ABSTRACT

A DECISION SUPPORT SYSTEM FOR FORECASTING PRODUCT AND WASTE DISPOSAL OVER TIME

A current barrier to the end-of-life product strategies is a lack of knowledge of the quantity and timing of product returns or waste generation. Consequently, a Decision Support System (DSS), to predict the timing and quantity of waste generation is needed. Therefore a web-based system that predicts the rate of product entering the waste-stream has been developed. The system accepts information relating to sales, reliability, storage and disposal behavior. This data is used to simulate the return waste flow. The DSS can be used to simulate the effect of different policies and to provide data for end-of-life and multi-lifecycle strategy formulation. Cathode Ray Tubes (CRTs) are evaluated as a test case.

In the test case, the amount of CRT based color televisions entering the waste-stream is estimated using the Forecasting software. The effects of certain parameters like pre-disposal storage and disposal due to obsolescence of the televisions are computed. Effect of the introduction of televisions using the newer Flat Panel Display technology is also estimated. The effect of a legal ban on the disposal of CRT based televisions in the state of Massachusetts is also modelled.

A DECISION SUPPORT SYSTEM FOR FORECASTING PRODUCT AND WASTE DISPOSAL OVER TIME

by
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This thesis is dedicated to my beloved parents

and my late uncle Dr. Pradeep G. Amte

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CHAPTER 1

INTRODUCTION

1.1 Background Information

Concern over environmental damage caused by products at their end-of-life is growing. In 1996, 209.7 million tons of household municipal solid waste was generated in the United States [1]. A high percentage of waste directly enters the landfills. For example, between 38% and 99% of small and medium appliances go into landfills. This waste has some residual value. However, the lack of understanding of the quantity and timing of product disposal prevents the capture of this value. This is not only a failure of the market system[2] resulting in reduced output and profitability, but also a major societal problem. A further problem is that the cost of reclamation of contaminated land is high [3]. And finally, landfill space is being depleted. (The number of municipal solid waste landfills declined from more than 16,000 in 1976 to about 3,500 in 1995, as small facilities have been closed or consolidated [4].) The current rate of waste generation and associated resource depletion is unsustainable[5].

Consequently there is a need to predict the quantity and timing of waste generation. By predicting waste flows we will be able to develop strategies to extract potential value out of waste streams , thereby reducing or eliminating waste. This strategy is frequently referred to as Industrial Ecology [6, 7] or Multi-lifecycle Engineering [8, 9].

1.2 Aims and Objectives

The aim of this study is to develop a decision aid to model the timing of disposal of products. This is accomplished by applying forecasting techniques to sales data, or sales forecasts, to estimate the rate and timing of the product under study, entering the waste stream.

Two different forecasting models are utilized: standard normal distribution model and the bath-tub model [10]. Cathode Ray Tubes (CRTs) are offered as an example to illustrate some of the different issues that the decision aid can be used to address.

The software described by this document is web-based and modular. It applies existing theory to be used as a decision support system (DSS). The two models that are currently in the decision support system are building blocks and additional models can be added on an as needed basis. It is intended that, new models for forecasting the end-of-life product flow shall be incorporated into the DSS as they are identified. Hence, the modular design of the software which easily allows addition of new models.

1.3 Research Need

DSSs can be used to determine the implications of a variety of variables. In this regard, this decision aid software is a decision support system (DSS) as it supports a scenario or "what if" analysis.

From the turn of the century, when people, first recognized the "garbage nuisance", public officials have been attempting to find ways to deal with the mountains of waste that have built up[4]. Burial and landfills were the primary way of waste disposal, but other methods like incineration, ocean dumping, recycling and storage were also used. (Legislation has banned ocean dumping.) Legislation also limits the kind of waste that can be disposed using the traditional techniques. For example, the state of Massachusetts has constituted a ban on the disposal of Cathode Ray Tubes in publicly owned landfills, effective 1st January 1999[11].

One way of managing the waste problem is to decrease the amount of waste that is generated. Various companies have implemented policies to reduce waste generation at the source: also termed as "*source reduction*"[4]. Economic feasibility is a major concern in the formulation and implementation of such policies. Toyota Motor Manufacturing switched to standardized reusable shipping containers, which saves the company millions of dollars each year[4]. AT&T reduces office paper waste by encouraging double-sided copying[4]. Both these examples have resulted in some form of monetary gain to the organizations in addition to resource conservation.

In the formulation of policy regarding management of generated waste a number of questions arise.

- What is the quantity of waste generated?
- If the waste generation is regulated by law; how much material does it affect?
- Does the waste need special processing facilities or can it be processed in publicly owned waste treatment plants?

The nature of the waste generated may mandate development of waste processing facilities. These facilities may simply process the waste to make it environmentally benign and fit for disposal, or perform remanufacturing, demanufacturing or recycling operations in order to extract un-harvested value in the waste-stream. If such an option is being considered, the following points have to be noted:

- Can the product be reused or remanufactured?
- Can the end-of-life product be used as a feedstock for a new product?
- What size of operation does the volume of waste generation support?
- What is the best location(s) for waste processing facilities?

Facilities to capture end-of-life value from the solid waste stream do exist and are being used to remanufacture products and components and to recycle materials. For example, IBM processes old equipment at a demanufacturing facility in Endicott, New York. Xerox Corporation remanufactures certain components of its copiers to exact specifications[12]. Eastman Kodak recycles parts of its one-time use cameras[12].

Multi-lifecycle engineering fundamentals provide a multi-pronged approach to reduce waste generation and improve the environmental performance of a product throughout its lifecycle[8]. The Multi-lifecycle engineering approach is discussed in section 1.5.

1.4 Research Scope

The standard normal distribution and the bath-tub models that have been developed for this forecasting software are generic and can be applied to a wide variety of products.

The reliability (bath-tub) model is widely accepted for modelling failure of electronic products[10], but can also be used for other products that exhibit similar properties. The standard normal distribution is a statistical distribution model that is applicable to a wide range of phenomena. Cathode Ray Tubes (CRTs) are used as a test case to demonstrate the use, flexibility and value of the system.

CRTs have a high lead content. Disposal of CRTs using traditional disposal techniques is considered to be hazardous to the environment due to the fear of the lead in the CRT glass leaching into the soil. They are also the focus of recent legislation. In fact, there is a legal ban on CRT disposal in municipal solid waste landfills in the state of Massachusetts. It is possible that other states in the United States will follow with similar legislation. Furthermore, the forecasts from the decision aid can help CRT manufacturers to remain compliant with current and expected legislation. The decision aid applies scientific forecasting techniques to predict the amount and timing of waste that might be generated, which is needed in order to plan for and put in place the required infrastructure. Thus a waste-stream analysis of CRT disposal will assist in planning for the management of the CRTs diverted from municipal solid waste landfills and identify the potential uses of this waste-stream.

1.5 Multi-Lifecycle Engineering

Current practices of material use and management have created a linear flow from raw material extraction and processing into products and packaging which are all too frequently used once and then discarded into a landfill. According to the National Academy of Sciences, 94% of all natural resources extracted from the earth enter the waste-stream within months[13]. Consumer electronics, computers, and household appliances contribute significantly to the environmental burden placed on public waste disposal facilities. If discarded products and waste streams such as these can be recovered and reengineered into valuable feed streams, then we can break this trend and come closer to achieving sustainability[5, 14].

Multi-lifecycle engineering represents a new approach, that takes a systems perspective and considers fully the potential of recovering and reengineering materials and components from one product to create another, not just once, but many times. This is not simply recycling or design for the environment, but rather a complex, next-generation engineered system that transcends traditional discipline boundaries. This scientifically rigorous, systems approach is termed as *Multi-lifecycle Engineering*[8, 9].

1.6 Thesis Format

The remainder of this thesis consists of five chapters:

Chapter 2 discusses forecasting techniques and waste stream forecasting. A brief overview of decision support systems is also given. The background information related to this research in the form of literature review is given.

Chapter 3 discusses the two forecasting models that are used in this research and form the core of the decision aid software.

Chapter 4 examines the design and implementation issues in the development of the software. Issues specific to the two forecasting models are also considered.

Chapter 5 demonstrates some of the applications of the software by way of a CRT case study. The application of the software is demonstrated by analysis of the CRT sales data through the consideration of both the forecasting models.

Chapter 6 concludes the thesis by summarizing the results obtained. Suggestions for further improvements to the software are presented.

CHAPTER 2

LITERATURE REVIEW

Forecasting waste streams involves both business forecasting and decision support systems. Thus, the background and development of both are considered in this chapter.

2.1 Business Forecasting

Business forecasts are the result of in-depth analysis of current business patterns and trends - using information like sales and marketing figures and leading economic indicators to forecast the future sales. Business forecasts are critical inputs to a wide range of business decision-making processes. Business decisions are almost always based on some forecast of future events. All the functional areas of an organization need and make use of forecasts. The most commonly used forecast is the sales forecast, which is the root forecast with other more specific forecasts being derived from it [15].

Forecasting is used in many ways to help an organization make preemptive and proactive decisions regarding its operations. Forecasts are necessary since all organizations operate in an atmosphere of uncertainty and decisions must be made that affect the future of the organization[16]. More specifically:

i. The power of forces such as economics, competition, markets, social concerns and the ecological environment to affect the individual firm is severe and continues growing.

ii. Forecast assessment is a major input in management's evaluation of different strategies at business decision-making levels.

iii. The inference of *no* forecasting is that the future either contains "no significant change" or there is ample time to react "after the fact."

Every organization, uses forecasting either explicitly or implicitly, because every organization must plan to meet the conditions of the future for which it has imperfect knowledge[16]. For an organization to remain competitive, it has to develop its own forecasting model so that its own course of action can be plotted. Since any forecast is only as good as the data that it is based on, the forecaster continually updates and examines the assumptions of the model.

Mohn[15] defines forecasts as: *"numerical estimates by date of the future that can be achieved with a specified level of support."* Predictions made with forecasts should be reproducible through a system of logic; that is, the system should be independent of the analyst making the predictions. The elements in a forecast are therefore: involvement of future and time, reliance on historical data and uncertainty.

With the development of more sophisticated forecasting techniques and the advent of inexpensive and powerful computers, forecasting has received greater attention[15,16,17].

2.1.1 Types of Forecasts

Business forecasting is based on three assumptions:

1. Economic indicators such as levels of production, interest rates, prices, wages and consumer expenditures are linked together into a system that has considerable stability over time.

2. Changes can occur in these indicators in future due to present events and these changes can be deduced by observing the current conditions.
3. The nature of the changes in the economic indicators and their possible effects can be deduced by studying past experiences.

Forecasting procedures can be classified as *long* or *short term*[15,16]. *Long term predictions* are necessary to set the general course of an organization for the long run; thus they become the particular focus of upper management. *Short term forecasts* are used by middle-management to assist in designing immediate strategies and meeting immediate goals[16, page 4].

Forecasts are also classified on the level of detail that they encompass. Forecasts of the economic performance of a country are referred to as *macro-forecasts.* And forecasts of a single product in a company product line are referred to as *micro-forecasts*. The targeted audiences for these macro/micro forecasts are, different.

The three basic strategies for business forecasting are: deterministic, symptomatic and systematic strategies[17]. The *deterministic* strategy assumes that the future has a close casual relationship with the past. Much like predicting the construction expenditure by knowledge of construction contracts already made. This is the simplest forecasting method with emphasis on full, fast and accurate reporting as part of the forecasting process.

The *symptomatic* strategy assumes that current variables indicate how the future is developing. For example, there are certain key economic indicators; these "leading indicators" foreshadow the rise or fall of the general business activity. Symptomatic strategy concentrates on one of the most important problems for the business forecaster in a free economy: the determination of a coming turning point in the business cycle. Some analysts will consider only a handful of the "leading" economic indicators; others might consider a larger combination. There is no "ideal set" of economic indicators to be considered, different forecasters might consider different sets of indicators and come up with similar or totally diverse forecasts.

Finally, the *systematic* strategy assumes that, though the real world might seem chaotic or accidental, careful observation will reveal certain regularities. Sometimes these "regularities" are called theories, principles or laws. The way to find these regularities is to consider only the abstractions that make up the system, for example the solar system or the economic system. The theories that emerge from this process of abstraction might seem "unreal" but may have a profound effect on the world, provided the theories are sound. A theory can be accepted only if it is consistent with reality. For example, a price cut that results in increased sales confirms the hypothetical demand curve that is otherwise thought to be non-existent.

2.1.2 The Forecasting Process

Forecasting procedures operate on the data generated by past historical events. Consequently, all formal forecasting procedures involve extending the experiences of the past into the uncertain future. Thus, the following four steps are part of the forecasting process[16]:

1. Collecting data: the data that is collected has to be in the proper format and should be as current and accurate as possible.

2. Reducing or condensing the data: it might be necessary to discard certain irrelevant data that might affect the accuracy of the forecast.
3. Model building: involves fitting the data to an appropriate model that minimizes the forecasting error. The model needs to be simple enough for the end-users to understand and use. It is important to have a simple model that is easily comprehended by the end-user, thus encouraging its continued use.
4. Forecasting: involves the generation of an actual forecast. The forecast is checked against known values for validation and if errors are observed they are identified.

Examination of errors and error patterns are used to modify the forecasting model to produce results with a lower margin of error. The forecasting process should be considered to be an advisor to the manager or "decision maker". The "decision maker" should ideally consider a variety of factors, along with the forecast, before making a decision. The forecast should not be used as a automated decision making tool, since there is a element of uncertainty regardless of how accurate the forecasting model has been in the past.

2.1.3 Waste-stream Forecasting

There are a number of models for business forecasting that are widespread in terms of use and availability. Accepted methods for business forecasting include regression methods, multiple regression methods, time-series decomposition and Box-Jenkins (ARIMA) method[15,16,17,18,19]. Several commercial software packages offer these models along with powerful report generation facilities, making them easy to use[15,18,19].

However, there is no standard model for forecasting the disposal of product at the end of its life. This is the first time that such a software model is being developed, to the best of the authors knowledge.

2.2 Decision Support Systems (DSSs)

Claims about the benefits and capabilities of DSSs are substantial. DSSs are said to make managers more effective; improve managerial decision making, especially in relatively unstructured tasks; and to extend the manager's cognitive capabilities, while leaving the manager free to exercise his or her judgment where that is needed [20].

DSSs are defined as follows [21, page 77]: *"A DSS is an interactive, flexible, and adaptable Computer Based Information System (CBIS) specially developed for supporting the solution of a non-structured management problem for improved decision making. It uses data, provides an easy user interface, and can incorporate the decision-maker's own insights.*

In addition, a DSS may use models, is built by an iterative process (often by end-users), supports all phases of decision making, and may include a knowledge component."

Decision making processes fall along a continuum that ranges from highly structured to highly unstructured decisions. The focus on decision making also requires an understanding of the human decision making process[21]. Thus there can be a *structured decisions* where the procedures are standardized, the objectives are clear and the input and outputs are known. An *unstructured decision* will have no procedures or clear-cut objectives. And a *semi-structured* decision will have some of the system components well defined but some unclear.

Supporting and improving the decision-making process is *the* goal of a DSS. Another proposed definition is given as[20, page 12]:

"A DSS is a computer-based information system used to support decision making activities in situations where it is not possible or not desirable to have an automated system perform the entire decision process."

DSSs are defined broadly. Hence, there are no distinguishing characteristics between DSS software and other software. For example, spreadsheet software containing business data can be used as a decision support system.

Technological advances will result in the migration of computational power from a centralized data processing model towards the locus of decision making, increasing user familiarity with computers and providing more opportunities for the application of DSS[20 page 26]. The important considerations in DSS software design involve human decision-making, hence even if, technological advancement determines what can be done; behavioral research determines what should be done and how, so that organizational goals can be met[20].

2.2.1 DSS Components

The objective of a DSS is to improve or support the decision making process. According to Sprague and Carlson[21], DSS are developed to: establish a power base and control (or other hidden agendas), focus attention to certain areas which might have a potential to have an impact on the business, change the decision-making process, change the organizational goals, and to challenge the "old-line" (status-quo).

The generic DSS framework maintains that any decision support software can be viewed as having three components: the Language System (LS), the Knowledge System (KS) and the Problem Processing System (PPS). (See figure 2.1) A user submits a problem to the decision support system using a *language system*. A decision support system's *Knowledge System* holds the relevant facts about the application area.

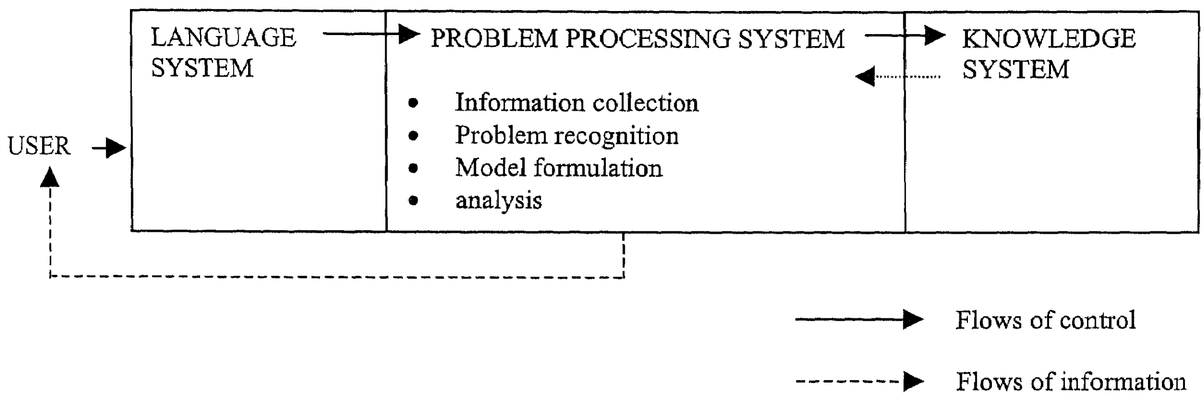

Figure 2.1 Decision Support System Components
[Source 20]

These facts are used to solve the problems arising for that application. The *Problem Processor* lies at the heart of the DSS. It utilizes the application specific knowledge from the *Knowledge System* along with the problems presented using the *Language System* and generated information for decision support.

The *Language System* and *Knowledge System* are representation systems. They exist basically to provide input to the dynamic *Problem Processing System*. The *Problem Processing System* is the component that displays some behavior. The syntax and semantics of the *Language System* determine the allowable problem statements that can be made to the DSS. While the quality of the output generated by the *Problem Processing System* depends greatly on the thoroughness, accuracy and organization of the data in the *Knowledge System*.

