting into totally unintended consequences. In social systems, the environment which might also include people, technological systems, environmental systems seek to restore the disturbed balance causing totally unanticipated behavior. Forrester calls such phenomenon as 'Counter intuitive behavior'. In the world of corporate management it is called as policy resistance. Meadows (1982) defines policy resistance as the tendency for interventions to be delayed, diluted, or defeated by the response of the system to the intervention itself.

Policy resistance is a result of our tendency to interpret experience as a series of events. Usually every effect is attributed to some cause. This event oriented view leads to an event oriented approach to problem solving. Often the failure to understand the entire range of feedbacks operating in the system and presumption that the cause and effects are closely linked in time and space and failure to take into account the delays that are inherent in the system are the main causes of policy resistance. (Sterman, 2000)

2.2.2 Dynamic complexity

Usually, complexity is defined in terms of a number of components in a system or the number of combinations one must consider in making a decision. This is called as combinatorial complexity. Dynamic complexity can arise even in simple systems with low combinatorial complexity (Sterman, 2000). Dynamic complexity results from the combination of interactions among system elements over time. Even the systems with low combinatorial complexity can exhibit high level of dynamic complexity. The complex behavior is observed in the systems that are dynamic, tightly coupled, governed by feedback, non-linear, adaptive, counterintuitive and policy resistant.

2.2.3 Feedback

Feedback is an important concept in the field System Dynamics. In complex systems nothing is stand alone, everything is connected to everything else. They interact with each other through feedbacks. In fact the most complex behaviors usually arise from the interactions among the components of the system, not from the complexity of the component themselves.

Consider a system of two elements that affect each other. The change in one element will affect the other. This effect will act as a cause and will in turn affect the first element; this is a simple example of feedback. This grows in its complexity as the number of elements and the interactions between them increases. Feedback processes along with the stock and flow structures, time delays and nonlinearities determine the dynamics of the system (Sterman, 2000). To analyze behavior of the complex system it has to be modeled and simulated using digital computers.

There are two basic types of feedback loops – positive (self reinforcing) loops and negative (balancing) loops. As the name suggests, positive loops reinforces the effect to grow exponentially and negative loop approaches the equilibrium state by continuously reducing the gap between current state of the system and the equilibrium state.

2.2.4 Causal loop diagrams

Feedback is one of the core concepts of system dynamics. It captures interaction among the elements. Causal loop diagrams are used for representing the feedback structure of systems. Causal loop diagrams consist of two or more causal links that connect the various elements in the model. Each link is assigned a polarity, as shown in the figure below, to indicate the direction of change of the affected element with respect to the causing element.

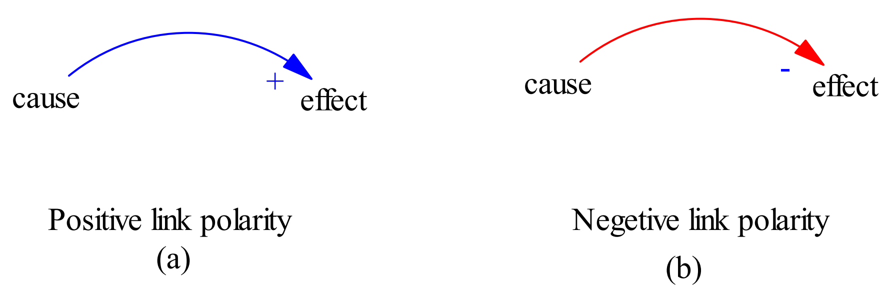


Figure 2-1 : Polarity

A positive link means that is the cause increases the effect increases above what it would have been and is the cause decreases the effect decreases below what it would otherwise have been.

A negative link means that is the cause increases the effect decreases below what it would have been and is the cause decreases the effect increases above what it would otherwise have been.

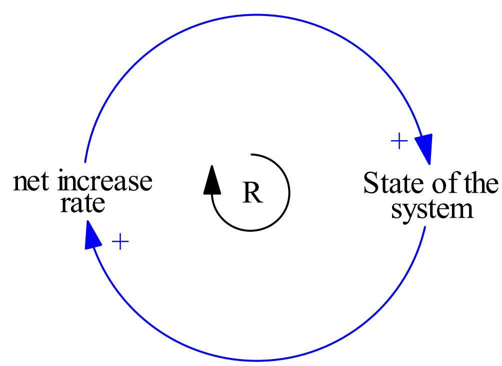
It is important to note that link polarities describe the structure of the system and not the behavior of the variables.

2.2.5 Fundamental modes of Dynamic Behavior

There are three fundamental modes of behavior and three derived modes of behavior. Each of these modes is generated from a particular type of system structure, which included a positive loop, a negative loop and balancing loops with delays.

Exponential Growth

Exponential growth results from positive feedback loop.



Positive (self reinforcing) loop

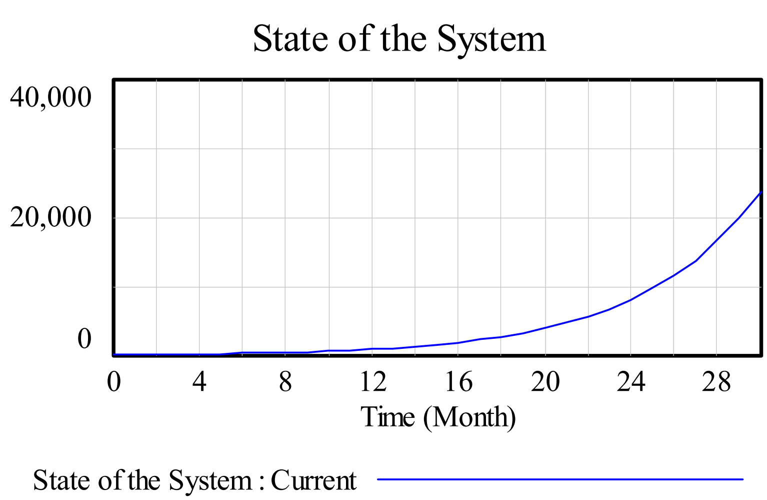
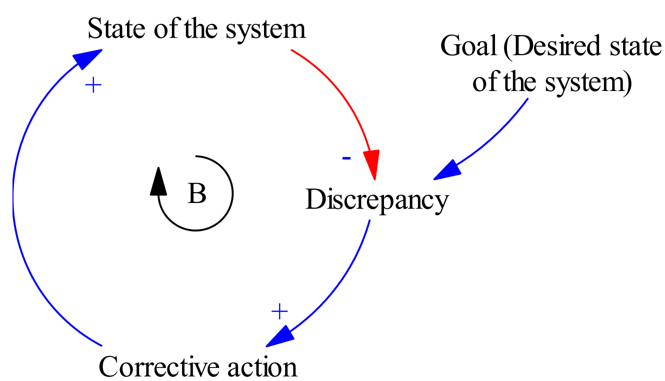


Figure 2-2 : Positive reinforcing behavior

The above loop shows the general structure of a positive feedback loop. With increase in state of the system net increase rate increases, this further increases the state of the system. This causes the state of the system to grow exponentially as shown in the graph above. The paradigm cases are the population growth and compound interest. Larger the population larger will be the net birth rate. This will add to the current population and will further increase the net birth rate.

Goal seeking

Goal seeking behavior arises from negative feedback loop. Negative loops seek balance, equilibrium and stasis. General structure of the negative loop is shown below.



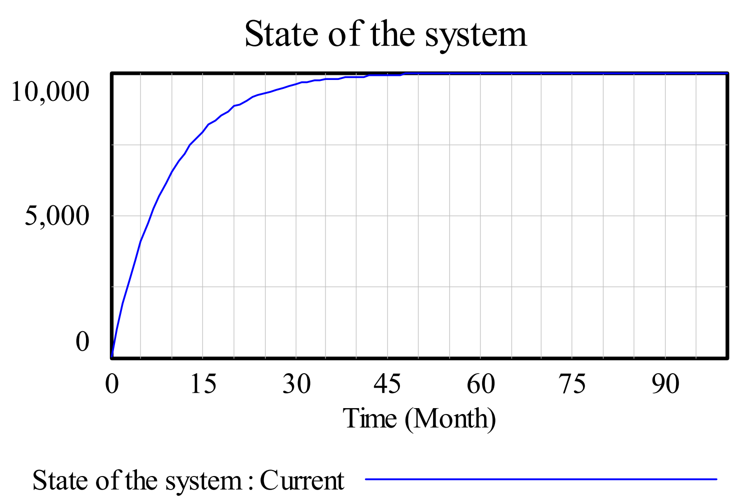
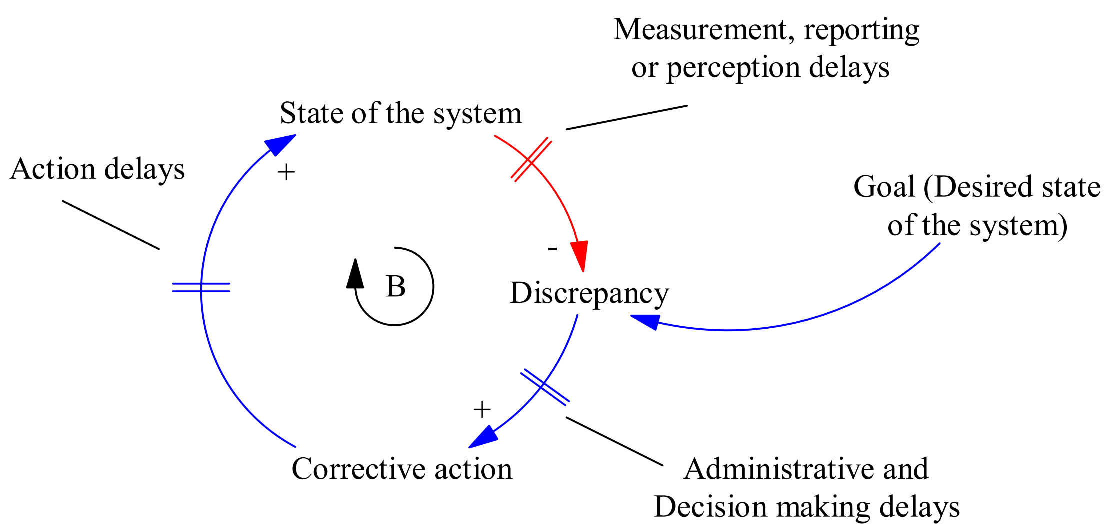


Figure 2-3 : Goal seeking behavior

The above causal loop diagram shows the general structure of a negative (balancing) feedback loop. In this type of structure the state of the system is compared with the goal or desired state. The corrective action is taken in proportion to the discrepancy between the current and desired state. Some systems have explicit goals while some have implicit goals. A simple example of balancing feedback system with explicit goal can be the inventory system. A company has a policy to maintain some minimum level of raw material inventory in order to sustain the market fluctuations. If the inventory drops below this minimum level, more parts are procured. Lot size of the new procurement depends on the difference between minimum level and the current level of inventory.

Oscillation

Oscillations are observed very frequently in dynamic systems. Oscillations arise when significant time delays exist in the negative loop. These time delays cause corrective actions to continue even beyond the goal and by over adjusting the system it triggers the corrective action in other direction.



Oscillations (Negative loop with delays)

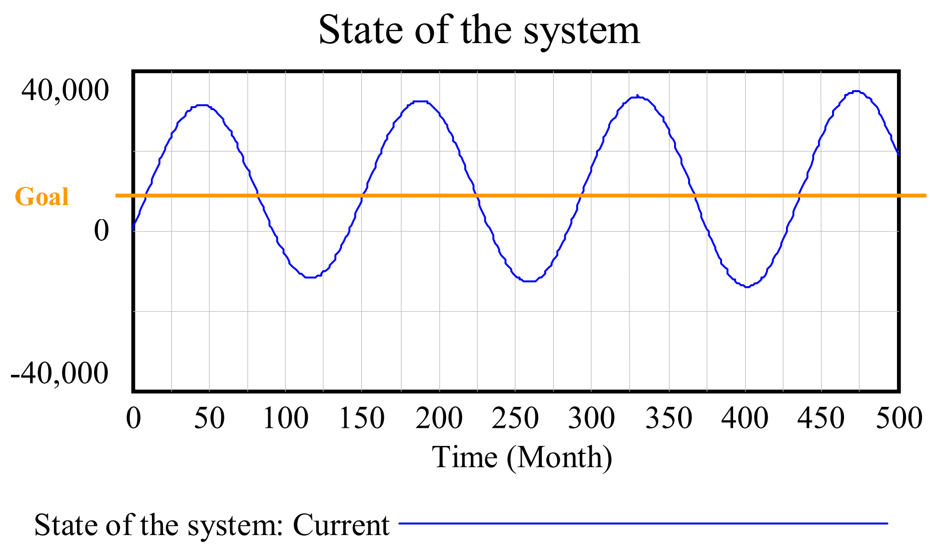


Figure 2-4 : Oscillations

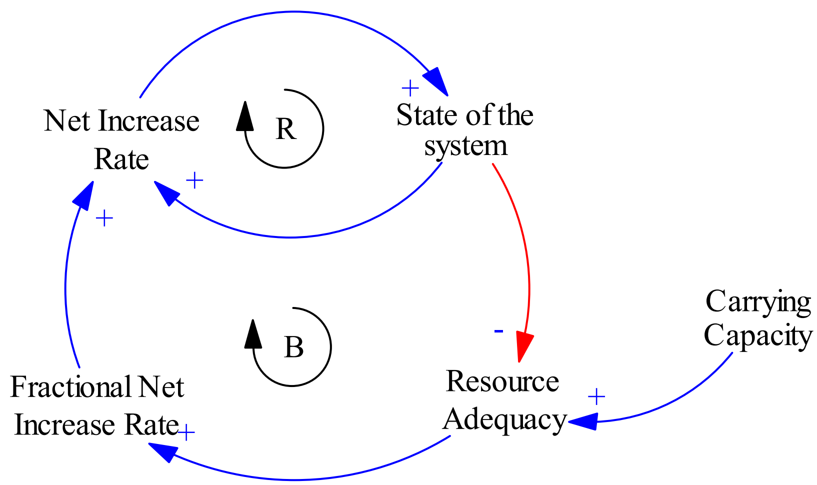
As shown in the causal loop diagram above, delays can be of different types – administrative, reporting or perception delays, administrative or decision making delays and action delays. With increase in sales, a manufacturing organization increases the utilization of its existing facility. Due to production delays, the system gets over-adjusted. Higher utilization results in the higher inventory and until this higher inventory gets reported to the management, it keeps on building. The higher inventory levels require management to take corrective action in reverse direction by decreasing the utilization and involve some decision making time delays. This cycle repeats causing the capacity utilization and so the inventory level to oscillate about the mean.

2.2.6 Interactions of the fundamental modes

Non- linear interaction of the fundamental modes results into some typical behaviors that are discussed below.

S Shaped Growth

S shape growth can be observed as a result of non-linear interaction on a positive and a negative loop. This is also a commonly observed behavior in complex and dynamic systems. At first the growth is exponential in nature but then it gradually slows down until the equilibrium position is reached. In order to generate S shaped growth, a system should not include any time delays and the carrying capacity must be fixed. The causal loop structure below shows a typical structure that generates S shaped growth.



S shaped growth structure

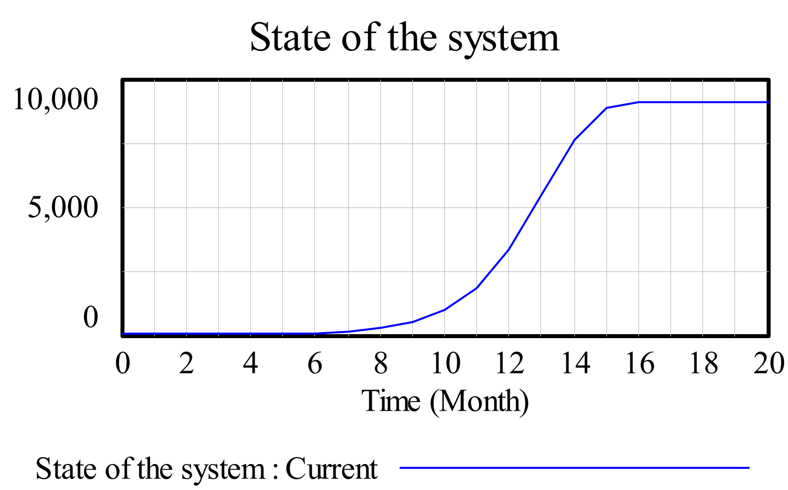
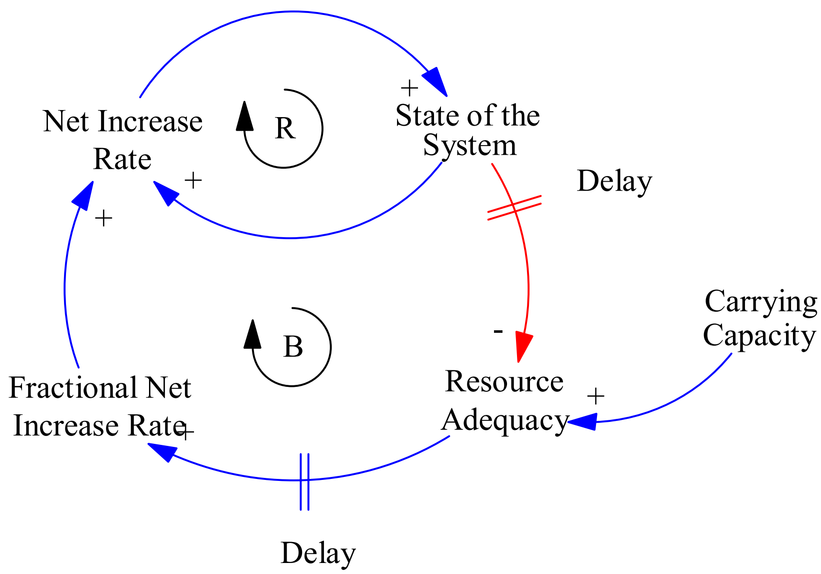


Figure 2-5 : S shaped growth

S shaped growth with overshoot

Existence of time delay in the negative loop of the S shaped growth structure will result into overshoot and oscillations about the equilibrium.



S shaped growth with overshoot

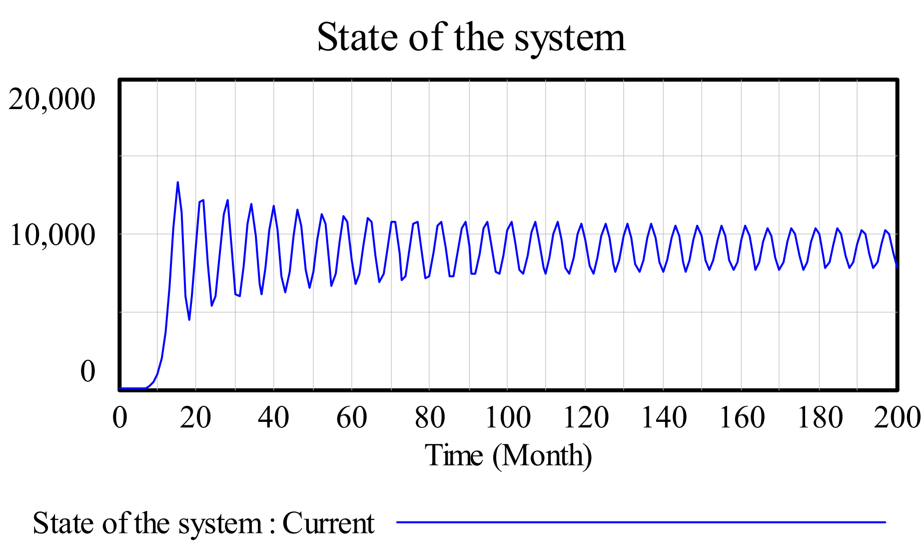


Figure 2-6 : S shaped growth with overshoot and oscillations

Overshoot and Collapse

One of the assumptions for S shaped growth is fixed carrying capacity. If we relax this assumption and try to model it by adding a balancing loop as shown in the causal loop diagram below, we get 'overshoot and collapse' behavior.

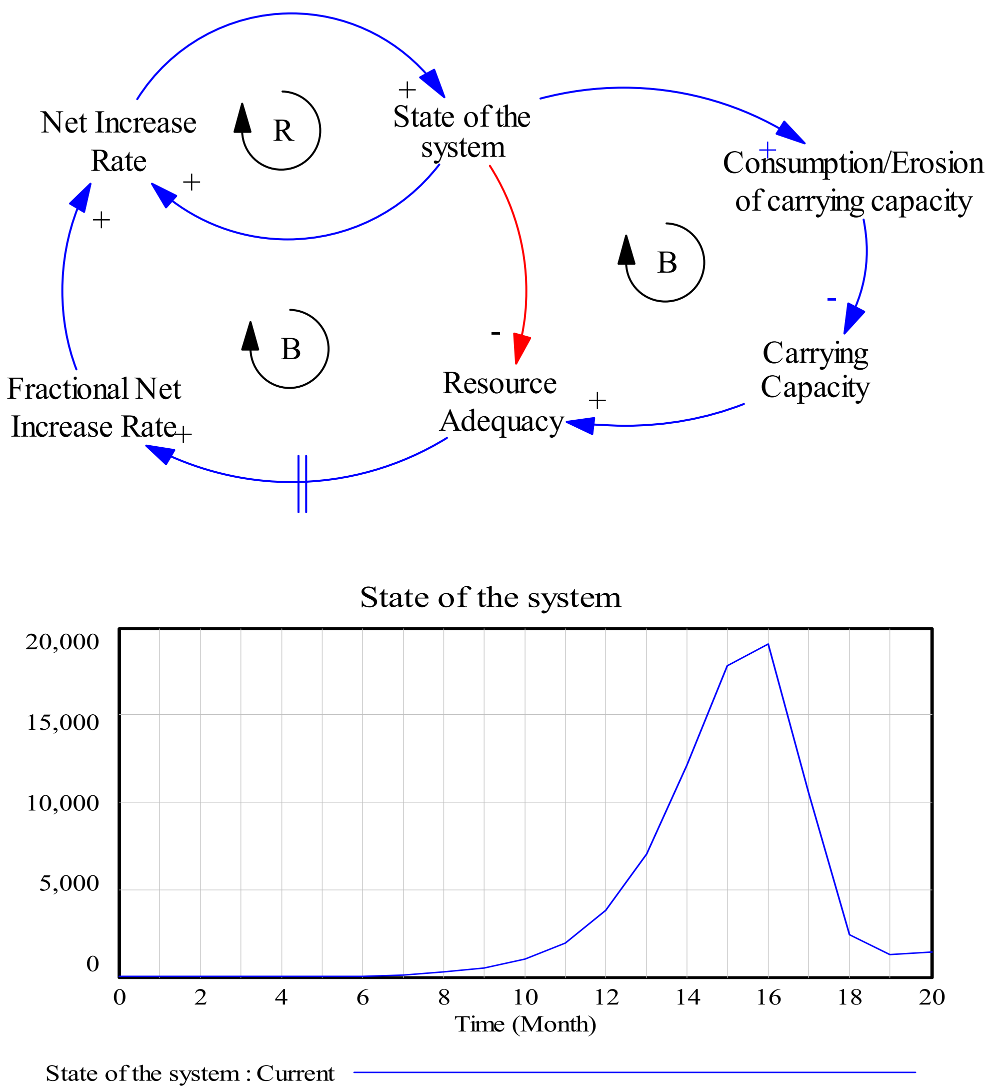


Figure 2-7: Overshoot and collapse

Other modes of behavior

Apart from the above explained behaviors there are few other modes of behavior such as stasis or equilibrium, randomness and chaos. Many variables appear to vary randomly. When we say that some variable is varying randomly, we are actually revealing our limitation of not knowing the reason for these variations. Chaos is a form of oscillation. But unlike limit cycles, chaotic systems exhibit irregular oscillations, never exactly repeating. External shocks hardly have any contribution in the generation of chaotic behavior. It occurs primarily due to endogenous interactions among the system components.

2.2.7 Stock and Flow diagram

Causal loops are useful to represent the interdependencies and feedback processes and to capture mental models at the beginning of the modeling process but they lack the ability to capture the stock and flow structure of the systems. Following diagram shows the general structure of a stock and flow.

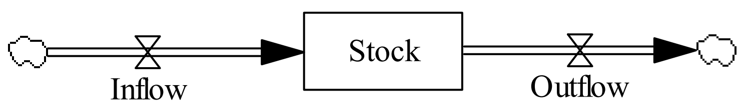


Figure 2-8 : General structure of a Stock and Flow

Here stock represents state of the system and flows affect the rate at which state of the system, stock, changes. Clouds at the origin of inflow arrow and at the end of the outflow arrow represent the source and sink respectively. Stocks basically generate the information on which decisions and actions are based.

Mathematical representation of Stocks and Flows

Stocks are accumulations. Stock can be considered as an accumulation of water in a bathtub. Inflows and outflows represent the rate at which water is filled into the tub and is drained out of the tub respectively.

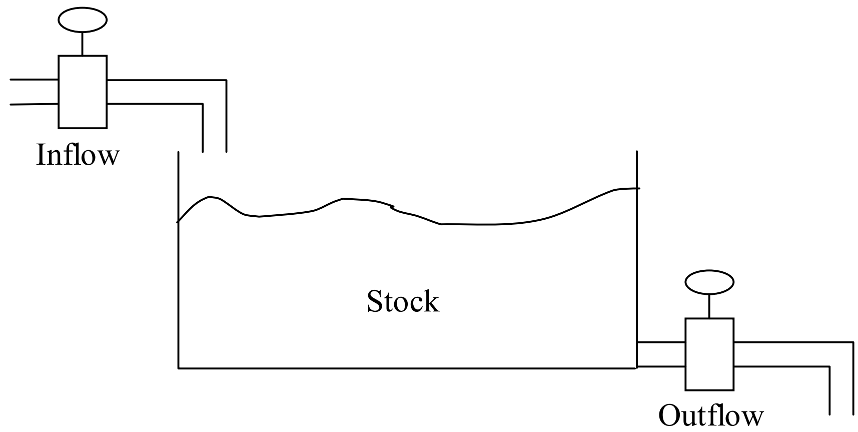


Figure 2-9 : Hydraulic metaphor of stock and flow

Mathematically equations for the stock element can be formulated as follows -

$$Stock(t) = \int [Inflow(s) - Outflow(s)]ds + Stock(t_0)$$

Thus, the value of stock at time t is the sum of the value of stock at time t_0 and the integral of difference between inflow and outflow rates from t_0 to t. In other words, we can also state that the rate of change in stock at any point in time is equal to the difference between inflow and outflow at that point.

2.2.8 Mental models

Mental models are the filter through which we perceive the world. Mental models are developed over time about the network of cause and effects that describe how the system operates. They are iteratively updated through our experience of the real world. They also determine the way we think. In fact we base our decisions on our mental models (Forrester, 1961).

Assumptions and models described by various researchers in their literature, in the field of maintenance policy design, can be assumed to reflect their mental models. In this research endeavor an attempt has been make to capture these mental models and some other logical relationships though our own perception of the system to model the system structure.

2.3 Maintenance, Reliability and System Failure

In some systems especially in defense systems, power plants and other continuously operated complex systems, it is extremely important to avoid failure during the operation as it can be dangerous or disastrous. Also given the huge cost associated with these systems and their importance for the organizational performance, availability and degradation of these systems over its operational phase is extremely important. Lee, Jay, Kramer and Bruce (1993) identified that the economic impact of machine availability, reliability as well as corrective maintenance costs are demanding considerable improvement in maintenance techniques and operations to monitor machine degradation and defect faults in the production systems

In order to improve system availability and reliability, various maintenance policies have been proposed based on different assumptions and considerations. These maintenance policies could be broadly divided into age dependent preventive maintenance policies, periodic replacement policies, repair cost limit policies, repair time limit policies, sequential preventive maintenance policies, repair number counting policies and failure limit policies (Wang, 2002).

According to Wang (2002), for most of the systems described above, periodic preventive maintenance policy is more practical than the age dependent policy. Christer and Lee (1997) mentions Navy's preference for constant inspection period due to its pragmatism, Most of the preventive maintenance policies focus on optimum replacement time at component or subsystem level. Also minimizing maintenance cost (Juang and Anderson, 2004) is another optimization criterion used by the researchers but they ignore availability performance of the system. Wang (2002) also pointed out that most of the literature on maintenance theory neglects the maintenance time which makes availability modeling impossible or unrealistic.

System maintenance can be divided into three main categories preventive maintenance, predictive maintenance and reactive maintenance. Preventive and predictive maintenance are the proactive strategies for avoiding equipment breakdowns (Swanson, 2001). The preventive and predictive maintenance are very similar in concept with some differences in the criterion for determining the need for specific maintenance activities (Swanson, 2001). According to military standard (MIL-STD-721B), preventive maintenance represents all the actions performed in order to retain an item in a specified condition by providing systematic inspection, detection and prevention of incipient failures. According to the same standards, corrective maintenance represents all the actions performed as a result of failure (Wang, 2002).

The state of a system can be divided into three states – good upstate, degraded upstate or down state. The term upstate is used to indicate that the system is in operation. There is a tolerance limit on degradation dictated by the application and structure of the system. As the name indicates, predictive maintenance determines the existing system state and decided whether the maintenance should be performed or not. If the system is found in intolerably degraded state then predictive maintenance is initiated. Though this type of maintenance generates additional work at the beginning it will avoid future system failures and reduce failure intensity. The amount of work generated by predictive maintenance increases with time, levels off and then begins to decline (Wheaton, 1997).

Chan and Shaw (1993) developed a model for determining preventive maintenance schedules for a general repairable system in which they state that the failure rate depends on age and on the number of preventive maintenance (PM) activities. The system failure rate can be reduced with each preventive maintenance instance but preventive maintenance can also change the speed of deterioration. Kim, Djamaludin and Murthy (2004) state that the system degradation is dependent on age and usage of the system. Preventive maintenance controls the degradation. Hence it is important to determine the optimal preventive maintenance schedule. Zhao (2003) states that equal time intervals between preventive maintenance activities will provide decreasing reliabilities.

Another factor that contributes to the failure rate is the effective age of the system. The age of the system can be considered as a relative factor since it differs from the systems chronological age because of the factors such as environmental and operational conditions in which it operates (Martorell, Sanchez and Serradell, 1999). For example, consider that a system is expected to break down after time T when it is operated for n hours per day. If we operate it for more than n hours per day, it will break before time T. This means its effective operational age is increasing at higher rate. This relationship between the age and system failure rate is also validated by Juang and Anderson (2004).

Considering the criticality of the reliability factor, managers prefer the preventive maintenance (PM) policies that are based on an acceptable reliability level. It is also very important for decision makers to proactively allocate resources for the future preventive maintenance activities. In order to allocate these resources effectively and efficiently, analyzing the relation between preventive maintenance and system performance over time is very important. Zhao (2003) states that the preventive maintenance cost and its effect in general have a non-linear relationship. In other words the cost per unit time for PM may increase rapidly when the effect is over a critical level.

Irrespective of the policy we adopt, system failures are unavoidable. We can reduce their frequency and intensity but can not assure their non-occurrence.

Corrective maintenance is initiated as a result of system failure to restore the state of the system to acceptable operating condition. Corrective maintenance activities are the most demanding activities in terms of resources. While considering the cost, Lofsten (1999), assumes that the expected corrective maintenance cost increases with time elapsed since the last preventive maintenance service.

Also time consumed by the maintenance activities vary with their nature. Preventive maintenance requires less time as compared to the corrective maintenance because of the unexpected and random events associated with system failure. Corrective maintenance can also cause secondary damage to other subsystems in the whole system (Bahrami, Prince and Mathew, 2000). Scheduled preventive maintenance work will require less time since the breakdown work will take three to five times as long to complete, and often as high as 10 times as long (Wheaton, 1997).

Tsai, Wang and Tsai (2004) uses system availability maximization as a performance criterion for scheduling periodic preventive maintenance. The preventive maintenance is assumed to combine three typical preventive maintenance actions; service, repair and replacement. Typically preventive maintenance time involves the access time, inspection and diagnosis time, repair/replacement time and verification and alignment time. Corrective maintenance includes supply delay and maintenance delay in addition to the above time factors. According to the model developed by Tsai, Wang and Tsai (2004) the corrective and preventive maintenance times determine the preventive maintenance interval. Also the reliability characteristics of individual subsystems are used to determine the optimum preventive maintenance interval for the total system.

2.4 Maintenance management and policies

Maintenance management refers to the application of the appropriate planning, organization and staffing, program implementation and control methods to the maintenance activity. Often, decision making is concerned with optimal allocation of resources to various activities with the final aim of lowering the operating costs by increasing reliability, availability, quality and safety. Maintenance is seen as a strategic functional area which has the potential to reduce the overall cost while improving the quality, productivity or availability and reliability. Various approaches have been proposed with different criterion to formulate the maintenance policies with the common objective of optimizing the system performance. Some of these maintenance methodologies are Condition Based Maintenance, Reliability Centered Maintenance and Total Productive Maintenance.

Condition based maintenance

The fundamental concept behind CBM is if the condition of the system can be monitored continuously or intermittently it will be possible to carry out preventive maintenance only when the system failure is imminent. This approach will prevent premature replacement of system components.

Reliability centered maintenance

RCM methodology is used to determine the kind of maintenance that is best suitable for a particular type of system or equipment. Various types of failure mode analyses specific to the system under consideration have to be performed to determine the kind of maintenance and the frequency of the maintenance. This type of analysis is quite intense and requires commitment and efforts. It is also costly and lengthy and has to be implemented to selective systems or subsystems.

Total Productive Maintenance

TPM is an integrated, top down, system oriented, life cycle approach to maintenance with the objective of maximizing productivity (Blanchard, 2004).

It focuses on improving system functionality and maintainability with the objective of minimizing maintenance downtime and requirements for resources, improving productivity and reducing life cycle cost. It also provides management framework for maintenance activities with a motivation for continuous improvement in maintenance.

These methods are often time consuming to implement and only valid for a special class of equipment or a specific industry (Pintelon and Waeyenbergh, 1999, cited by Waeyenbergh and Pintelon, 2003).

OSCAM – Operating and Support Cost Analysis Model

It is a joint US/UK program providing the rapid assessment of O & S costs of high cost capital assets and their component systems. This program includes System Dynamic models to represent the interrelationship between business processes that drive costs and management policies in order to assess the impact of alternative maintenance strategies and operating policies on the life cycle cost and availability of the system (OCSAM website, 2003).

OSCAM program was initiated in 1996 by the Naval Center for Cost Analysis (NCCA) to improve the Navy's operating and support cost estimation capabilities. The models developed under this program were used as backbone to develop the customized models for Air and Land Defense Systems.

3. The Model

Models are developed to facilitate the solving of real world problems. Modeling is also a part of the learning process. It is an iterative, continual process of formulating hypotheses, testing and revision, of both formal and mental models (Sterman 2000). Modeling is not an individual effort. It requires active involvement of the decision makers and the individuals who are familiar with the system. Inputs from these subject matter experts ensure the integrity of the model structure with the actual system structure. The modeled interrelationships among variables depict mental models of the decision makers on which the decisions are based in the real world.

Modeling activity has to follow a systematic step by step approach else our efforts can very easily digress from the main problem under consideration. Various researchers have organized the modeling activities varying from three to seven different stages each using a different set of arguments. The table below summarizes and maps the steps prescribed by various researchers.

Randers(1980)	**Richardson and Pugh (1981)**	**Roberts et al. (1983)**	**Wolstenholme (1990)**	**Sterman (2000)**
Conceptualization	Problem definition	Problem definition	Diagram construction and analysis	Problem articulation
	System conceptualization	System conceptualization		Dynamic Hypothesis
Formulation	Model formulation	Model representation	Simulation phase(stage 1)	Formulation
Testing	Analysis and model behavior	Model behavior		Testing
	Model evaluation	Model evaluation		
Implementation	Policy analysis	Policy analysis and model use	Simulation phase(stage 2)	Policy formulation and evaluation
	Model use			

Source: Luna Reyes and Anderson, 2003

Table 3-1: Comparison of various modeling approaches

Although the way of grouping these activities vary, the activities considered within different stages remain fairly constant across them. For this research, in order to build the model we follow the steps prescribed in Business Dynamics by Sterman (2000). Following sections explain in detail the steps taken toward building the model.

3.1 Steps of The Modeling Process

Sterman (2000) divides the complete modeling cycle into five main steps as follows:

1. Problem Articulation (Boundary Selection)
2. Formulation of Dynamic Hypothesis
3. Formulation of a Simulation Model
4. Testing
5. Policy Design and Evaluation.

There are sub-steps within each of these steps, which we will follow as we proceed. This chapter includes steps 1, 2 and 3. Steps 4 and 5 are explained in the following chapters.

3.2 Problem Articulation

Problem articulation is the most important step in modeling (Sterman 2000). Sterman (2000) recommends modeling a problem and not a system. Modeling a system might involve large number of variables and may spoil the purpose of the simulation model. Modeling a problem will limit the number of variables by considering only those that are relevant to the particular problem. Apart from clearly defining a problem, problem articulation also involves defining reference modes and time horizon.

3.2.1 Problem Definition

Maintenance management is becoming a complex task with the advent of new complex and expensive technologies which are expected to be available continuously and perform up to the expected standards. According to the experts in the maintenance field, degradation in system performance and increase in maintenance cost has been observed over time. In order to achieve their performance objectives there is a need to understand the dynamics of maintenance function and how it affects systems performance. System availability and cost of the maintenance are two of the few maintenance performance issues that are widely discussed in the literature. These two objectives are considered as conflicting objectives.

3.2.2 Key Variables

System Degradation – System degradation is a measure of state of the system or the fitness of the system to be used at recommended load. This variable reflects the level of deterioration of the system.

Maintenance Cost – This is the amount of money spent on the preventive and corrective maintenance. It does not explicitly include cost of procurement and other administrative costs.

Cumulative system availability – This variable measures the time period in which system was available over its operations phase.

3.2.3 Reference Modes

In System Dynamics the problems are characterized dynamically. In other words, the problems are defined as the pattern of behavior, unfolding over time. Reference modes help us break out the short term event oriented world-view and see the forest view or the bird's eye view of the problem. Reference modes can be drawn in the form of charts or graphs to portray the behavior of the problem over time.

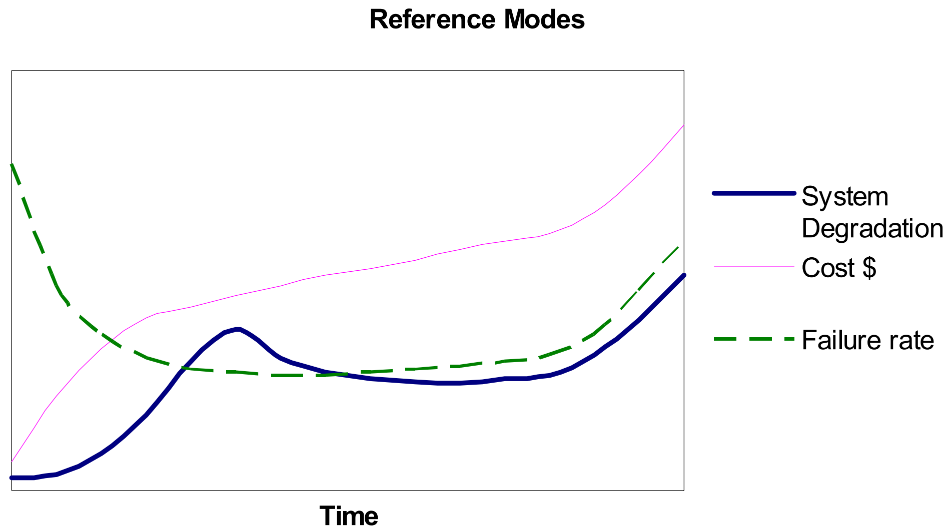


Figure 3-1 : Reference modes

The above diagram shows the reference modes for System Degradation, failure rate and maintenance cost. It has been observed over the time that system degradation increases at higher rate during the initial period of operations phase and then takes the downward trend to stabilize at a certain level and again increases in the later phase where failure rate due to wear-out defects increases. Cost increases at higher rate in the initial phase due to birth defects. The rate of increase in cost stabilizes during the useful phase of the operational phase and then increases again in the wear-out or death phase. Failure rate shows the bath tub behavior over time. Initially it is high due to manufacturing defects and the little knowledge about the system. It gradually decreases as the learning improves and stabilizes at a certain level when only operating defects contribute towards failures. An interesting trend with increasing failure rate is seen towards the end of system life cycle. This increase can be attributed to the aging factor of the system.

3.2.4 Time Horizon

A principle deficiency in our mental models is our tendency to think of cause and effect as local and immediate. But in dynamically complex systems, similar to the one under consideration, cause and effect are distant in time and space. To account for this we should model the problem considering the time horizon far enough in past to show how the problem emerged and far enough into future to capture the delayed and indirect effects of potential policies (Sterman, 2000).

Operations phase of a technological system may vary from a few years to a few decades. We will analyze the behavior of the system for 1000 weeks time period. This time period for simulation was decided based on the experts' opinions during the initial modeling sessions.

3.3 Formulation of Dynamic Hypothesis

Now we have better methods such as Condition Based Maintenance (CBM), Reliability Centered Maintenance (RCM) and Total Productive Maintenance (TPM), for planning the maintenance activities before the system failures occurs. Undoubtedly adoption of these methodologies saves us a lot of money and improves the system availability. But the link or the feedback that exits between these methodologies and management policies is still obscure and has a wide scope for improvement especially in the implementation of new technologies whose failure data is hardly available. Also implementation of these methodologies is time consuming and valid only for certain systems (Pintelon and Waeyenbergh, 1999, cited by Waeyenbergh and Pintelon, 2003).

The resources available for maintenance activities are limited. There is a high cost and time delay in the process of acquiring more capacity. The other measure to improve the system performance is through proper planning of preventive and corrective maintenance activities. It is believed that frequent preventive maintenance results into better system performance in terms of availability and reliability. This belief is based on an assumption that complete preventive maintenance is done at each interval irrespective of the maintenance interval duration. This increases the overall maintenance cost.

Most of the times funds and manpower are the scarce resources. In the context of this research, the focus is on selecting an optimal preventive maintenance interval while keeping the preventive maintenance cost constant. The amount of corrective maintenance generated during the operational phase evolves from the effectiveness of the maintenance management policy. The cost associated with this kind of maintenance can only be anticipated with some limitations of bounded rationality of human mind during the planning phase. The maintenance system on the surface seems simple and very straightforward but in fact, the system is dynamically complex with various feedbacks inherent is the system. This research is aimed towards explaining the resulting complex dynamics of the system.

Simulating maintenance system would help us determine the effectiveness of different maintenance policies in terms of corrective maintenance cost, overall maintenance cost, system availability and system degradation.

3.3.1 Dynamic Hypothesis

The following hypotheses are proposed:

1. Frequent periodic preventive maintenance improves system performance by reducing system degradation and increasing availability over time
2. Increase in load factor increases system degradation, maintenance cost and decreases system availability under constrained preventive maintenance capacity over time

3.3.2 Mapping System Structure

Categorizing the variables as endogenous, exogenous and excluded, and listing them together help us decide the boundary of our model. It also helps in focusing on the issue that is under consideration.

Model Boundary Chart

Endogenous	Exogenous	Excluded
System degradation	Operational load factor	Disposal
Preventive maintenance	Preventive maintenance capacity	Training
Corrective maintenance	Corrective maintenance capacity	Aging
Sub-system failures	Preventive Maintenance Interval	Material availability
Deferred maintenance		
Defects		
Critical failures		

Table 3-2 : Model boundary chart

Subsystem Diagram

There are various subsystems involved in the whole structure representing different functions. Mapping these subsystems and depicting their relationships diagrammatically is important to gain a broad overview of the model. Subsystem diagram also conveys information on the boundary and level of aggregation in the model.

There are three subsystems that play an important role in the model. These are

1. Preventive maintenance subsystem

   This subsystem represents the preventive maintenance function along with the preventive maintenance scheduling function.

2. Corrective maintenance subsystem

   This system links system degradation to corrective maintenance through defects and system failures.

3. Performance subsystem

This subsystem captures performance parameters such as system degradation and cumulative system availability. This subsystem interacts with the preventive and corrective maintenance subsystem to change the requirements based on the current performance of the system.

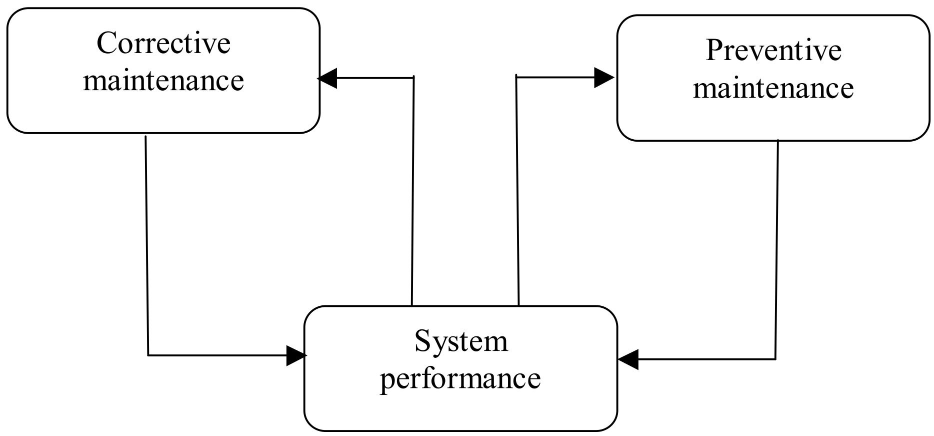


Figure 3-2 : Subsystem Diagram

In this model, maintenance activities are primarily divided into corrective maintenance and preventive maintenance. Preventive maintenance is not divided into different categories such as predictive replacement or adjustments. It is assumed that all necessary actions such as replacement, calibration, alignment are taken to complete the required preventive maintenance.

Also, preventive maintenance schedule is fixed and can not be changed over the entire useful period of operations phase. Corrective maintenance is generated only when the system is operational.

3.3.3 Assumptions

- System is in its useful life phase of its life cycle. This phase is in between infant mortality and wear-out phase of the operations phase.

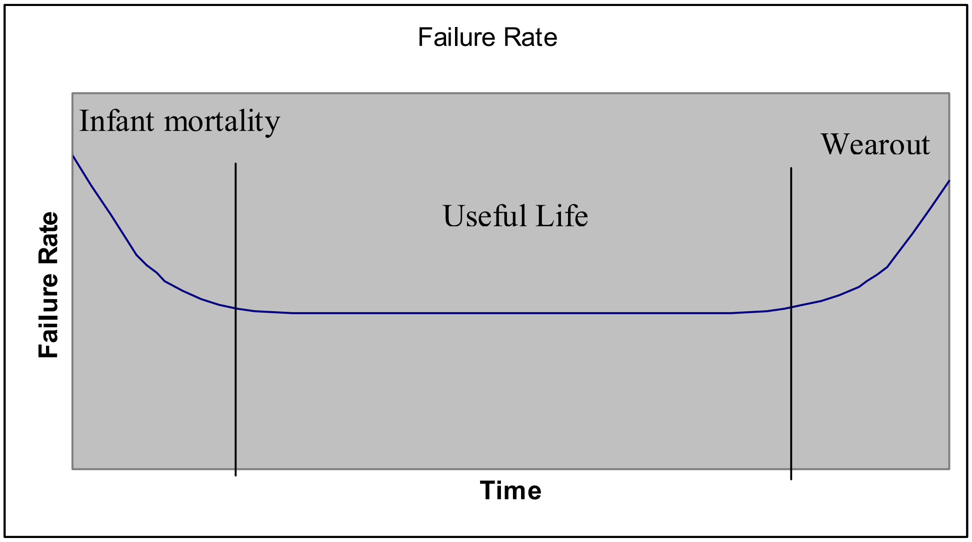


Figure 3-3 : Failure rate curve

- Preventive maintenance can only be completed during scheduled preventive maintenance cycle
- Number of hours of corrective maintenance generated due to failures is distributed normally (Blanchard, 1995)
- 80% of the non-critical system failures generate relatively less corrective maintenance per failure than the remaining 20% non-critical failures. This assumption does not restrict one from changing the 80-20 ratio in order to use this model. The ratio of 80-20 is assumed in this model as a base case value.
- The corrective maintenance generated by due to critical failures is relatively higher than that of the non-critical failures
- A certain percentage of the corrective maintenance generated is deferred. This deferred corrective maintenance is completed at a constant rate which is independent of the resource constraints
- The number of defects responsible for causing a failure is normally distributed.
- System is in continuous operational mode
- System has to be stopped for corrective maintenance

- Preventive maintenance can be performed without stopping the system

3.3.4 Definition of variables

1. Sub-system failures –These are the number of sub-system failures that are present in the system.
2. Required/deferred preventive maintenance – This is the total preventive maintenance that has to be completed to bring the system back to 'Good as new' state.
3. Completed preventive maintenance – This is the amount of preventive maintenance that has already been done.
4. Scheduled preventive maintenance – This is the total amount of preventive maintenance that is generated during each time step. It includes the amount of maintenance that is added due to system degradation, operational load factor and the fixed regular maintenance.
5. Operational load factor – Every system is designed to perform at full capacity for a specific period of time under specific operational conditions. If this system is subject to adverse operational conditions or is operated at higher load than the specified one or is operated at full capacity for more than the prescribed time period then the system is considered to be overloaded. Operational load factor can be used to account for such conditions.
6. Collateral damage – Failure of a system can also damage the surrounding or connected equipment. This is called as secondary or collateral damage. This kind of damage ultimately increases the required preventive and/or corrective maintenance. The extent to which a failure causes collateral damage is captured by this variable.
7. Required corrective maintenance – Corrective maintenance is the one that is generated as a result of system failure or inability of a sub-system to operate. Required corrective maintenance is the amount of corrective maintenance generated at the current time to rejuvenate the system back to operable condition.

8. Completed corrective maintenance – This is the amount of corrective maintenance completed.
9. System degradation – It is the measure of the state of the system. System degradation can be measured on the scale from 0 to 1. Zero system degradation means system is New or as good as new. The system is said to be in degraded state if the probability of system failure is higher than that of the new system. System degradation of 1 indicated that the system is in the worst possible condition.
10. Deferred corrective maintenance – This is the amount of corrective maintenance that is deferred due to some reason and is assumed to have little impact on system performance.
11. Maintenance acquisition factor – This is the factor that accounts for technology specific maintenance requirements, which are specified by the technology development and integration process.
12. Available man-hours – These are the resources available to complete the required and deferred corrective maintenance.
13. Preventive maintenance schedule – Preventive maintenance is carried out the specific time interval. This variable determines when to initiate preventive maintenance cycle. This is assumed as an exogenous variable and hence is not changed for the simulation time period.

3.3.5 Causal Loop Diagram (CLD)

Causal loop diagram is a useful tool to map feedback loops and causal relationships among individual variables. Arrow originates from cause and leads to effect denoting the causal influence among variables and its polarity indicate the direction of effect with respect to cause. Thus causal loop diagrams are excellent for quickly capturing the hypothesis about the cause of dynamics, eliciting and capturing the mental models and communicating important feedbacks (Sterman, 2000).

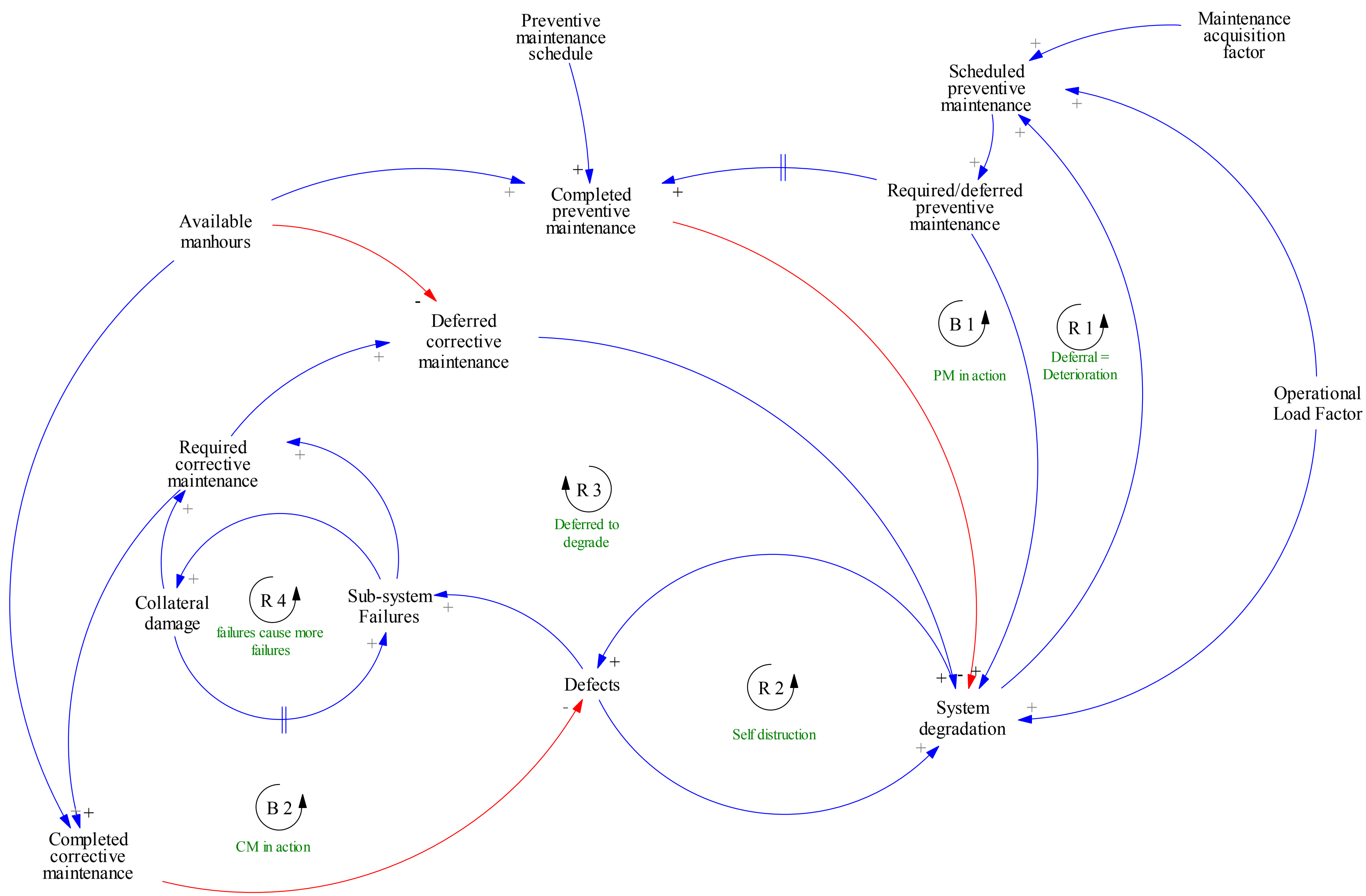


Figure 3-4 : Causal loop diagram

B1 – Completed preventive maintenance loop

Required preventive maintenance → Completed preventive maintenance → System degradation → Scheduled preventive maintenance → Required preventive maintenance

Required preventive maintenance is the maintenance that is generated at a particular point in time to bring the system back to the good as new condition. Increase in required preventive maintenance leads us to complete as much as possible considering the availability of resources such as man hours. Completion of preventive maintenance reduces system degradation. With reduction is system degradation, Scheduled maintenance also reduces. Ultimately it reduces required preventive maintenance.

R1 – Deferred preventive maintenance loop

Required preventive maintenance → Deferred preventive maintenance → System degradation → Scheduled preventive maintenance → Required preventive maintenance

Increase in Required preventive maintenance can also force us to defer it due to unavailability of sufficient resources and system availability for maintenance. Thus increase in deferred preventive maintenance will increase system degradation which ultimately increases the required preventive maintenance.

R2 – Defects loop

System degradation → Defects → System degradation

As system degradation increases, it increases the chances of failures and hence the mean time between failures increases which in turn increases the defects. Increase in defects increases system degradation,

R4 – Collateral damage loop

Sub-system failure → Collateral damage → Sub-system failure

Increase in number of defects increases the system failures. We can assume that certain numbers of defects contribute to a failure or we can also introduce a random factor to account for number of failures. Increase is system failures also cause damage to the surrounding or connected system which has been modeled as collateral damage. This damage is sometimes detected immediately or remains hidden until it results into system failure. Both system failures and collateral damage increases the required corrective maintenance.

B2 – Completed corrective maintenance loop

Required corrective maintenance → Completed corrective maintenance → Defects → System failure → Required corrective maintenance

Required corrective maintenance is the amount of corrective maintenance that is generated at a particular point in time that needs to be completed to convert the state of the system from non-operable condition to the operable condition. Some part of this required corrective maintenance might be deferred without affecting the system performance. The remaining corrective maintenance is considered as critical and has to be completed as soon as possible. The completion of this critical corrective maintenance reduces the number of failures.

3.3.6 Stock and Flow Diagram

The stock and flow diagram has been divided into three subsystems.

1. Preventive maintenance subsystem
2. Corrective maintenance subsystem
3. Performance subsystem

3.3.6.1 Preventive maintenance subsystem

The stock and flow structure shown below reflects the preventive maintenance subsystem. Scheduled Preventive maintenance is generated continuously as the system is operated. The amount of preventive maintenance generated depends on the system degradation, load factor, anticipated preventive maintenance during operational cycle and operational cycle time.

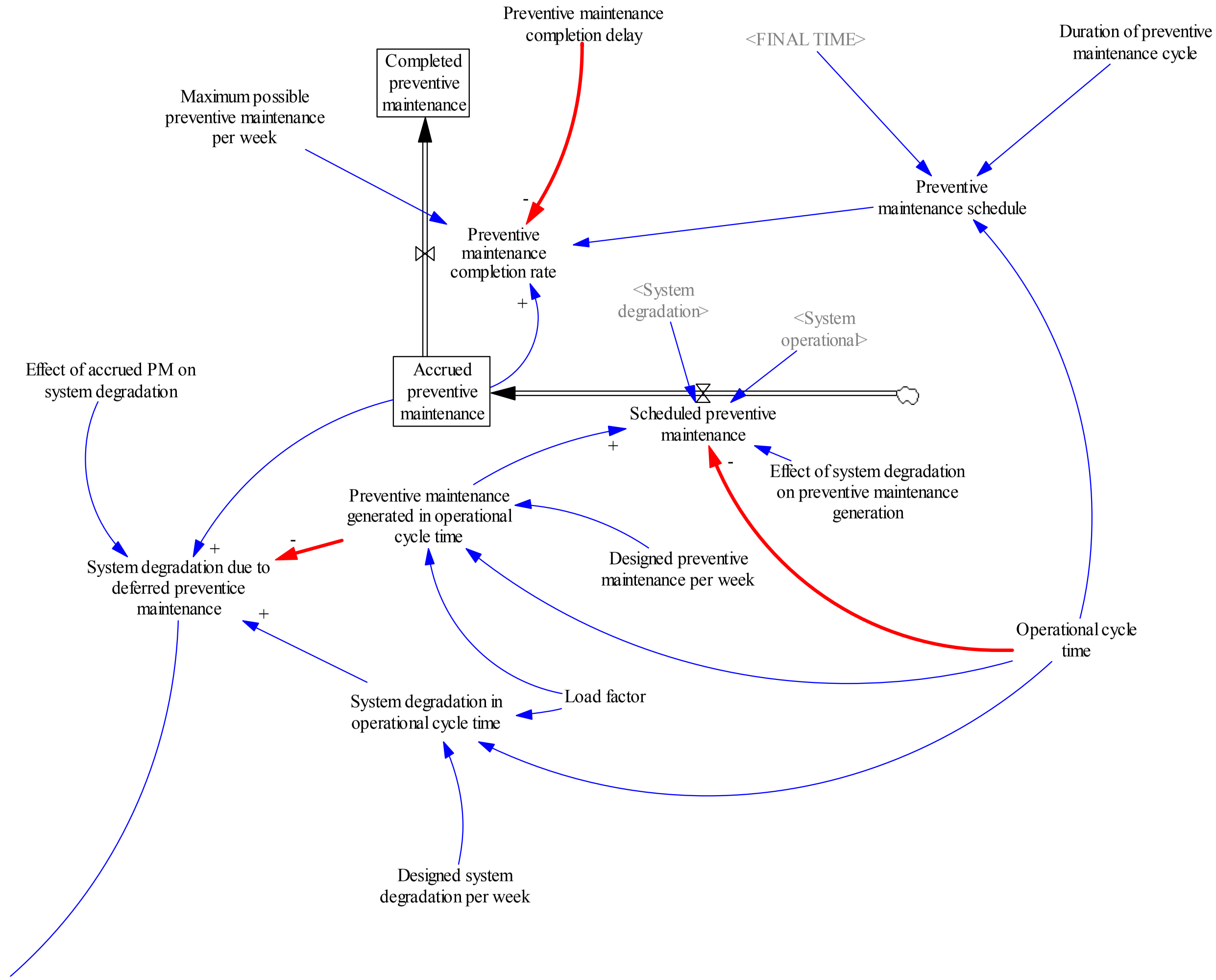


Figure 3-5 : Preventive maintenance sub-system

Scheduled preventive maintenance = Effect of system degradation on preventive maintenance generation (System degradation)(IF THEN ELSE (System operational=1, Preventive maintenance generated in operational cycle time, 0)/Operational cycle time)*

There is a non-linear relationship between system degradation and scheduled preventive maintenance. The rate of scheduled preventive maintenance generation increases at the increasing rate with increase in system degradation. The lookup table below shows the non-linear relationship in graphical format.

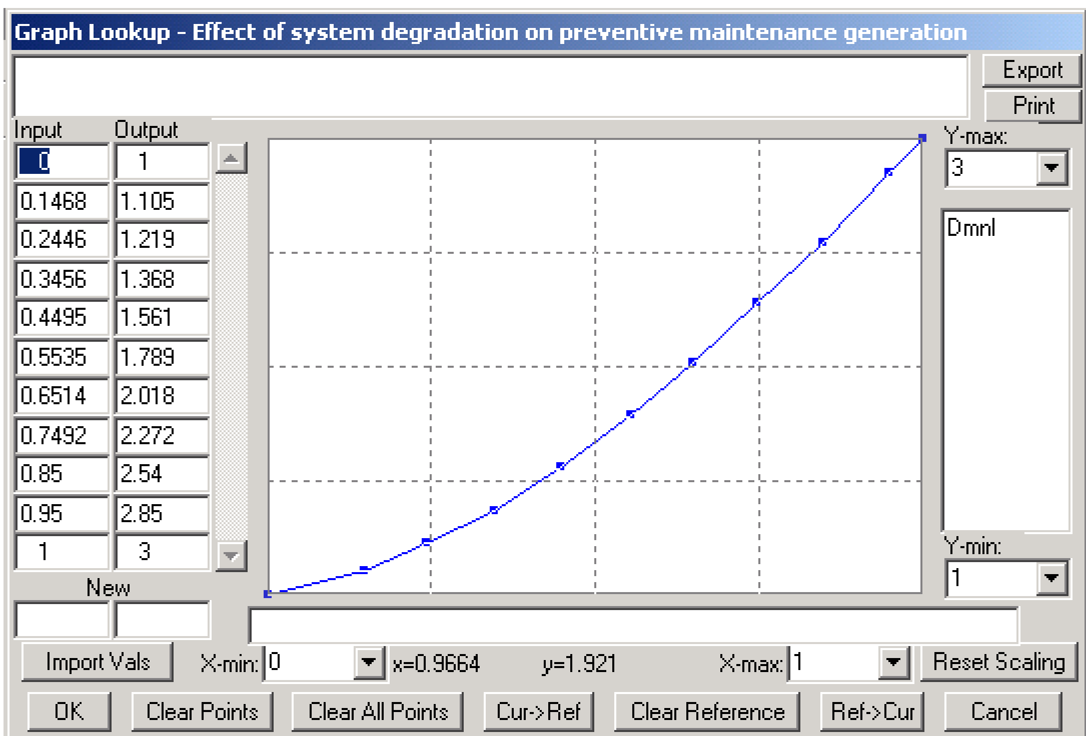


Figure 3-6 : Effect of system degradation on preventive maintenance generation

If the system is operational then preventive maintenance generated during 1 week time period is the anticipated preventive maintenance generated per week times the effect of system degradation. If system degradation is 0, the amount of preventive maintenance generated would be equal to the anticipated. As preventive maintenance increases from 0 to 1, preventive maintenance generated increases at exponential rate and could increase to three times the anticipated preventive maintenance when system degradation is maximum that is 1.