2.2.2 DSS Classification

Various authors in the field of decision support systems have proposed different methods of classifying DSS[23,24,25,26]. Alter [23] divides DSS software into seven types based on the functions they perform. Three of these types are *data-oriented*, performing data retrieval or data analysis. The remaining four types are *model-oriented*, that offer a simulation, optimization or "answer suggestion" capability. Donovan and Madnick [24] and Sprague[25], classify DSS software on the nature of decision situation they are designed to support. For example, several banks use a *Portfolio Management System* to help their portfolio managers to take informed decisions. Bonczeck et al. [26] based a classification scheme on the degree of *non-procedurality* of the data retrieval and modelling languages provided by the DSS. Procedural languages require a step-by-step specification of how data is to be used or computations are to be performed. Non-procedural languages require the user to specify only *what* is required.

The various approaches to classifying DSS are summarized in table 2.1 below.

Table 2.1 DSS Software Classification Schemes
[Source 20, page 11]

Source	Classification Scheme
Alter (1977) [19]	Data-oriented vs. Model-oriented
Donovan and Madnick (1977) [20]	Ad-hoc vs. Institutional
Sprague (1980) [21]	Specific DSS vs. DSS generators
Bonczek, et al. (1980) [22]	Procedural vs. non-procedural

2.2.3 Practical DSS Application

As stated earlier, a DSS is a decision support tool. It can be a specifically designed software or it can just be a simple program that helps in decision making.

For example[22]:

The multi-national pharmaceuticals company Pfizer used a DSS to their advantage in a court case against another pharmaceutical company. The subject of the case was a drug introduced by both the companies in the market simultaneously. Pfizer contended that the other company had violated the patent owned by Pfizer. And that Pfizer suffered due to the loss of sales of the drug to the competition. When the case was presented in court, Pfizer used a DSS to assist them. Using this DSS model Pfizer could provide answers to questions like the estimated sales and profits from the drug *if* the competitor had not violated the patent and introduced the competing drug. A rapid "what-if" analysis of the situation was done using the DSS to provide the court with accurate analysis. In effect, the DSS was used to plan the legal tactics. The end result was that Pfizer won the case and the effective use of a DSS was boldly highlighted.

As illustrated by this example, the "what-if" scenario analysis feature of a DSS can be used to examine the effects of policy, strategy or external decisions relating to the products at their end-of-life.

CHAPTER 3

FORECASTING MODELS

The forecasting software is intended to provide support for decision making. It is statistical rather than either a rule-based or knowledge-based Decision Support System. Two different models have been used for forecasting the quantity of product in the waste-stream: The standard normal distribution and the bath-tub model.

3.1 Bath-tub Model

The bath-tub model is based on the bath-tub curve. The bath-tub curve is characterized by its three distinct phases. (1) Exponentially decreasing initial phase, (2) steady state, and (3) exponentially increasing final phase. This model, therefore, can be used for products exhibiting similar failure characteristics. The AT&T Reliability model[6] is based on the exponential bath-tub curve model.

Important definitions associated to reliability are now reviewed. *Reliability* is defined by the Webster's Dictionary[27] as "the quality or state of being reliable" or "the extent to which an experiment, test, or measuring procedure yields the same results on repeated trials". An alternative definition is offered by the "*Quality Vocabulary*"[28] from the British Standards Institution, "*Reliability* is the ability of an item to perform a required function under stated conditions for a stated period of time." The *stated period of time* is commonly known as the service life.

The overall reliability of product depends greatly on the reliability of individual components. Various factors like the usage pattern and the application environment play a role in determining the reliability of the product as a whole. Currently, there are no methods for obtaining the exact reliability data for each of the components. What can be done, however, is to "treat large populations of components probabilistically, and thereby predict average lifetimes"[10].

A distinction can be made between maintained and non-maintained systems too. Maintained systems are those which, upon failure, are serviced and brought back to their initial operative state. Parameters like Mean-Time-Between-Failure (MTBF) are associated with such kind of systems. Non-maintained systems on the other hand are not serviced when they fail and although MTBF does not apply to these systems, Mean-Time-To-Failure (MTTF) plays a significant role. This distinction is not being considered in this study and all the systems are assumed to be non-serviceable.

Having addressed the relevant definitions, the shape of the reliability curve is considered. Basically a "bath-tub" shaped curve is used for reliability studies (See figure 3.1). The bath-tub curve is divided into three portions, each with distinct characteristics. The bath-tub curve represents device failure rate over time: also referred to as Device Operating Failure (DOF). Products that fail in tests before the consumer ever uses them are referred to as Dead On Arrivals (DOA). The DOA parts never leave the manufacturing facility.

Infant mortality (figure 3.1(a)) is characterized by an initially high but rapidly decreasing failure rate. Infant mortality begins as soon as the product arrives in the field. This phenomenon can be explained by the fact that some "weak" units pass the initial tests, but fail shortly afterwards due to defects that are not immediately fatal. After the initial high failure rate of the infant mortality period, the device failure rate enters a

Steady-State region (figure 3.1 (b)). The hazard rate or failure rate during this period of time is either constant or changes very slowly.

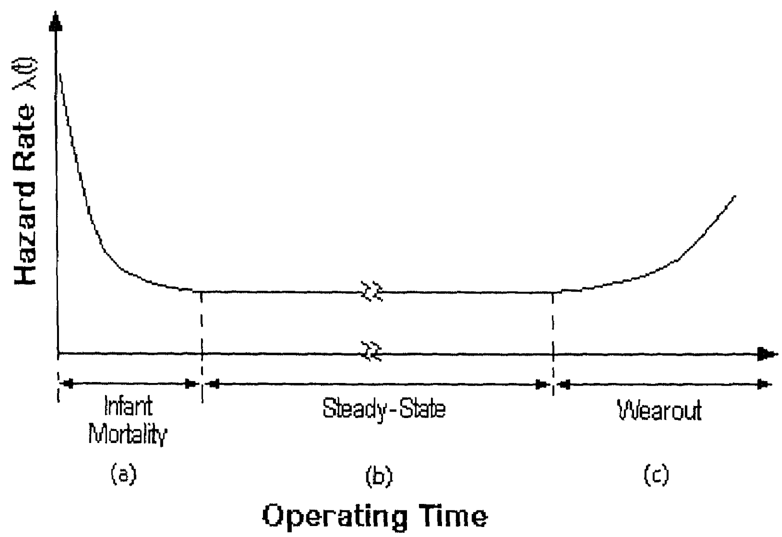

Figure 3.1 Bath-tub curve model of hazard rate.
[Source 6]

Wearout occurs as the hazard rate rises and the surviving units fail at an ever increasing rate (see figure 3.1(c)). In mechanical devices, failure occurs due to the physical wear-out of the parts. In non-mechanical (electronic) parts, the failure may occur due to other reasons such as thermal fatigue.

The *exponential distribution* is widely used in reliability analysis. It is the simplest distribution and is characterized by a constant device hazard rate. The exponential distribution model is used for modeling the reliability of products once the infant mortality period is complete. The exponential distribution is modeled as follows:

- Probability density function

$$f(t) = \lambda e^{-\lambda t} \quad (t \geq 0 \; \lambda > 0) \tag{3.1}$$

- Cumulative distribution function

$$F(t) = \int_0^t f(x)\, dx = 1 - e^{-\lambda t} \tag{3.2}$$

- Survivor function

$$S(t) = 1 - F(t) = e^{-\lambda t} \tag{3.3}$$

- The hazard rate is constant

$$\lambda(t) = \frac{f(t)}{S(t)} = \lambda \tag{3.4}$$

To use the exponential model one assumes that adequate tests have been conducted and the hazard rate data for the product under consideration is known. The model has been modified for the current study. The general structure of the model is the same. Instead of the device hazard rates, however, percentage failure rates are used. By making this change, the model becomes more intuitive for the user who does not consider exponents and integration intuitive.

3.2 Standard Normal Distribution Model

The normal distribution for a continuous random variable is defined by two characteristics: mean and variance (or standard deviation) [15]. A graph of the normal distribution is shaped like a bell (see figure 3.2.1).

All normal distributions are symmetrical around their mean. Consequently, fifty percent of the distribution is above the mean and fifty percent is below the mean. The mean and the median are equal when a population has a normal distribution.

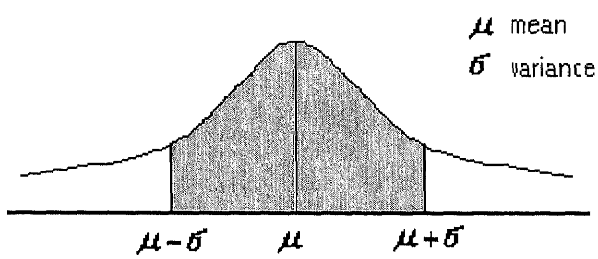

Figure 3.2.1 Normal Distribution

In the figure 3.2.1, the shaded area represents the events that are within a variance of $\pm\sigma$ of the mean μ. An important property of the normal distribution is that $\mu\pm\sigma$ represents roughly sixty eight percent of the area under the curve. Also the two un-shaded tails of the curve represent thirty two percent of the area under the curve, (figure 3.2.1) and the un-shaded portions on one side of the mean represents about sixteen percent of the area under the curve. If the area plus or minus two standard deviations is considered, then the area covered is close to ninety five percent of the total population. For a standard normal distribution [15]:

$\mu \pm 1\sigma$	Includes about 68% of the population
$\mu \pm 2\sigma$	Includes about 95% of the population
$\mu \pm 3\sigma$	Includes about 99% of the population

Any normal distribution can be transformed into a *standard distribution,* referred to as a Z-distribution. The transformation to a standard normal distribution is accomplished using [12]:

$$Z = \frac{X - \mu}{\sigma} \tag{3.5}$$

Where X is the observed value, μ is the mean and σ is the variance of the value to be transformed.

Using the above formula any observed value X can be standardized to its corresponding Z-value.

If $Z = 0$ then $Z = 0$
If $Z > 0$ then $X > \mu$
If $Z < 0$ then $X < \mu$

The mapping of any normal distribution to a standard normal distribution can be illustrated as follows:

Assume a normal distribution for product sales (X) with $\mu = 40$ and $\sigma = 10$ (see figure 3.2.2). For every value X there is a corresponding Z value. This Z value is computed using equation 3.5. For example, for $X = 20$ and $X = 65$.

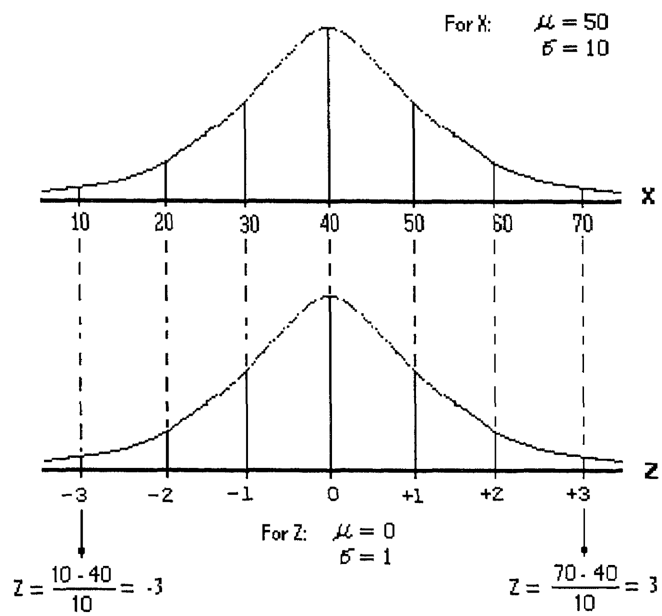

Figure 3.2.2 Mapping of normal distribution to standard normal distribution

For X=20 $Z = \frac{20 - 40}{10} = -1$

For X=60 $Z = \frac{65 - 40}{10} = 2.5$

Thus, every normal variable can be converted into the standard normal variable Z.

The percentage of the population that is between the mean 40 and 65 can be determined from the corresponding Z-value 2.5. The value of 2.5 in the z-table (see Appendix A-2) gives an answer of 49.38% of the population.

The standard normal distribution is a versatile and generic distribution that can be applied to a variety of products with the knowledge of the product's average life expectancy and the variance of the life expectancy. For the purpose of this study, no modifications have been made to the standard distribution model. The data obtained from the user provides the DSS with the mean time period for failure and the variance. The DSS software is used to obtain the percentage failure of the products after a certain period of time has passed. Instead of calculating the percentage of products failing at a particular time around the mean, a summation is obtained. For example, given the average product failure of 6 months with a variation of two months, figure 3.2.3 shows the monthly failure rate, whereas figure 3.2.4 shows the cumulative failure rate for the same period.

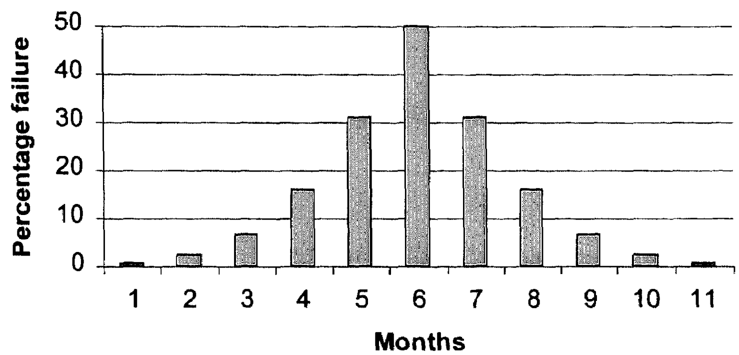

Figure 3.2.3 Monthly Failure Rate

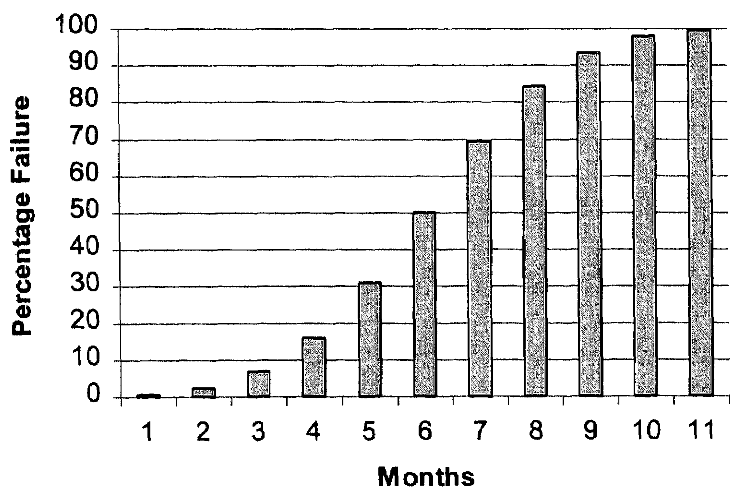

Figure 3.2.4 Cumulative Failure Rate

CHAPTER 4

DESIGN AND IMPLEMENTATION

This forecasting software is web-based and modular. Two forecasting models are currently part of the software. Additional models can be added in the future on an "as required" basis. The modularity ensures that refinements to the existing models or addition of new models are easy to implement. Web-based software facilitates ongoing updates and wide-spread distribution.

4.1 Requirement Analysis

4.1.1 Problem definition

This forecasting software is to be used as a decision support tool to assist with decisions relating to products in the waste-stream. The objective is to predict the quantity and timing of waste generation for a particular product or product range. The input to the forecasting software is the product sales data per unit time and the product's failure rate. Using this input data, the system provides forecasts of the timing and quantity of product entering the waste stream.

Two different models are available to examine disposal behavior: the bath-tub model and the standard normal distribution. The bath-tub curve is used to model the failure rates of products that experience a "bath-tub" curve failure behavior. The standard normal distribution is used to model the failure rate of a product that has a "bell curve" or normal distribution around an average failure time.

Obsolescence and storage factors are also considered. Three kinds of obsolescence factors are considered:

1. Out of fashion: the product under study may become out of fashion and is simply discarded. The product is functional, but is discarded nevertheless.
2. Technologically obsolete: advances in technology render the product undesirable. The consumer discards the product under study in favor of a more technologically advanced product. For example, a Liquid Crystal Display (LCD) panel may replace a bulky Cathode Ray Tube (CRT) computer monitor.
3. Other reasons: a category that allows for considerations not foreseen by the system designers.

The obsolescence factors increase the total product quantity in the waste-stream. However, storage factors temporarily reduce the quantity of product in the waste-stream. Storage of waste product is included in the forecasting software to account for product storage, after failure or obsolescence, at the consumer's premises. Storage applies to both products that fail in the field and those that become obsolete.

The formula that describes the rate at which product enters the waste-stream follows:

$$Y_t = f_{failed}(x) + f_{obsolete}(x) - f_{into\ storage}(x) + f_{out\ of\ storage}(x) \quad (4.1)$$

Where:

- Y_t: the quantity of product entering the waste-stream, at time 't'.
- x: the quantity of product in use
- $f_{failed}(x)$ is a function that determines then number of units failing at time 't'. The function uses either the bath-tub model or the standard normal distribution model, as specified by the user.
- $f_{obsolete}(x)$ is a function that determines the number of units that become obsolete at time 't'. This includes technical, fashion-related or other reasons for obsolescence.
- $f_{into\ storage}(x)$ determines the number of units that go into storage upon failure or obsolescence, at time 't'.
- $f_{out\ of\ storage}(x)$ is a function that determines the number of units entering the waste-stream at a time 't', after being placed into storage at an earlier time.

As mentioned above, there are three separate components of the obsolescence factor:

$$f_{obsolete}(x) = f_{technically\ obsolete}(x) + f_{unfashionable}(x) + f_{other\ reasons}(x) \quad (4.2)$$

Where:

- $f_{technically\ obsolete}(x)$ is a function that determines the number of units that are rendered undesirable due to advances in technology, at time 't'.
- $f_{unfashionable}(x)$ is a function that determines the number of units discarded because they are no longer fashionable, at time 't'.

- $f_{\text{other reasons}}(x)$ is a function that determines the number of units discarded at time 't', due to reasons other than those mentioned above.

Furthermore,

$$f_{\text{into storage}}(x) = f_{\text{failed into storage}}(x) + f_{\text{obsolete into storage}}(x) \tag{4.3}$$

Where:

- $f_{\text{failed into storage}}(x)$ is a function that determines the number of failed units placed into storage by their users, at time 't'.
- $f_{\text{obsolete into storage}}(x)$ is a function that determines that number of obsolete units placed into storage by their users, at time 't'.

$f_{\text{into storage}}(x)$ is the amount of product not immediately discarded after it is either defective or obsolete. There are two components to this factor because the amount of time a failed product is stored may be different from the amount of time an obsolete product is stored.

Finally,

$$f_{\text{out of storage}}(x) = f_{\text{failed out of storage}}(x) + f_{\text{obsolete out of storage}}(x) \tag{4.4}$$

- $f_{\text{failed out of storage}}(x)$ is a function that determines the number of failed units that enter the waste-stream after being placed in storage by their users, at time 't'.
- $f_{\text{obsolete out of storage}}(x)$ is a function that determines the number of obsolete units that enter the waste-stream after being placed in storage by their users, at time 't'.

$f_{out\ of\ storage}(x)$ is the quantity of product, entering the waste-stream after being stored by their users. Similarly, $f_{into\ storage}(x)$, it too has two components for the products that are stored after failure or obsolescence.

The input data requirement for the bath-tub model and the standard normal distribution model are different.

4.1.1.1 Bath-tub Model: Reliability is modelled as a "bath-tub" curve. Recall from section 3.1 that there are three distinct phases: infant mortality, use and wear-out. The user is not expected to have detailed information about the product failure rate. Since hazard rate (FITs) for product are obtained by rigorous testing procedures and are generally unavailable, a simplification of this model is employed..

The software performs computations based on percentage failure. The user provides the desired time unit — days, weeks, months, quarterly, semi-anually or yearly.

The user provides values for the parameters a, b, c, d, t_0, t_1, t_2 and t_3 (See figure 4.1). An explanation of each of the parameters follows:

- t_0 is the start of a product's life.
- The period from time t_0 to t_1 is the length of the infant mortality period.
- The time period between t_1 and t_2 is the length of the use phase.
- The time period between t_2 and t_3 is the length of the wear-out phase.

The relationship $t_3 > t_2 > t_1$ must be maintained in the specification of the time parameters t_1 through t_3.

- Parameter 'a' is the initial percentage failure rate at time t_0.

- Parameter 'b' is the percentage failure rate at time t_1.
- Parameter 'c' is the percentage failure at time t_2.
- Parameter 'd' is the percentage failure at time t_3.

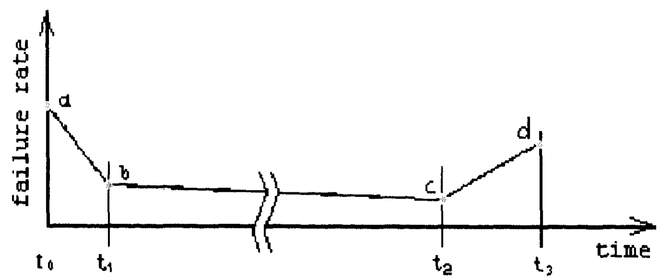

Figure 4.1 Reliability model

To find out the percentage failure rate of the product at any given point of time, integration, as described in section 3.1 on the bath-tub model, can be used. However this only provides accurate results if the input parameters are precise. Furthermore, the end value is extremely sensitive to the parameters supplied due to the high degree of iterative computations involved. To counter this problem a method that is more intuitive to the user is employed to calculate product failure using the bath-tub model. This method is less precise, but should be more preferable to practitioners since it is more intuitive and practical for cases where hazard rate has not been determined using the recommended rigorous reliability testing procedures.

The algorithm used by this program is:

1. Start
2. Get the time unit from the user
3. Obtain the time related parameters t_1, t_2, and t_3 from the user
4. Get the percentage failure rates a, b, c and d, which correspond to the time points t_0, t_1, t_2, t_3 respectively (See figure 4.1)
5. Check the percentage failure at the end of the time period t_3 using the failure percentages entered by the user
6. If the total percentage failure is outside of the acceptable range (which is, between 90% and 110%) ask the user if the current values are acceptable. Also, provide the user with an option of either revising input values or using the values as they stand
7. For every data point provided by the user

   7.1. Find percentage failure for a single user-specifed time period starting from the initial point. Subsequently increment this period by one scale unit at a time, keeping the initial point constant, until failure reaches 100 % or the forecast time frame is exhausted. Record the failure rate at each point

   - If current time $< t_1$ use the percentage failure range a to b
   - If $t_1 <$ current time $< t_2$ use the percentage range b to c
   - If $t_2 <$ current time $< t_3$ use the percentage range c to d
   - If current time $> t_3$ – check if the percentage failure at that point > 100%
   - If percentage failure < 100% find the percentage failure using the trend given by the range c to d

   7.2. Go to the next data point and follow the procedure outlined in 7.1, above
8. Stop

The algorithm that is used to obtain the actual percentage failure value for a given range in this program is now considered.

Figure 4.2 illustrates that the percentage failure at user specified time period is given by the average percentage failure over the specified time period. In the case of the bath-tub model there are two possibilities: failure rate is constant or changing with time.

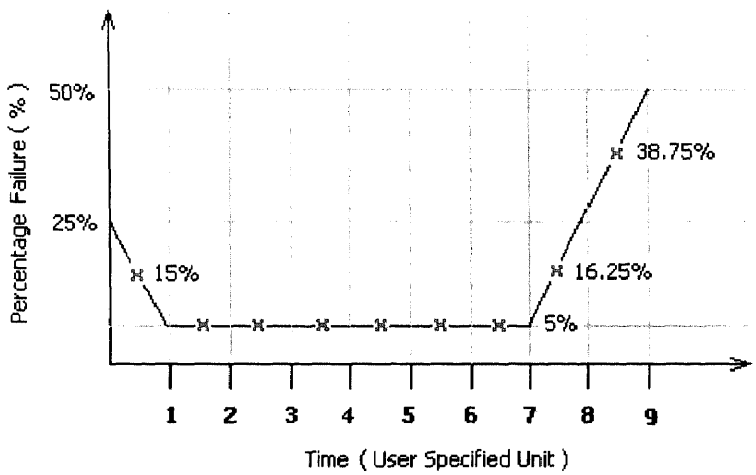

Figure 4.2 Calculating percentage failure using the bath-tub curve model

In the example (see figure 4.2), the percentage failure rate during infant mortality is initially 25%. This failure rate reduces to a constant rate of 5% in the use phase. Failure then increases to 50% at the end of the wear-out phase. The values of the time parameters t_1 through t_3 are: $t_1 = 1$ unit; $t_2 = 6$ units; $t_3 = 8$ units.

Percentage failure for time period 1 is given as : $\frac{(25-5)}{2} + 5 = 15\ \%$

Percentage failure in the use phase is constant at 5 %

Percentage failure in the wear-out phase for time period 7 : $\frac{(27.5 - 5)}{2} + 5 = 16.25\ \%$

Thus the percentage failure rates can be computed for all the time periods. The results of the computations for yearly failure rates for figure 4.2 are summarized in Table 4.1 below.

Table 4.1 Percentage failure rates for the bath-tub model

Time Period	Percentage Failure (%)
1	15 %
2	5 %
3	5 %
4	5 %
5	5 %
6	5 %
7	5 %
8	16.25 %
9	38.75 %
Total	**100 %**

4.1.1.2 Standard Normal Distribution Model: If the "bell-curve" model is specified by the user, the data requested is the Mean Time to Failure (MTTF) or mean and the standard deviation about that mean. Both the mean and standard deviation are in units of time. By the MTTF, fifty percent of the product will have failed and the standard deviation will determine the rate of failure around the MTTF. Thus, if the variance is very small, time from the onset to the end of rapid failure will be short.

The algorithm for this model is similar to the bath-tub curve model (section 4.1.1.1), except for changes due to differences in parameters utilized. The standard normal distribution algorithm follows:

1. Start
2. Get the Mean Time to Failure (MTTF) from the user
3. Get the standard deviation from the user
4. For every data point provided by the user, do the following processing
5. Find percentage failure for a single user-specifed time period starting from the initial point. Subsequently increment this period by one scale unit at a time, keeping the initial point constant, until failure reaches 100 % or the forecast time frame is exhausted. Record the failure rate at each point
6. Go to the next data point and follow the procedure outlined by the point 5 above
7. Stop

An example is presented (see figure 4.3) to illustrate this model. The MTTF is given as 5 time units with a variance of 3 time units. The values obtained over a period of 10 years are shown in the figure.

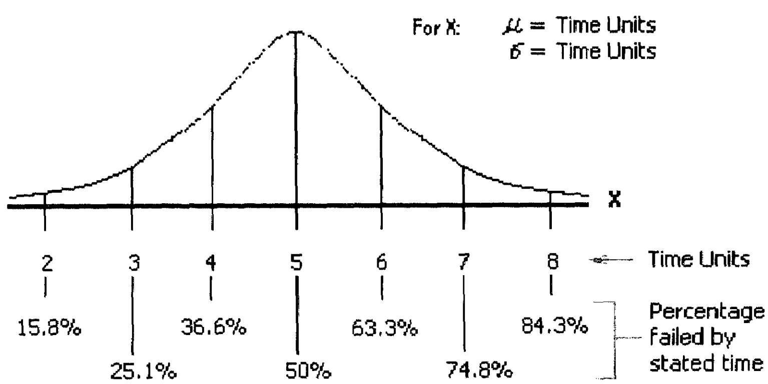

Figure 4.3 Time-to-date percentage failures

The values are time-to-date percentages, and the actual percentage failure *during* a particular time period can be obtained by subtracting the preceding percentage value from the current one.

For example, the percentage failure for time unit 3 is:

25.1% - 15.8% = 9.3%

Also, for figure 4.3, at year 11 failure is approximately 100%.

4.1.2 Hardware Requirements

The software is to be integrated with the Multi-lifecycle Engineering Research Center web-site at www.njit.edu/MERC. Consequently, the software is hosted on the internet using the resources of the New Jersey Institute of Technology (NJIT).

The hardware requirement for hosting the software is a computer system connected to the internet and capable of supporting a number of concurrent users using the Hyper-Text Transfer Protocol (HTTP). During development the software was hosted on the NJIT web server.

To use the software, a computer must have access to the internet via a TCP/IP network. The software is platform independent, hence any computer system capable of supporting the use of a graphical browser and accessing the software over the internet is acceptable.

4.1.3 Software Requirements

The software has been written on a Unix system using the Perl language to implement the Common-Gateway-Interface (CGI) functionality. A Perl language interpreter (version

5.0), is required on the server side in order to run the software scripts. The user requires a graphical web-browser that can support Java applets: either Netscape® Navigator or the Internet Explorer.

4.2 Design

The problem statement requires that the design of the software be based on the client server model. See figure 4.4.

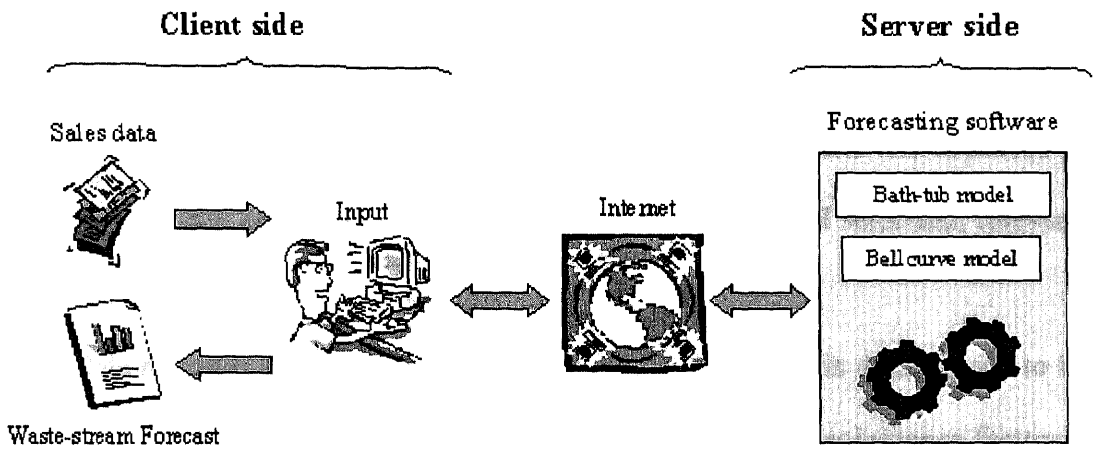

Figure 4.4 System model.

HTML forms were used to allow the user to input data using the graphical web-browser. It is assumed that target users have already used a graphical web-browser and are comfortable entering data using HTML forms.

Figure 4.4 presents a schematic view of the system as a generic client-server system with the client being any graphical web-browser. Perl scripts implement the server side Common Gateway Interface (CGI) to take in the information provided by the user through HTML forms. Using pre-compiled binaries, implementing the mathematical calculations, this data is processed iteratively for the given time range. The pre-compiled binaries have been written in the C and C++ programming languages. After the iterative calculations have been performed, the data that has been generated is shown in the form of a graph embedded in a HTML document. The graph is actually a Java applet specifically written to graphically present the analysis. A text file containing the data generated during the analysis is also created. Figure 4.5 shows the flow-chart of the software.

The bath-tub and the bell-curve models are implemented as explained in the previous sections. The model selection portion of the flowchart gives an opportunity to select the different models available for analysis. Also, new models can be added in this part of the software, as they are developed. After the initial model selection, relevant data is obtained from the user and the input sales data is processed.

Data relating to obsolescence factors is obtained next. This data is used to further compute the number of units what will be discarded due to the obsolescence factors.

Storage factors act on the units that fail and also on the units that become obsolete. The following sections will discuss about the implementation of the modules handling the storage and obsolescence factors.

4.2.1 System Flowchart

Presented in figure 4.5 is the flowchart for the entire forecasting software. The individual models have been described in detail earlier or are described below.

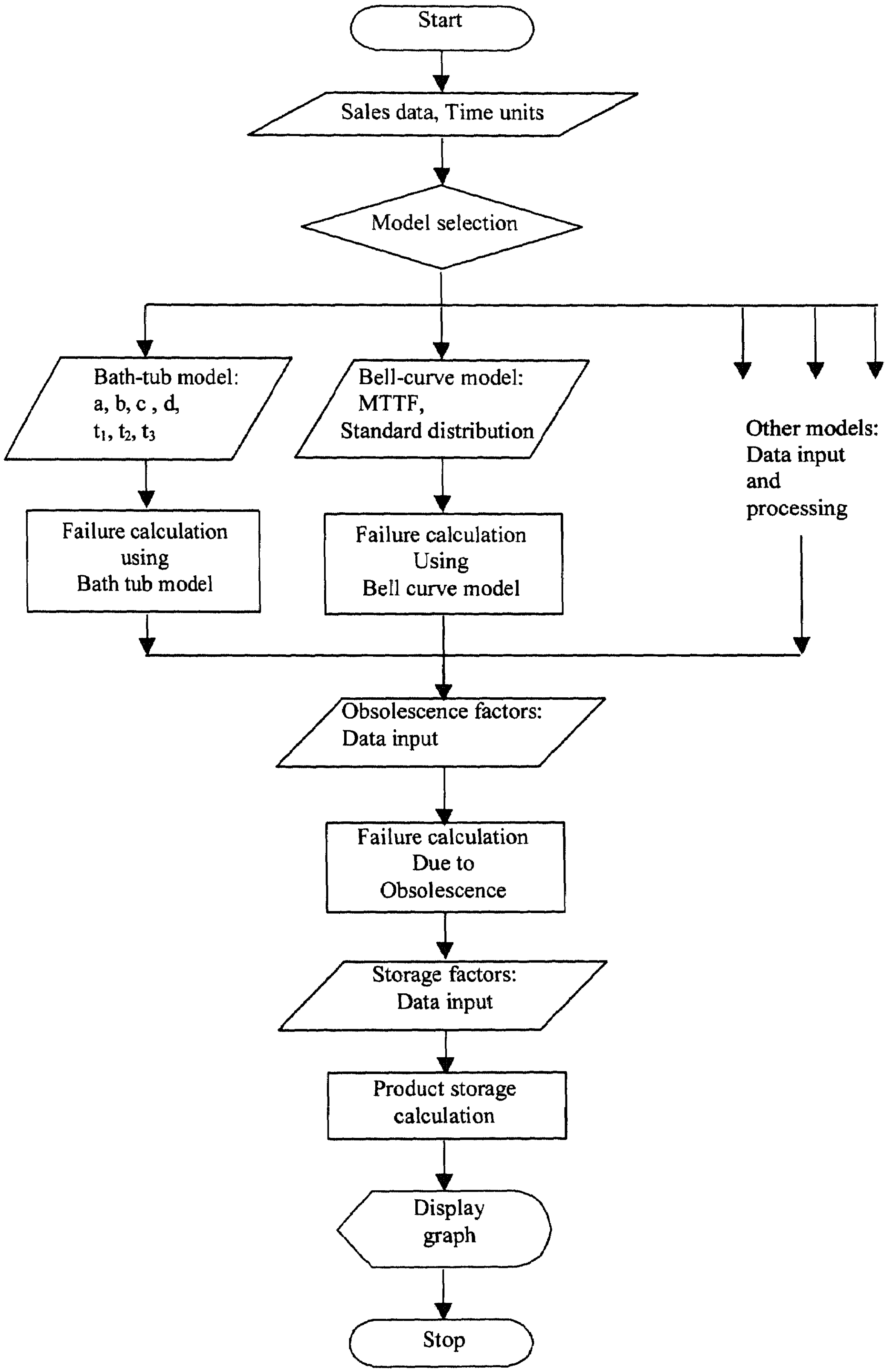

Figure 4.5 Flowchart for the software

4.2.2 Obsolescence Factors Module

As explained in the problem definition (section 4.2.1), three obsolescence factors have been introduced in the computation of the quantity and timing of products entering the waste-stream: product out-of-fashion, technical obsolescence, and other reasons for obsolescence. The effect of the obsolescence factors, either singular or in combination, on the products in the field can be modelled using the standard normal distribution. Information is obtained from the user as regards to the approximate time when each of the factors start affecting the product in the field, the standard deviation and the percentage of product that is affected by the obsolescence factor. Using the standard normal distribution model, the quantity of product that enters the waste stream due to these obsolescence factors is then computed. Obsolescence is illustrated in figure 4.8.

4.2.3 Storage Factors Module

Storage factors are also modelled using the standard normal distribution model. The storage period of product that fail in the field and those units that become obsolete is frequently different. Hence, the product quantity that is stored is computed separately for the products that have failed and for the products that have become obsolete.

Upon failure or obsolescence, specified percentage of product quantity goes into storage. These products do not enter the waste stream immediately. After the time duration specified for storage elapses, the product enters the waste stream depending on the distribution specified by the user (see figure 4.9).

4.3 Working Examples

Examples are presented to demonstrate the two models. These graphs and figures are print-outs obtained from the software during its operation. The previous example for the reliability model is carried forward to demonstrate the effect of the obsolescence and storage factors.