The generated preventive maintenance does not get done until the start of preventive maintenance cycle. The amount of preventive maintenance completed during preventive maintenance cycle depends on the man-hours available.

*Preventive maintenance completion rate = MIN (Maximum possible preventive maintenance per week, Accrued preventive maintenance/Preventive maintenance completion delay)*Preventive maintenance schedule*

Preventive maintenance schedule is a binary variable. It takes the value of 1 during the preventive maintenance cycle and 0 otherwise. The base case value for maximum possible preventive maintenance per week is 8 man-hours. If the Accrued preventive maintenance is more that 8 man-hours then the remaining maintenance is deferred until the next cycle else it is completed right away. The system is assumed to be in continuous operation during preventive maintenance cycle.

Preventive maintenance schedule is determined by the operational cycle and the duration of preventive maintenance cycle.

Preventive maintenance schedule = PULSE TRAIN (Operational cycle time, Duration of preventive maintenance cycle, Duration of preventive maintenance cycle + Operational cycle time, FINAL TIME)

It is also assumed that preventive maintenance is completed periodically at equal intervals. Thus operational cycle time determines the Preventive Maintenance interval, duration of preventive maintenance determines the number of continuous weeks the preventive maintenance would be carried out.

Increase in accrued preventive maintenance increases system degradation at exponential rate.

> *System degradation due to deferred preventive maintenance = Effect of accrued PM on system degradation (Accrued preventive maintenance/Preventive maintenance generated in operational cycle time)*System degradation in operational cycle time*

The ratio of accrued preventive maintenance to the preventive maintenance generated in operational cycle gives us the number of operational cycles no preventive maintenance has been completed. The effect of this ratio on system degradation is shown graphically in the diagram.

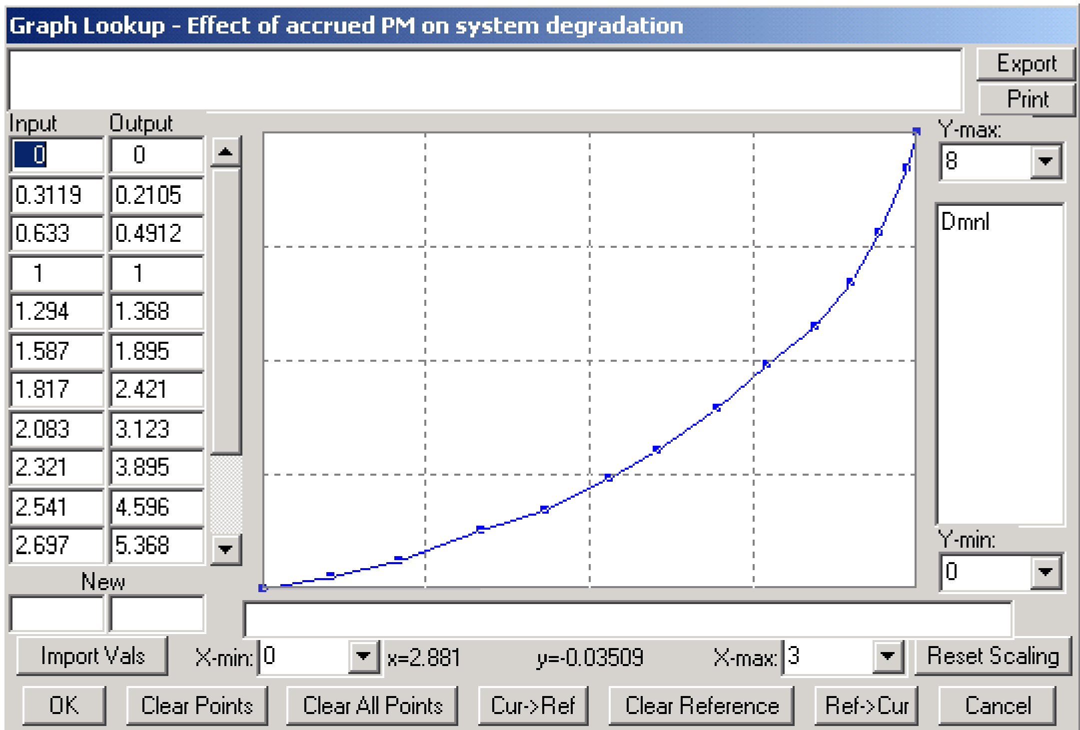


Figure 3-7 : Effect of accrued preventive maintenance on system degradation

The above lookup function provides a multiplication factor for system degradation in operational cycle. If the accrued preventive maintenance is equal to the preventive maintenance generated during operational cycle then this multiplication factor becomes 1 and hence the system degradation is equal to the system degradation in operational cycle. But as this ratio goes up multiplication factor increases at higher rate and hence the system degradation increases at higher rate.

3.3.6.2 Corrective maintenance subsystem

The corrective maintenance subsystem has been modeled in detail. It incorporates variables such as defects, sub-system failures and critical failures.

3.3.6.2.1 Defects

Increase in system degradation decreases the mean time between failures which in turn increases the probability of defect generation. With increase in system degradation and increase in the probability of defect generation, rate of defect generation increases which increases the number of defects in the system. Rate of defect correction, which depletes the stock of defects, is governed by the rate of critical repairs and rate of non-critical repairs. Increase in defects increases system degradation due to defects which in turn increases system degradation. The stock and flow structure below shows the reinforcing loop.

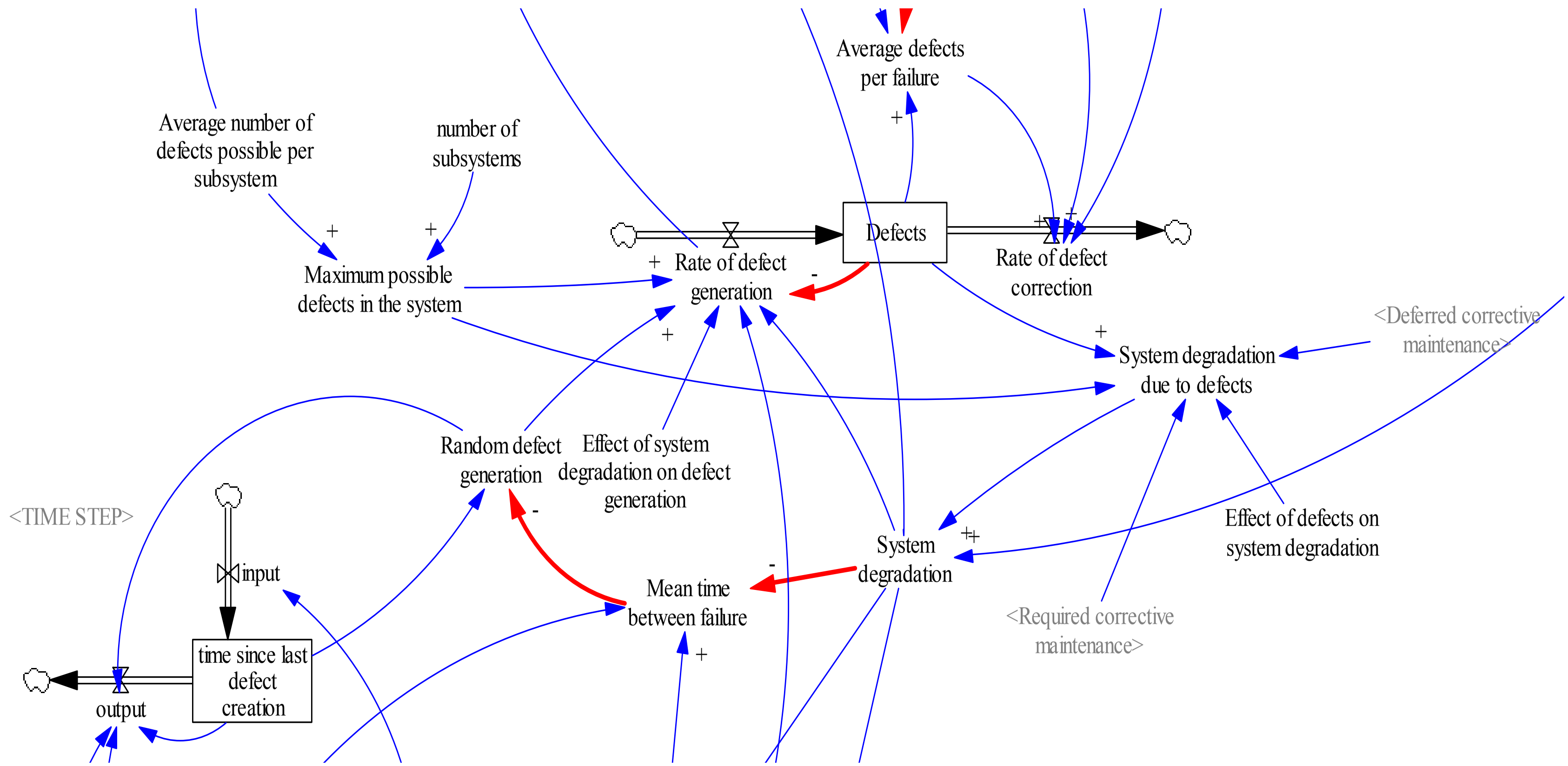


Figure 3-8 : Defects stock and flow diagram

System degradation is caused because of two factors; defects and accrued preventive maintenance.

System degradation = IF THEN ELSE (System degradation due to defects + System degradation due to deferred preventive maintenance>1, 1, System degradation due to defects +System degradation due to deferred preventive maintenance)

System degradation is the addition of system degradation due to defects and system degradation due to deferred preventive maintenance. System degradation varies from 0 to 1. It can not take value greater than 1. If the the additive impact of defects and deferred preventive maintenance in system degradation is more than 1, its value is limited to 1 which indicated that the system is totally degraded.

Increase in system degradation decreases the mean time between failures. In other words mean time between defect generation.

Mean time between failures = IF THEN ELSE (System operational=1, XIDZ (Model time step, System degradation, 1e+007), 1e+007)

Defects are generated only when the system is operational. Rules for taking the system down for corrective maintenance and putting it back into operational phase are discussed in chapter 5. If the system is down for corrective maintenance, obviously, no failures can take place. Hence the mean time between failures takes a very high value of 10^7. If the system is operational then the mean time between failures is the ratio of model time step, which is set to 1 week, to the system degradation. For example, if the system degradation is 0.1 then the mean time between failures would be 10 weeks. Let's consider the extreme conditions of system degradation. When system degradation is minimum, 0, mean time between failures would be 10^7

weeks and when system degradation is maximum, 1, mean time between failures would be 1 week.

Increase in mean time between failures decreases the probability of defect generation.

*Random defect generation = IF THEN ELSE (RANDOM UNIFORM (0, 1, 0) <= (1-EXP (-1*time since last defect creation/Mean time between failures)), 1, 0)*

A small stock and slow structure tracks the time since last defect creation. As mean time between failures increases probability of defect generation decreases. When mean time between failures becomes equal to the time since last defect creation, the right hand term in the conditional statement takes the value of 0.632. This means that there is a probability of 0.63 that defects will be created at that time. As the ratio of time since last defect creation to the mean time between failures increases probability of defect creation increases exponentially. A random number is generated from the uniform distribution between 0 and 1. Thus the generated number also reflects the cumulative probability of the generation of random number equal to or less than the number itself. This probability is compared with the probability of failure to determine if the system fails at that particular time period.

The rate of defect generation increases with increase in random defect generation and system degradation.

*Rate of defect generation = IF THEN ELSE (System operational=0, 0, Random defect generation * Effect of system degradation on defect generation (System degradation) * (Maximum possible defects in the system-Defects))*

No defects are generated if the system is not operational. When the system is operational, the number of defects generated is non-linearly related to the level of system degradation. Total number of defects in the system can never exceed the maximum possible defects in the system. Thus the gap between existing defects and maximum possible defects is filled at increasing rates with increase in system degradation. The figure below shows the effect of system degradation on the rate of defect generation.

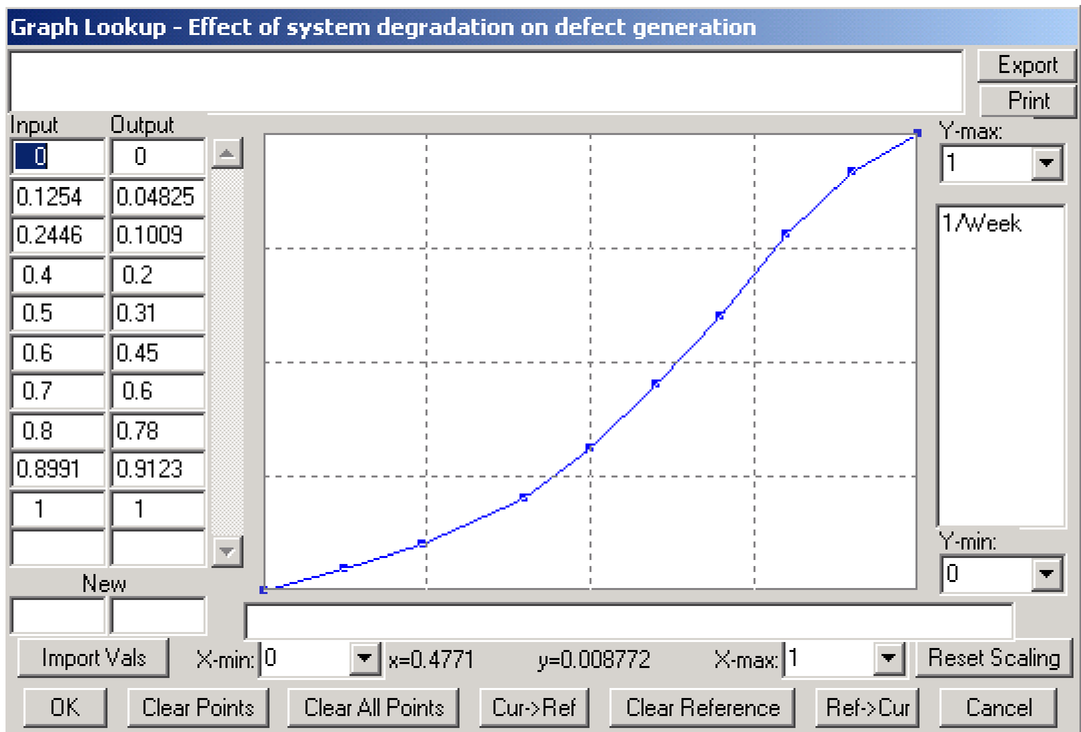


Figure 3-9 : Effect of system degradation on defect generation

Initially rate of defect generation increases slowly with increase in system degradation. It increases at increasing rate as the system degradation exceeds 0.25.

With increase in defects generation rate, the level of stock of defects increases.

Defects = INTEG (+Rate of defect generation-Rate of defect correction, 0)

It is assumed that there are no defects present in the system at the beginning of useful section of operations phase.

Rate of defect correction varies with the rate of critical and non-critical repairs which depend upon the corrective maintenance completion rate.

Rate of defect correction = Average defects per failure("Rate of non-critical repairs" + Rate of critical repairs)*

Average defects per failure are calculated by taking the ratio of defects to the sum of critical and non-critical failures. A co-flow structure has been formed where the information about defects flows along with the subsystem failures. Rate of defect correction depletes the stock of defects.

Increase in defects increases the system degradation. According to experts, not all defects impact the system immediately and hence the corresponding corrective maintenance is usually deferred. Thus the impact of defects on system degradation is modeled using following equation.

System degradation due to defects = Effect of defects on system degradation (Defects(XIDZ (Required corrective maintenance, Required corrective maintenance + Deferred corrective maintenance, 1)) / Maximum possible defects in the system)*

The ratio of required corrective maintenance to the sum of required corrective maintenance and deferred corrective maintenance gives the percentage of defects that are critical to the system's operation. The ratio of critical defects to the maximum possible defects in the system increases the system degradation. The relationship of this ratio and system degradation is shown in the figure below.

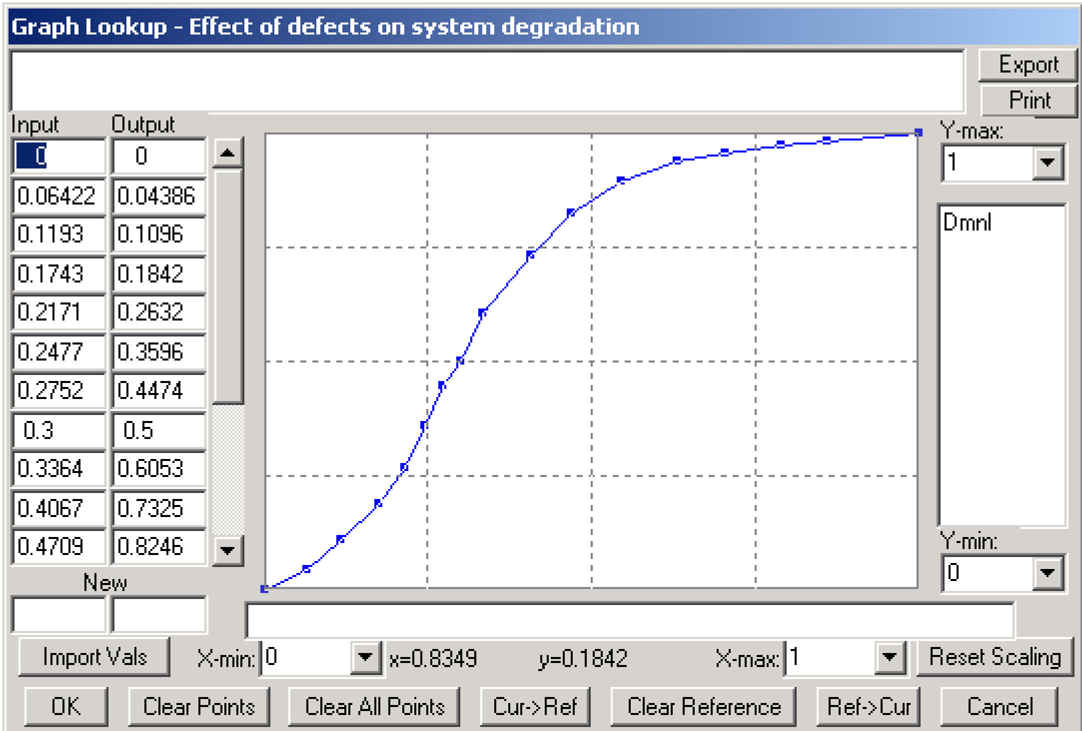


Figure 3-10: Effect of defects on system degradation

As the ratio of critical defects to the maximum possible defects increases from 0 to 1, initially system degradation increases at higher rate than in the later part. According to the above graph, when 60% of the maximum possible defects are present in the system and are critical to the system, the system has been degraded to the level of 0.93.

3.3.6.2.2 Subsystem failures

Increase in the rate of defect generation increases the rate of subsystem failures. The sub-system failures are divided into two kinds of failures, critical and non-critical failure. The complete system has to be taken down for corrective maintenance when there is an occurrence of critical failure. There is some level of tolerance with respect to non-critical sub-system failures.

Critical and non-critical failures are repaired as the corrective maintenance generated by them is completed. Priority is given to the repair of critical failures.

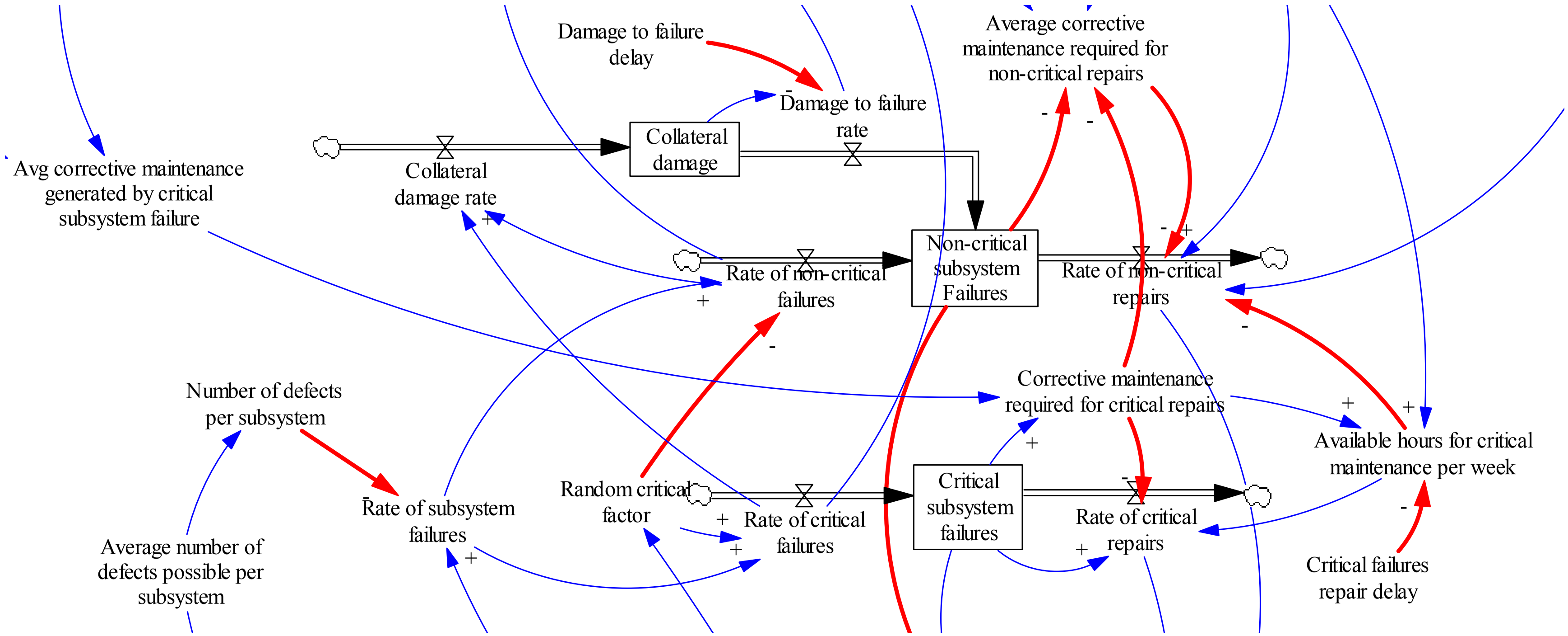


Figure 3-11 : Sub-system failures stock and flow diagram

Number of defects responsible for a subsystem failure is generated from normal distribution with average number of defects possible per subsystem as mean and 25 as standard deviation. With 25 as standard deviation for normal distribution with mean of 125 (average number of defects possible per subsystem) suggests that 95% of the times the value would be generated between 75 and 175.

Rate of subsystem failures = Rate of defect generation/Number of defects per subsystem

Rate of subsystem failure is determined using the above equation. Rate of defect generation over number of defects per subsystem gives the number of subsystem failures at a given time step.

If the system is in highly degraded state then probability of critical failure is high. The variable Random critical failure compares the system degradation against a random number generated from an uniform distribution to determine if the critical failure occurs or not.

Random critical factor = IF THEN ELSE (RANDOM UNIFORM (0, 1, 1) <= System degradation, 0.1, 0)

If the condition is satisfied then 10% of the total subsystem failures are critical failures and the remaining 90% of the failures are non-critical failures.

All the critical failures generate collateral damage while non-critical failures generate collateral damage only 6% of the times.

*Collateral damage rate = (Rate of critical failures+IF THEN ELSE (RANDOM UNIFORM (0, 1, 2) <= 0.06, "Rate of non-critical failures", 0)) * 0.1*

The collateral damage generated is considered to be equal to 10% of the total failures. This collateral damage is transformed into non-critical subsystem failure over 4 weeks. This delay period is modeled as Damage to failure delay.

The rate of critical and non-critical repairs increases with increase in the corrective maintenance completion rate. Again, a co-flow structure is formed where average required corrective maintenance is computed by taking the ratio of required corrective maintenance and non-critical subsystem failures.

Average corrective maintenance required for non-critical repairs = XIDZ ((Required corrective maintenance + Deferred corrective maintenance - Corrective maintenance required for critical repairs), "Non-critical subsystem Failures", 1000000)

If there are no non-critical subsystem failures present then average required corrective maintenance is set to a very high value.

Corrective maintenance required for critical repairs is computed using the number of critical failures present in the system and the average corrective maintenance generated by critical sub-system failure.

*Corrective maintenance required for critical repairs = Critical subsystem failures * Avg corrective maintenance generated by critical subsystem failure*

The rate of critical repairs is determined by the available corrective maintenance hours for critical repairs and required corrective maintenance for critical subsystem failure repairs.

*Rate of critical repairs = XIDZ (Available hours for critical maintenance per week*Critical subsystem failures, Corrective maintenance required for critical repairs, 0)*

The ratio of available hours to the required hours determines the percentage of critical subsystem failures that can be repaired. If corrective maintenance required for critical repairs is 0, the rate of critical repairs is zero. This construct prevents the stock from going negative.

As mentioned above critical subsystem failures are repaired before non-critical sub-system failures. Hence in corrective maintenance completion rate is compared with the corrective maintenance required for critical maintenance. IF required is greater than the corrective maintenance completion rate then all the corrective maintenance is used to repair the critical failures. If required corrective maintenance for critical failures is less than the corrective maintenance completion rate then the remaining corrective maintenance is used to repair the non-critical sub-system failures.

Available hours for critical maintenance per week = MIN (Corrective maintenance completion rate, Corrective maintenance required for critical repairs/Critical failures repair delay)

Also it is assumed that the critical failures are repaired as soon as they occur. Hence Critical failure repair delay is assigned a value of 1 week.

The rate of non-critical repairs is determined using the following equation

"Rate of non-critical repairs" (Corrective maintenance completion rate-Available hours for critical maintenance per week + Deferred corrective maintenance completion rate)/"Average corrective maintenance required for non-critical repairs"

This equation essentially determines value of non-critical repairs by taking the ratio of the corrective maintenance contributing towards non-critical repairs to the average corrective maintenance required for non-critical repair.

3.3.6.2.3 Corrective maintenance

Corrective maintenance is generated as a result of subsystem failures. Most of the non-critical sub-system failures generate the corrective maintenance with the mean of 6 man-hours and the remaining generates the corrective maintenance with the mean of 10 man-hours. These values are system dependent and hence could take different values for different systems. These particular values were selected based on the parameter assessment tests conducted for calibrating the model. Critical sub—system failures generate relatively more corrective maintenance. Out of the total corrective maintenance generated by non-critical failures, certain percentage is deferred because it is believed that it does not impact the system operations and performance.

It is also assumed that the corrective maintenance capacity is fixed. The deferred corrective maintenance is completed slowly before it becomes critical to complete that maintenance.

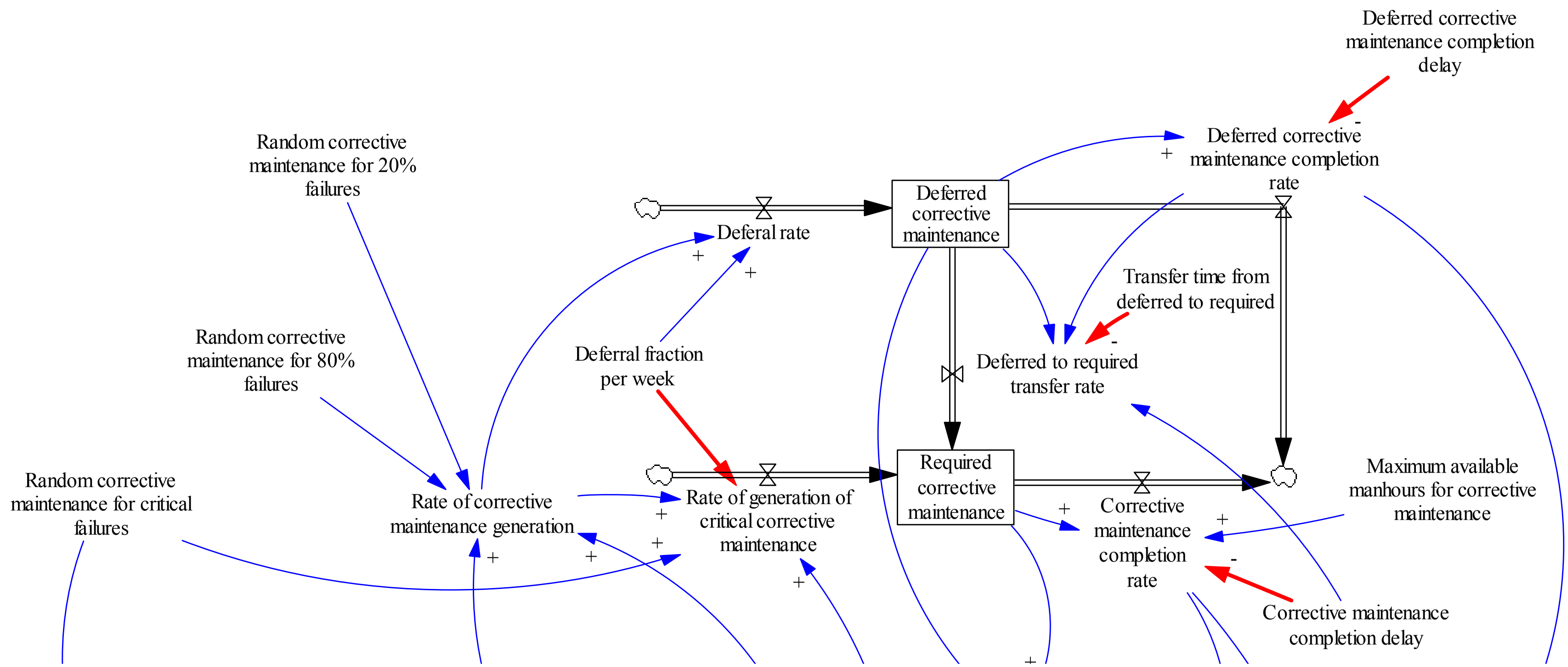


Figure 3-12 : Corrective maintenance stock and flow stucture

Corrective maintenance time probability distribution usually falls into following three forms

1. Normal distribution – suitable for mechanical or electromechanical hardware
2. Exponential distribution – suitable for electronic equipment with built-in test capability
3. Log Normal distribution - suitable for electronic equipment without a built-in test capability (Blanchard, Verma and Peterson, 1995)

The corrective maintenance generated by 80% of the non-critical failures is assumed to be normally distributed with the mean of 6 and standard deviation of 1 man-hour and the corrective maintenance generated by remaining 20% of the non-critical failures is also assumed to be normally distributed with the mean of 10 man-hours and standard deviation of 1 man-hour. Critical failures generate relatively more corrective maintenance with the mean of 15 and standard deviation of 2 man-hours. The values of for and standard deviation were selected based on the experts' inputs and parameter assessment tests. The percentage distribution (80-20) was determined based on the perception of the technological systems and does not for a limiting assumption.

"Random corrective maintenance for 80% failures" = RANDOM NORMAL (2, 8, 6, 1, 0)

"Random corrective maintenance for 20% failures" = RANDOM NORMAL (7, 13, 10, 1, 0)

Random corrective maintenance for critical failures = RANDOM NORMAL (10, 20, 15, 2, 0)

The fraction of the total corrective maintenance deferred is modeled as an exogenous variable with the base case value of 0.3.

Thus the rate of generation of critical corrective maintenance is the sum of the non-deferred corrective maintenance generated due to non-critical maintenance and critical maintenance.

*Rate of generation of critical corrective maintenance = (1-Deferral fraction per week)*Rate of corrective maintenance generation + (Rate of critical failures*Random corrective maintenance for critical failures)*

The deferred corrective maintenance is completed slowly while it gradually becomes critical to the systems operations and performance. The deferred corrective maintenance which was believed not to have impact on systems operations and performance becomes critical gradually over 12 weeks.

*Deferred to required transfer rate = (Deferred corrective maintenance-(Deferred corrective maintenance completion rate*Corrective maintenance completion delay))/Transfer time from deferred to required*

The required corrective maintenance stock has two inflows; rate of generation of critical corrective maintenance and deferred to required transfer rate, and one outflow, rate of corrective maintenance completion.

Corrective maintenance completion rate = MIN (Maximum available manhours for corrective maintenance, Required corrective maintenance/Corrective maintenance completion delay)

As mentioned above the corrective maintenance capacity is limited and hence is modeled as an exogenous variable. If the available man-hours for corrective maintenance are more than the required then all the required corrective maintenance is completed otherwise the maximum corrective maintenance is limited to the available man-hours. Again, corrective maintenance has to be completed as soon as possible and hence the corrective maintenance completion delay has been given a value of 1 week.

3.3.6.3 Performance subsystem

Performance subsystem determined when to take the system down for corrective maintenance and when to put it back into operations. There are various factors that govern this decision. These decision rules are decided based on the expert's inputs.

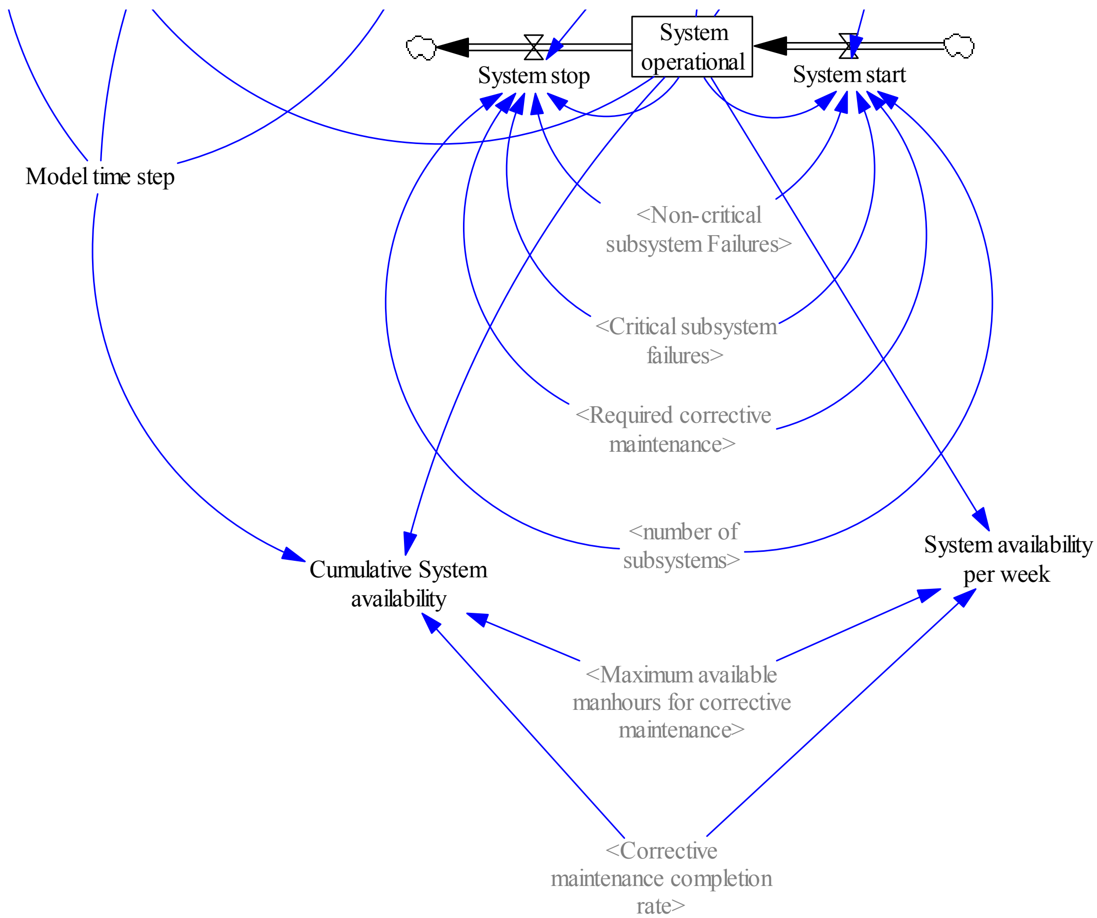


Figure 3-13 : System start and stop structure

System stop = IF THEN ELSE (System operational=0, 0, IF THEN ELSE (System degradation>=0.5 :OR: "Non-critical subsystem failures">=0.3*number of subsystems :OR: Critical subsystem failures >=0.001 :OR: Required corrective maintenance>=40,1,0))

System start = IF THEN ELSE (System operational=1, 0, IF THEN ELSE (System degradation<0.5 :AND: "Non-critical subsystem Failures"<=0.05*number of subsystems :AND: Critical subsystem failures <=0.001 :AND: Required corrective maintenance<10, 1, 0))

If 30% of the sub-systems are in failure state then the complete system has to be taken down until no more than 5% sub-systems are in failure state. If there is any critical failure the system has to be taken down until most of the critical failures are repaired. If the required corrective maintenance exceeds 40 man-hours then the system has to be taken down until it reduces below 10 man-hours.

Performance of the system is measured using three variables; cumulative system availability, system degradation and total maintenance cost. System degradation has been discussed in section 3.3.6.2.1. Cumulative system availability indicated the overall system availability over operational phase.

Cumulative System availability =INTEG (IF THEN ELSE (System operational=1, System operational-(Corrective maintenance completion rate/Maximum available manhours for corrective maintenance), System operational)/Model time step, 1)

Cumulative system availability is the integral of system availability per week. If the system is operational then system availability could be calculated as the ratio of the time system was up to the maximum time system was supposed to be up. Model time step is set to 1 week.

Cost is another important performance measure of interest. Preventive and corrective maintenance costs are tracked separately along with the total maintenance cost.

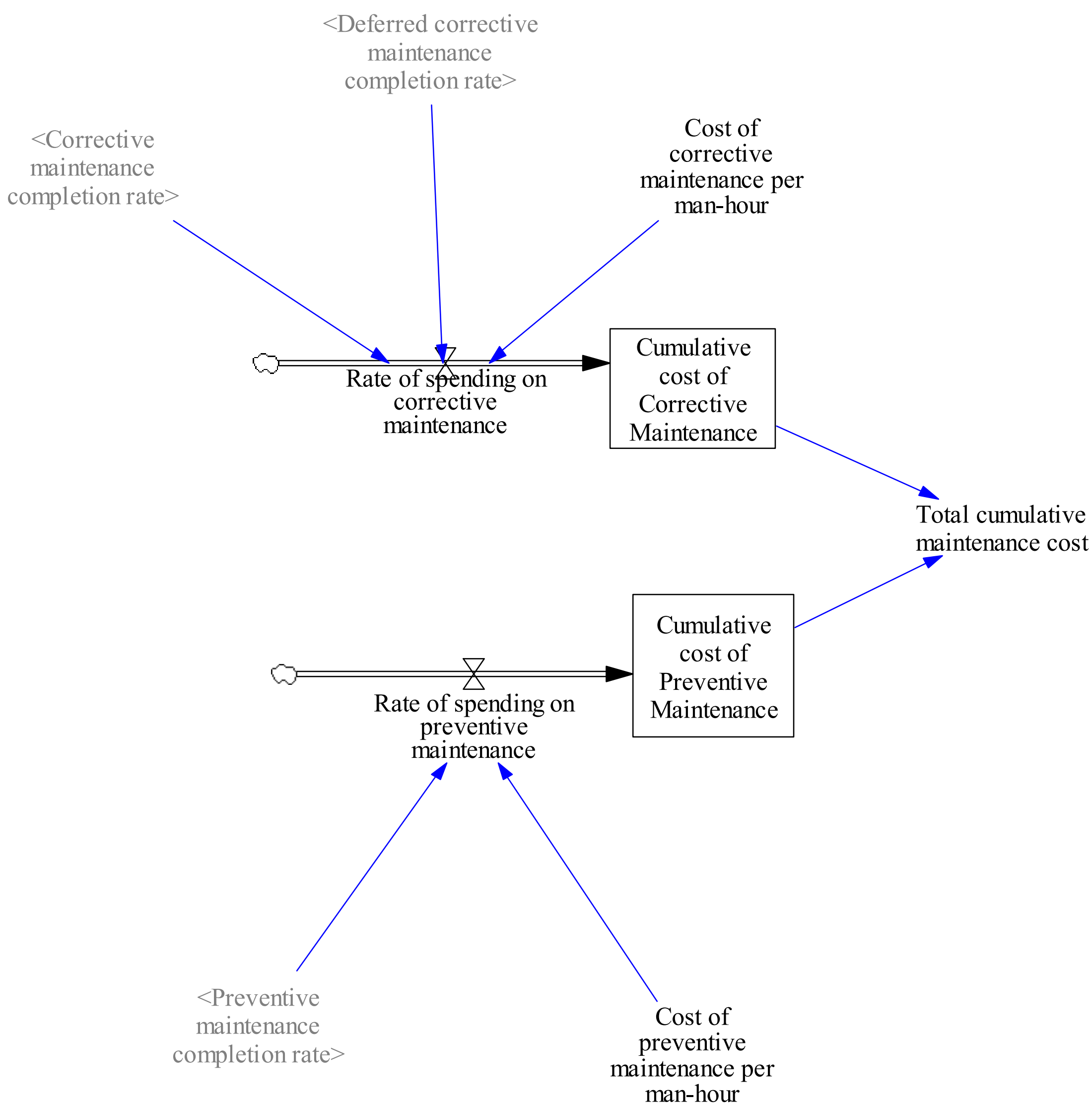


Figure 3-14 : Cumulative maintenance cost stock and flow structure

The rate of spending on corrective maintenance is the product of total corrective maintenance completion rate and the cost of corrective maintenance per man-hour. Similarly, the rate of spending on preventive maintenance is the product of preventive maintenance completion rate and the cost of preventive maintenance per man-hour.

Rate of spending on corrective maintenance = "Cost of corrective maintenance per man-hour"(Deferred corrective maintenance completion rate + Corrective maintenance completion rate)*

*Rate of spending on preventive maintenance = "Cost of preventive maintenance per man-hour"*Preventive maintenance completion rate*

The total cumulative maintenance cost is simply the sum of cumulative cost of corrective and preventive maintenance.

Total cumulative maintenance cost = Cumulative cost of Corrective Maintenance + Cumulative cost of Preventive Maintenance

4. Results, Testing, Validation and Verification

The model discussed in chapter 3 was developed using Vensim DSS v5.4a simulation software. The simulation results with base case values and with different test scenarios are presented in this chapter. The base case values were selected based on the experts experience in the field of maintenance of technological systems. These values should be changed to the technology specific values when using this model for a different technology (Please refer to chapter 5 for the list of technology specific inputs). This model has been structured primarily based on the inputs from the experts in the field of maintenance of defense systems and the insights from the research literature as discussed in chapter 2.

The structure of the model is very generic and hence could easily be adapted for various technologies with a few changes in its quantitative assumptions. Generally any typical technological system undergoes two major kinds of maintenances; preventive and corrective. These activities have been modeled in detail to analyze their impact on system's performance over the Operations, Support and Disposal phase of the system's life cycle.

4.1 Simulation Values

Listed below, are the simulation control parameters that were used for conducting various simulation runs with different scenarios including the base case values.

FINAL TIME = 1000 weeks

TIME STEP = 1 week

Time step of 1 week was chosen. This time step is used to calculate some parameters in the simulation model. The change in model time step will affect the accuracy of the results and hence the model has not been tested for shorter or longer time steps.

4.1.1 User Defined Parameters

The following table lists all the user defined parameters and their base case values.

Parameter	**Definition**	**Base case Value**
Average number of defects possible per subsystem	The average number of defects required to occur before any subsystem fails	125
Number of subsystems	Total number of subsystems present in the system	100
Critical failure repair delay	The time required to repair the critical failure when all the required resources are available	1 week
Damage to failure delay	The time required for the collateral damage to completely transform into a failure	4 weeks
Random corrective maintenance for critical failures	The amount of corrective maintenance generated due to a critical failure	N(15, 2) man-hours
Random corrective maintenance for 80% of the failures	The amount of corrective maintenance generated due to a failure among the 80% of the non-critical failures	N(6, 1) man-hours
Random corrective maintenance for 20% of the failures	The amount of corrective maintenance generated due to a failure among the 20% of the non-critical failures	N(10, 1) man-hours
Deferral fraction per week	The percentage of the newly generated corrective	0.3

	maintenance that is knowingly deferred	
Transfer time from deferred to required corrective maintenance	The time after which deferred corrective maintenance become critical corrective maintenance	12 weeks
Maximum available man-hours for corrective maintenance	The amount of man-hours available for corrective maintenance per week	40 man-hours
Deferred corrective maintenance completion delay	The time required to complete the deferred corrective maintenance	24 weeks
Corrective maintenance completion delay	The time required to complete the corrective maintenance	1 week
Maximum possible preventive maintenance per week	The availability of the system for preventive maintenance per week during each preventive maintenance cycle	8 manhours
Load factor	The extent to which system is used as compared to the design specifications	1
Anticipated system degradation per week	The anticipated degradation in system performance per week when operated under unit load factor	0.01
Anticipated preventive maintenance per week	The anticipated amount of preventive maintenance generated per week when	8 manhours

	the system is operated under unit load factor	
Operational Cycle Time	The time for which system is operated before it is taken down for the scheduled preventive maintenance	20 weeks
Duration of preventive maintenance cycle	The time in weeks, allocated for preventive maintenance	1 week
Cost of corrective maintenance per man-hour	The dollars required for completing 1 man-hour of corrective maintenance	100 dollars
Cost of preventive maintenance per man-hour	The dollars required for completing 1 man-hour of preventive maintenance	75 dollars

Table 4-1 : User defined parameters and assumptions

These variables were used to simulate the model and obtain initial results. These initial results were then compared with the results obtained from the model by varying some of these variables. The simulation outputs from different scenarios have been discussed in the following section.

4.2 Simulation runs and results

4.2.1 Results and Behaviors

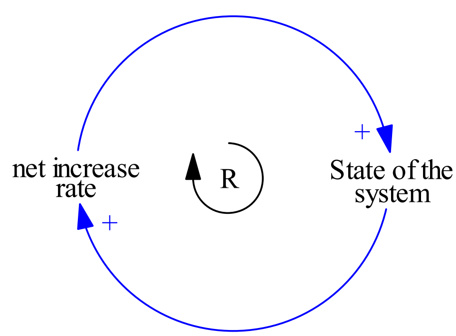
Various runs were conducted and the results were relatively compared against each other. These results were also thoroughly validated by the subject matter experts.

The behaviors observed result from the interactions of numerous feedback loops present in the structure. Sometimes it might be difficult to attribute the observed behavior to any particular feedback loop. Partial simulation runs were conducted to ensure the appropriateness of the formulation. The values of exogenous variables, to certain extent, determine the dominance of feedback loops which ultimately result into specific system behavior. These values can be changed to observe their impact on the system's behavior.

The variables that reflects performance of the system, system degradation, cumulative system availability and cumulative maintenance cost, have been primarily used to compare the results of various scenarios. The other critically observed factors include variables such as number of subsystem failures, accrued preventive maintenance, and Required corrective maintenance.

4.2.1.1 Exponential growth

Exponential growth arises from positive (self-reinforcing) feedback. The following figure shows the generic structure responsible for exponential growth.



Positive (self reinforcing) loop

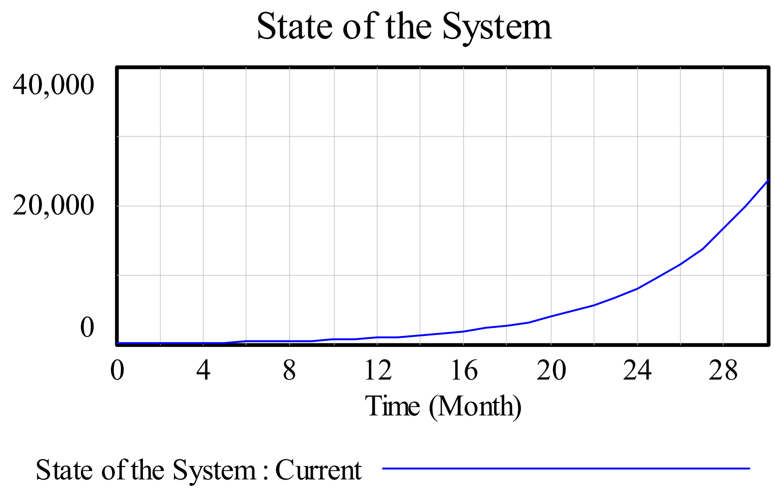


Figure 4-1 : Exponential growth behavior

Increase in state of the system increases the net increase rate which in turn increases the state of the system. Exponential growth is observed in every-day situation, for example, growth in population. The net birth rate increases with increase in population and hence population increases. Similar phenomenon is observed in the performance of technological systems where increase in system degradation increases the system failures which in turn increases the system degradation..

Increase in system degradation (state of the system) increases the maintenance requirements. The required maintenance is either completed or deferred based on the resources available. Deferral of maintenance in turn causes increase in system degradation. This exhibits exponential increase in system degradation until all the required and deferred maintenance is completed. The complete causal loop diagram is depicted below. Loops R1 and R3 explains the exponential growth mentioned above.

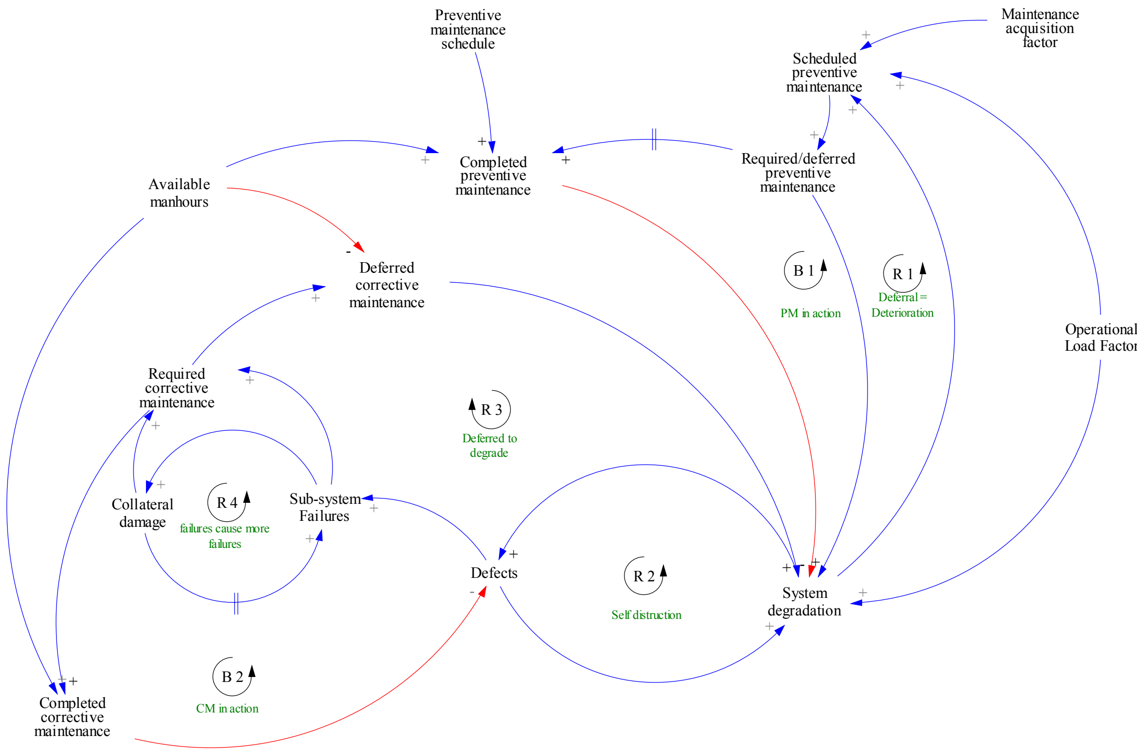


Figure 4-2 : Overall causal loop diagram

Loops R2 and R3- The system gets degraded as it is continuously used. The load factor determines the extent of degradation per hour of usage. The increase in system degradation increases the number of defects present in the system which not only increases system degradation but also in turn increases the number of subsystem failures. Subsystem failures increases required corrective maintenance which is either deferred or completed based on the available man-hours. As deferred corrective maintenance increases system degradation increases.

Loop R2 was simulated separately with 100 initial defects in the system. In other words this partial simulation means that the system is continuously used without performing any preventive or corrective maintenance.

As defects in the system increases system degradation due to defects increases. Increase in system degradation increases the probability of failure and hence mean time between failures decreases which increases the chances of generating random defects. The variable random defect generation determines if any defects are created during each time step. It is a binary variable which can take value of 1 or 0 where 1 indicates that defects were generated and 0 indicated that no defects were generated. As system degradation increases rate of defect generation increases which increases the defects present in the system. The stock and flow structure of loop R2 is shown below.

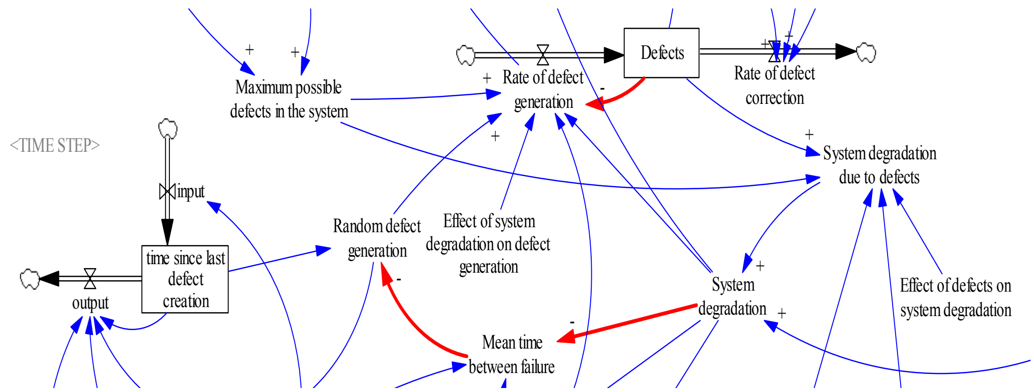


Figure 4-3 : Defects reinforcing loop stock and flow structure

The resulting behavior is exponential growth in system degradation as shown in the graph below.

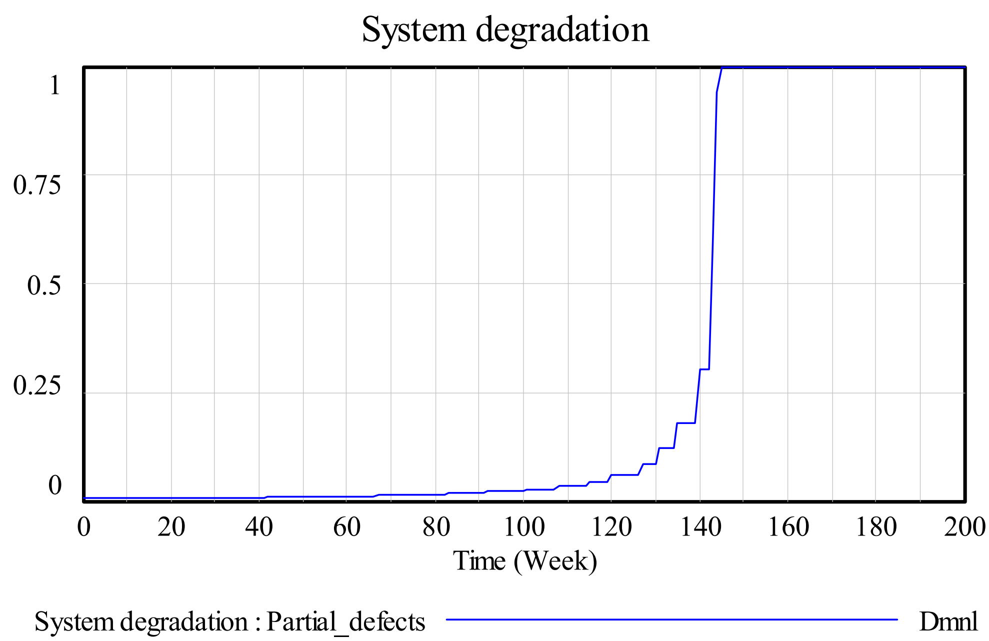


Figure 4-4 : Partial simulation – defects

System degradation is measured on the scale of 0 to 1. Also maximum possible defects in the system are set to 12500. Once this limit has been reached, no new defects can be created and thus the system reaches an equilibrium stage which is undesirable.

Loop R1 – The increase in system degradation increases scheduled preventive maintenance. Thus preventive maintenance is generated continuously but it is completed only during the scheduled maintenance cycle. This deferral of preventive maintenance until the preventive maintenance cycle results in increase in system degradation at increasing rate as the system continues to operate. The graph below shows this phenomenon. It should be noted that the system degradation increases exponentially until the preventive maintenance cycle (every 20 weeks) and then drops drastically during the preventive maintenance cycle (duration 1 week) when loop B1 dominates loop R1.

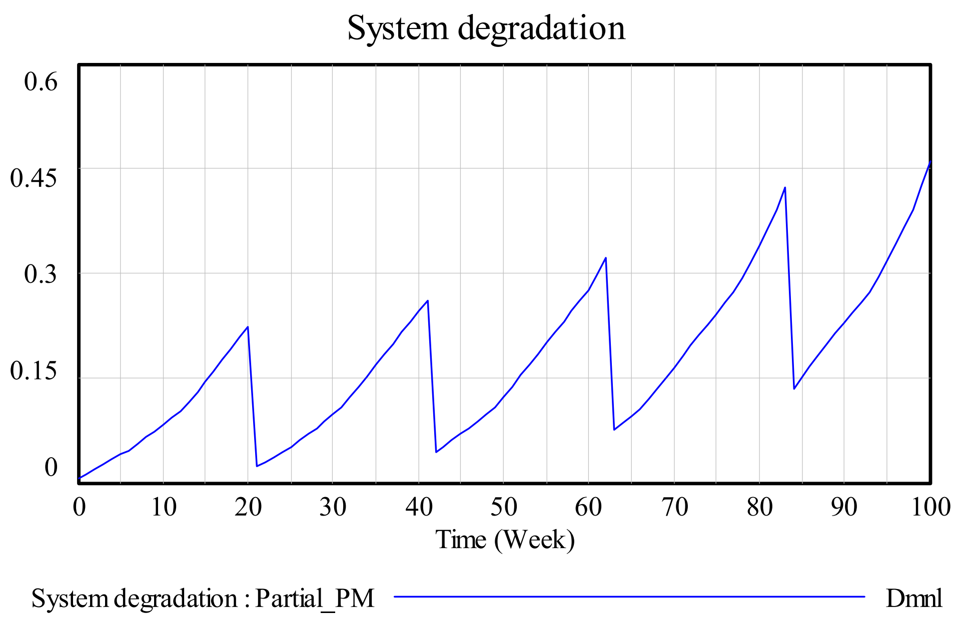


Figure 4-5 : Partial simulation – preventive maintenance

Loop B1 – The required as well as deferred preventive maintenance is completed during the preventive maintenance cycle, which reduces the system degradation which in turn reduces the scheduled preventive maintenance. Loop B1 becomes active only during the preventive maintenance cycle and hence results into a sudden drop in system degradation.

4.2.1.2 Goal Seeking behavior

Increase in the rate of non-critical failures increases subsystem failures and also increases the rate of corrective maintenance generation. Increase in the rare of corrective maintenance generation increases required corrective maintenance. This required corrective maintenance is gradually completed based on the available resources, which decreases the subsystem failures by increasing the rate of non-critical repairs.

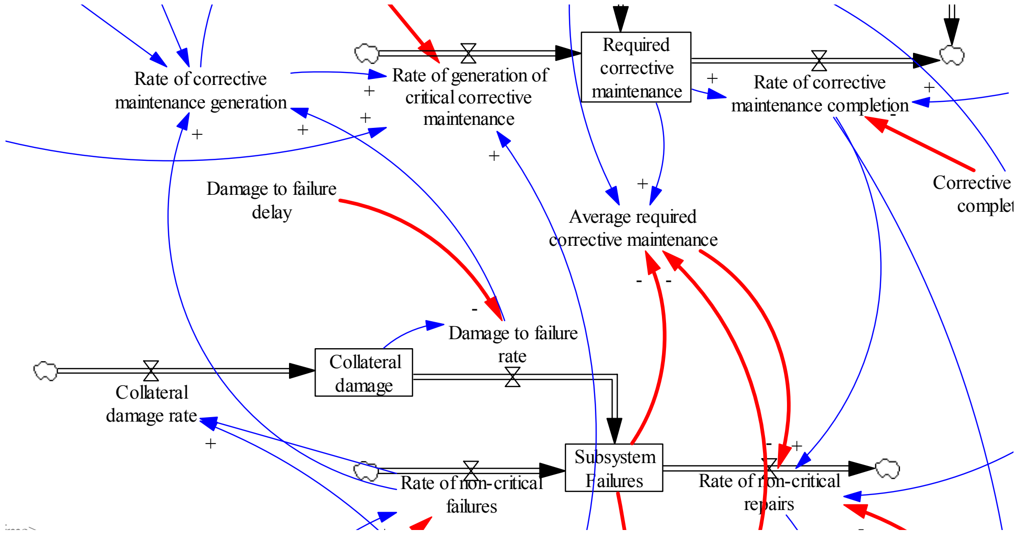


Figure 4-6 : corrective maintenance balancing loop structure

The above stock and flow structure is responsible for the goal seeking behavior shown in the graph below.

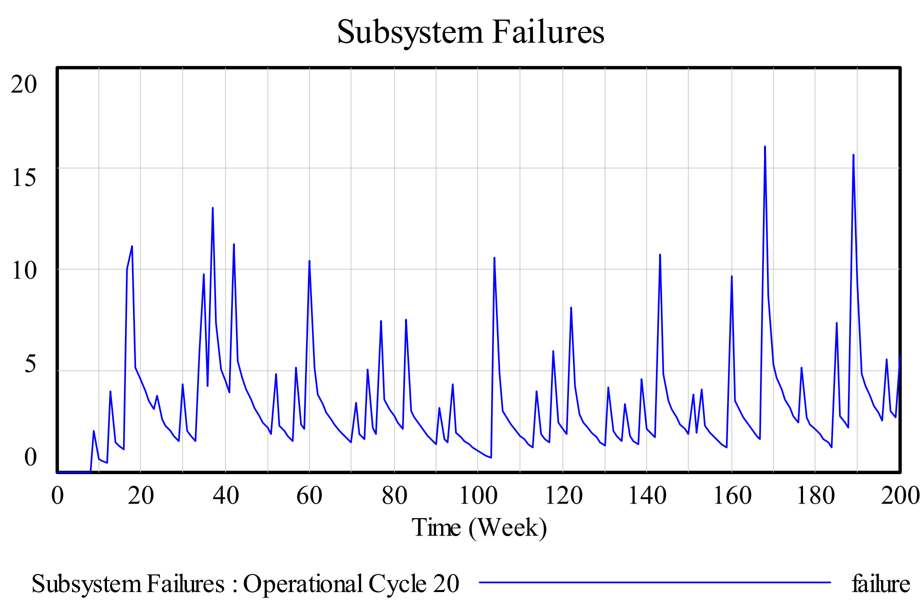


Figure 4-7 : Goal seeking behavior of system failures

It should be noted that increase in subsystem failures is seen before the balancing loop starts dominating system's behavior. This increase in sub-system failures can be attributed to the reinforcing loop R2 and R3. Also the goal of zero for the subsystem failures is inherently modeled in the system. In the above graph, for example, goal seeking behavior can be observed between time period 19 and 30. At time period 30 reinforcing loops start dominating the balancing loop B2.