4.3.1 The Bath-tub Model

An example of the bath-tub model (reliability model) follows: The parameter 'a' is the initial failure rate, parameter 'b' is the failure rate at the start of the use phase, parameter 'c' is the failure rate at the end of the use phase and finally parameter 'd' is the failure rate at the end of the wear-out phase (see figure 4.1). The time parameters t_1, t_2 and t_3 are assigned the values: 1 year, 7 years and 9 years respectively. The values of the parameters provided to the model are summarized in table 4.2 below. Sales of 1,000 units were specified at time t_0.

Table 4.2 Parameters for the bath-tub model

Percentage Failure Parameters		Time Parameters	
a	25%	t_1	1 Year
b	5%	t_2	7 Years
c	5%	t_3	9 Years
d	50%		

Thus, as expected, we obtain the graph depicting the amount and timing of products entering the waste-stream over a period of 15 years (see figure 4.6).

Figure 4.6 is print-out from the software of the example that was discussed in section 4.2.1.1. The product failure in the field is same as was calculated manually (see table 4.1).

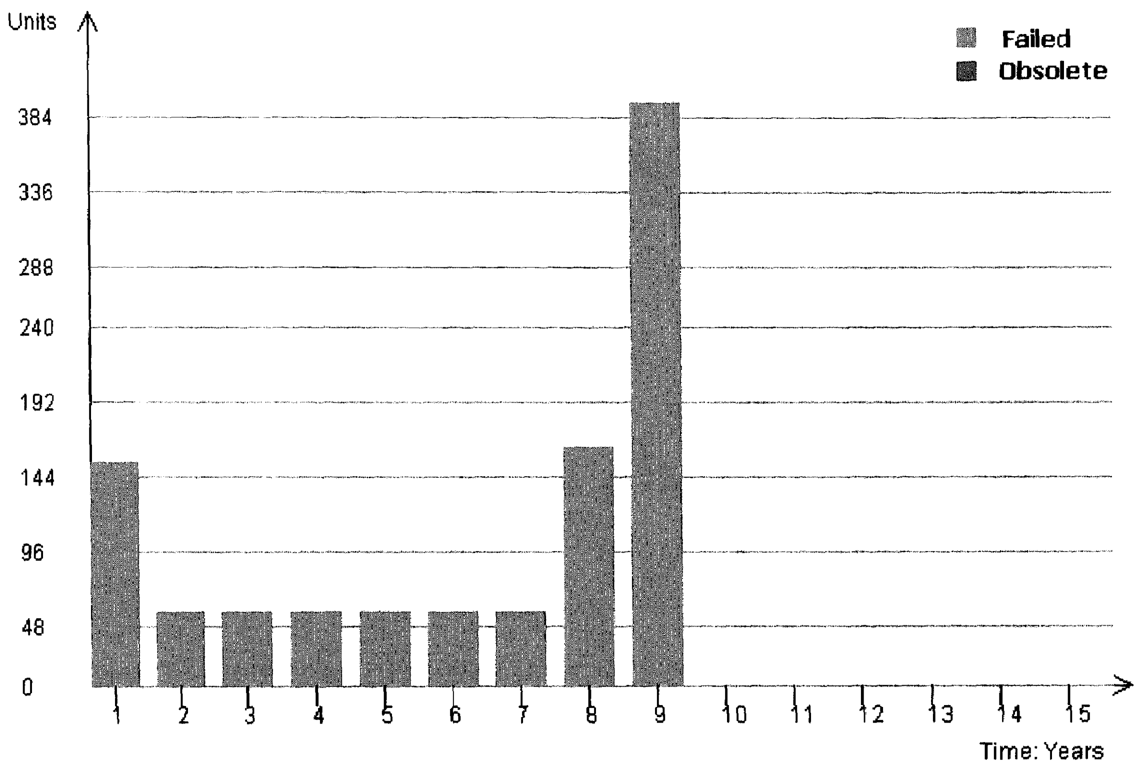

Figure 4.6 Output from the Bath-tub Model

The user can see that, based on the data provided, we have 15% failure in the first year amounting to 150 units. The constant failure rate of 5% for years two through seven results in an annual yield of 50 units. Finally, the rate of failure rises from 5% to 25% in two years. During the eight and ninth year, the percentage failure is 16.25% and 38.75% respectively. This translates to 162 units in the waste-stream during the eight year, and approximately 387 units in the ninth year.

4.3.2 The Standard Normal Distribution Model

Figure 4.7 shows the output from the forecasting software using the standard normal distribution model. The number of units sold in the third year are 1,000. No units were introduced into the market other than those introduced in the third year. The MTTF is five years and the standard deviation is three years.

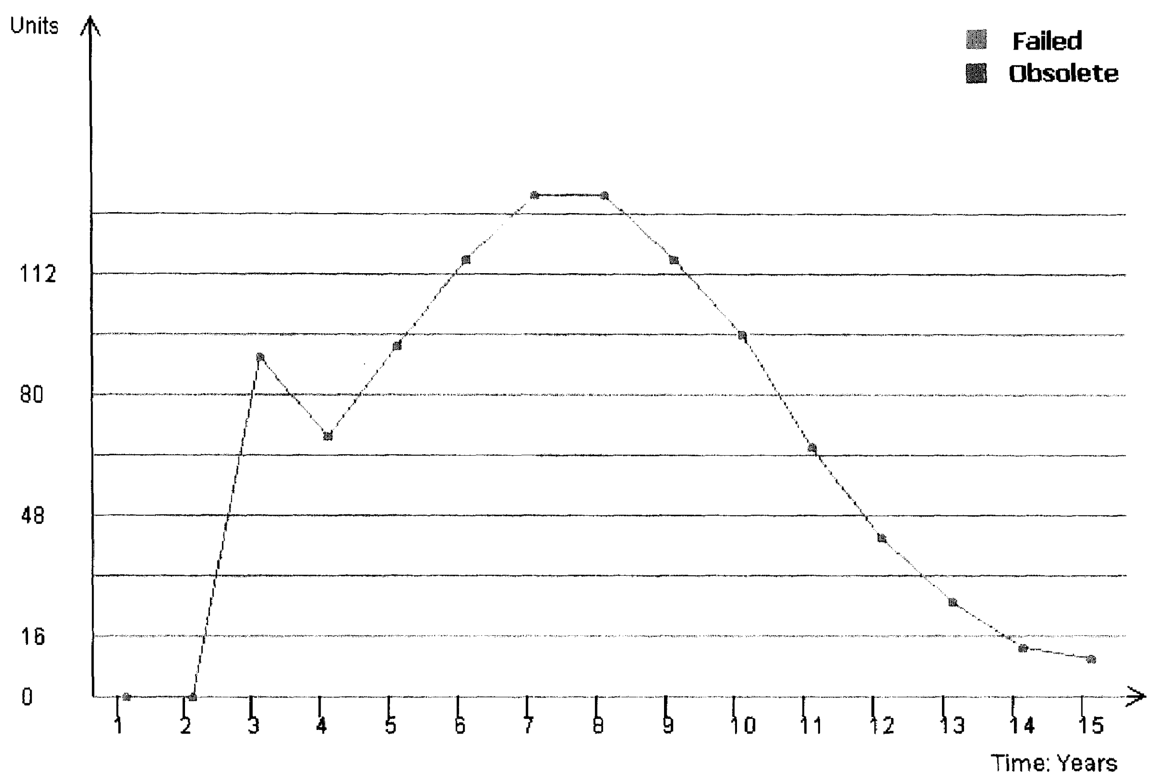

Figure 4.7 Output from the Standard Normal Distribution Model

As explained earlier in section 4.2.1.2, the percentage failure obtained from the standard normal distribution model are year-to-date percentages. The actual percentage failure for a particular time period is the difference between the current failure rate and the failure rate during the preceding time period. Since the initial failure rate is zero, the first percentage value that is obtained is higher than expected and is inconsistent with the bell-shape. This behavior can be explained by observing the actual percentage values obtained from the model. See table 4.3 below.

Table 4.3 Percentage failure rates for the Standard Normal Distribution Model

Time Period	Actual Percentages	Difference
1	9.01	9.01
2	15.87	6.86
3	25.13	9.26
4	36.68	11.55
5	50	13.32
6	63.3	13.3
7	74.86	11.56
8	84.37	9.51
9	90.98	6.61
10	95.25	4.27
11	97.77	2.52
12	99.04	1.27
13	99.62	0.58
14	100	0.38

The cumulative percentage rises with time. The difference between successive percentage failure values rises till the mean time period (in this case the fifth time period), and then declines till the cumulative failure reaches 100%.

4.3.3 Bath-Tub Model with Obsolescence Factors

Continuing with the data used for the bath-tub curve example (figure 4.6 and section 4.3.1), obsolescence factors are now introduced. The assumption introduced by this example is that some of the products become "technically obsolete," due to the introduction of a technologically superior product in the market.

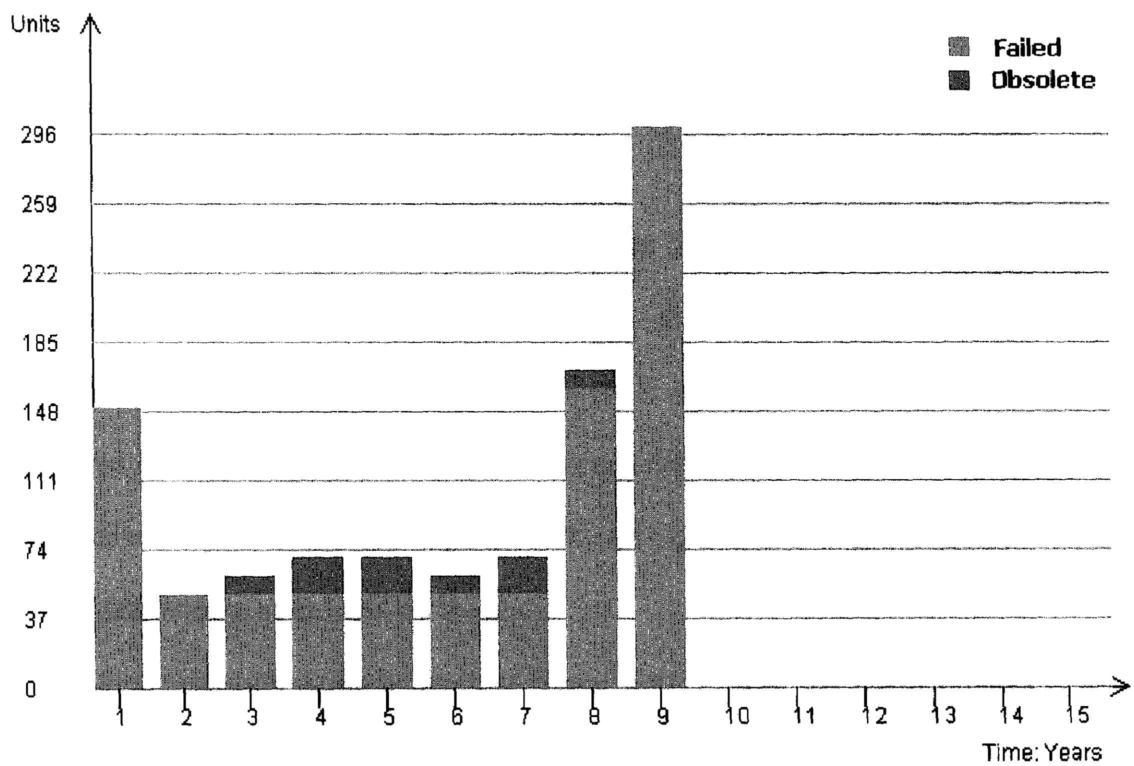

Figure 4.8 Bath-tub Model with obsolescence factors

It is assumed that 10% of the product becomes obsolete on the introduction of a technologically advanced product in the market. This technological obsolescence will have a standard normal distribution over the life-span of the product and will have a mean (MTTF) of five years with a variance of two years. (See figure 4.8)

From the figure we can observe the obsolescence factor begin to affect the waste-stream at year three (μ - σ) with maximum contribution to the waste-stream around the fifth year (μ). Thus we observe the obsolescence factor positively affecting the quantity of product entering the waste-stream.

There are three kinds of obsolescence factors built into the system and these can be used separately or in combination. All three obsolescence factors act as demonstrated in this section.

4.3.4 Bath-Tub Model with Storage Factors

An example of the use of the storage factors that have also been incorporated into the software is now offered. As explained earlier, storage initially reduces the product quantity in the waste-stream. Since, the product in question is not discarded immediately but stored for a certain period of time. Eventually these products *are* discarded and enter the waste-stream. The eventual disposal of the stored products is governed by a standard normal distribution, as defined by the user.

In the example given below (see figure 4.9), 25% of the failed product is stored for an average period of three years with a standard distribution of one year. The product quantity in the field is assumed to be 1000 units. From figure 4.9 we can see that 25% of the failed product goes into storage and then reappears after the storage period, as modelled by the standard normal distribution, expires. Comparing figure 4.9 with figure 4.6 (example of the bath-tub model without the storage factor), we can observe the delayed entry of the stored product into the waste-stream. Figure 4.9 shows two distinct "bell" shapes, in what would otherwise have been similar to figure 4.6.

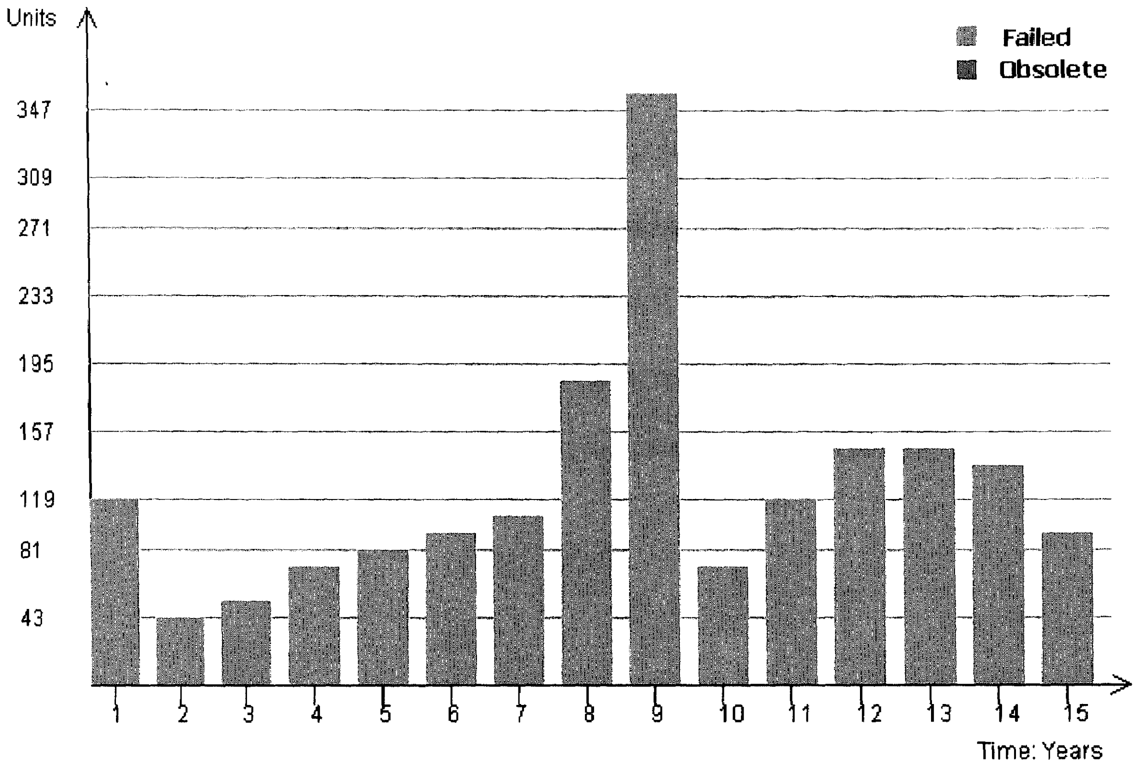

Figure 4.9 Bath-tub Model with storage factor

CHAPTER 5

CRT CASE STUDY

Color television sets sold in the United States from the years 1954 to 1998 are considered to demonstrate some of the applications of this tool. The figures indicate sales to U.S. dealers[29]. The units are in thousands of color TV receivers. The values for the years 1997 and 1998 are the estimated and projected values respectively. A graph of the sales figures is shown in figure 5.1. The sales data is presented in Appendix B-1.

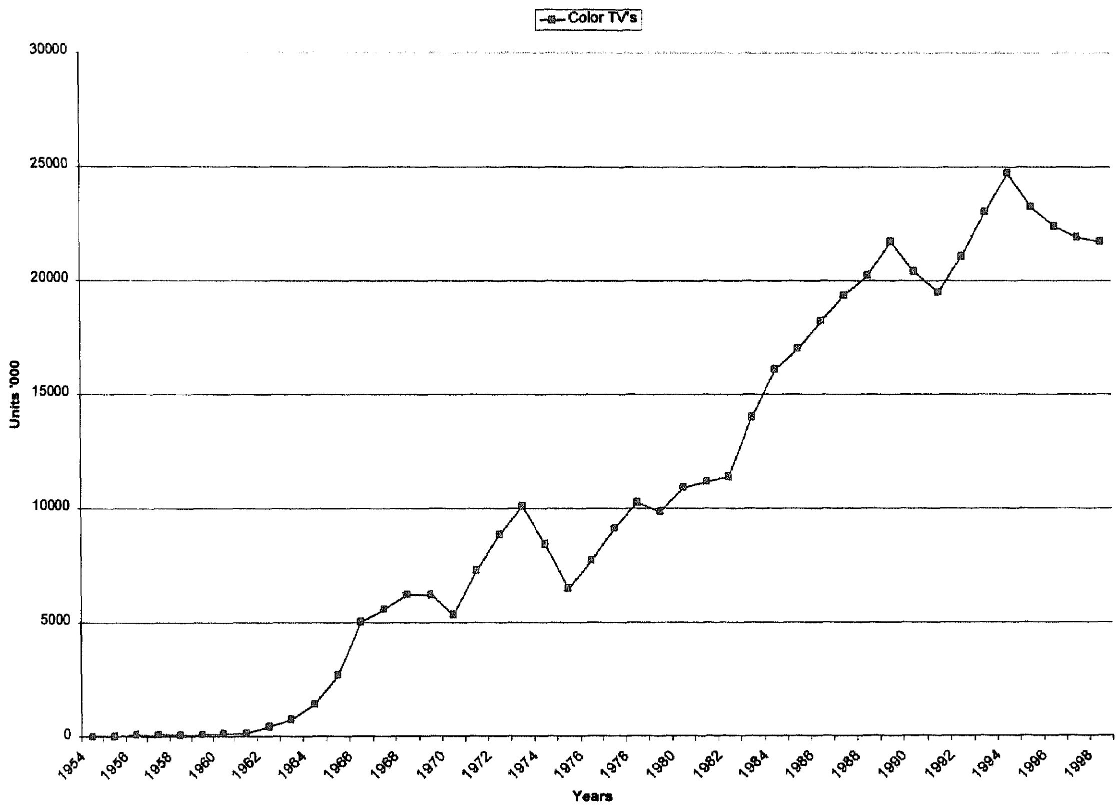

Figure 5.1 Color TV Receivers – U.S. Sales to Dealers
[Source 29]

5.1 Current Situation – Using the Bath-tub Model

Using the data in figure 5.1 as an input, the failure rate using the bath-tub model is predicted. See figure 5.3. (See data in Appendix B-2) The following assumptions were made (See figure 5.2):

i. An initial failure rate of 1.5%, which then drops down to 0.5% at the end of the first year. (Infant mortality)

ii. Failure rate increases to 1% over the next 7 years. (Use)

iii. Thereafter the failure rate increases at the rate of 5% every year. (Wear-out)

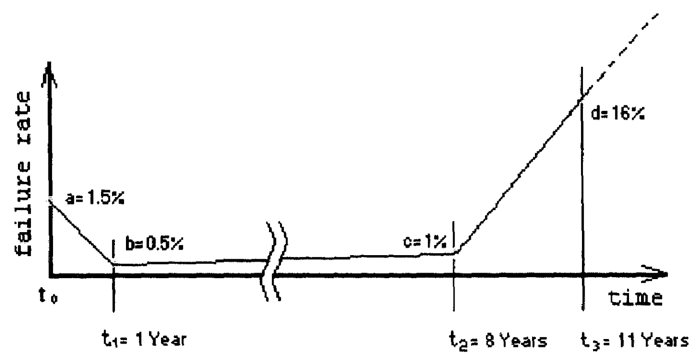

Figure 5.2 Failure characteristics used for the Bath-tub model

From figure 5.2 we can see that the Bath-tub curve continues beyond the time t_3. The rate of increase is 5% per year and the computations will continue beyond the time period t_3 till the net percentage failure reaches 100%.