4.2.1.3 Base Case Results

Following graphs show the system behavior with base case values

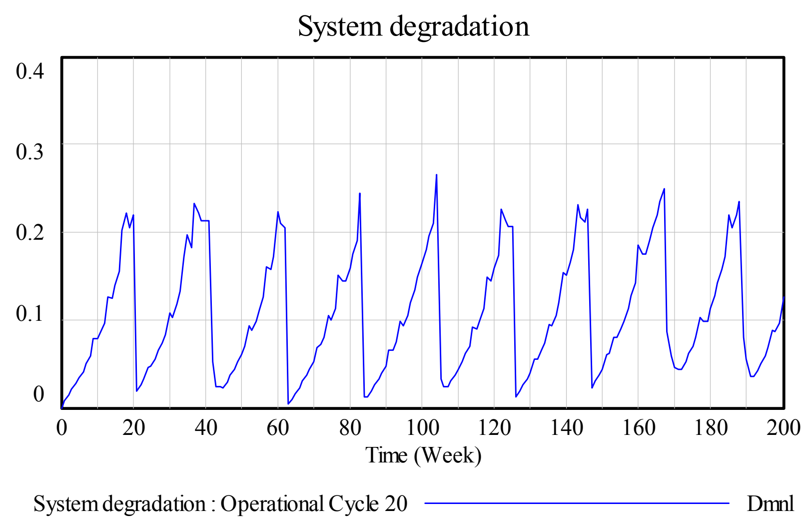


Figure 4-8 : System degradation – base case results

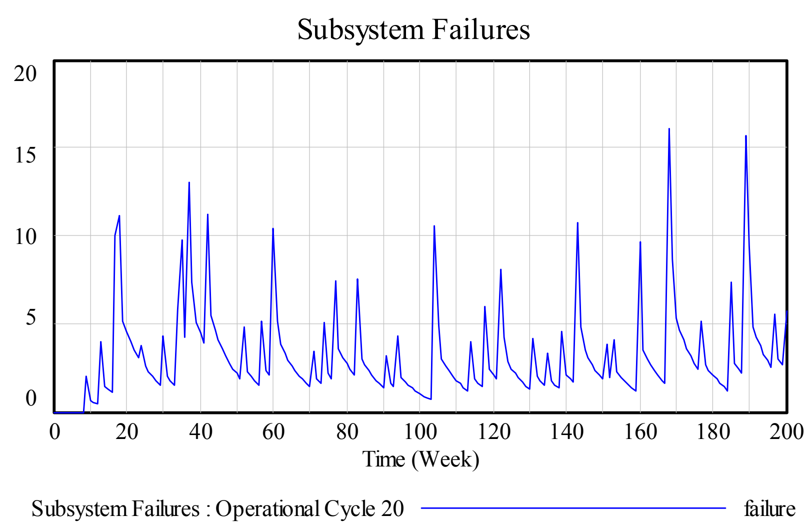


Figure 4-9 : Sub-system failures – base case results

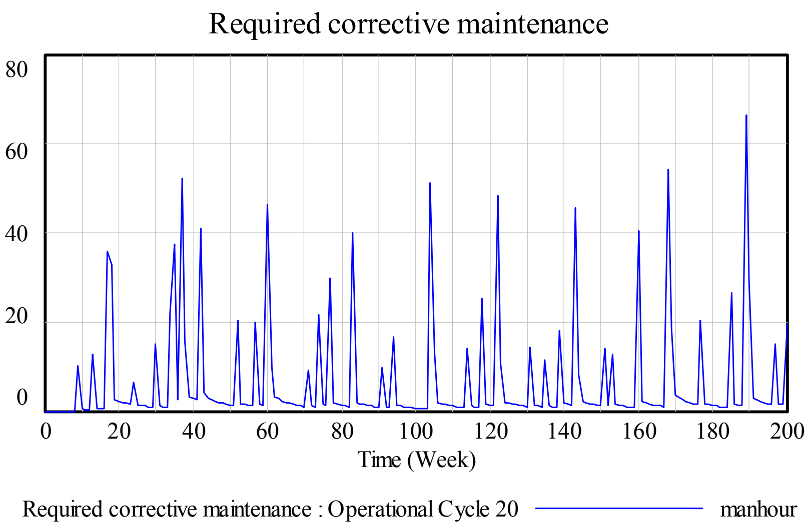


Figure 4-10 : Required corrective maintenance – base case results

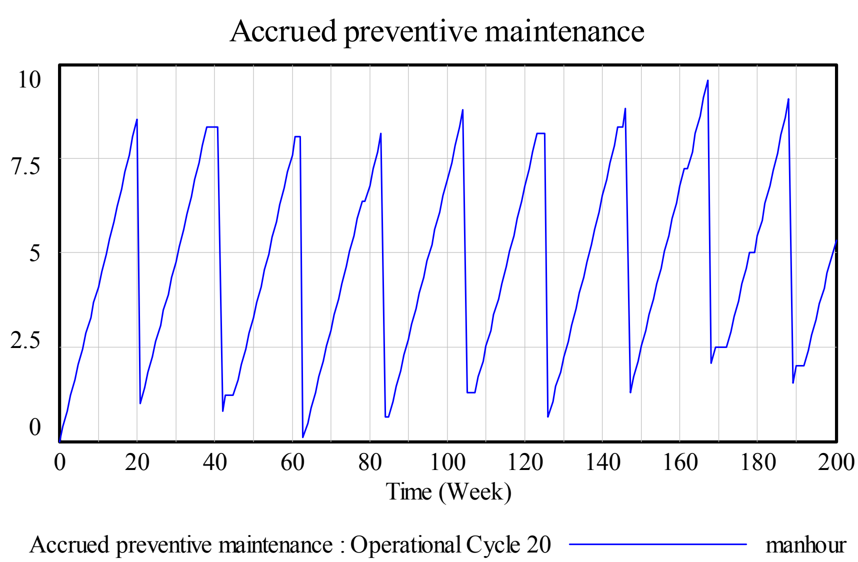


Figure 4-11 : Accrued preventive maintenance – base case results

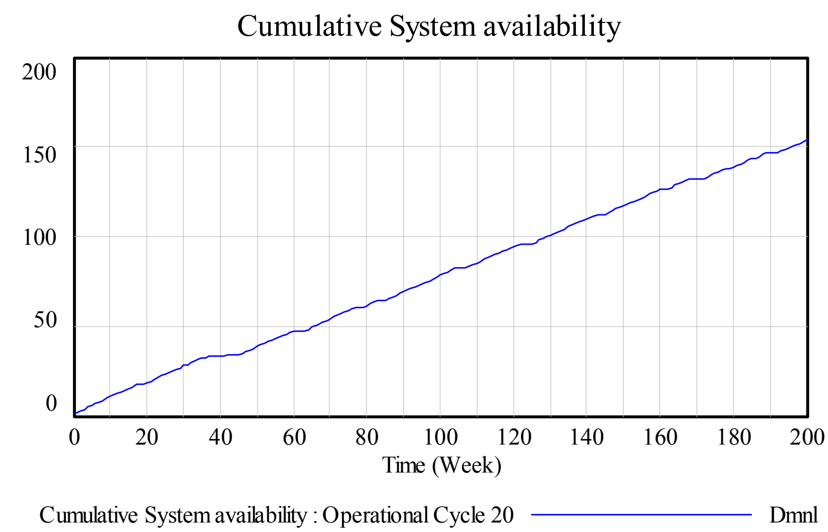


Figure 4-12 : Cumulative system availability – base case results

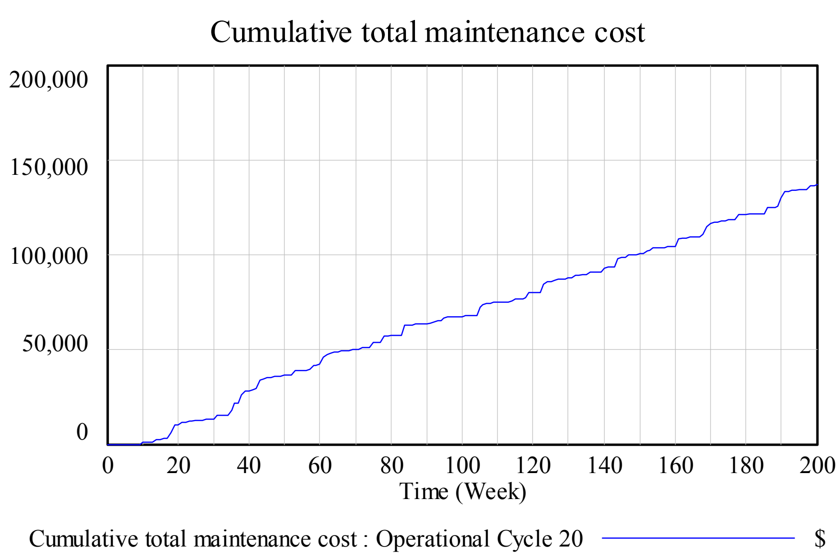


Figure 4-13 : Total cumulative maintenance cost – base case results

The above graphs show systems behavior over 200 weeks. System degradation increases exponentially until the inception of preventive maintenance cycle when it drops suddenly as the preventive maintenance is completed. The increase is system degradation is not a smooth exponential curve. Some spikes can be seen which are due to incomplete corrective maintenance. Cumulative system availability is about 155 weeks and cumulative total maintenance cost is about $140,000. The following few sections compare various scenarios.

4.2.2 Operational Cycle

The base case value for operational cycle was set to 20 weeks. Different simulation runs were conducted to compare the impact of change in operational cycle duration, in other words frequency of preventive maintenance, on the system's performance. It should be noted that available man-hours for preventive maintenance were also changed in proportion to the operational cycle time to represent the constrained maintenance capacity.
Below is the list of parameter values for this scenario.

Run Name	Operational Cycle	Maximum possible preventive maintenance per week (man-hours)
Operational Cycle 10	10 weeks	4
Operational Cycle 20	20 weeks	8
Operational Cycle 40	30 weeks	12

Table 4-2 : Operational cycle scenarios

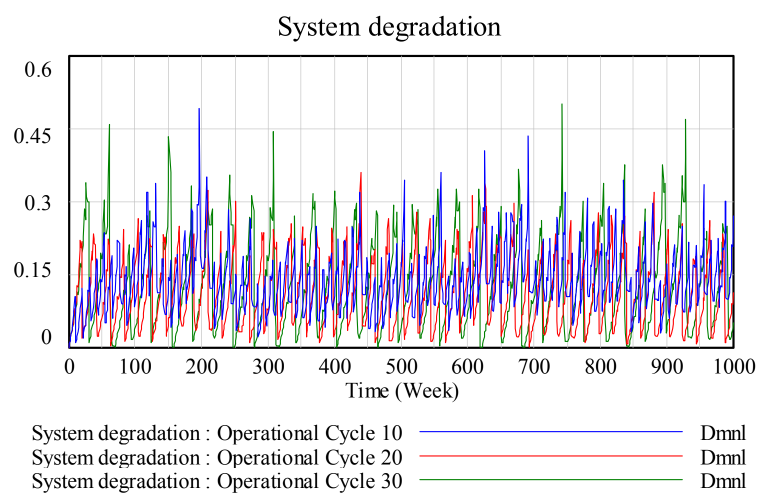


Figure 4-14 : System degradation for various operational cycles

From the above graph it can be noted that the variation in system degradation for 30 week operational cycle is very high and is certainly not desirable. The variation in system degradation decreases with decrease in operational cycle duration. The graph below shows system degradation for initial 200 weeks.

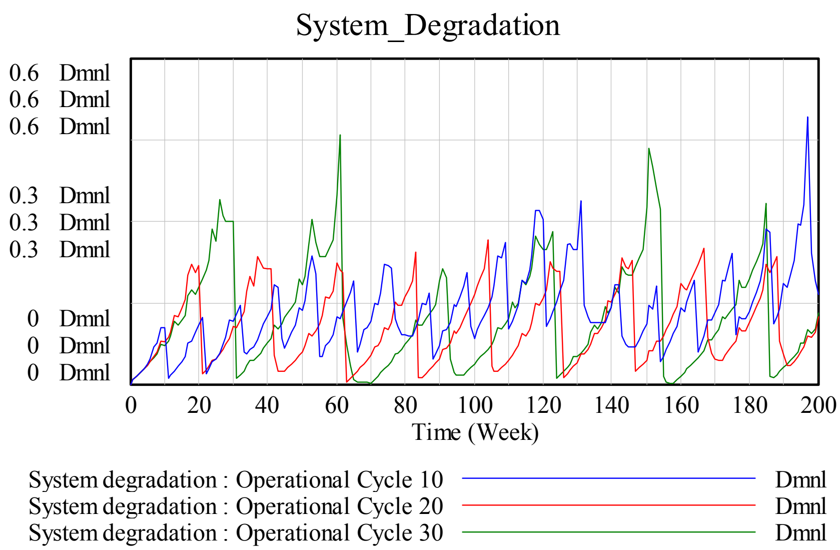


Figure 4-15 : System degradation for various operational cycle – 200 weeks

The above graph shows that even though the amplitude of variation in system degradation is smaller for 10 week operational cycle the mean system degradation is higher than that of 20 week operation cycle. Another parameter of interest is the cumulative system availability.

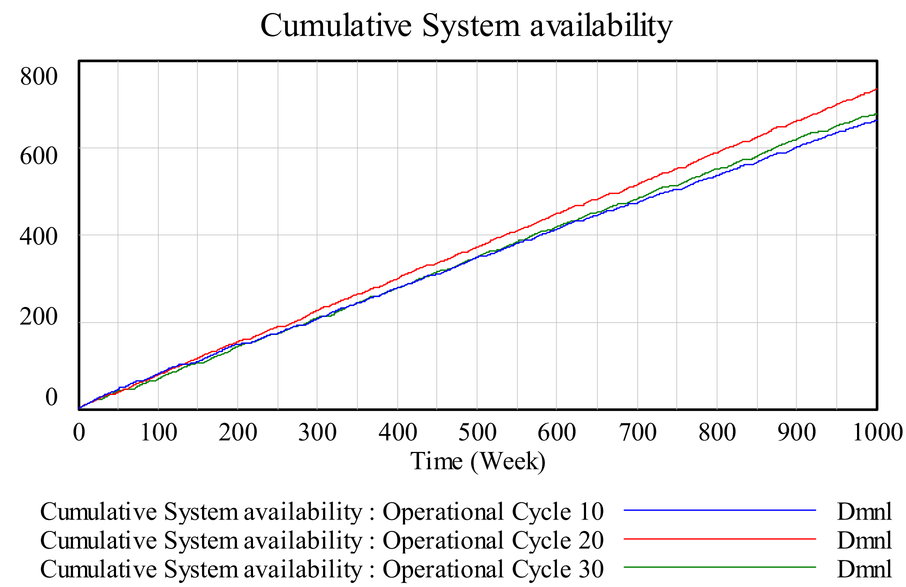
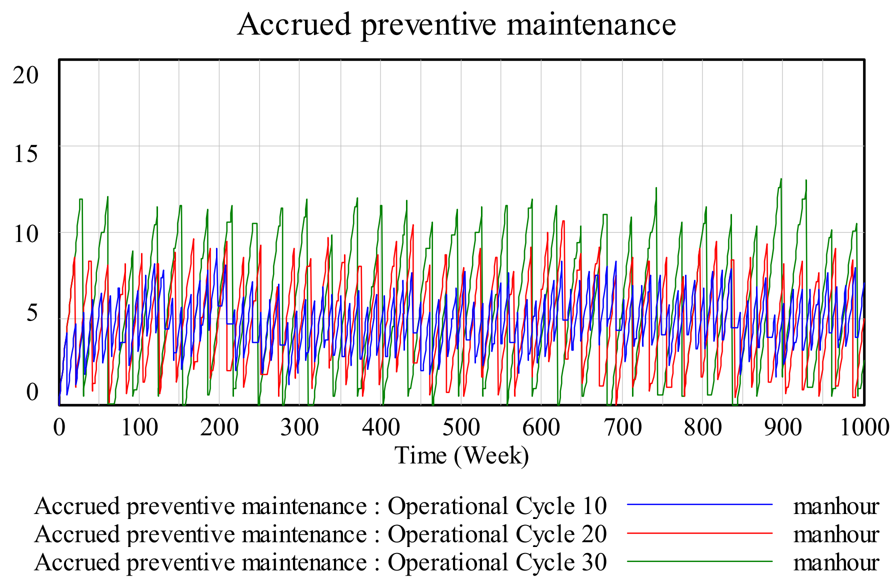


Figure 4-16 : cumulative system availability for various operational cycles

The graph of cumulative system availability shows that higher cumulative system availability can be achieved with 20 week operational cycle than with the 10 week or 30 week operational cycle. The above results are counterintuitive since one would believe that more frequent preventive maintenance would give higher system availability and lower system degradation. It can be related back to the system degradation results where system degradation for 20 week operational cycle falls below that of 10 week operational cycle. Hence it creates less failures and hence less corrective maintenance and hence less downtime.

The graph below shows accrued preventive maintenance for the above scenario.



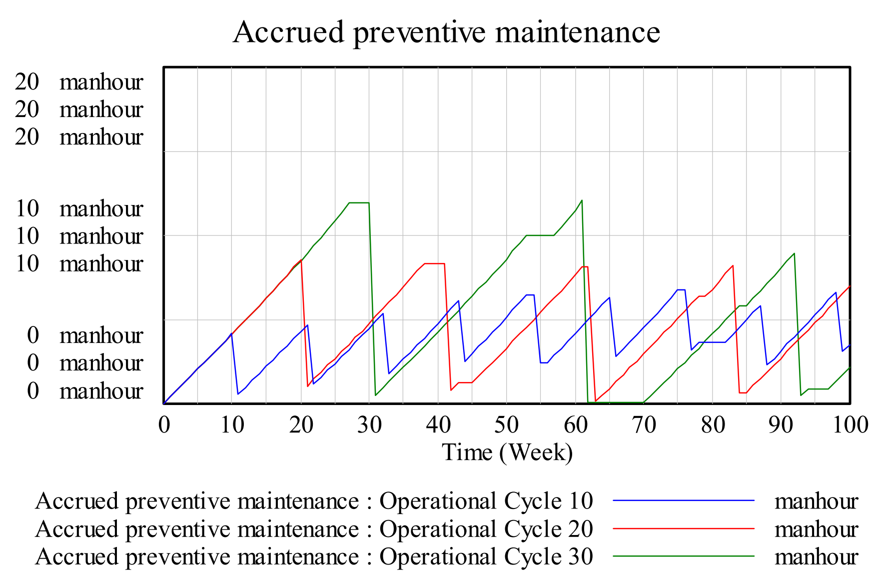


Figure 4-17 : Accrued preventive maintenance for various operational cycles

The above graph shows that with 10 week operational cycle some portion of accrued preventive maintenance never gets completed. It can be noted that this portion is higher for 10 week operational cycle than that of 20 week operational cycle. Hence 10 week operational cycle shows higher mean system degradation as compared to 20 week operational cycle.

The flat potions on the accrued preventive maintenance curves are observed when the system is not operational.

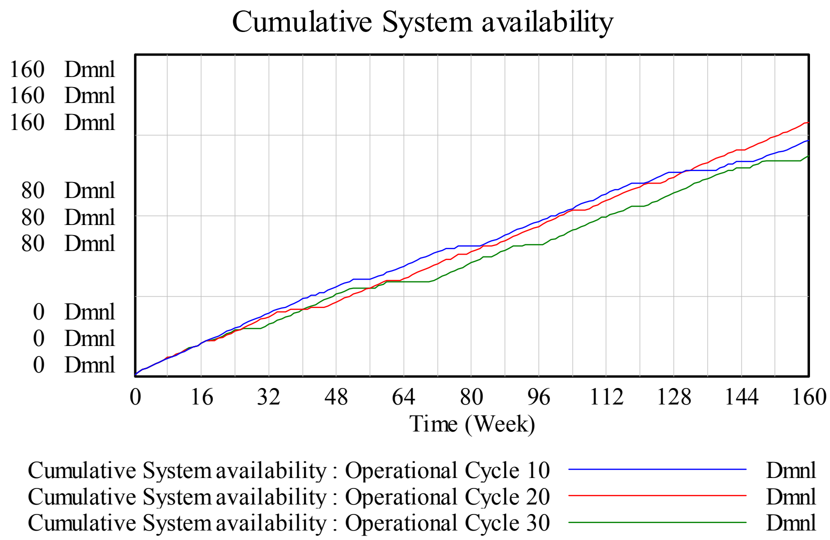


Figure 4-18 : Point of inflection - cumulative system availability

The above graph shows that until week 130, 10 week operational cycle shows higher cumulative system availability than that of 20 week operational cycle. As explained above the mean deferred preventive maintenance for 20 week operational cycle is less than 10 week operational cycle. Hence after week 130 cumulative system availability for 10 week operational cycle increases at slower rate than that of 20 week operational cycle. Hence the cumulative system availability over 1000 week period with 20 week operational cycle is greater than the other two scenarios.

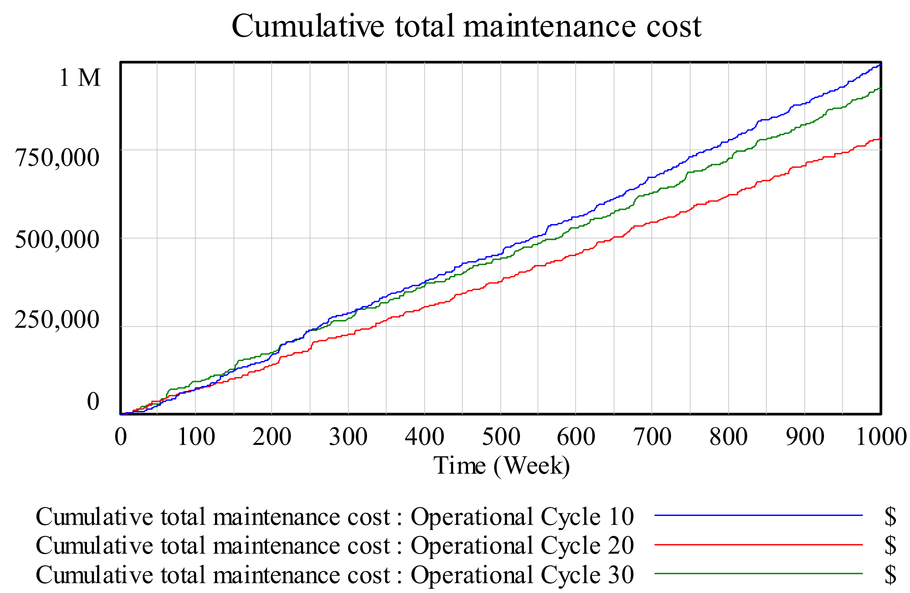


Figure 4-19 : Cost performance for various operational cycles

It can also be noted that the cumulative total maintenance cost for the scenario with operational cycle 20 weeks is lower than the other two scenarios.

Various other scenarios with operational cycle value close to 20 weeks were run to identify the optimal value (Please refer to Appendix A for graphs). Based on those results, it was observed that 20 week operational cycle results into optimal performance under the given constraints and assumptions.

4.2.3 Load factor

Load factor is another important variable which is believed to have significant impact on the system performance. Load factor of 1 represents that the system is operated in prescribed operational conditions and for the prescribed time. Higher load factor means that the system is operated for either longer time or in the harsher operational conditions. In certain situations, mission critical systems such as weapon systems have to be continuously operated for longer duration than prescribed and hence they degrade at the higher rate. Three simulation runs were conducted with load factors of 0.8, 1 and 1.5. All other parameters are set to the base case values. The graphs below show simulation output for such scenarios.

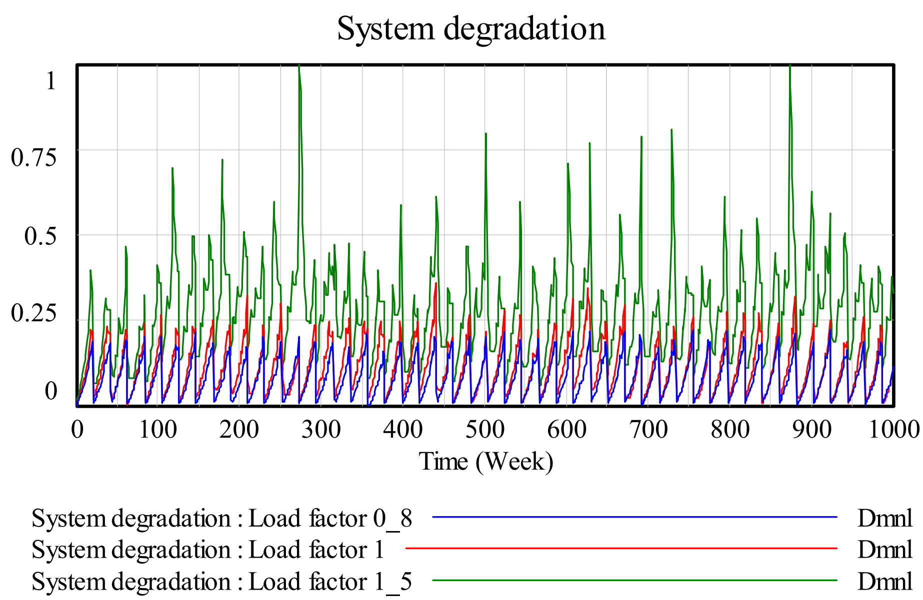


Figure 4-20: System degradation at various load factors

The level of system degradation increases with increase in load factor. This phenomenon is consistent with the mental models of the decision makers. Numerous spikes in system degradation were seen with load factor of 1.5. Most of these spikes can be attributed to the critical failures which are highly undesirable.

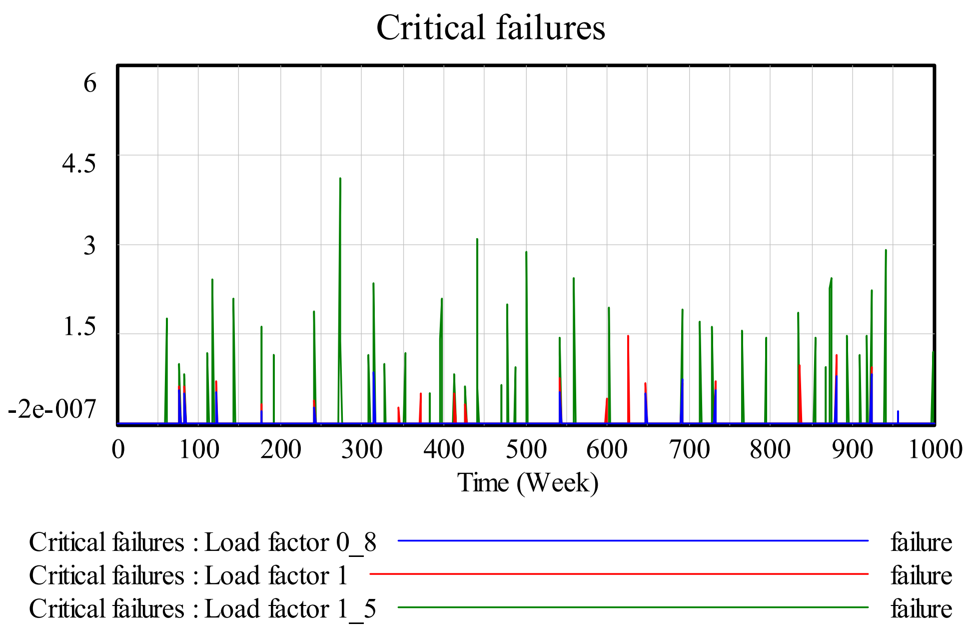


Figure 4-21 : Critical failures at various load factors

Also higher accrued preventive maintenance and higher required corrective maintenance is observed with higher load factor.

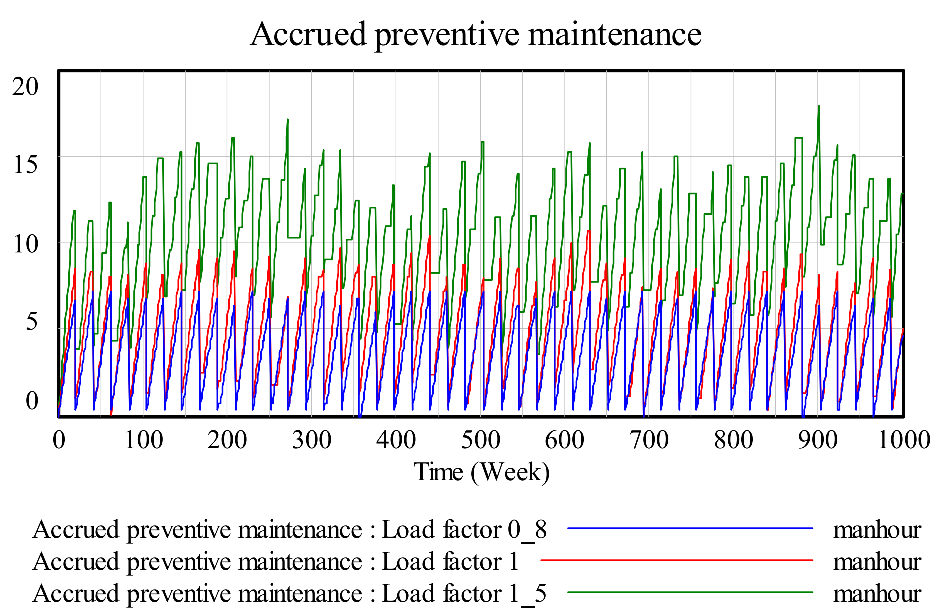


Figure 4-22 : Accrued preventive maintenance at various load factors

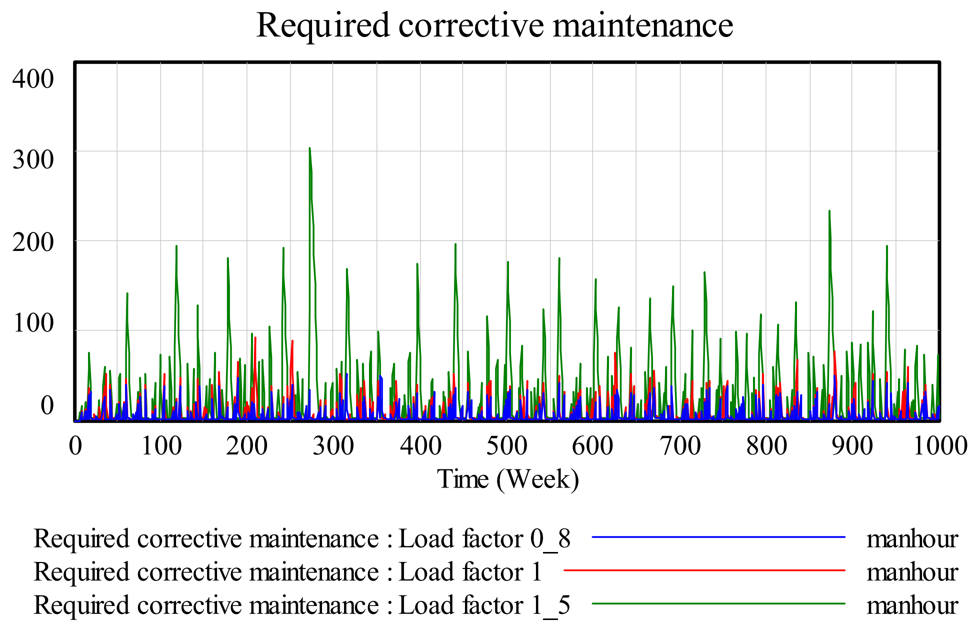
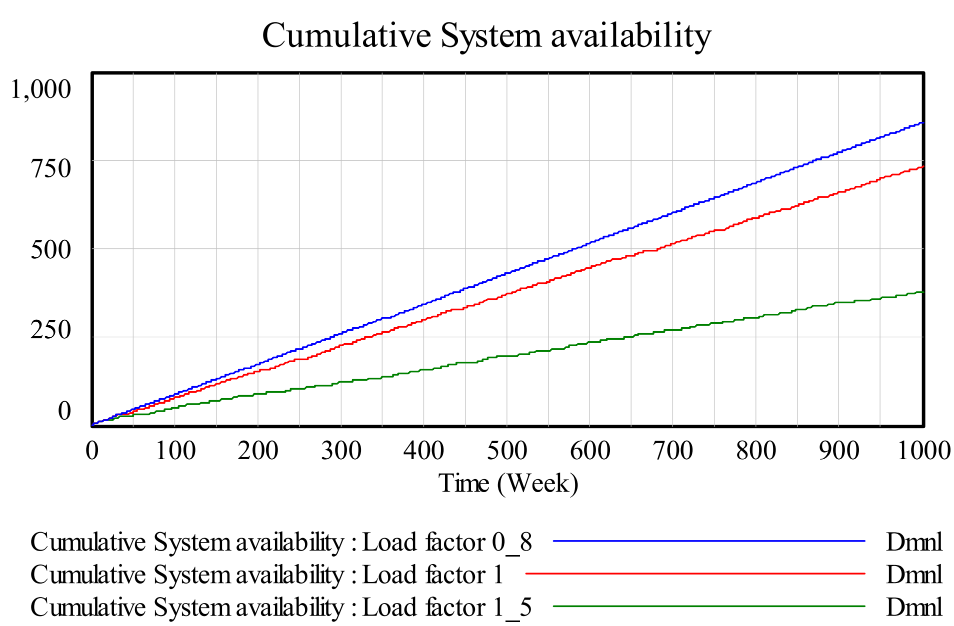


Figure 4-23 : Required corrective maintenance at various load factors

As a result of higher system degradation, and higher preventive and corrective maintenance requirements at higher load factor, system availability is lower and cumulative total maintenance cost is higher.