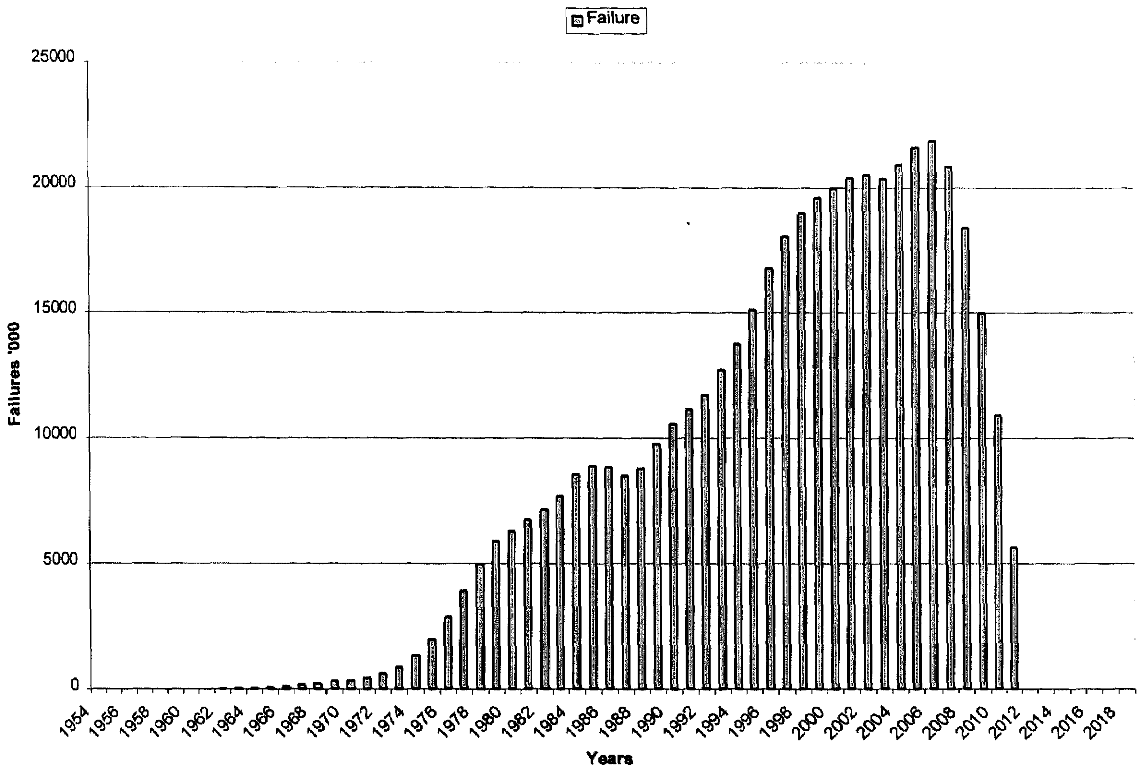

Figure 5.3 Color Television Failure using the Bath-tub model

5.2 Current Situation – Using the Standard Normal Distribution Model

Using the data in figure 5.1 the bell-curve model is used to predict the failure of the color televisions. See figure 5.4. (See data in Appendix B-2) The following assumptions were made for the standard normal distribution model:

i. The life-span (MMTF) of a typical Color TV receiver is assumed to be 11 years (μ=11 years).

ii. The standard distribution is assumed to be 2 years (σ=2years).

Figure 5.4 illustrates the parameters that have been used for this model.

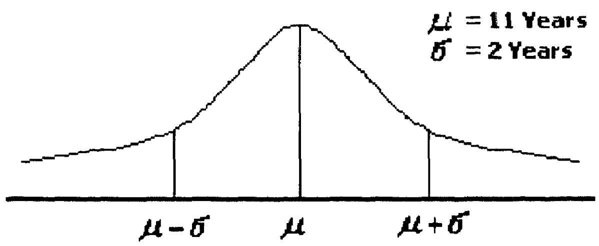

Figure 5.4 Failure characteristics used for the Standard Normal Distribution model

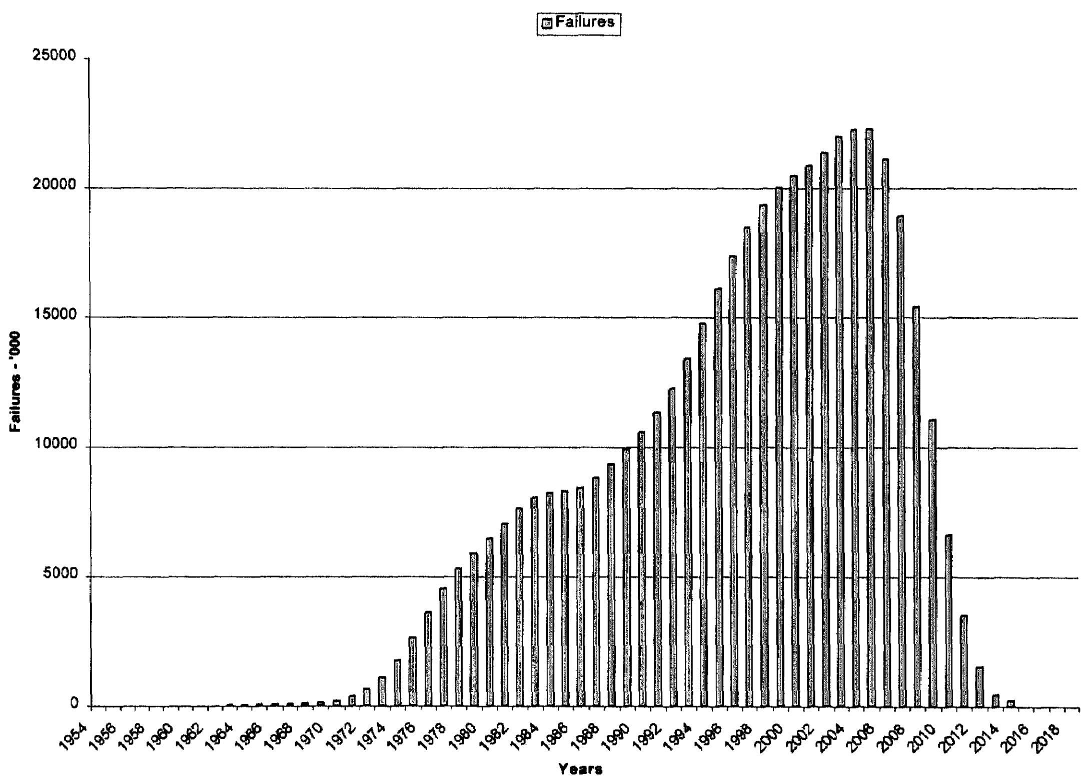

Figure 5.5 Color Television Failure – Estimated using the Standard Normal Distribution model

5.3 Effect of Storage

As stated earlier (section 4.1.1), sometimes the failed product is not discarded immediately. A certain proportion of product quantity is stored, for a period of time. Thus, upon failure, 100% of the product does not immediately appear in the waste-stream. The stored products are eventually discarded and may appear in the waste-stream over a period of time. Figure 5.6 shows the effect of storage on the quantity and timing of the product quantity entering the waste-stream. Three different storage durations are considered: no storage, 30% storage over one year and four years. The standard deviation is held constant at 6 months for all three scenarios. See figure 5.6.

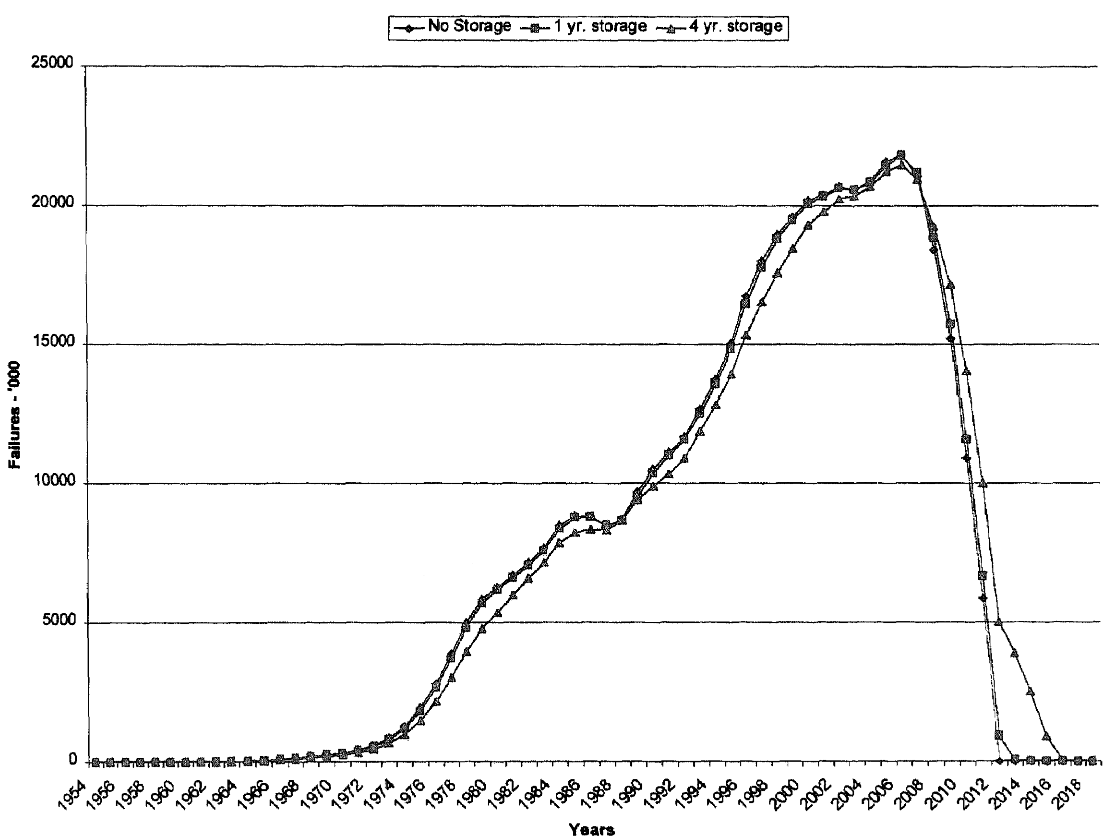

Figure 5.6 Effect of Storage

5.4 Effect of Massachusetts CRT Disposal Ban

As stated earlier (section 1.3), current or impending legislation will have an effect on the policy for processing of waste. Disposal of cathode ray tubes in publicly operated waste disposal facilities has been banned in the state of Massachusetts[11]. The forecasting software is used to estimate the quantity of CRTs that will be disposed and will need processing as per the new law.

The number of television units sold in the state of Massachusetts is estimated by considering the state population in relation to the population of the entire United States.

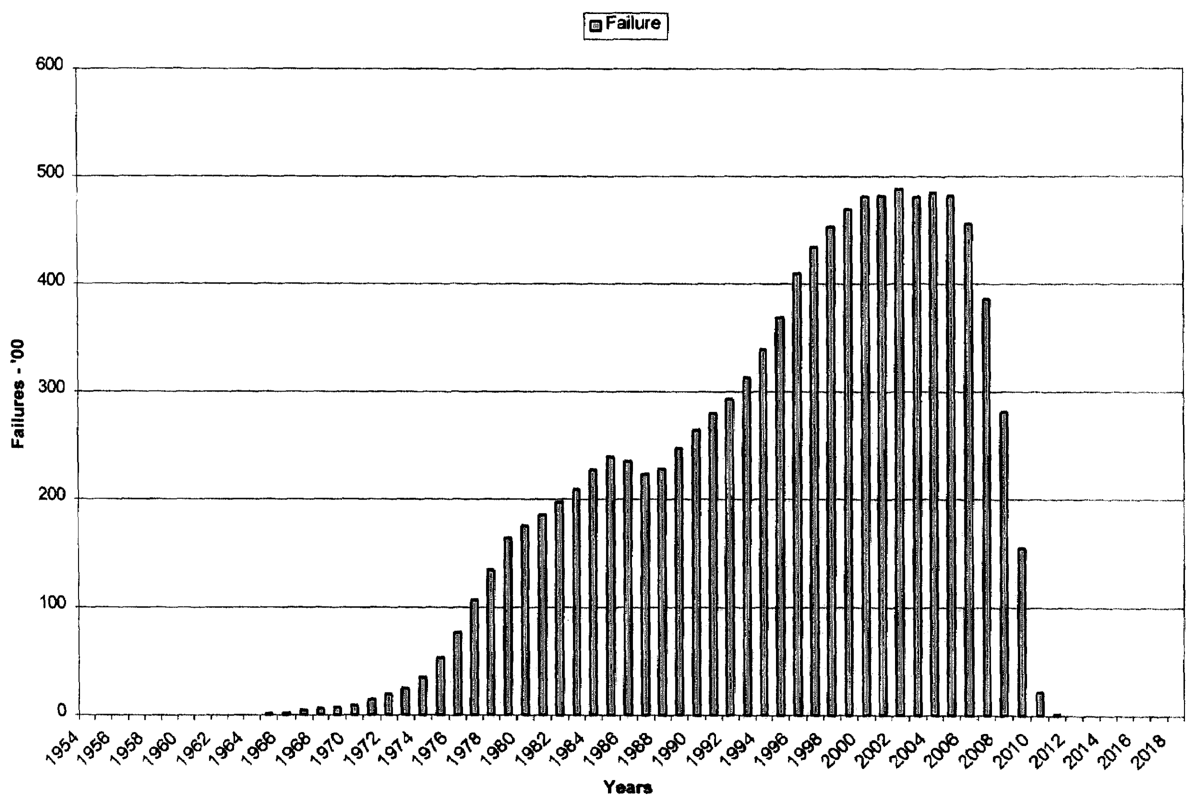

Figure 5.7 Color Television Failure in Massachusetts - Estimated using the Bath-tub model

Per-decade population figures available for the entire United States as well as for the state of Massachusetts were used. The per-decade values were converted to per-year values by assuming a steady rise in the population over the intermediate years. For this test case, annual population figures for the years 1954 through 1996 were estimated. See Appendix B-3 for population data and Appendix B-4 for the generated forecast data.

Similar results are obtained by using the standard normal distribution model. The figure 5.8 shows the rate of color television disposal using the standard normal distribution model.

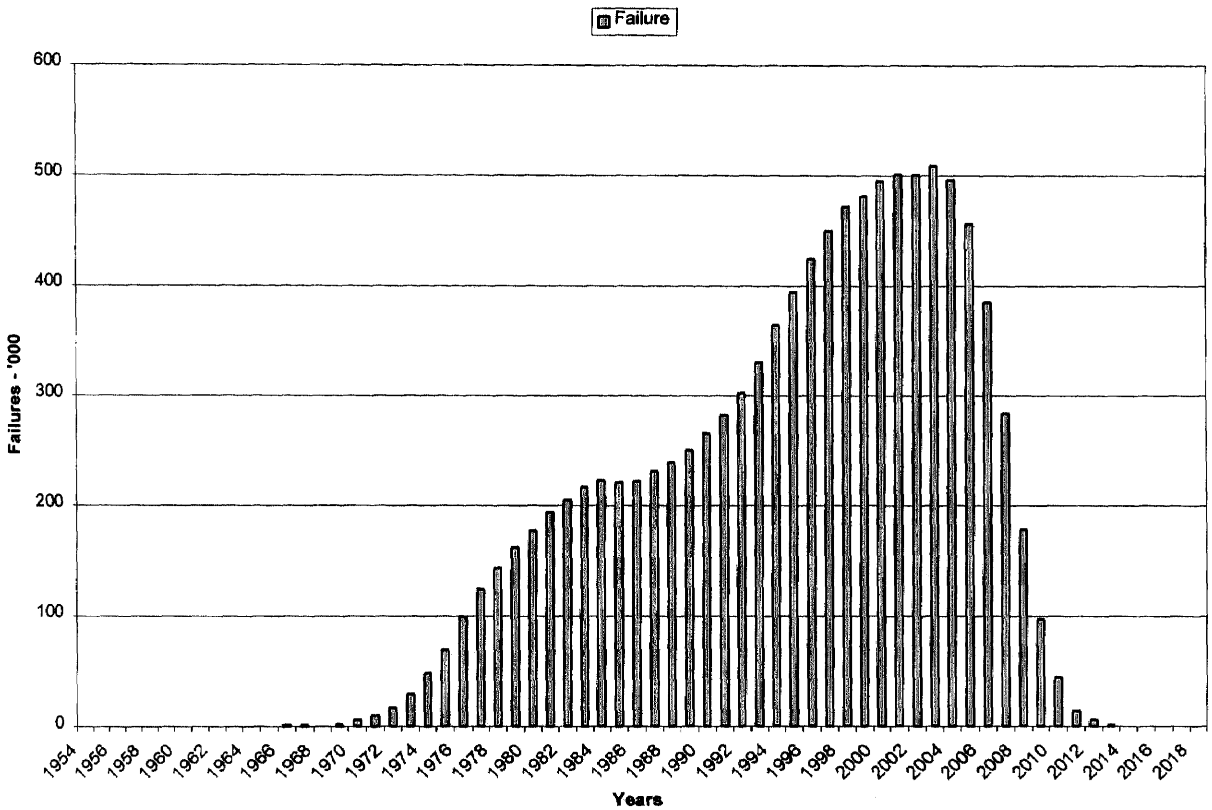

Figure 5.8 Color Television Failure in Massachusetts - Estimated using the Standard Normal Distribution model

The forecasts generated using either models suggest that approximately 500,000 color televisions will enter the waste-stream each year, in the state of Massachusetts, until the year 2005. This prediction is based on the available sales figures of color televisions up to and including the year 1996.

5.5 Effect of Flat Panel Technologies

The majority of televisions sold in the world use cathode ray tubes for projection of images. Cathode ray tubes are, however, faced with competition from Flat Panel Display (FPD) technologies - Liquid Crystal Display (LCD) and Plasma Display Panels (PDPs). For televisions with diagonal screen size greater than 40 inches, FPD systems are preferred. A CRT set of this size would not only be expensive, but would weigh hundreds of kilograms[30]. Flat-panel display technologies are likely to displace the currently used CRT based televisions, due to lighter weight, lower bulk and potential for large screen size. FPDs can be hung on the wall like a picture frame.

Televisions based on the CRT projection technology offer brighter color, intensity and wider viewing angle than competing FPD technologies. However, large screen sizes are not practical with CRT technology. Furthermore, LCD and PDP projection technologies are improving on many important performance dimensions, like picture intensity and refresh speed. Diagonal screen sizes of up to 60 inches can be currently achieved with flat-panel projection technologies.

Newer television transmission technologies like Digital Television (DTV) and High Definition Television (HDTV) have proven themselves technically and will be introduced soon. Both these technologies enable the transmission of high resolution images. DTV broadcasting will completely replace the current National Television System Committee (NTSC) format broadcasting in the United States by the year 2006

[31]. This change in format will make the current television sets, which are capable of receiving only NTSC signals, obsolete[31]. The conventional wisdom is that the additional picture quality offered by the new broadcasting format will offer little perceived benefit, unless it is displayed on a screen with a diagonal measurement greater then 40 inches [30]. The combination of new broadcasting technology and the development of larger flat-screen televisions will result in the current CRT based televisions becoming obsolete.

This scenario has been modelled using the forecasting software. The effect of introduction of these two new technologies, in the scenario illustrated here, is assumed to be equivalent to the introduction of color televisions (in 1954) in a market where black and white televisions were already being sold. Color television sales overtook the sales of black and white television sets after just over 10 years (in 1967) and have been strong since then. Affordable television sets with the dual advantage of a large screen and DTV support may replace the demand for conventional CRT based television sales in a similar fashion.

This example assumes that Flat Panel Displays are introduced to the market in the year 1998 and that the sales of FPDs take a similar proportion of annual sales as did color televisions when they were introduced in 1954. Total sale of televisions (market size) from 1998 to 2018 is assumed to be constant. The forecast of annual sales over this period is taken as the average of actual color television sales from 1988 to 1997. Figure 5.9 shows the estimated Color TV sales figures along with the estimated sales of televisions with flat panel display technology.

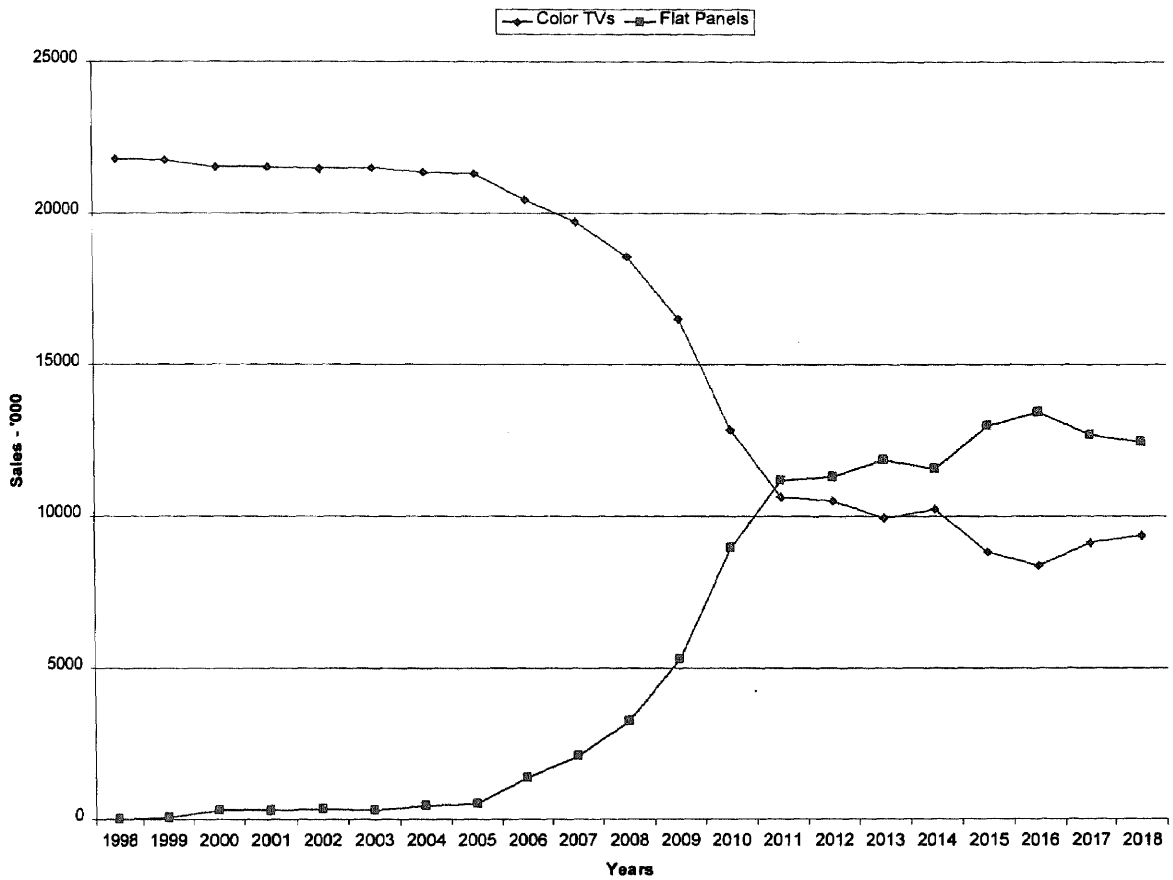

Figure 5.9 Estimated sales of Color Televisions and Flat Panel Displays

Color television sales data that was used for the forecast is shown in figure 5.10. It consists of actual sales figures for the period 1954 through 1997, and then the estimated sales figures based on the assumptions and calculations described earlier.

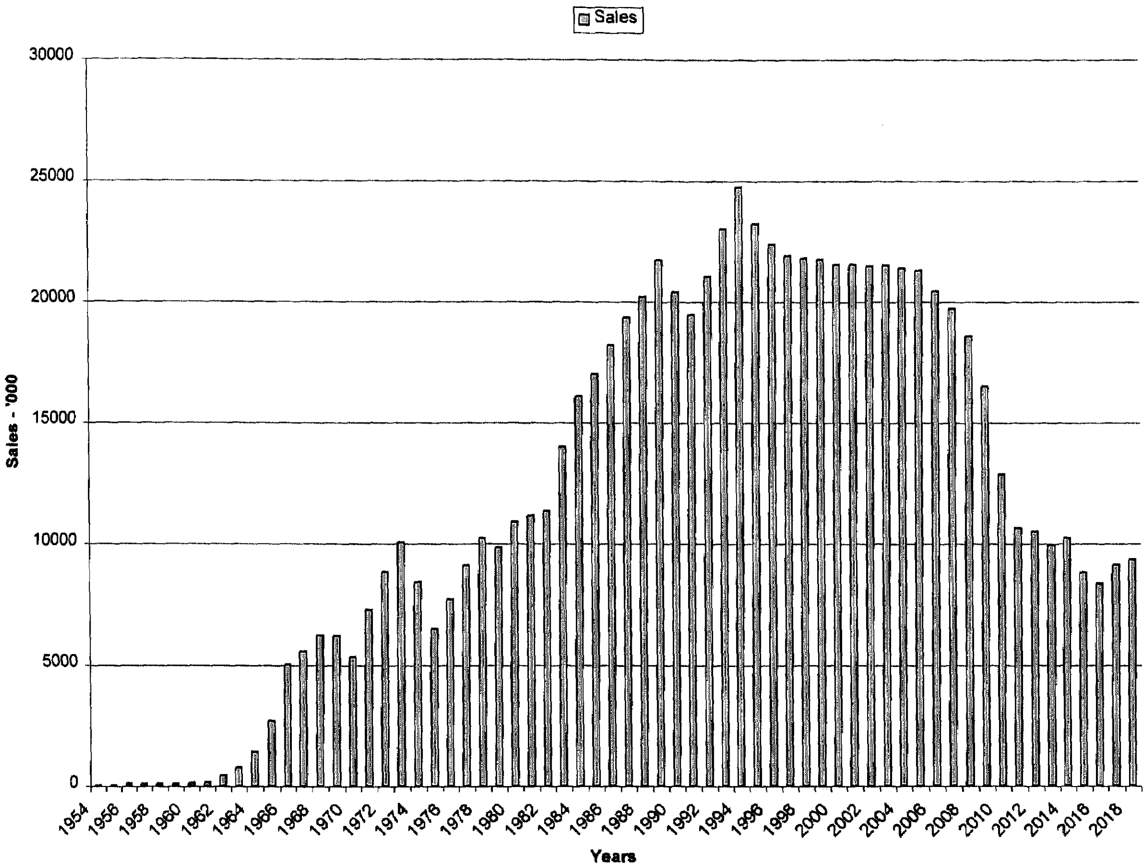

Figure 5.10 Estimated Sales Figures for CRT based Color Televisions

Table 5.1 gives the estimated sales of color televisions as depicted in figure 5.10. Figure 5.10 shows the sales forecast for CRT based color televisions. Sales decline over time as the consumers prefer FPDs instead of CRTs. In figure 5.11 the failure of these CRT based color televisions is shown. See Appendix B-5 for the forecast output.

Table 5.1 Estimated Color Television Sales – '000 units

Year	Sales	Year	Sales
1998	21792	2009	16516
1999	21751	2010	12849
2000	21514	2011	10629
2001	21521	2012	10506
2002	21467	2013	9946
2003	21499	2014	10237
2004	21358	2015	8821
2005	21298	2016	8372
2006	20442	2017	9122
2007	19710	2018	9354
2008	18561		

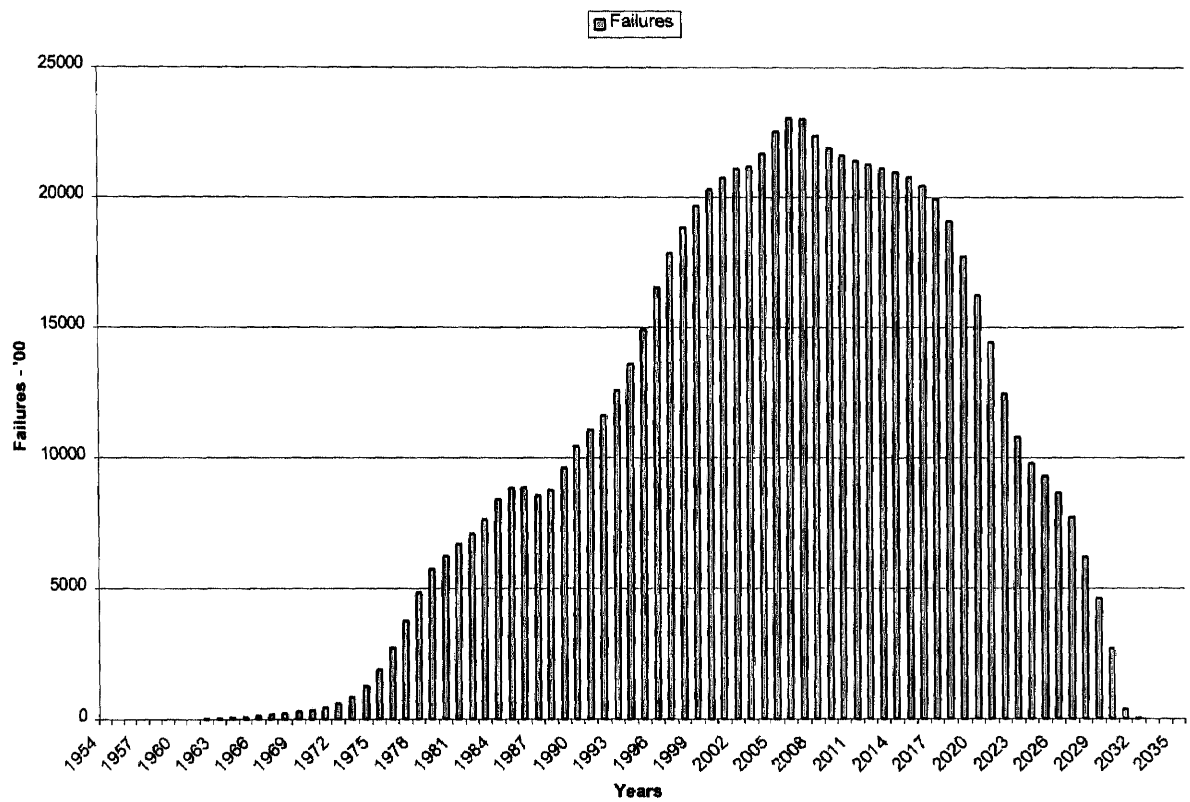

Figure 5.11 Color Television Failure - Estimated using the Bath-tub model

CHAPTER 6

SUMMARY AND CONCLUSION

This chapter summarizes the results and conclusions of the research conducted in this thesis. The first section summarizes the two forecasting models and the case study presented. The second section recommends areas for future research possibilities and general conclusions are presented in the final section.

6.1 Summary of the Forecasting Models

Two forecasting models have been built for waste-stream analysis. The rate and timing with which the products enter the waste-stream can be modelled using these models. Factors like product failure and obsolescence, along with storage of product before disposal have been considered and incorporated in the models.

Products whose operating life can be divided into three phases: initial, use and wear-out phase are perfectly suited for the bath-tub model. Products containing mechanical parts which are subject to wear and tear over use generally fall into this category. Of course, this does not limit the use of the model to products having mechanical components, any product exhibiting a bath-tub curve failure characteristic can be modeled using the bath-tub model.

The standard normal distribution model can be used to model the failure of any kind of product. Product failure occurs at a certain mean time (Mean Time To Failure) with a variance about that mean time.

Color television disposal was modelled using the forecasting software. The current situation, effect of storage, legislation and new technology was also studied.

Color television failure forecast for the entire United States was generated using the two models. Sales data from the year 1954 through 1998 was used. Based on certain assumptions, forecasts using both the models seem to suggest that an average of 21 million color televisions will enter the waste-stream from now on until 2009. The actual number may be higher because future sales of televisions will definitely add to this amount.

Color television disposal behavior in the state of Massachusetts was modelled. The state of Massachusetts was chosen because of the legal ban on CRT disposal in the state. The ban will force proper processing of the CRTs before they can be discarded. The forecasting software estimates the approximate number of CRTs that might be disposed off in the state and consequently might need processing. Both the forecasting models suggest an approximate quantity of around 500,000 color televisions to be in the waste-stream from the year 1998 to 2006.

The effect of a technically advanced product displacing a current product was also studied. Flat Panel Displays are slated to replace current Cathode Ray Tube based televisions due to large screen size and less bulky design. For the purpose of generating the forecast, sales data for CRT based color televisions was generated through the year 1998 to 2018. It was assumed that the relationship of sales of FPD televisions with CRT based color televisions will be similar to that of black and white televisions and color televisions. Using both models on the extended sales data for the color televisions we can observe that on an average approximately 20 million televisions will be discarded from the year 1999 to 2020.

6.3 General Conclusions

Several issues related to waste-stream forecasting are discussed below:

- Although well known business forecasting models exist, this is the first time a model for forecasting product disposal pattern has been developed, to the best of the authors knowledge.
- The forecasting software can be used as an aid in decision making.
- The forecasting software provides a way of evaluating several scenarios and the affect they might have on product disposal.
- This software can be used in a wide variety of industries to evaluate the future availability of failed or discarded product for recycling/remanufacturing/de-manufacturing or even planning the introduction of newer product models. The potential uses of this software are numerous.

6.2 Future Scope and Research Recommendation

- Waste disposal scenario should be generated for more products across a broad range of industries. The data obtained should be used to further validate and refine the existing forecasting models.
- New forecasting models should be added to the software, possibly tailored for a specific product or a product range displaying similar disposal behavior.

- A permanent database of user case studies should be maintained for further analysis and comparative studies.
- The final iterative computations are currently performed by a perl script. This should be converted to a pre-compiled binary which would execute faster and reduce the time required for the iterative compilations.