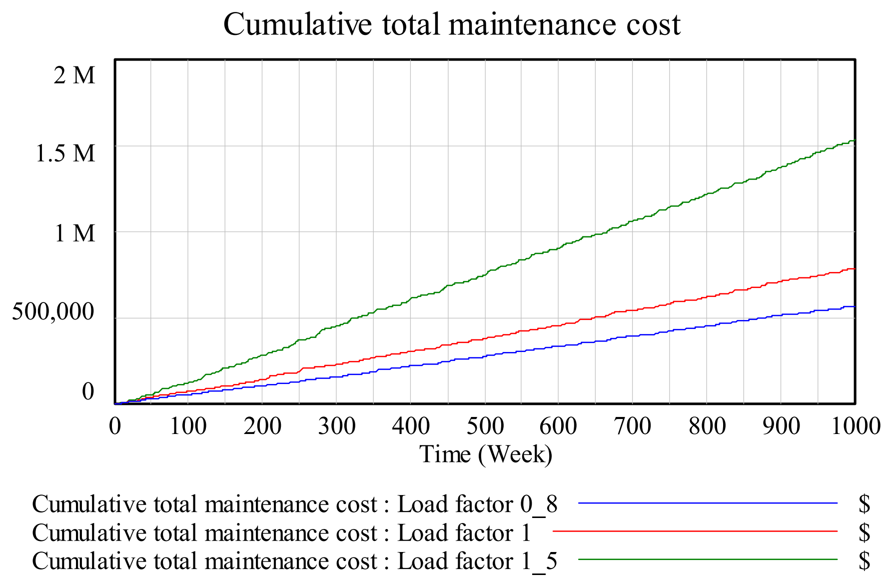


Figure 4-24 : Cost and availability performance at various load factors

4.2.4 Load factor and operational cycle

The other three scenarios were run with different load factors in order to determine the consistency of results and gain more insights into the behavior. Following table lists the parameter values for these scenarios

Run Name	Load Factor	Operational Cycle	Maximum possible preventive maintenance per week (man-hours)
Load_0_6_OC_10	0.6	10	2.4
Load_0_6_OC_20		20	4.8
Load_0_6_OC_30		30	7.2
Load_0_6_OC_40		40	9.6
Load_1_OC_10	1	10	4
Load_1_OC_20		20	8
Load_1_OC_30		30	12
Load_1_5_OC_5	1.5	5	3
Load_1_5_OC_15		15	9
Load_1_5_OC_20		20	12

Table 4-3 : Load factor and operational cycle scenarios

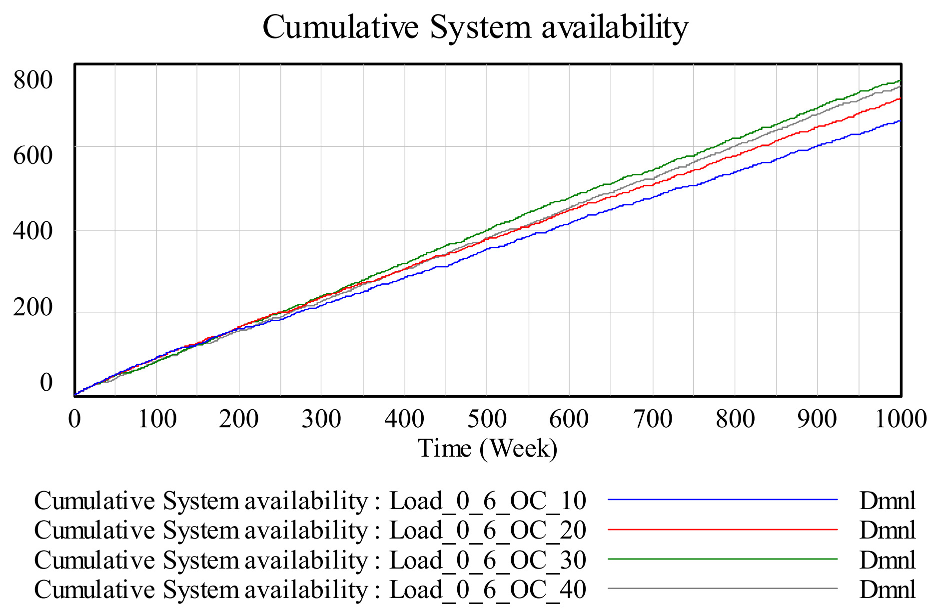


Figure 4-25 : Availability performance at load factor 0.6

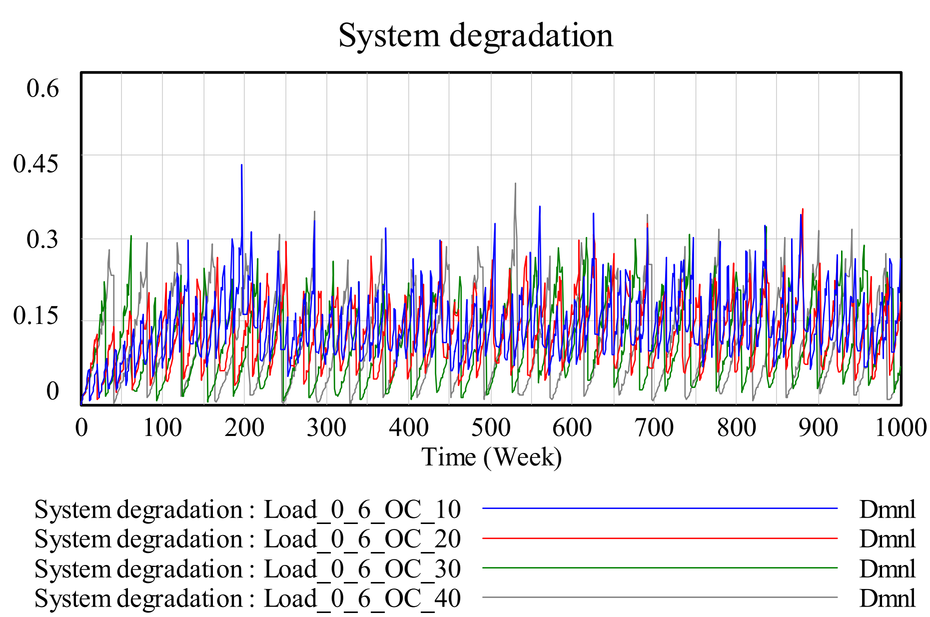


Figure 4-26 : System degradation at load factor 0.6

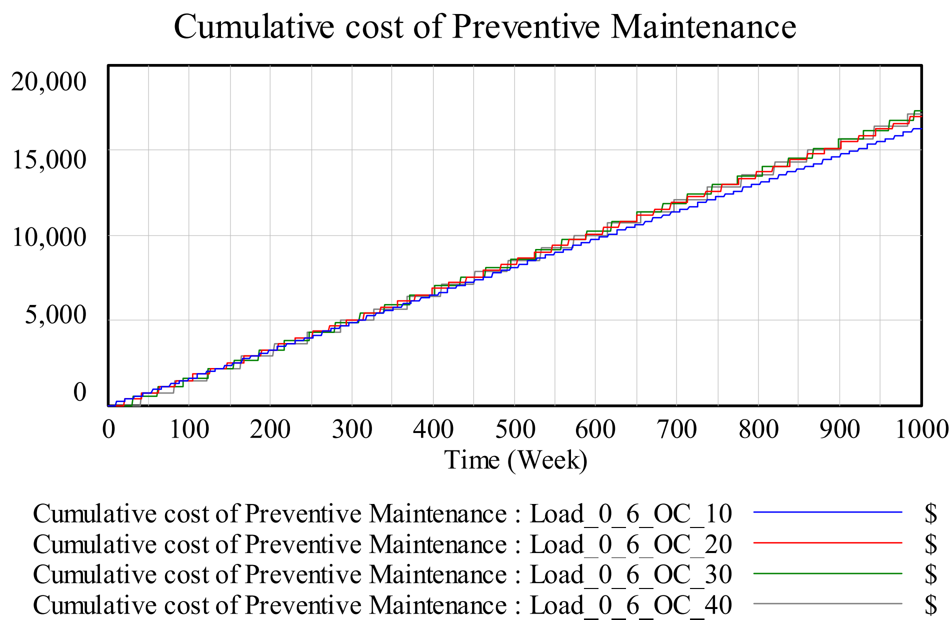


Figure 4-27 : Preventive maintenance cost at load factor 0.6

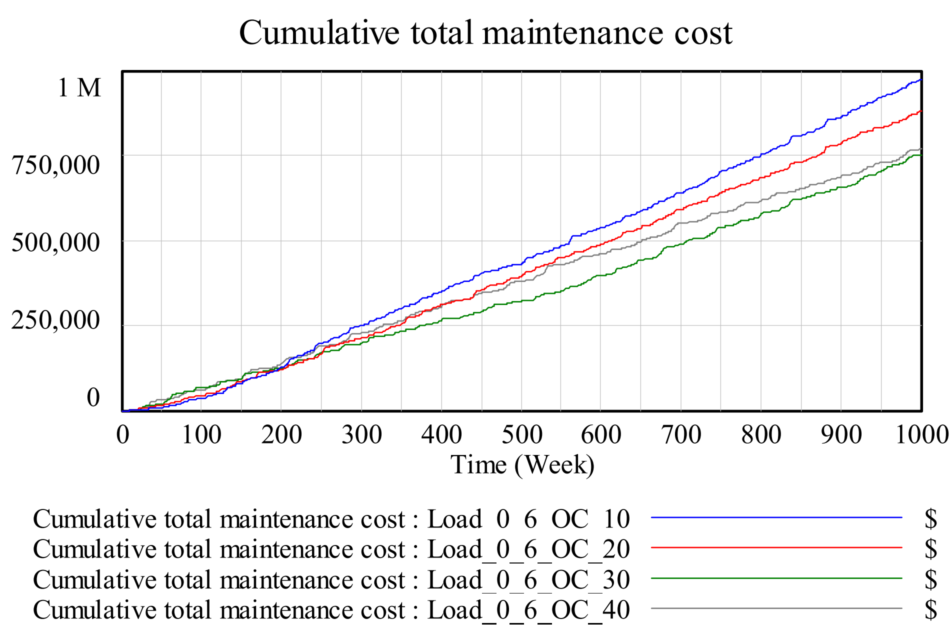


Figure 4-28 : Total cumulative maintenance cost at 0.6

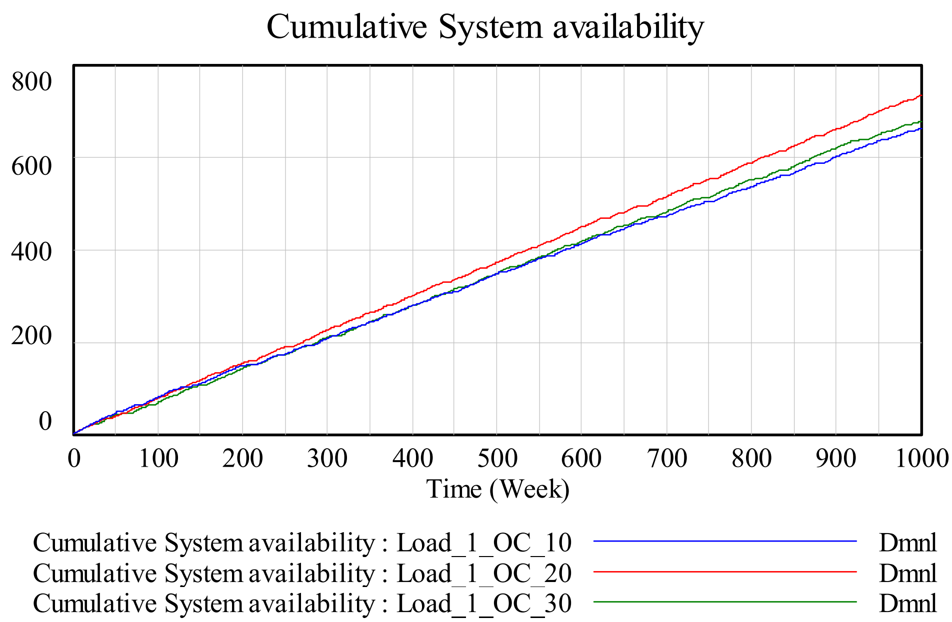


Figure 4-29 : Availability performance at load factor 1

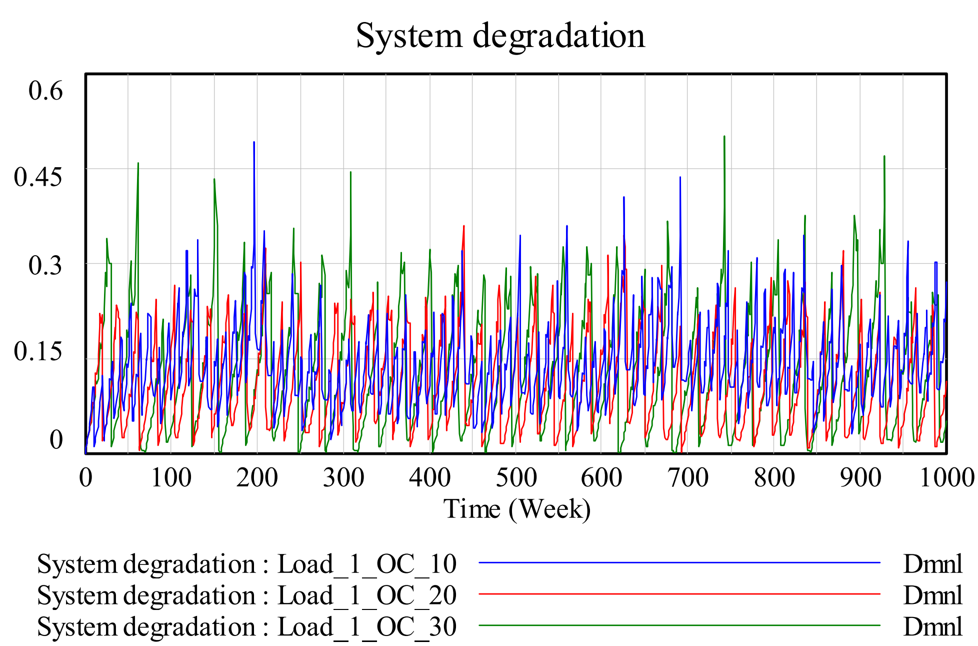


Figure 4-30 : System degradation at load factor 1

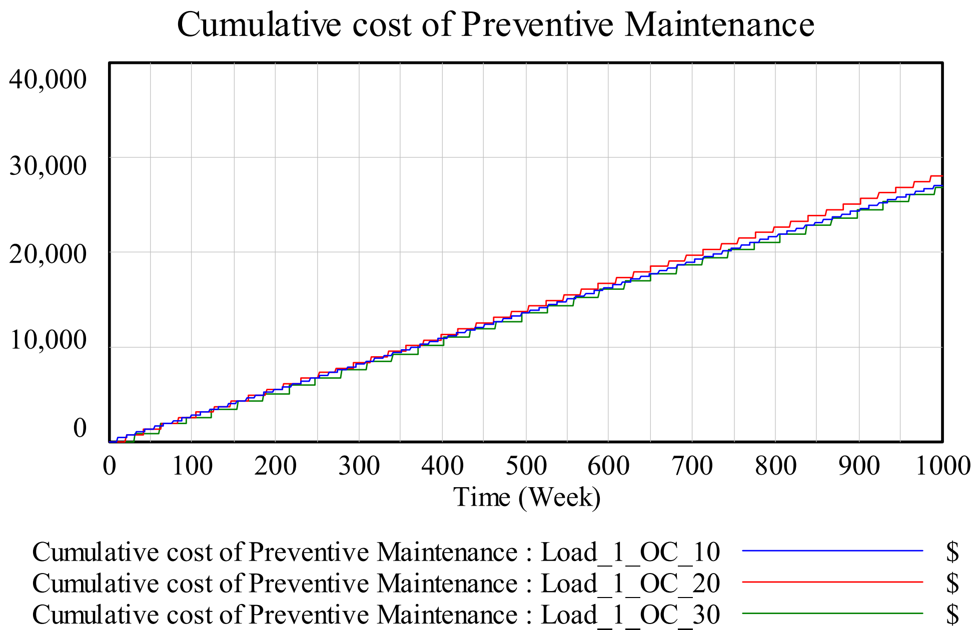


Figure 4-31 : Cumulative preventive maintenance cost at load factor 1

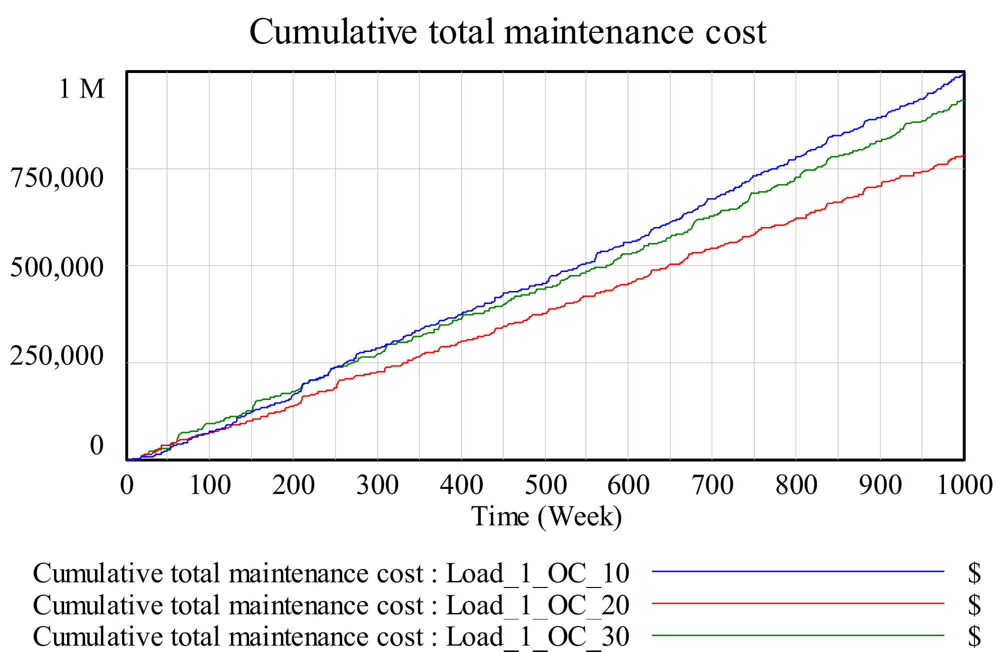


Figure 4-32 : Cumulative total maintenance cost at load factor 1

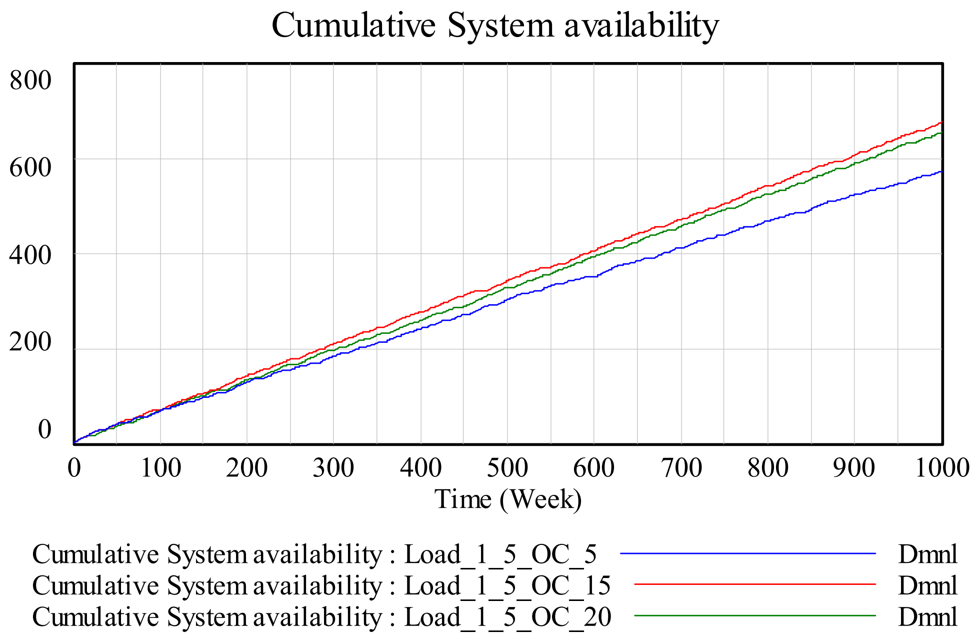


Figure 4-33 : Availability performance at load factor 1.5

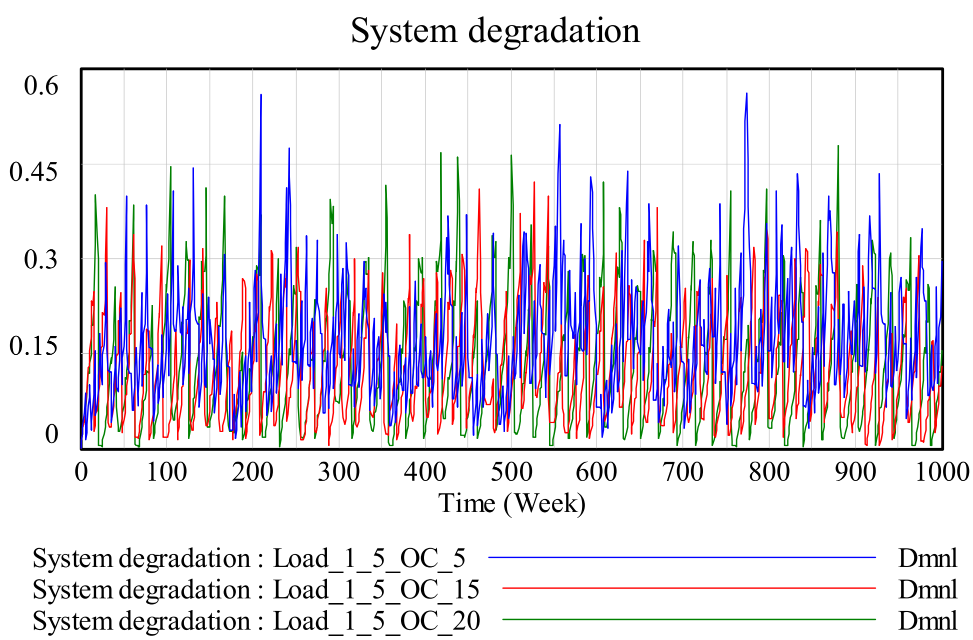


Figure 4-34 : System degradation at load factor 1.5

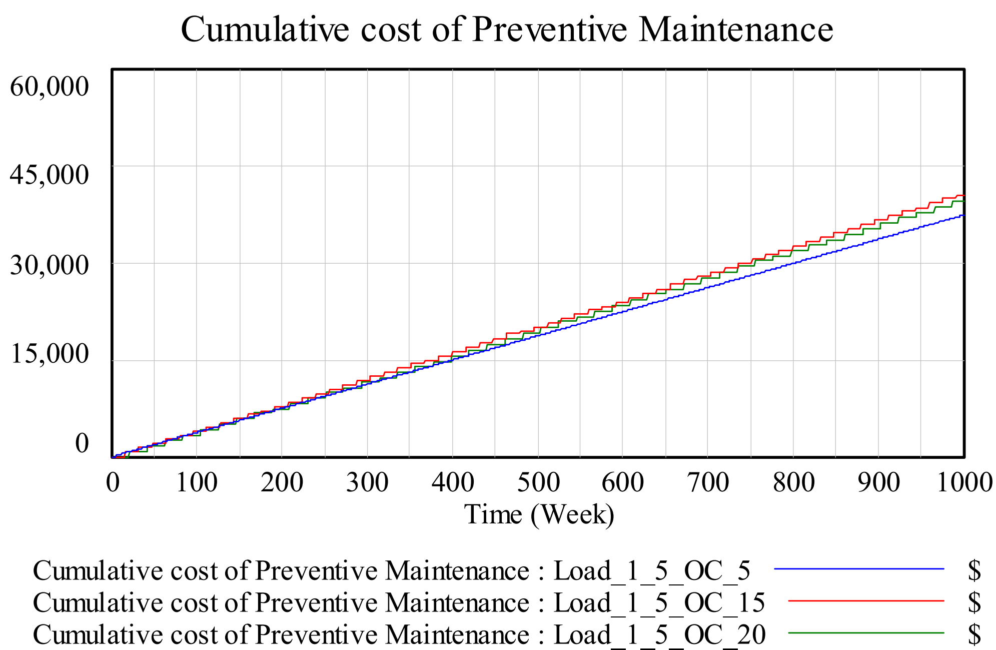


Figure 4-35 : Cumulative preventive maintenance cost at load factor 1.5

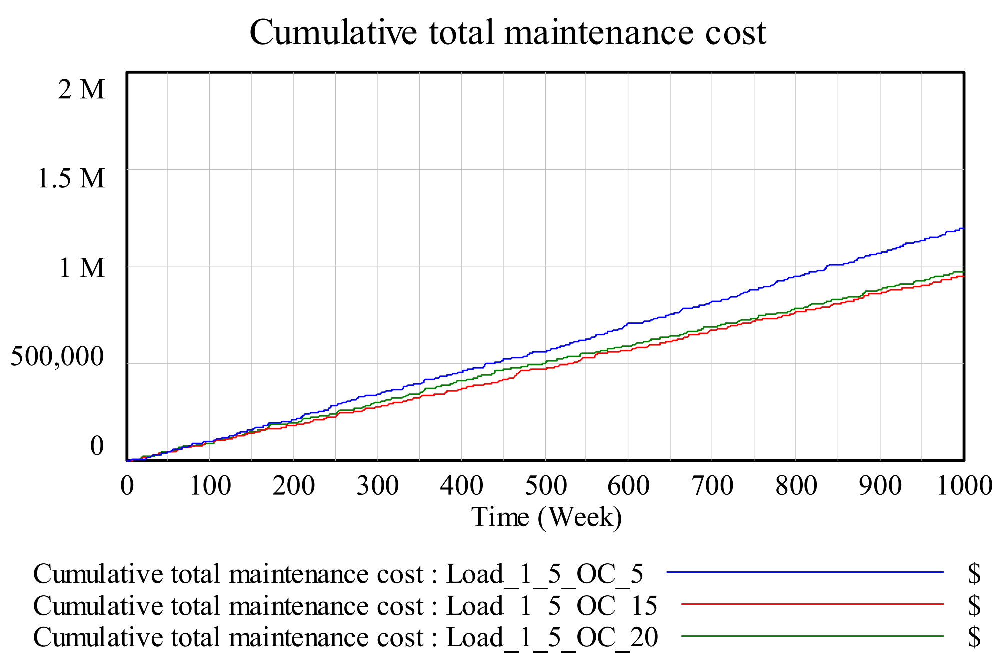


Figure 4-36 : Total cumulative maintenance cost at load factor 1.5

Based on the observations from the above three scenarios it can be noted that for each load factor there exists an optimal level of operational cycle i.e. preventive maintenance interval given the capacity constraints and the assumptions listed in chapter 3. It should also be noted that the cost of preventive maintenance is almost constant in each scenario and hence the difference in cumulative total maintenance cost among different scenarios is governed by the corrective maintenance. The table below summarizes the results from the above discussed scenarios.

Load factor	Optimal Operational Cycle
0.6	30 weeks
1	20 weeks
1.5	15 weeks

Table 4-4 : Summary of load factors and corresponding optimum operational cycle

Higher load factor demands more frequent preventive maintenance as compared to the lower load factors but as mentioned in the discussion above there exists an optimal level of operational cycle for each load factor. (For graphical results from the related simulations runs, please refer to appendix A)

4.3 Hypothesis Testing

Hypothesis 1 - Frequent periodic preventive maintenance improves system performance by reducing system degradation and increasing availability over time

This hypothesis was tested at various load factors by changing the operational cycle from 10 weeks to 40 week. The results indicate that highly frequent preventive maintenance and less frequent preventive maintenance results into lower cumulative system availability and higher system degradation in the light of given capacity constraints and assumptions. Thus the results of this model overturn the traditional mental models that we possess and encourage us to investigate system structure in more detail.