APPENDIX A-1

Source Code

```
#!/opt/local/bin/perl

require "cgi-lib.pl";
&ReadParse;


# first check if the file is complete.
open (F, "../../data/$in{cookie}");

$ctr=0;

while($lin=<F>)
{
 if($lin eq "[STEP 1]\n") { $ctr++;  }
 if($lin eq "[STEP 2]\n") { $ctr++;  }
 if($lin eq "[STEP 3]\n") { $ctr++;  }
 if($lin eq "[STEP 4]\n") { $ctr++;  }
 if($lin eq "[STEP 5]\n") { $ctr++;  }
 if($lin eq "[STEP 6]\n") { $ctr++;  }
}

if($ctr<6)
{
  print "Content-type: text/html\n\n";
  print "<HTML><BODY><CENTER>\n";
  print "<H1>Data not complete or file damaged !</H1><BR>\n";
  print "Please input all the relevant information and try again!<BR>\n";
  print "If you think this message is in error .. please contact:<BR>\n";
  print "<BR>Amit P. Amte<BR>\n";
  print "Research Assistant<BR>Multi-lifecycle Engineering Research Center\n";
  print "<BR>NJIT, Newark, NJ<BR>\n";
  print "<a href=\"mailto:amte\@homer.njit.edu\">amte\@homer.njit.edu</A>\n";
  print "</CENTER></BODY></HTML>\n";
  exit;
}


# reset the file pointer to beginning of file.
seek F,0,0;
```

APPENDIX A-1
(Continued)

```
while($lin=<F>)
{
 if($lin eq "[STEP 1]\n")
 {
  # read 4 lines here
  for($i=0;$i<4;$i++)
  {
    $lin=<F>;
    chop $lin;
    ($param, $value) = split(":", $lin);
    @step1{$param} = $value;
  }
 }

 if($lin eq "[STEP 2]\n")
 {
  # read 2 lines here
  # dataSize will contain the number of data points available
  # $data[] will contain the values

  $lin=<F>;
  chop $lin;
  ($param, $dataSize) = split(":", $lin);
  $lin=<F>;
  chop $lin;
  @data = split(",",$lin);
 }

 if($lin eq "[STEP 3]\n")
 {
    # variable number of lines to be read
    &model;
 }

 if($lin eq "[STEP 4]\n")
 {
    # variable number of lines to be read
    &obsolete;
 }

 if($lin eq "[STEP 5]\n")
 {
  # read 6 lines here  -- two pairs of 3 lines each
```

APPENDIX A-1
(Continued)

```
$lin=<F>;
chop $lin;
($param, $value) = split(":", $lin);
if($value =="") { $value=0; }
@step5{$param} = $value;
for($i=0;$i<2;$i++)
{
   $lin=<F>;
   chop $lin;
   ($param, $value, $duration) = split(":", $lin);
   if($value =="") { $value=0; }
   @step5{$param} = $value;
   $param .= "_unit";
   @step5{$param} = $duration;
}

$lin=<F>;
chop $lin;
($param, $value) = split(":", $lin);
if($value =="") { $value=0; }
@step5{$param} = $value;
for($i=0;$i<2;$i++)
{
   $lin=<F>;
   chop $lin;
   ($param, $value, $duration) = split(":", $lin);
   if($value =="") { $value=0; }
   @step5{$param} = $value;
   $param .= "_unit";
   @step5{$param} = $duration;
}

}

if($lin eq "[STEP 6]\n")
{
 # read 3 lines here
 for($i=0;$i<3;$i++)
 {
    $lin=<F>;
    chop $lin;
    ($param, $value) = split(":", $lin);
    @step6{$param} = $value;
```

APPENDIX A-1
(Continued)

```
  }
 }
}

#--------------------------------------------------------------------
# all data is in associative arrays
# proceed with the forecasting process from here

# variables used in the obsFactors and storedQty procedures !
# don't touch these anywhere else !
$obsFlg= $storeFlg = 0;

# date format mm-dd-yyyy
@startDate = split("-",@step1{'Date'});
@endDate = split("-",@step1{'Date'});
&findEndDate;

$finalTimeHours = @step6{'Duration'} * timeInHours(@step6{'TimeUnit'});

$numberOfSteps=findNumberOfSteps(@step6{'Duration'},@step6{'TimeUnit'},@step6{
'ScaleTimeUnit'});

# $parts contains the number of units of the initial time duration that can
# be fitted inside the scaleTimeUnit.
# ScaleTimeUnit < step1{Duration}  IMPORTANT !!!

$parts = timeInHours(@step6{'ScaleTimeUnit'})/timeInHours(@step1{'TimeUnit'});
$parts =~ s/\..*//;

$runOut = $numberOfSteps;

open(TABLE, ">output.txt");
print TABLE "Output file for the forecast software ..\n";
print TABLE "format : failed, obsolete, failStore, obsStore\n";
print TABLE "--------------------------------------------------";
print TABLE "---------------------------------\n\n";

$loopCount=0;

for($i=0; $i<$dataSize;$i++)
{
   print TABLE printDate(@step1{'Date'}, $i+1, @step1{'TimeUnit'});
   print TABLE " :  ";
```

APPENDIX A-1
(Continued)

```
$percentage = $old_percentage = $ytd = 0;
$o_percent = $o_old_percent = 0;
$obsFlg = $storeFlg = 0;
$end_flag=0;
$prev_fail = $prev_obs = 0;

$at=$i*$parts;

if( ($model eq "SND") && ($data[$i]>0) )
{
  $ytd_percent=0;

  for($j=0; $end_flag!=1; $j++)
  {
    $com  = "./snf.cgi ";
    $com .= @SND{'MTTF'};
    $com .= " ";
    $com .= reformatTimePeriod(@SND{'TimeUnit'});
    $com .= " ";
    $com .= @SND{'StDev_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@SND{'StDev_time_unit'});
    $com .= " ";
    $com .= $j+1;
    $com .= " ";
    $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});

    open(C, "$com |");
    $percentage = <C>;
    close(C);
    chop $percentage;
    $percentage = formatNumber($percentage);

    $o_percent = ObsFactors($j+1, $i);
    $o_percent = formatNumber($o_percent);

    $ytd_percent += $percentage-$old_percentage;
    $ytd_percent += $o_percent-$o_old_percent;

    if($ytd_percent>=100)
    {
      $factor  = $ytd_percent - ($percentage-$old_percentage);
      $factor -= $o_percent - $o_old_percent;
```

APPENDIX A-1
(Continued)

```
          $factor = 100 - $factor;

          $fail_factor = $factor*($percentage-$old_percentage)/(($percentage-
$old_percentage) + ($o_percent-$o_old_percent));
          $percentage = $old_percentage + $fail_factor;

          $fail_factor = $factor*($o_percent-$o_old_percentage)/(($percentage-
$old_percentage) + ($o_percent-$o_old_percent));
          $o_percent = $o_old_percentage + $fail_factor;

          $end_flag=1;
        }

        $value = $data[$i]*($percentage-$old_percentage)/100;
        $value = formatNumber($value);

        $old_percentage = $percentage;
        $final[$at] += $value;
        $tmp_fail = $value;
        $ytd += $value;

        print TABLE $value;
        print TABLE ",";

        $value = $data[$i]*($o_percent-$o_old_percent)/100;
        $value = formatNumber($value);

        $o_old_percent = $o_percent;
        $obs[$at] += $value;
        $tmp_obs = $value;
        $ytd += $value;

        print TABLE $value;
        print TABLE ",";


        # obtain the products that are stored after they fail.
        $value=$tmp_fail*@step5{'failed_per'}/100;
        $value = formatNumber($value);

        $fail_stor[$at] += $value;
        $loopFailStore[$j] = $value;
```

APPENDIX A-1
(Continued)

```
      print TABLE $value;
      print TABLE ",";

      # obtain the products that are stored after they are obsolete.
      $value=$tmp_obs*@step5{'obs_per'}/100;
      $value = formatNumber($value);

      $obs_stor[$at] += $value;
      $loopObsStore[$j] = $value;

      print TABLE $value;
      print TABLE "___";

      $at++;
      $old_percentage = $percentage;

    }
    $loopCount=$j;
}


if( ($model eq "RM") && ($data[$i]>0) )
{
    $ytd_percent=0;
    for($j=0; $end_flag!=1; $j++)
    {
      $com  = "./relValue.cgi ";
      $com .= @RM{'a'};
      $com .= " ";
      $com .= @RM{'b'};
      $com .= " ";
      $com .= @RM{'c'};
      $com .= " ";
      $com .= @RM{'d'};
      $com .= " ";
      $tmp = reformatTimePeriod(@RM{'t1_time_unit'});
      $com .= "@RM{'t1_time'} $tmp ";
      $tmp = reformatTimePeriod(@RM{'t2_time_unit'});
      $com .= "@RM{'t2_time'} $tmp ";
      $tmp = reformatTimePeriod(@RM{'t3_time_unit'});
      $com .= "@RM{'t3_time'} $tmp ";
      $com .= $j+1;
      $com .= " ";
```

APPENDIX A-1
(Continued)

```
$com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});

open(C , "$com |");
$percentage = <C>;
close(C);
chop $percentage;
$percentage = formatNumber($percentage);

$o_percent = ObsFactors($j+1, $i);
$o_percent = formatNumber($o_percent);

$ytd_percent += $percentage-$old_percentage;
$ytd_percent += $o_percent-$o_old_percent;

if($ytd_percent>=100)
{
   $factor  = $ytd_percent - ($percentage-$old_percentage);
   $factor -= $o_percent - $o_old_percent;
   $factor = 100 - $factor;

   $fail_factor = $factor*($percentage-$old_percentage)/(($percentage-
$old_percentage) + ($o_percent-$o_old_percent));
   $percentage = $old_percentage + $fail_factor;

   $fail_factor = $factor*($o_percent-$o_old_percentage)/(($percentage-
$old_percentage) + ($o_percent-$o_old_percent));
   $o_percent = $o_old_percentage + $fail_factor;

   $end_flag=1;
}

$value = $data[$i]*($percentage-$old_percentage)/100;
$value = formatNumber($value);

$old_percentage = $percentage;
$ytd += $value;
$final[$at] += $value;
$tmp_fail = $value;

print TABLE $value;
print TABLE ",";

$value = $data[$i]*($o_percent-$o_old_percent)/100;
```

APPENDIX A-1
(Continued)

```
    $value = formatNumber($value);

    $o_old_percent = $o_percent;
    $ytd += $value;
    $obs[$at] += $value;
    $tmp_obs = $value;
    print TABLE $value, ",";

    # obtain the products that are stored after they fail.

    $value=$tmp_fail*@step5{'failed_per'}/100;
    $value = formatNumber($value);

    $fail_stor[$at] += $value;
    $loopFailStore[$j] = $value;


    print TABLE $value, ",";

    # obtain the products that are stored after they are obsolete.

    $value=$tmp_obs*@step5{'obs_per'}/100;
    $value = formatNumber($value);

    $obs_stor[$at] += $value;
    $loopObsStore[$j] = $value;

    print TABLE $value;
    print TABLE "--";

    # loop varible .. don't change !
    $at++;
  }
  $loopCount=$j;

} # end of if loop for the RM model check condition

print TABLE "\n";

# put the failed-stored products BACK to the waste-stream

if( (@step5{'failed_per'} > 0) && ($data[$i]>0) )
{
```

APPENDIX A-1
(Continued)

```
  for($p=0; $p<$loopCount; $p++)
  {
    $at = ($i*$parts) + $p;
    $q=1;
    $fsPercent=0;
    do
    {
      $failReturn = failStored($q);

      $ value = ($failReturn-$fsPercent)*$loopFailStore[$p]/100;
      $value = formatNumber($value);

      $final[$at] += $value;

      $fsPercent = $failReturn;
      $at++;
      $q++;
    }while($failReturn<100);
  }
}

# put the obsolete-stored products BACK into the waste-stream
if( (@step5{'obs_per'}>0) && ($data[$i]>0))
{
  for($p=0; $p<$loopCount; $p++)
  {
    $at = ($i*$parts) + $p;
    $q=1;
    $osPercent=0;
    do
    {
      $obsReturn = obsStored($q);

      $ value = ($obsReturn-$osPercent)*$loopObsStore[$p]/100;
      $value = formatNumber($value);

      $final[$at] += $value;
      $osPercent = $obsReturn;
      $at++;
      $q++;
    }while($obsReturn<100);
  }
}
```

APPENDIX A-1
(Continued)

```
  print TABLE "\n";

} # end of for loop.
close(TABLE);

#---------generation of the html file with the applet tags -----------
$max=0;
$scale=1;

open(OP, ">data.txt");

for($i=0;$i<$numberOfSteps;$i++)
{
  $value = $final[$i] - $fail_stor[$i];
  if($value>$max) { $max = $value; }
  $value = $obs[$i] - $obs_stor[$i];
  if($value>$max) { $max = $value; }
}

while($max>30000)
{
  $scale *= 10;
  $max /= $scale;
}

print "Content-type : text/html\n\n";
print "<HTML>\n";
print "<CENTER>\n";
print "<IMG SRC=\"graphics/banner.gif\">\n";
print "<HR width=80% size=2>\n";
print "<TABLE border=0 WIDTH=\"80\%\"><TR><TD>";
print "<BR><IMG SRC=\"graphics/legend.gif\" ALIGN=\"right\"><BR>\n";
print "</TD></TR>\n</TABLE>\n";
print "<APPLET CODE=graph.class WIDTH=620 HEIGHT=450>\n";
print "<PARAM NAME=totalValues VALUE=\"$numberOfSteps\">\n";
$scaleTimeUnit = @step6{'ScaleTimeUnit'};
print "<PARAM NAME=timeUnit VALUE=\"$scaleTimeUnit\">\n";
print "<PARAM NAME=scale VALUE=\"$scale\">\n";

for($k=1;$k<=$numberOfSteps;$k++)
{
  $value = $final[$k-1] - $fail_stor[$k-1];
  if( ($value%$scale) >= ($scale/2) )
```

APPENDIX A-1
(Continued)

```
    {
      $value /= $scale;
      $value++;
    }
    else
    {
      $value /= $scale;
    }
    $value = formatNumber($value);

    print OP "$value\n";

    print "<PARAM NAME=value_$k VALUE=\"$value\">\n";
    $value = $obs[$k-1] - $obs_stor[$k-1];
    if( ($value%$scale) >= ($scale/2) )
    {
      $value /= $scale;
      $value++;
    }
    else
    {
      $value /= $scale;
    }

    $value = formatNumber($value);
    print "<PARAM NAME=valueo_$k VALUE=\"$value\">\n";
}
print "</APPLET>\n";
print "<BR>Raw data format:<BR>\n";
print "<A href=\"output.txt\">Contribution of each input value</A><BR>";
print "</CENTER></HTML>\n";

#--------------------------------------------------------------

sub formatNumber
{
  @param = @_;
  my $number = $param[0];
  my $last_digit = ($number*10)%10;

  $number =~ s/\..*//;

  if($last_digit>= 5)
```

APPENDIX A-1
(Continued)

```
  {
   $number++;
  }
 if($number<=0) { $number=0; }
 return $number;
}

# $val = failStored($p+1)
# will pick up the distribution from the global variables and give the
# percentage product that will go BACK in the waste-stream

sub failStored
{
   @param = @_;
   my $when = $param[0];
   my $percentage = 0;

   my $com = "./snf.cgi ";
   $com .= @step5{'failed_AvgTime'};
   $com .= " ";
   $com .= reformatTimePeriod(@step5{'failed_AvgTime_unit'});
   $com .= " ";
   $com .= @step5{'failed_StDev'};
   $com .= " ";
   $com .= reformatTimePeriod(@step5{'failed_StDev_unit'});
   $com .= " ";
   $com .= $when;
   $com .= " ";
   $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});
   open (Z, "$com |");
   $percentage = <Z>;
   close(Z);
   chop $percentage;

   if($percentage == -1)
   {
      $percentage = 0;
   }

   return $percentage;
}

# $val = obsStored($p+1)
```

APPENDIX A-1
(Continued)

```
# will pick up the distribution from the global variables and give the
# percentage product that will go BACK in the waste-stream


sub obsStored
{
  @param = @_;
  my $when = $param[0];
  my $percentage = 0;

  my $com = "./snf.cgi ";
  $com .= @step5{'obs_AvgTime'};
  $com .= " ";
  $com .= reformatTimePeriod(@step5{'obs_AvgTime_unit'});
  $com .= " ";
  $com .= @step5{'obs_StDev'};
  $com .= " ";
  $com .= reformatTimePeriod(@step5{'obs_StDev_unit'});
  $com .= " ";
  $com .= $when;
  $com .= " ";
  $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});

  open (Z, "$com |");
  $percentage = <Z>;
  close(Z);
  chop $percentage;

  if($percentage == -1)
  {
    $percentage = 0;
  }

  return $percentage;
}

# $val = ObsFactors(remaining qty, $j+1, $i);
# uses the same time unit step6{ScaleTimeUnit}

sub ObsFactors
{
  @param = @_;
  my $when = $param[0];
```

APPENDIX A-1
(Continued)

```
my $current_i = $param[1];
my $percentage = 0;
my $percent = 0;
my $com = "";
my $tmp=0;
my $obsValue=0;

if( (exists $step4{TO_Proportion}) && ($step4{TO_Proportion}>0) )
{
  if($model eq "RM")
  {
    $com = "./relValue.cgi ";
    $com .= @RM{'a'};
    $com .= " ";
    $com .= @RM{'b'};
    $com .= " ";
    $com .= @RM{'c'};
    $com .= " ";
    $com .= @RM{'d'};
    $com .= " ";
    $tmp = reformatTimePeriod(@RM{'t1_time_unit'});
    $com .= "@RM{'t1_time'} $tmp ";
    $tmp = reformatTimePeriod(@RM{'t2_time_unit'});
    $com .= "@RM{'t2_time'} $tmp ";
    $tmp = reformatTimePeriod(@RM{'t3_time_unit'});
    $com .= "@RM{'t3_time'} $tmp ";
    $com .= @step4{'TO_When_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@step4{'TO_When_period'});
    open(C, "$com |");
    $percentage = <C>;
    close(C);
    chop $percentage;

    if($percentage<95)
    {
      $com  = "./snf.cgi ";
      $com .= @step4{'TO_When_time'};
      $com .= " ";
      $com .= reformatTimePeriod(@step4{'TO_When_period'});
      $com .= " ";
      $com .= @step4{'TO_StDev_time'};
      $com .= " ";
```

APPENDIX A-1
(Continued)

```
      $com .= reformatTimePeriod(@step4{'TO_StDev_period'});
      $com .= " ";
      $com .= $when;
      $com .= " ";
      $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});
      open(C , "$com |");
      $percent = <C>;
      close(C);
      chop $percent;
      if($obsFlg == 0)
      {
        if($percent!=-1)
        {
          $obsValue += @step4{'TO_Proportion'}*$percent/100;
        }
      }
      if( ($percent eq 100)|| ($percent==-1)) { $obsFlg=1; }
    }
  }
  if($model eq "SND")
  {
    $com  = "./snf.cgi ";
    $com .= @SND{'MTTF'};
    $com .= " ";
    $com .= reformatTimePeriod(@SND{'TimeUnit'});
    $com .= " ";
    $com .= @SND{'StDev_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@SND{'StDev_time_unit'});
    $com .= " ";
    $com .= @step4{'TO_When_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@step4{'TO_When_period'});
    open(C, "$com |");
    $percentage = <C>;
    close(C);
    chop $percentage;
    if($percentage < 95)
    {
      $com  = "./snf.cgi ";
      $com .= @step4{'TO_When_time'};
      $com .= " ";
      $com .= reformatTimePeriod(@step4{'TO_When_period'});
```