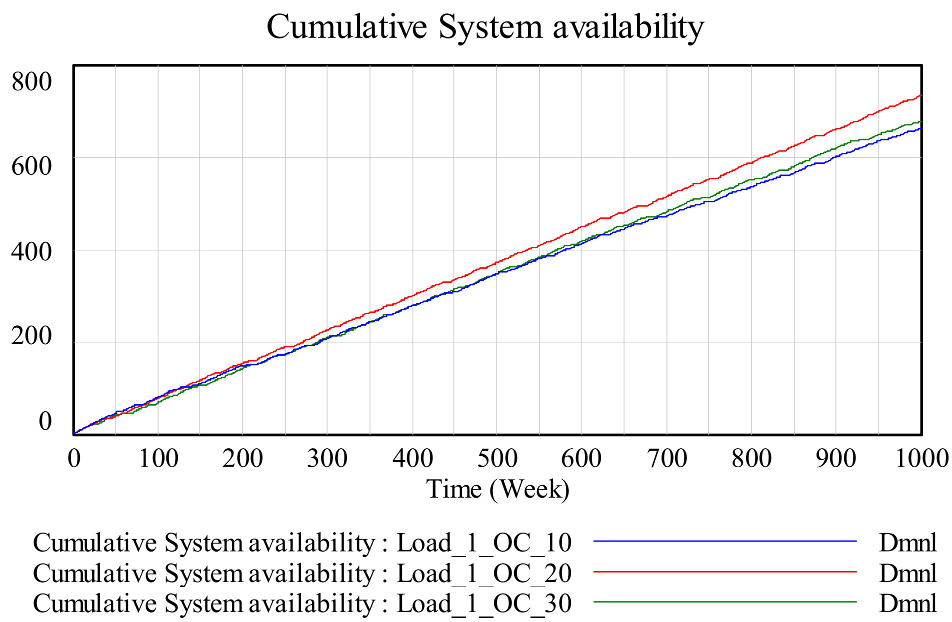


Figure 4-37 : Cumulative system availability at various operational cycles

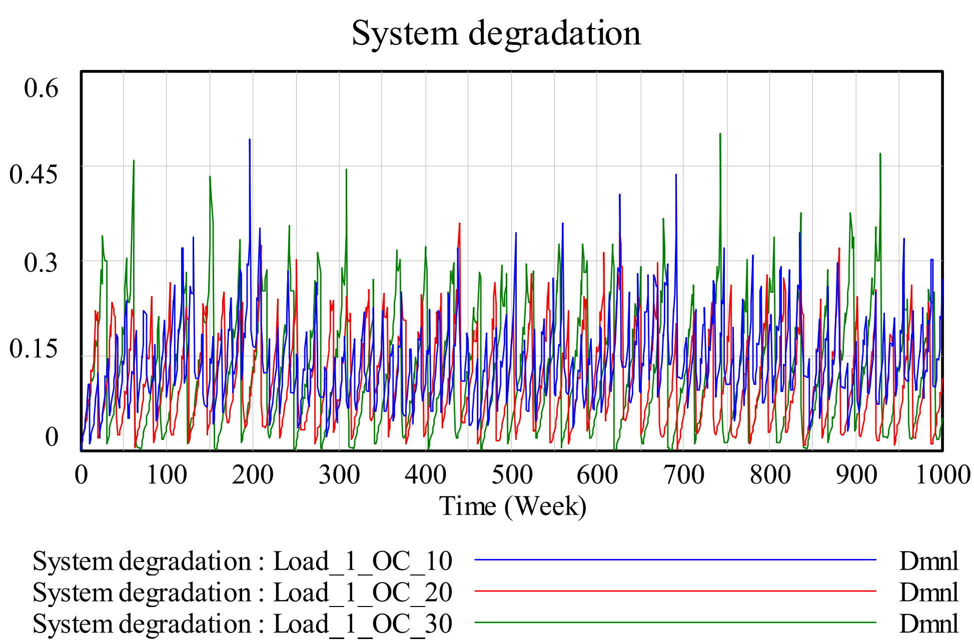


Figure 4-38 : System degradation at various operational cycles

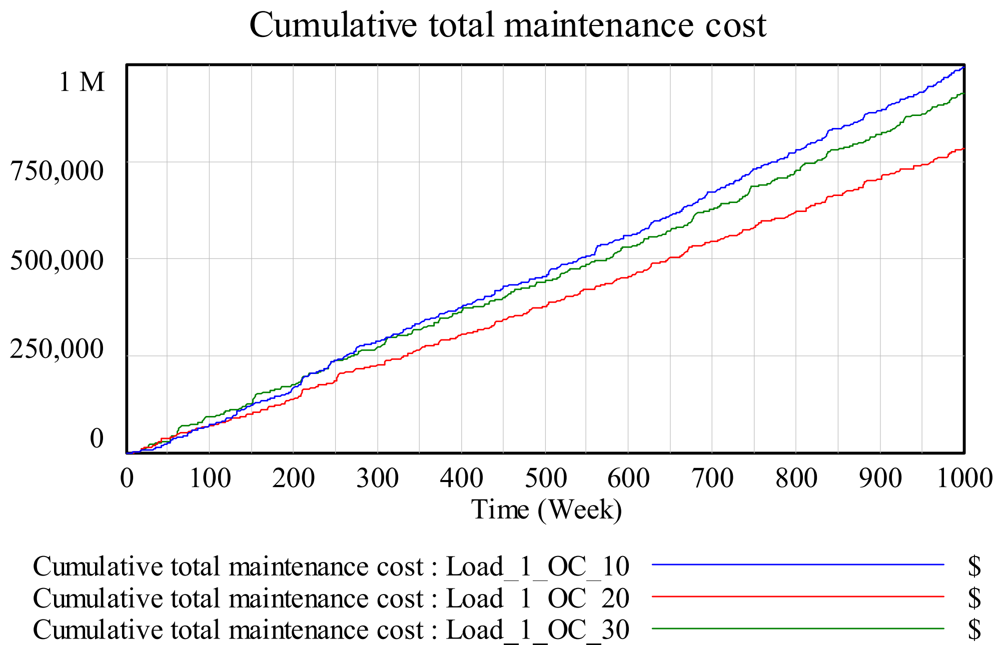


Figure 4-39 : Cumulative total maintenance cost at various operational cycles

It should be noted that the numerical values obtained from the above graphs are relative to the input values. These values may change for specific technology, hence are only representative of the phenomenon in this context.

Hypothesis 2 - Increase in load factor increases system degradation, maintenance cost and decreases system availability under constrained preventive maintenance capacity over time

The section 4.2.3 discusses the scenario with different load factors. The simulations results support the hypothesis that under limited maintenance capacity higher load factor increases system degradation and maintenance cost and decreases system availability over time.

4.4 Sensitivity Analysis

The model must be tested for robustness of the conclusions to uncertainty in the assumptions. One of the important assumptions in the model is that the maximum corrective and preventive maintenance that can be performed in a week that is maintenance capacity is constant. But in actual practice, there is some level of uncertainty associated with these factors. The sensitivity analysis was done for analyzing the impact of uncertainty in these values on the system's behavior.

There are three types of sensitivities: numerical, behavior mode and policy sensitivity. The type of sensitivity depends on the purpose of the model. For most purposes behavior mode sensitivity and policy sensitivity are important (Sterman, 2000).

Ideally it is desirable to conduct a comprehensive sensitivity analysis which requires testing of all combinations of assumptions over their plausible range of uncertainty. But given the resource constraints, sensitivity analysis should focus on the influential parameters.

The policy sensitivity analysis was performed for the uncertainty in maximum corrective and preventive maintenance that can be performed in a week. This analysis was done for different operational cycles.

Sensitivity analysis was conducted using standard feature provided in Vensim DSS 5.4a simulation software. The multivariate sensitivity analysis generates the dynamic confidence bounds which represent envelop of values in a sample of simulations and not a particular trajectory.

Operational Cycle 10

Model assumes that the maximum preventive maintenance per week is 4 man-hours with 10 week operational cycle. Maximum possible preventive maintenance per week is assumed to be distributed normally and independently with standard deviation of 12.5% of its base case value.

Maximum possible preventive maintenance per week =

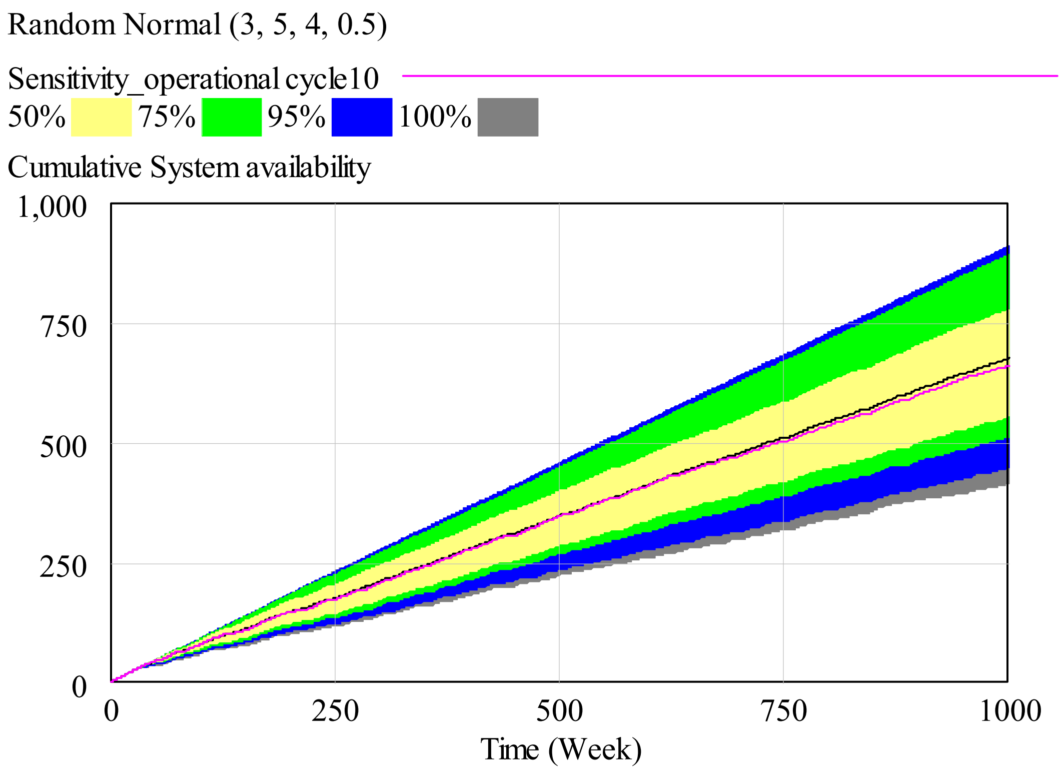


Figure 4-40 : Sensitivity analysis results with uncertainty in preventive maintenance capacity for 10 week operational cycle

The above graph shows that there is 75% chance that the cumulative system availability over 1000 week cycle will be between 510 and 890, 95% chance that it will be between 445 and 909. The mean at week 1000 is 673.

It should be noted that there is also some level of uncertainty involved in the maximum available man-hours for corrective maintenance. In order to account for this uncertainty, maximum available man-hours for corrective maintenance was assumed to be normally distributed with a mean of 36 man-hours, minimum of 30 man-hours and maximum of 40 man-hours. The standard deviation was set as 10% of maximum man-hours available. These particular values were selected for the analysis based on the assumption that maximum of 40 man-hours of corrective maintenance can be performed in a week and there is a chance that as low as 30 man-hours are available during certain week.

Maximum possible preventive maintenance per week = Random Normal (3, 5, 4, 0.5)

Maximum available man-hours for corrective maintenance = Random Normal (30, 40, 36, 4)

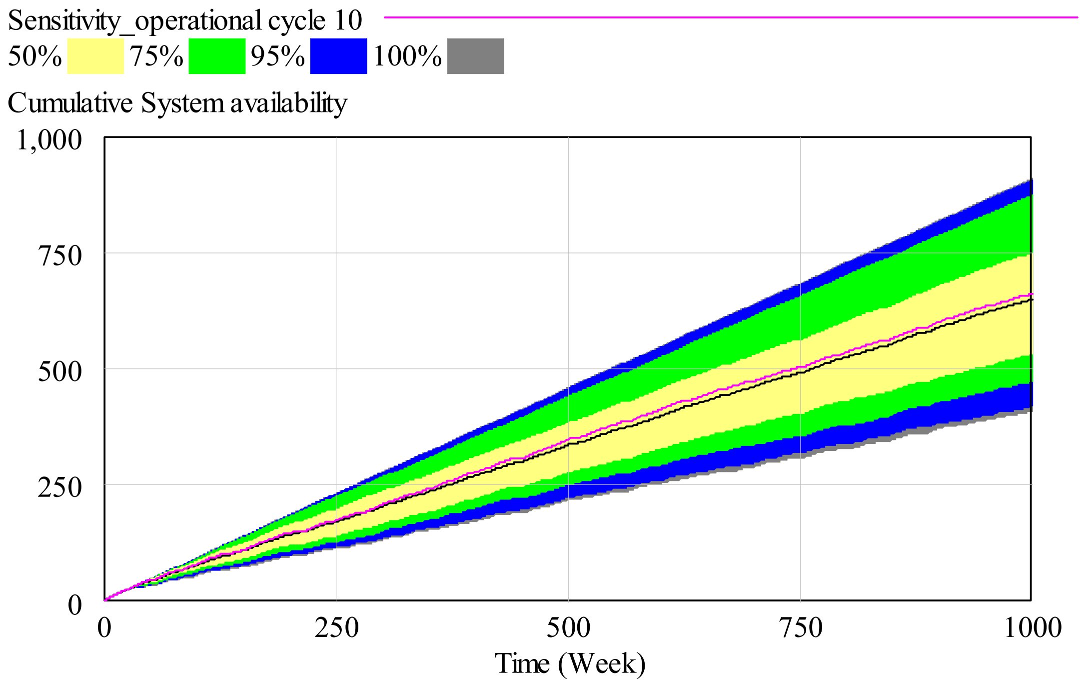


Figure 4-41 : Sensitivity analysis results with uncertainty in preventive and corrective maintenance capacity for 10 week operational cycle

The above graph shows that there is a 75% chance that the cumulative availability will vary between 471 and 872, and 95% chance that it will vary between 419 and 906. The mean at 1000 week is 649. These intervals are wider and also the mean is considerably lower than the one discussed above.

Operational Cycle 20

With 20 week operational cycle, the model assumes that maximum possible preventive maintenance is 8 man-hours. It was assumed to be distributed normally with standard deviation of 12.5% of the base case value.

Maximum possible preventive maintenance per week = Random Normal (6, 10, 8, 1)

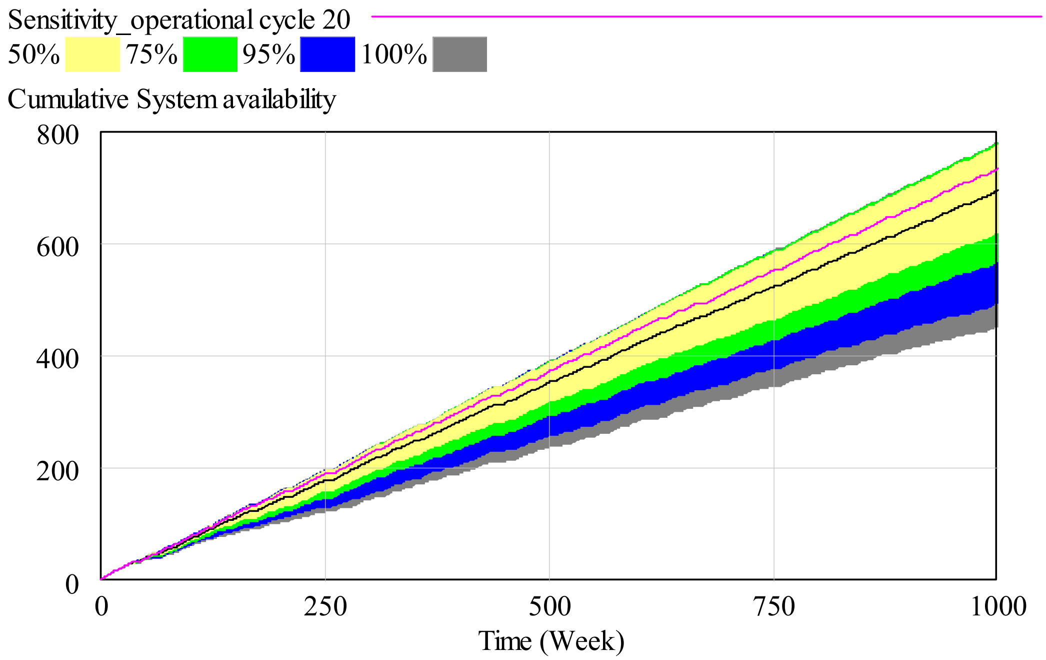


Figure 4-42 : Sensitivity analysis results with uncertainty in preventive maintenance capacity for 20 week operational cycle

The graph above shows that there is 75% chance that the cumulative system availability would vary between 560 and 780 and 95% chance that it would vary between 490 and 780. The mean at week 1000 is around 692.

The uncertainty in maximum corrective maintenance increases the variation is response on the lower side of mean value as shown in the graph below.

Maximum possible preventive maintenance per week = Random Normal (6, 10, 8, 1)

Maximum available man-hours for corrective maintenance = Random Normal (30, 40, 36, 4)

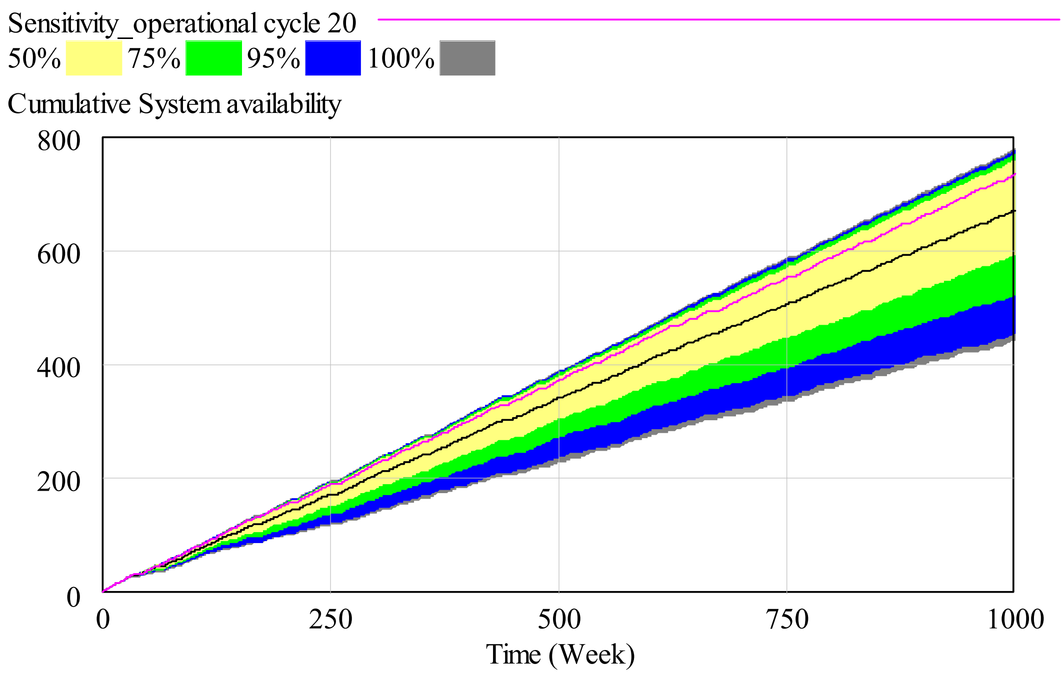


Figure 4-43 : Sensitivity analysis results with uncertainty in preventive and corrective maintenance capacity for 20 week operational cycle

There is a 75% chance that the cumulative system availability will vary between 522 and 768 and 95% chance that it will vary between 454 and 775. The mean at 1000 week is 670. It should be noted that these intervals are wider and the mean is lower than the case discussed above where only uncertainty was in maximum preventive maintenance.

Operational Cycle 40

With the operational cycle of 40 weeks, it was observed that the variation in cumulative system availability due to uncertainty in maximum possible preventive maintenance is not as severe as with the two cases discussed above.

Maximum possible preventive maintenance per week = Random Normal (12, 20, 16, 2)

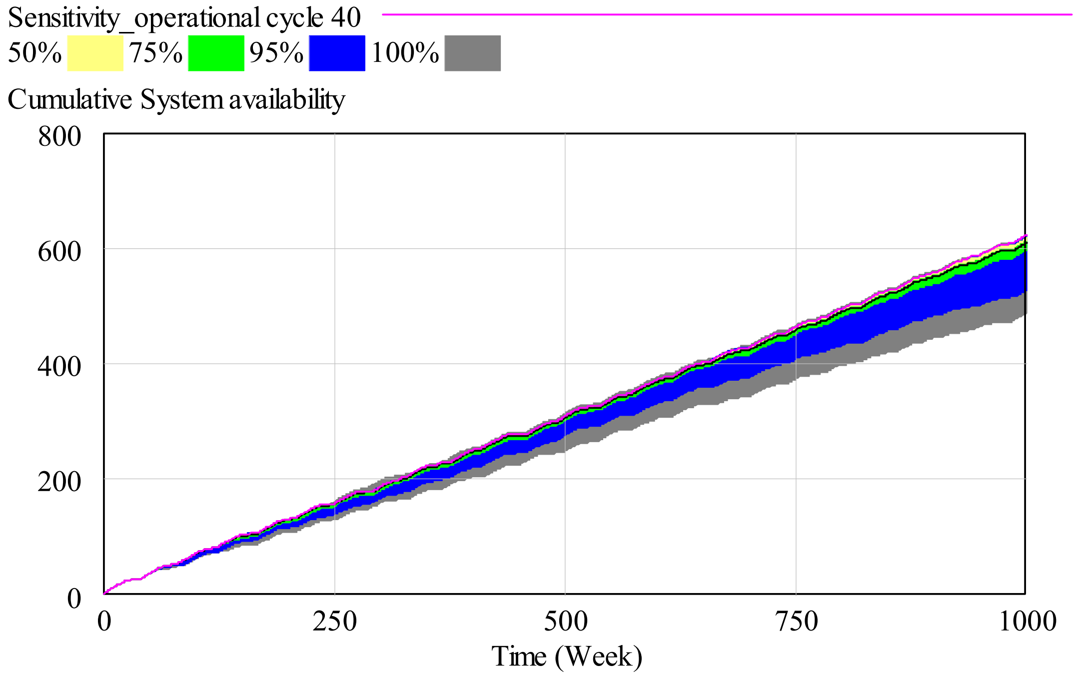


Figure 4-44 : Sensitivity analysis results with uncertainty in preventive maintenance capacity for 40 week operational cycle

The graph above shows that there 75% chance that the cumulative system availability would vary between 594 and 621, and 95% chance that it will vary between 525 and 621 over 1000 weeks. At week 1000 the mean is 609.

Maximum possible preventive maintenance per week = Random Normal (12, 20, 16, 2)

Maximum available man-hours for corrective maintenance = Random Normal (30, 40, 36, 4)

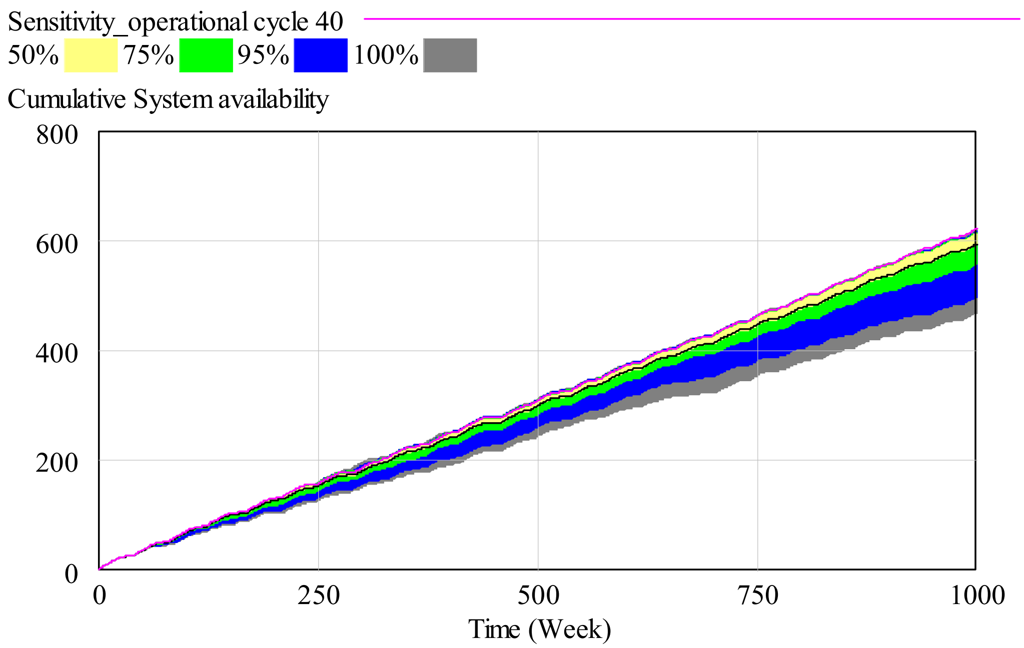


Figure 4-45 : Sensitivity analysis results with uncertainty in preventive and corrective maintenance capacity for 40 week operational cycle

Uncertainty in maximum corrective maintenance widens the distribution of response. In other words it increases the variability in the response. In the above curve it can be seen that there is a 75% chance that the cumulative system availability will vary between 556 and 615 and 95% chance that it will vary between 496 and 617. The mean at 1000 week is 594 which is marginally less than 609 observed with uncertainty only in maximum preventive maintenance.

The table below shows the summery of the analysis discussed above

Scenario	Uncertainty in													
	Maximum Preventive Maintenance							Maximum Preventive and Corrective Maintenance						
	CI 75%			CI 95%			Mean	CI 75%			CI 95%			Mean
	Min	Max	Width	Min	Max	Width		Min	Max	Width	Min	Max	Width	
Operational Cycle 10	510	890	380	445	909	464	673	471	872	401	419	906	487	649
Operational Cycle 20	560	780	220	490	780	290	692	522	768	246	454	775	321	670
Operational Cycle 40	594	621	27	525	621	96	609	556	615	59	496	617	121	594

Table 4-5 : Summary of sensitivity anaysis

From the above table it can be noted that the mean cumulative system availability for 20 week operational cycle is always greater than that of 10 week or 40 week operational cycle. Also it should be noted that confidence interval is narrower for operational cycle 20 than that of operational cycle 10.

Operational cycle 40 exhibits much smaller variation than the other two cases but the mean cumulative availability is also considerably less than the other two cases. Thus though the variability in response due to uncertainty in maximum preventive and corrective maintenance is smaller, this scenario is not desirable due to smaller mean values.

4.5 Testing Validation and Verification

Testing, validation and verification is inevitable part of any modeling process. These processes help modelers and other stakeholders build confidence in the appropriateness and usefulness of the model.

Sterman (2000) emphasizes that the testing is iterative process and is carried out throughout the modeling process. He also notes that majority of the testing focuses on the replication of historical data and undermines the importance of underlying assumptions, robustness and sensitivity of results to assumptions about the model boundary and feedback structures. There are various types of qualitative and quantitative tests which can help the modeler uncover flaws and test usefulness of the model.

According to Sterman (2000), all models are wrong; they are just simplified representations of the real world. Based on the Webster's definitions of the words "verify" and "valid", it is impossible to verify or validate any model. Greenberger, Crenson and Crissey (1976) concluded that "No model has ever been or ever will be thoroughly validated….Useful, illuminating, convincing or inspiring confidence are more apt descriptors applying to models than valid"

Though the truth of a model can not be established, surely its falsity can. This concept is also consistent with the hypothesis testing in statistical analysis in which we reject the null hypothesis based on the reason that we do not have enough evidence to accept it.

Usually the models are based on some limiting assumptions and are not exact replications of reality. Hence the verification and validation of those models should be done in the light of those assumptions. Sterman (2000) prescribes various tests for discovering errors and limitations of the model. Model testing is a continuous process and was carried out at every step during the modeling process. Based on the results and feedback from the tests model was revised accordingly. The tests that were carried out for verification and validation are discussed below.

4.5.1 Face Validity

Face validity compares causal loop diagram and stock and flow diagram with the actual system being modeled. Experts play a critical roll in this task. During the conceptual design phase, experts provide qualitative inputs about the structure of the system and various feedbacks. During later parts of model development phase, experts review the model and make qualitative decision as to whether or not the model reasonably portrays the real world being modeled.

The experts involved in this research provided the face validity during model development and testing phase. Initial causal loop diagram was created based on the inputs from experts. The causal loop was transformed into stock and flow and the equations were formed. Experts also reviewed the base case simulation results. The model was continuously improved based on their comments and inputs.

4.5.2 Structure Assessment Test

Structure assessment tests ask whether the model is consistent with knowledge of the real system relevant to the purpose. It focuses on the level of aggregation, the conformance of the model to basic physical realities and the realism of decision rules.

The model was developed with active participation of experts. The level of aggregation was discussed and determined during various modeling sessions. Also the care was taken during formulation to avoid any violation of basic physical realities such as stocks going negative. This was achieved by direct inspection of equations.

4.5.3 Dimensional Consistency

In order to be meaningful, each equation must be dimensionally consistent without the inclusion of arbitrary scaling factors that have no real world meaning. Dimensional inconsistency errors may reveal important flaws in the understanding of the structure or decision process that is being modeled.

Dimensional consistency was checked using a built in unit check feature of Vensim DSS v 5.4a software and through direct inspection of equations and model structure.

4.5.4 Testing for Intended Rationality and Parameter Assessment

The key structured in the model were tested individually to test for the intended rationality. Based on these tests the model parameter values and decision rules were revised where necessary. The following diagram shows preventive maintenance structure and the graph shows partial simulation results.

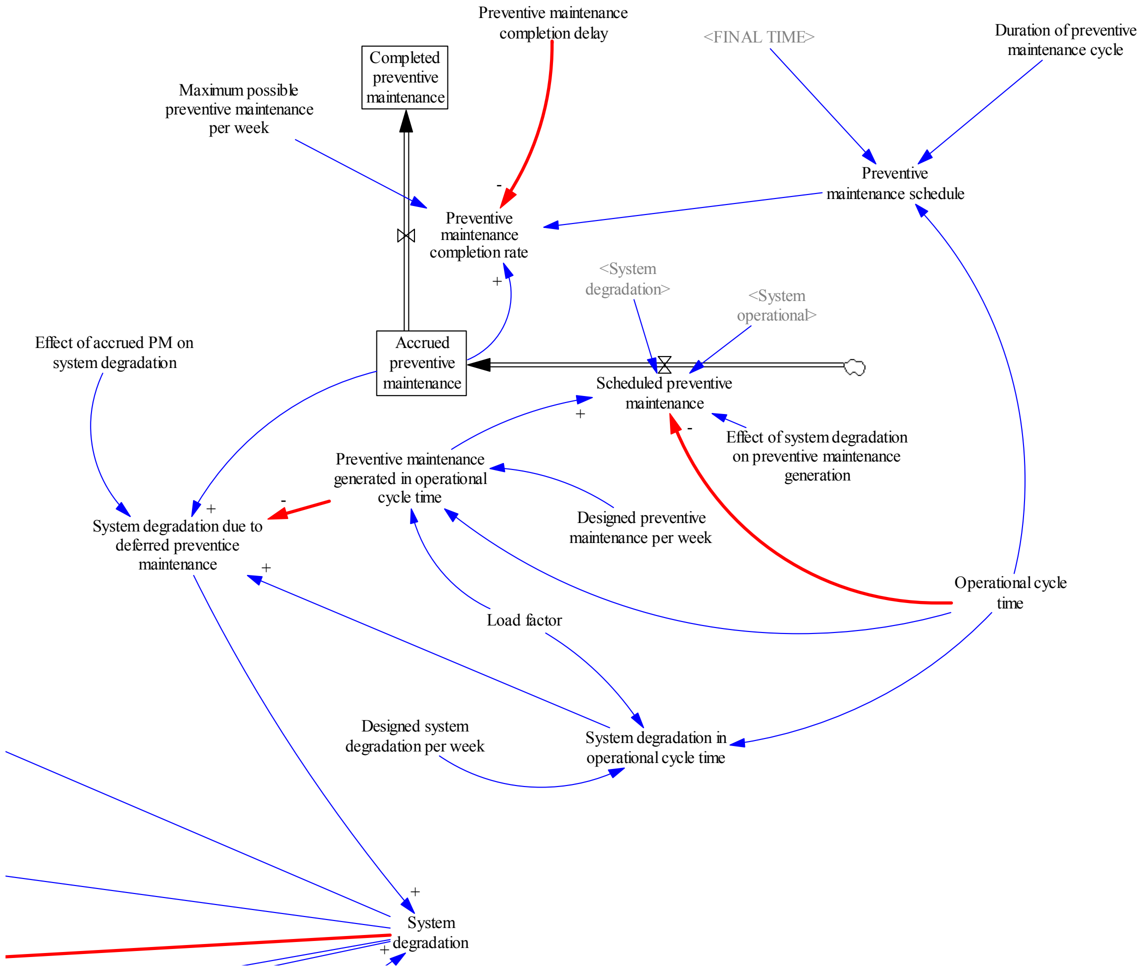


Figure 4-46 : Preventive maintenance subsystem

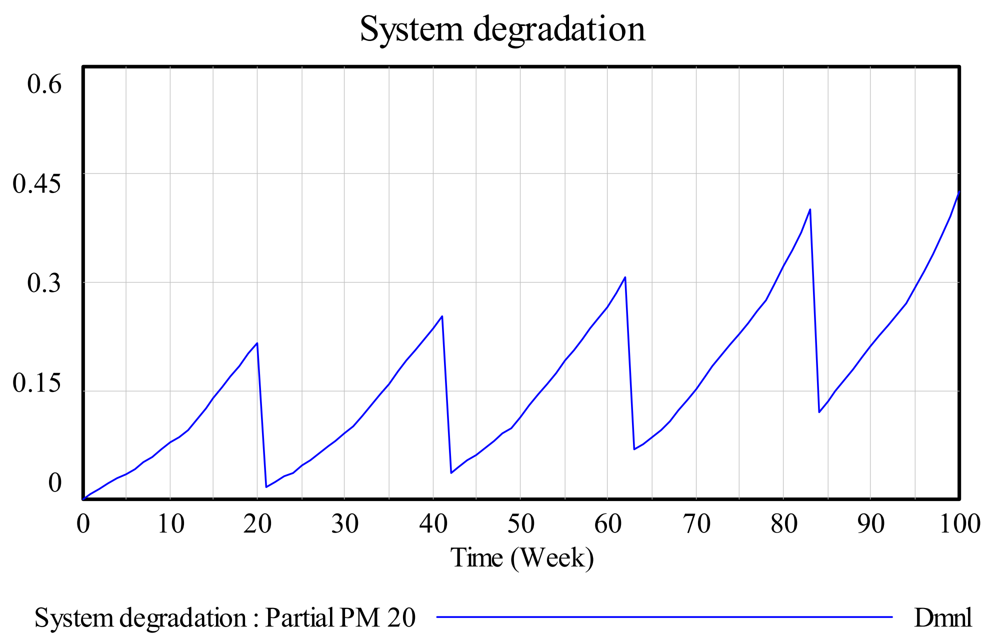


Figure 4-47 : Partial simulation results – preventive maintenance sub-system

The partial model was run for 100 weeks with 20 week operational cycle. The above graph was consistent with the mental models of experts involved with the modeling tasks.

Also the defects structure was partially simulated and the following results were observed.

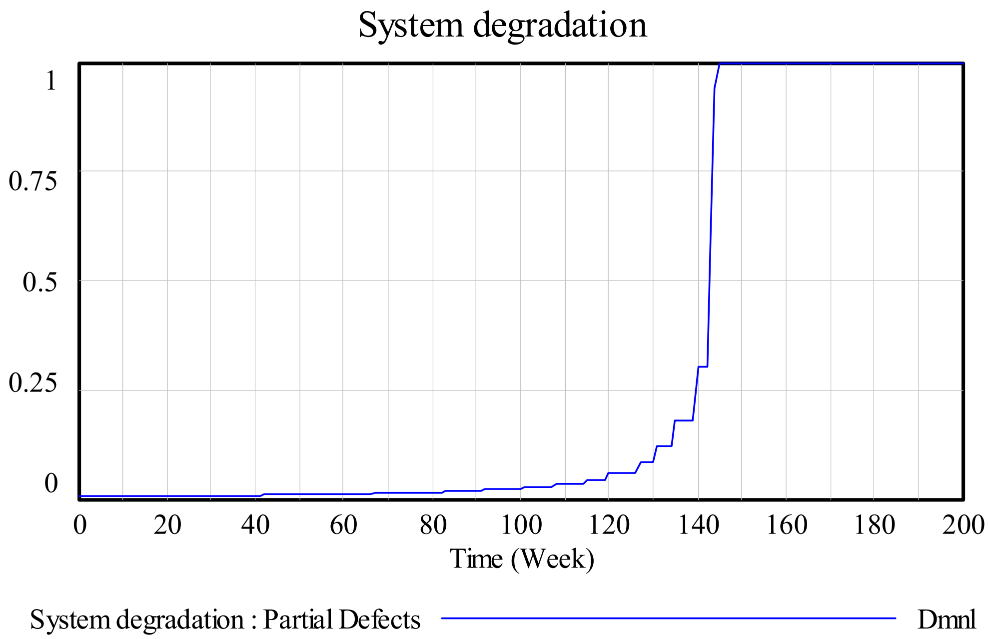


Figure 4-48 : Partial simulation results – defects

This behavior is consistent with the mental models of the experts. The above graphs show the system's behavior when it starts operating with 100 initial defects and is operated continuously without performing any corrective or preventive maintenance.

4.5.5 Extreme Condition Test

The model should be robust under extreme conditions. Robustness under extreme conditions means the model should behave in a realistic fashion no matter how extreme inputs or policies imposed on it may be.

The model was simulated under two extreme scenarios, the best scenario is when there are all the resources available to do the required corrective and preventive maintenance and the worst scenario is when there are hardly any resources available for these maintenance activities. Following graphs show model output under thee two extreme conditions.

Best and Worst Case

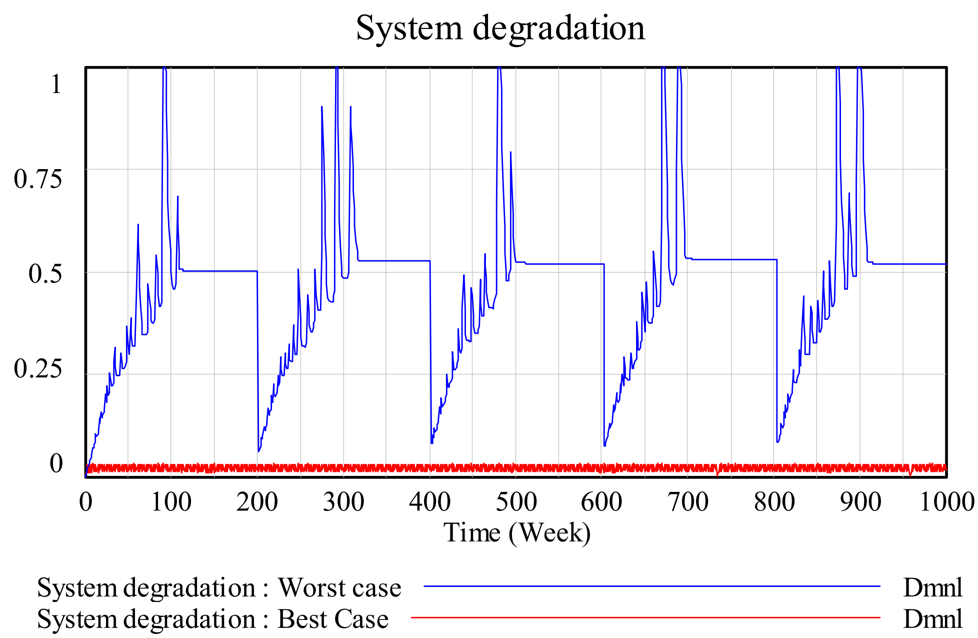


Figure 4-49 : System degradation – best and worst case

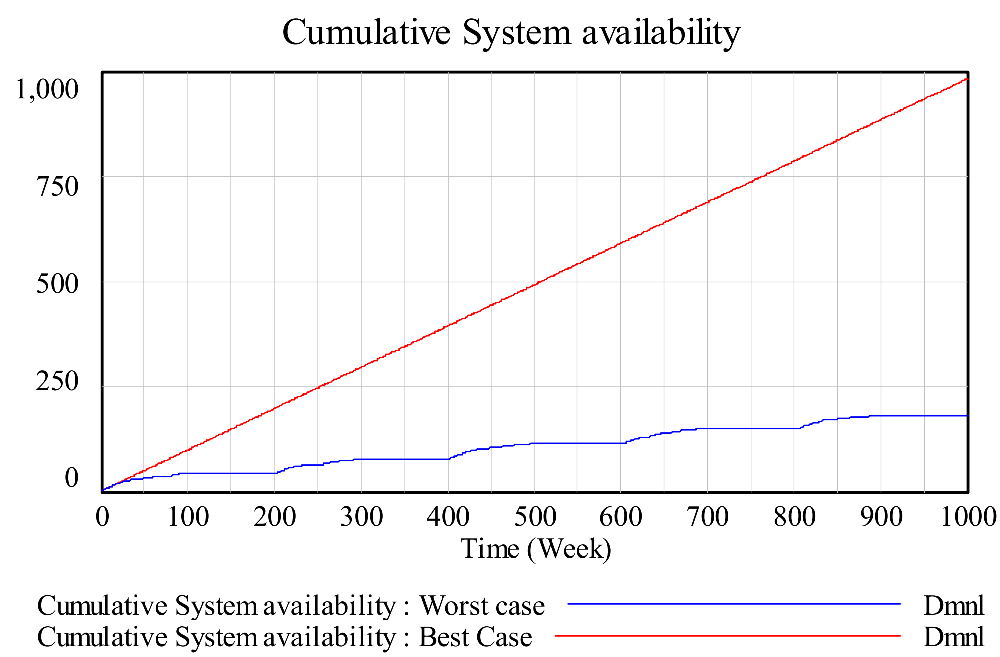


Figure 4-50 : Cumulative system availability – best and worst case

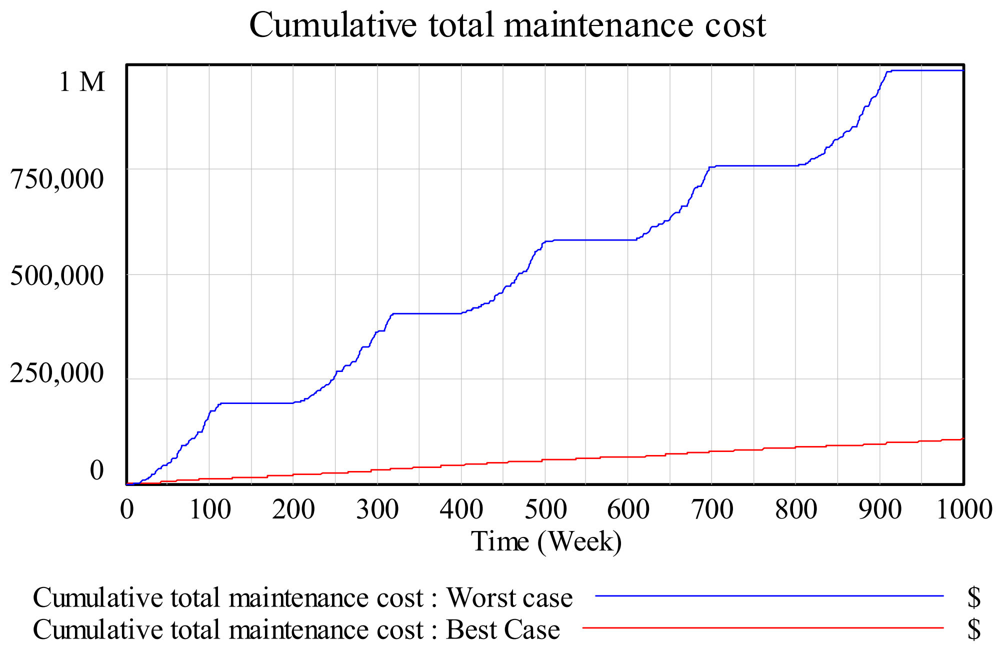


Figure 4-51 : Cumulative total maintenance cost – best and worst cost

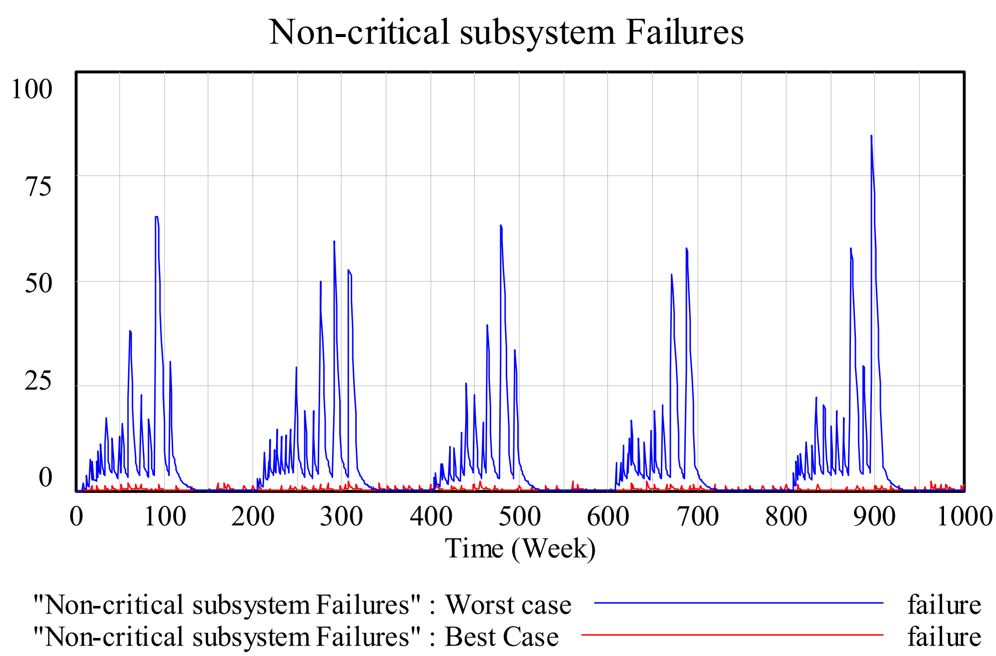


Figure 4-52 : Non-critical sub-system failures – best and worst case

The graphs shown above show the anticipated behavior under the worst and the best cases. It can also be noted that even though the best case assumes that the preventive maintenance is done every week there are some failures in the system. Also it should be noted that in the worst case scenario, system degradation falls to very small value at certain intervals. This behavior could be attributed to the decision rules that were set in the model for taking the system down for maintenance when system degradation exceeds 0.5 and putting it back in the operations when it falls below 0.5.

5. Conclusions

5.1 Overview of the results

The system dynamics model was developed using Vensim DSS 5.4a. The model was structured based on the inputs from the experts in the field of maintenance management. The model was extensively tested and the results were validated by the experts. It should be noted that the base case values used for simulation are not for any specific technology. These values were selected from the brainstorming sessions which involved professionals in the field of systems engineering, maintenance management and system dynamics. A different set of parameter values should be entered while using this model for a specific technology. Below is the table that lists the technology specific parameters that require attention while adapting the model developed in the research for a specific technology.

Parameter	System Specific Parameter	Technology Specific Assumption	Assumed Value	Comment
Number of sub-systems	Yes	No	100	
Avg. number of defects possible per subsystem	Yes	Yes	125	This number would be much smaller for electronic systems
Corrective maintenance generated due to each failure	Yes	Yes	Normally distributed	The distribution would change for different technology. For example, for electronic systems – exponential distribution would be more appropriate. Values of the parameters of the distribution are system dependent
Major/Minor non-critical failure	Yes	No	80-20	80% Non-critical failures are assumed to generate relatively less corrective maintenance as compared to the remaining 20%. This ratio is system specific and could be changed
Deferral fraction per week	Yes	No	0.3	This factor is subjective and is usually determined based on the overall understanding of the system
Maximum available man-hours for corrective maintenance	Yes	No	40	This variable is system specific and is determined by the available man-hours
Maximum possible preventive maintenance per week	Yes	No	8	This variable is determined by the man-hour availability and system availability
Anticipated system degradation per week	Yes	Yes	0.01	This variable is determined by the system design and the technology. Usually electronic systems have less system degradation as compared to the mechanical systems

Anticipated preventive maintenance per week	Yes	No	0.04	This variable is determined by the system design. It can be determined from maintainability specifications.
Impact of load factor on anticipated system degradation and preventive maintenance	Yes	Yes	Linear	It would also be reasonable to assume this as a linear relationship up to load factor 1 and non-linear thereafter
Number of defects per sub-system	Yes	No	Normally distributed	Normal distribution was selected based on the expert's inputs. This distribution can be changed to reflect the actual technological structure of the system
Preventive maintenance schedule	Yes	No	Periodic	Periodic preventive maintenance policy was assumed. It could be changed to reflect the actual maintenance management system in place or proposed

Table 5-1: User defined parameters and assumptions

The following conditions were used to set the decision rules for taking the system down for maintenance and putting it back again into operations. These rules could be changed to specific values for the system. These rules are determined by the importance of the system to overall organization/process/mission, minimum acceptable performance levels, and available resources.

Parameter	**Takedown for maintenance condition**	**Back in operations condition**
System degradation	> = 0.5	< 0.5
Non-critical subsystem failures	>= 30%	< = 5%
Critical sub-system failures	> 0.001	<=0.001
Required corrective maintenance	> = 40 man-hours	< = 10 man-hours

Table 5-2 Decision rule parameters

The results obtained from running the model are discussed in the previous chapter. The simulation runs showed two main modes of dynamic behavior.

Exponential growth

A positive reinforcing loop generates exponential growth. The interaction between system degradation and deferred preventive maintenance shows this phenomenon. Also increase in defects causes system to degrade at exponential rate. The simulation results explained in section 4.2.1.1.

Goal Seeking

A balancing loop generates goal seeking behavior. Sub-system failure rate shows goal seeking behavior. The goal of minimum failures is inherently modeled in the system. The maintenance system tries to regain the balance disturbed due to increase in defects. This phenomenon is discussed in detail in section 4.2.1.2.

5.2 Verification of Dynamic Hypotheses

The dynamic hypotheses stated in section 4.3 were tested using the system dynamics model developed using Vensim DSS 5.4a. The simulations results were observed to support or reject the hypothesis.

The primary hypothesis was that the frequent periodic preventive maintenance benefits or improves the system performance. The model was simulated with various operational cycle values and load factors. The preventive maintenance capacity was assumed to be constant over the simulation time period. The simulation results do not support the stated dynamic hypothesis. The results reveal that there exists an optimal level of preventive maintenance for load factor under the given assumptions and costraints. Frequent preventive maintenance under constrained maintenance capacity would not necessarily result into better system performance. Detailed discussion about the simulation runs and results could be found in section 4.3.

The results for various simulation runs support second hypothesis about the impact of load factor on systems performance. Overall system performance can be expected to degrade with increase in load factor.

5.3 Modeling features

Two co-flow structures were formed which track the average number of defects present in the system per subsystem failure and average number of corrective maintenance hours required for repairing each failure.

Increase in defects cause system failures. The number of defects required for a system failure is not constant. It varies according to the subsystems. Hence random normal distribution was used to generate the number of defect required for a system failure. Also the structural complexity of the subsystem determines the number of corrective maintenance hours generated by failure of that subsystem. Given the variation in complexity of the subsystems, the corrective maintenance generated due to critical and non-critical failures was modeled as a normal distribution.

A stock and flow structure was formed to keep the track of times since last failure. This acts as an input for determining the probability of sub-system failure.

5.4 Maintenance policy simulator

A simple simulator was designed to help the decision makers observe the impact of their decisions on the system's performance. The simulator has two parts; a dashboard and controls. The dashboard displays performance parameters such as system degradation, cumulative availability, accrued preventive maintenance and required corrective maintenance. The control section allows used to vary preventive maintenance internal (operational cycle), Maximum possible preventive maintenance per week, maximum available man-hours for corrective maintenance and load factor.

The user can choose the number of weeks for which the model should be run with the current set of control parameters. After those many weeks the simulation will halt for the user input for the next simulation period. The current structure of the simulator does not allow user to change the system dependent or technology dependent assumptions. Below is the screenshot of the simulate user interface.

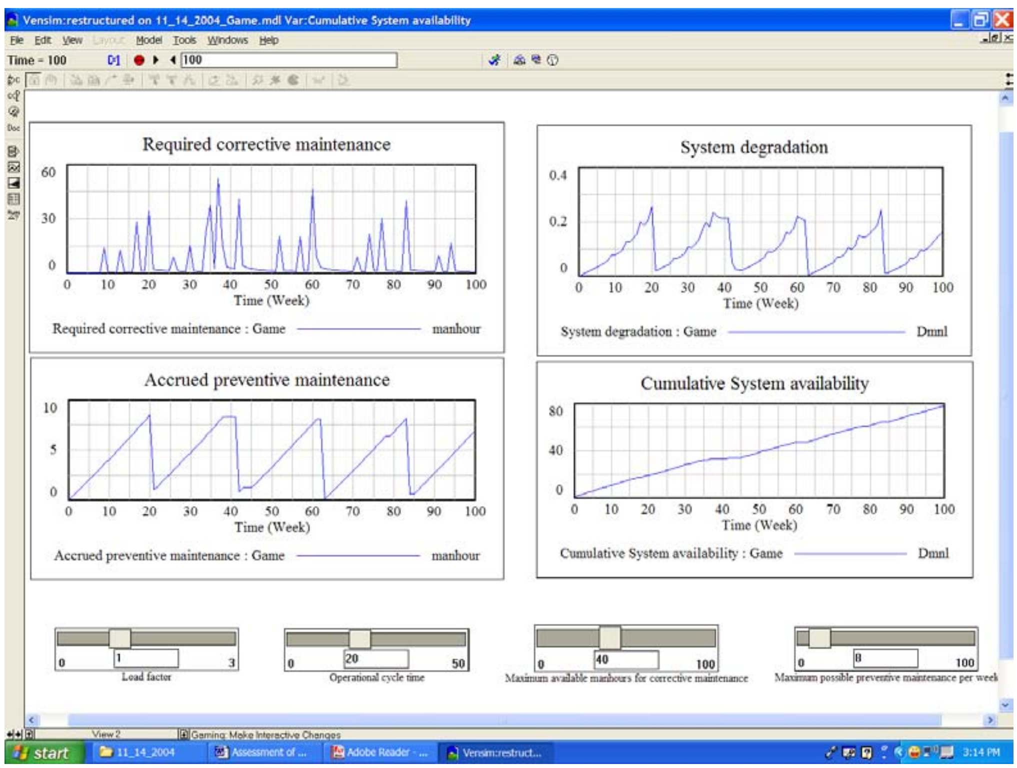


Figure 5-1 : Maintenance policy simulator screenshot

The above figure shows the simulator screen with the results of 100 week simulation. The simulation was temporarily stopped at this point for the user inputs. The operational cycle time was changed to 35 weeks for the further 200 week simulation. The following screen shows the simulation results for the following 200 weeks.

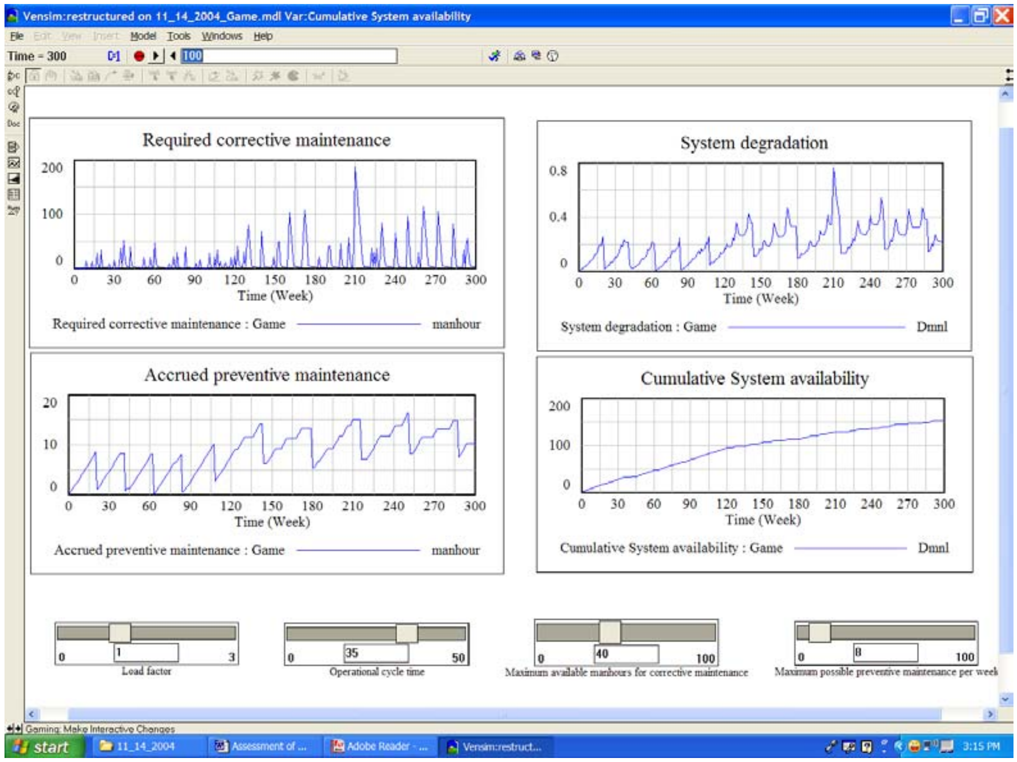


Figure 5-2 : Maintenance policy simulator screenshot

Thus the simulator provides a user friendly interface which can be used by decision makers for testing their policies. This simulator can further be modified to cater to the specific need for the decision makers. Cost related performance measures can also be integrated into dashboard and control sections.

5.5 Policy

Forrester (1961) defines policy as a rule that state how the day-by-day operating decisions are made. In other word it is describes how decision process converts information into action.

The model was run for higher load factors with different operational cycles. Even at higher load factors the simulation results show that there exist an optimum level of preventive maintenance interval for higher system availability and lower system degradation within the given constraints and assumptions of the problem. The preventive maintenance interval should be determined based on the maintainability factors such as mean preventive maintenance time, mean corrective maintenance time, maintenance man-hours required per operational cycle.

Also shorter preventive maintenance should be selected with higher load factors as compared to the lower load factors.

The required preventive maintenance should be completed during the preventive maintenance cycle. Deferred maintenance will leave the system in partially degraded state which may further degrade the system at higher rate and hence will result into substandard performance over the entire operational phase.

5.6 Areas of future research

This research opens up new doors for investigation of the following issues tied to this research.

Modeling maintenance methodologies such as condition based maintenance to analyze its impact of the system performance over time. There is a growing emphasis on condition based maintenance in defense systems such as submarines and aircraft systems. Modern continuous monitoring equipments enable us to determine the optimum replacement time in real time. This demands high maintainability characteristics of the system. Impact of these maintainability characteristics on system performance would be an interesting area to investigate.

The model developed as a part o this research could be modified to model condition based maintenance system by linking performance variables to the maintenance functions. Preventive maintenance subsystem could be replaced by condition based maintenance specific structure. But it should be noted that there are various issues such as procurement delays, system availability which become pertinent in condition based maintenance. Modeling these elements is essential to ensure the comprehensiveness of the model.

This research assumes continuous operation of the system and discrete preventive maintenance events. Integration of discrete event simulation and continuous time simulation would ease the modeling task and would also provide more flexibility in terms of modeling and analysis. It can potentially also provide further specific insights about the system structure and resulting behavior.

There are various delays associated with maintenance activities such as procurement delay and administrative delay. These delays were assumed to be inherent in the maintenance hour requirements for this research. This assumption can be relaxed by explicitly modeling these delays to understand their impact on system performance. Some of the other factors omitted from this research and worthwhile exploring are the impact of training on maintenance effectiveness and impact of budgeting policies on maintenance function.

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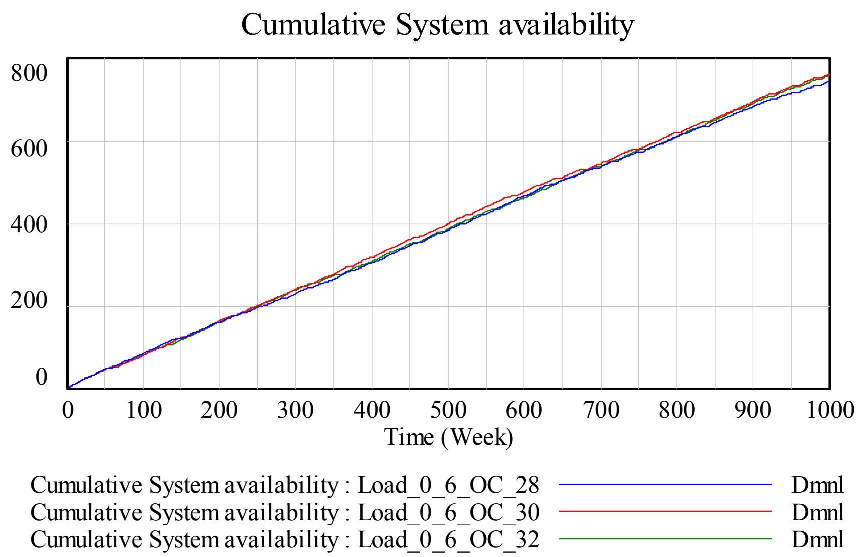
Appendix A

Below are the availability performance graphs for various load factor scenarios at near optimal and optimal values.

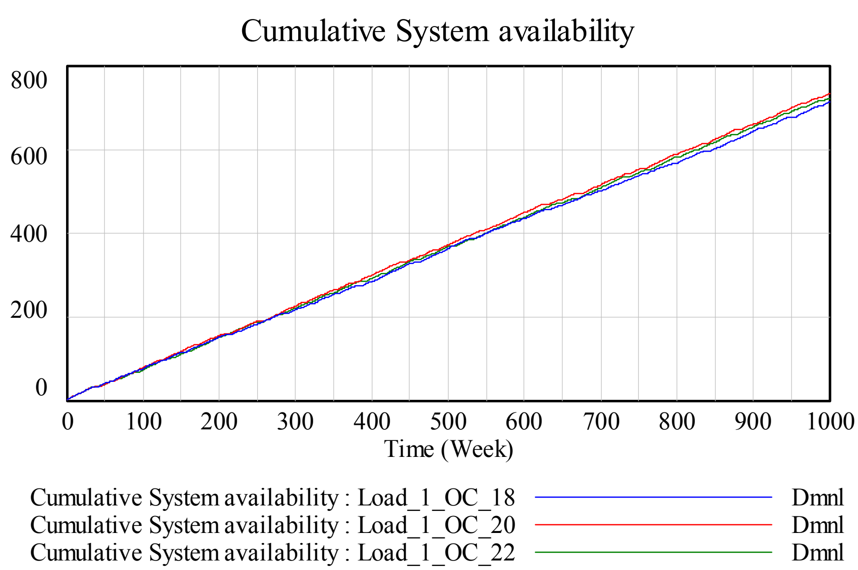
Load factor 0.6

- **Operational cycle 28**
- **Operational cycle 30 (optimal)**
- **Operational cycle 32**



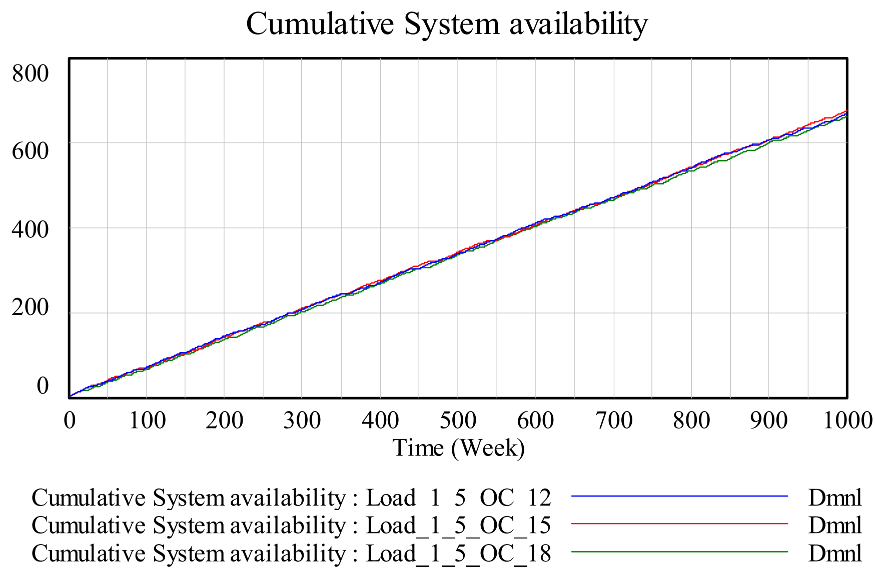
Load factor 1

- **Operational cycle 18**
- **Operational cycle 20 (optimal)**
- **Operational cycle 22**



Load factor 1.5

- **Operational cycle 12**
- **Operational cycle 15 (optimal)**
- **Operational cycle 18**



Appendix B

Function syntax

RANDOM NORMAL (min, max, mean, std dev, seed)

This function returns a series of normally distributed random number. The distribution is truncated at min and max values.

RANDOM UNIFORM (min, max, seed)

This function returns a series of uniformly distributed random numbers between min and max values.

XIDZ (numerator, denominator, default)

This function returns the ratio of numerator to denominator and returns default value if in case the denominator is zero.

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- Director, Information Infrastructure, Enterprise Systems Engineering Society, Virginia Tech, 2003-2004
- Rotaract Club, India 2001 -02