APPENDIX A-1
(Continued)

```
        $com .= " ";
        $com .= @step4{'TO_StDev_time'};
        $com .= " ";
        $com .= reformatTimePeriod(@step4{'TO_StDev_period'});
        $com .= " ";
        $com .= $when;
        $com .= " ";
        $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});
        open(C , "$com |");
        $percent = <C>;
        close(C);
        chop $percent;
        if($obsFlg == 0)
        {
          if($percent !=-1)
          {
            $obsValue += @step4{'TO_Proportion'}*$percent/100;
          }
        }
        if( ($percent eq 100) || ($percent==-1) ) { $obsFlg=1; }
      }
    }
}

if( (exists $step4{OO_Proportion}) && ($step4{OO_Proportion}>0) )
{
  if($model eq "RM")
  {
    $com = "./relValue.cgi ";
    $com .= @RM{'a'};
    $com .= " ";
    $com .= @RM{'b'};
    $com .= " ";
    $com .= @RM{'c'};
    $com .= " ";
    $com .= @RM{'d'};
    $com .= " ";
    $tmp = reformatTimePeriod(@RM{'t1_time_unit'});
    $com .= "@RM{'t1_time'} $tmp ";
    $tmp = reformatTimePeriod(@RM{'t2_time_unit'});
    $com .= "@RM{'t2_time'} $tmp ";
    $tmp = reformatTimePeriod(@RM{'t3_time_unit'});
    $com .= "@RM{'t3_time'} $tmp ";
```

APPENDIX A-1
(Continued)

```
  $com .= @step4{'OO_When_time'};
  $com .= " ";
  $com .= reformatTimePeriod(@step4{'OO_When_period'});
  open(C, "$com |");
  $percentage = <C>;
  close(C);
  chop $percentage;

  if($percentage<95)
  {
    $com  = "./snf.cgi ";
    $com .= @step4{'OO_When_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@step4{'OO_When_period'});
    $com .= " ";
    $com .= @step4{'OO_StDev_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@step4{'OO_StDev_period'});
    $com .= " ";
    $com .= $when;
    $com .= " ";
    $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});
    open(C , "$com |");
    $percent = <C>;
    close(C);
    chop $percent;
    if($obsFlg == 0)
    {
      if($percent !=-1)
      {
        $obsValue += @step4{'OO_Proportion'}*$percent/100;
      }
    }
    if( ($percent eq 100) || ($percent==-1) ) { $obsFlg=1; }
  }
}
if($model eq "SND")
{
  $com  = "./snf.cgi ";
  $com .= @SND{'MTTF'};
  $com .= " ";
  $com .= reformatTimePeriod(@SND{'TimeUnit'});
  $com .= " ";
```

APPENDIX A-1
(Continued)

```
    $com .= @SND{'StDev_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@SND{'StDev_time_unit'});
    $com .= " ";
    $com .= @step4{'OO_When_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@step4{'OO_When_period'});
    open(C, "$com |");
    $percentage = <C>;
    close(C);
    chop $percentage;
    if($percentage < 95)
    {
      $com  = "./snf.cgi ";
      $com .= @step4{'OO_When_time'};
      $com .= " ";
      $com .= reformatTimePeriod(@step4{'OO_When_period'});
      $com .= " ";
      $com .= @step4{'OO_StDev_time'};
      $com .= " ";
      $com .= reformatTimePeriod(@step4{'OO_StDev_period'});
      $com .= " ";
      $com .= $when;
      $com .= " ";
      $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});
      open(C , "$com |");
      $percent = <C>;
      close(C);
      chop $percent;
      if($obsFlg == 0)
      {
        if($percent!=-1)
        {
          $obsValue += @step4{'OO_Proportion'}*$percent/100;
        }
      }
      if( ($percent eq 100) || ($percent==-1)) { $obsFlg=1; }
    }
  }
}
if( (exists $step4{OR_Proportion}) && ($step4{OR_Proportion}>0) )
{
  if($model eq "RM")
```

APPENDIX A-1
(Continued)

```
{
  $com = "./relValue.cgi ";
  $com .= @RM{'a'};
  $com .= " ";
  $com .= @RM{'b'};
  $com .= " ";
  $com .= @RM{'c'};
  $com .= " ";
  $com .= @RM{'d'};
  $com .= " ";
  $tmp = reformatTimePeriod(@RM{'t1_time_unit'});
  $com .= "@RM{'t1_time'} $tmp ";
  $tmp = reformatTimePeriod(@RM{'t2_time_unit'});
  $com .= "@RM{'t2_time'} $tmp ";
  $tmp = reformatTimePeriod(@RM{'t3_time_unit'});
  $com .= "@RM{'t3_time'} $tmp ";
  $com .= @step4{'OR_When_time'};
  $com .= " ";
  $com .= reformatTimePeriod(@step4{'OR_When_period'});
  open(C, "$com |");
  $percentage = <C>;
  close(C);
  chop $percentage;

  if($percentage<95)
  {
    $com  = "./snf.cgi ";
    $com .= @step4{'OR_When_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@step4{'OR_When_period'});
    $com .= " ";
    $com .= @step4{'OR_StDev_time'};
    $com .= " ";
    $com .= reformatTimePeriod(@step4{'OR_StDev_period'});
    $com .= " ";
    $com .= $when;
    $com .= " ";
    $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});
    open(C , "$com |");
    $percent = <C>;
    close(C);
    chop $percent;
    if($obsFlg == 0)
```

APPENDIX A-1
(Continued)

```
        {
          if($percent!=-1)
          {
            $obsValue += @step4{'OR_Proportion'}*$percent/100;
          }
        }
        if( ($percent eq 100) || ($percent==-1)) { $obsFlg=1; }
      }
    }
    if($model eq "SND")
    {
      $com  = "./snf.cgi ";
      $com .= @SND{'MTTF'};
      $com .= " ";
      $com .= reformatTimePeriod(@SND{'TimeUnit'});
      $com .= " ";
      $com .= @SND{'StDev_time'};
      $com .= " ";
      $com .= reformatTimePeriod(@SND{'StDev_time_unit'});
      $com .= " ";
      $com .= @step4{'OR_When_time'};
      $com .= " ";
      $com .= reformatTimePeriod(@step4{'OR_When_period'});
      open(C, "$com |");
      $percentage = <C>;
      close(C);
      chop $percentage;
      if($percentage < 95)
      {
        $com  = "./snf.cgi ";
        $com .= @step4{'OR_When_time'};
        $com .= " ";
        $com .= reformatTimePeriod(@step4{'OR_When_period'});
        $com .= " ";
        $com .= @step4{'OR_StDev_time'};
        $com .= " ";
        $com .= reformatTimePeriod(@step4{'OR_StDev_period'});
        $com .= " ";
        $com .= $when;
        $com .= " ";
        $com .= reformatTimePeriod(@step6{'ScaleTimeUnit'});
        open(C , "$com |");
        $percent = <C>;
```

APPENDIX A-1
(Continued)

```
            close(C);
            chop $percent;
            if($obsFlg == 0)
            {
               if($percent!=-1)
               {
                  $obsValue += @step4{'OR_Proportion'}*$percent/100;
               }
            }
            if( ($percent eq 100) || ($percent==-1)) { $obsFlg=1; }
         }
      }
   }
   return $obsValue;
}


# reformat time periods
sub reformatTimePeriod
{
   my @temp = @_;
   if($temp[0] eq "Years") { return "YEAR"; }
   if($temp[0] eq "6 Months") { return "6MONTHS"; }
   if($temp[0] eq "3 Months") { return "3MONTHS"; }
   if($temp[0] eq "Months") { return "MONTH"; }
   if($temp[0] eq "Weeks") { return "WEEK"; }
   if($temp[0] eq "Days") { return "DAY"; }
}


# finds the endDate and puts it in @endDate
sub findEndDate
{
  for($i=0;$i<@step6{'Duration'};$i++)
  {
   if(@step6{'TimeUnit'} eq "Years")    { $endDate[2]++;  }
   if(@step6{'TimeUnit'} eq "6 Months") { $endDate[0] += 6; }
   if(@step6{'TimeUnit'} eq "3 Months") { $endDate[0] += 3; }
   if(@step6{'TimeUnit'} eq "Months")   { $endDate[0]++;  }
   if(@step6{'TimeUnit'} eq "Weeks")    { $endDate[1] += 7;}
   if(@step6{'TimeUnit'} eq "Days")     { $endDate[1]++;}

   if($endDate[1]>30)
```

APPENDIX A-1
(Continued)

```
  {
   $endDate[0]++;
   $endDate[1] -=30;
  }

  if($endDate[0]>12)
  {
   $endDate[2]++;
   $endDate[0] -=12;
  }
 } # found the endDate
}


# $tp2 = "Years";
# $tp = timeInHours($tp2);
# print "tp ... $tp\n";
sub timeInHours
{
 my @time = @_;
 if($time[0] eq "Days")     { return 24; }
 if($time[0] eq "Weeks")    { return 24*7; }
 if($time[0] eq "Months")   { return 2*365; }
 if($time[0] eq "3 Months") { return 6*365; }
 if($time[0] eq "6 Months") { return 12*365; }
 if($time[0] eq "Years")    { return 24*365; }
 return 0;
}

# advances the date by the unit and timePeriod specified
# usage: @new_date = printDate("01-01-1990",1,"6 Months");
sub printDate
{
  @param = @_;
  my $dd, $mm, $yy;
  my $startDate = $param[0];
  my $number = $param[1];
  my $unit = $param[2];
  ($dd, $mm, $yy) = split("-", $startDate);

  if($unit eq "Years")    { $yy+=$number; }

  if( ($unit eq "6 Months") || ($unit eq "3 Months") || ($unit eq "Months") )
```

APPENDIX A-1
(Continued)

```
  {
    if($unit eq "6 Months") { $mm += 6*$number; }
    if($unit eq "3 Months") { $mm += 3*$number; }
    if($unit eq "Months")   { $mm += $number; }
    while($mm>12)
    {
      $yy++;
      $mm -=12;
    }
  }

  if( ($unit eq "Weeks") || ($unit eq "Days") )
  {
    if($unit eq "Weeks") { $dd += 7*$number; }
    if($unit eq "Days")  { $dd += $number; }
    while($dd<31)
    {
      $dd -= 31;
      $mm++;
    }
  }
  $newDate = "$mm-$dd-$yy";

  return $newDate;
}


#print findNumberOfSteps("10", "6 Months","Days");
sub findNumberOfSteps
{
 my @param = @_;
 my $time = $param[0];
 my $unit = $param[1];
 my $sUnit = $param[2];
 my $tmp=0;
 my $b=0;

 if(timeInHours($unit) == timeInHours($sUnit))
 {
   return $time;
 }

 if(timeInHours($unit) > timeInHours($sUnit))
```

APPENDIX A-1
(Continued)

```
 {
   if( ($sUnit eq "Weeks") && ($unit eq "Years") )
   {
     $b = 52*$time;
     return $b;
   }

   if( ($sUnit eq "Weeks") && ($unit eq "6 Months") )
   {
     $b = 26*$time;
     return $b;
   }

   if( ($sUnit eq "Weeks") && ($unit eq "3 Months") )
   {
     $b = 13*$time;
     return $b;
   }

   if( ($sUnit eq "Weeks") && ($unit eq "Months") )
   {
     $b = 4*$time;
     return $b;
   }

   while($tmp<timeInHours($unit))
   {
     $tmp += timeInHours($sUnit);
     $b++;
   }
   $b *= $time;
   return $b;
 }

}

#-------------------------------------------------------------------
# take care of some tricky lines in the data file
# sub model takes care of [STEP 3]
# sub obsolete takes care of [STEP 4]

sub model
{
```

APPENDIX A-1
(Continued)

```
$lin=<F>;
if($lin eq "RM\n")
{
   chop $lin;
   $model = $lin;
   # read a total of 7 lines
   # 4 lines for a,b,c,d

   for($i=0; $i<4; $i++)
   {
      $lin=<F>;
      chop $lin;
      ($param, $value) = split(":", $lin);
      @RM{$param} = $value;
   }
   # 3 lines with the time periods
   for($i=0; $i<3; $i++)
   {
      $lin=<F>;
      chop $lin;
      ($param, $val, $value) = split(":", $lin);
      $param .="_time";
      @RM{$param} = $val;
      $param .="_unit";
      @RM{$param} = $value;
   }
}

if($lin eq "SND\n")
{
   chop $lin;
   $model = $lin;

   # read 3 lines here
   for($i=0;$i<2;$i++)
   {
      $lin=<F>;
      chop $lin;
      ($param, $value) = split(":", $lin);
      @SND{$param} = $value;
   }
   $lin=<F>;
   chop $lin;
```

APPENDIX A-1
(Continued)

```
      ($param, $val, $value) = split(":", $lin);
      $param .="_time";
      @SND{$param} = $val;
      $param .="_unit";
      @SND{$param} = $value;
   }
}


sub obsolete
{
   $number=<F>;
   chop($number);

   if($number>0)
   {
      for($i=0;$i<$number;$i++)
      {
         $lin=<F>;
         chomp $lin;
         $type=$lin;

         $lin=<F>;
         ($tmp, $value) = split(":",$lin);
         $param = $type;
         $param .= "_";
         $param .= $tmp;
         if($value =="") { $value=0; }
         @step4{$param} = $value;

         $lin=<F>;
         chop $lin;
         ($tmp, $val, $value) = split(":", $lin);
         $param = $type;
         $param .= "_";
         $param .= $tmp;
         $param .= "_time";
         if($val == "") { $val=0; }
         @step4{$param} = $val;
         $param = $type;
         $param .= "_";
         $param .= $tmp;
         $param .= "_period";
```

APPENDIX A-1
(Continued)

```
        @step4{$param} = $value;

        $lin=<F>;
        chop $lin;
        ($tmp, $val, $value) = split(":", $lin);
        $param = $type;
        $param .= "_";
        $param .= $tmp;
        $param .= "_time";
        if($val =="") { $val=0; }
        @step4{$param} = $val;
        $param = $type;
        $param .= "_";
        $param .= $tmp;
        $param .= "_period";
        @step4{$param} = $value;
      }
    }
  }
```

APPENDIX A-2

Z-Table

Area z	Area below z	from z to 0	Area above z
-3.50	.0002	.4998	.9998
-3.49	.0002	.4998	.9998
-3.48	.0003	.4997	.9997
-3.47	.0003	.4997	.9997
-3.46	.0003	.4997	.9997
-3.45	.0003	.4997	.9997
-3.44	.0003	.4997	.9997
-3.43	.0003	.4997	.9997
-3.42	.0003	.4997	.9997
-3.41	.0003	.4997	.9997
-3.40	.0003	.4997	.9997
-3.39	.0003	.4997	.9997
-3.38	.0004	.4996	.9996
-3.37	.0004	.4996	.9996
-3.36	.0004	.4996	.9996
-3.35	.0004	.4996	.9996
-3.34	.0004	.4996	.9996
-3.33	.0004	.4996	.9996
-3.32	.0005	.4995	.9995
-3.31	.0005	.4995	.9995
-3.30	.0005	.4995	.9995
-3.29	.0005	.4995	.9995
-3.28	.0005	.4995	.9995
-3.27	.0005	.4995	.9995
-3.26	.0006	.4994	.9994
-3.25	.0006	.4994	.9994
-3.24	.0006	.4994	.9994
-3.23	.0006	.4994	.9994
-3.22	.0006	.4994	.9994
-3.21	.0007	.4993	.9993
-3.20	.0007	.4993	.9993
-3.19	.0007	.4993	.9993
-3.18	.0007	.4993	.9993
-3.17	.0008	.4992	.9992
-3.16	.0008	.4992	.9992
-3.15	.0008	.4992	.9992

APPENDIX A-2
(Continued)

-3.14	.0008	.4992	.9992
-3.13	.0009	.4991	.9991
-3.12	.0009	.4991	.9991
-3.11	.0009	.4991	.9991
-3.10	.0010	.4990	.9990
-3.09	.0010	.4990	.9990
-3.08	.0010	.4990	.9990
-3.07	.0011	.4989	.9989
-3.06	.0011	.4989	.9989
-3.05	.0011	.4989	.9989
-3.04	.0012	.4988	.9988
-3.03	.0012	.4988	.9988
-3.02	.0013	.4987	.9987
-3.01	.0013	.4987	.9987
-3.00	.0013	.4987	.9987
-2.99	.0014	.4986	.9986
-2.98	.0014	.4986	.9986
-2.97	.0015	.4985	.9985
-2.96	.0015	.4985	.9985
-2.95	.0016	.4984	.9984
-2.94	.0016	.4984	.9984
-2.93	.0017	.4983	.9983
-2.92	.0018	.4982	.9982
-2.91	.0018	.4982	.9982
-2.90	.0019	.4981	.9981
-2.89	.0019	.4981	.9981
-2.88	.0020	.4980	.9980
-2.87	.0021	.4979	.9979
-2.86	.0021	.4979	.9979
-2.85	.0022	.4978	.9978
-2.84	.0023	.4977	.9977
-2.83	.0023	.4977	.9977
-2.82	.0024	.4976	.9976
-2.81	.0025	.4975	.9975
-2.80	.0026	.4974	.9974
-2.79	.0026	.4974	.9974
-2.78	.0027	.4973	.9973
-2.77	.0028	.4972	.9972
-2.76	.0029	.4971	.9971
-2.75	.0030	.4970	.9970
-2.74	.0031	.4969	.9969
-2.73	.0032	.4968	.9968

APPENDIX A-2
(Continued)

-2.72	.0033	.4967	.9967
-2.71	.0034	.4966	.9966
-2.70	.0035	.4965	.9965
-2.69	.0036	.4964	.9964
-2.68	.0037	.4963	.9963
-2.67	.0038	.4962	.9962
-2.66	.0039	.4961	.9961
-2.65	.0040	.4960	.9960
-2.64	.0041	.4959	.9959
-2.63	.0043	.4957	.9957
-2.62	.0044	.4956	.9956
-2.61	.0045	.4955	.9955
-2.60	.0047	.4953	.9953
-2.59	.0048	.4952	.9952
-2.58	.0049	.4951	.9951
-2.57	.0051	.4949	.9949
-2.56	.0052	.4948	.9948
-2.55	.0054	.4946	.9946
-2.54	.0055	.4945	.9945
-2.53	.0057	.4943	.9943
-2.52	.0059	.4941	.9941
-2.51	.0060	.4940	.9940
-2.50	.0062	.4938	.9938
-2.49	.0064	.4936	.9936
-2.48	.0066	.4934	.9934
-2.47	.0068	.4932	.9932
-2.46	.0069	.4931	.9931
-2.45	.0071	.4929	.9929
-2.44	.0073	.4927	.9927
-2.43	.0075	.4925	.9925
-2.42	.0078	.4922	.9922
-2.41	.0080	.4920	.9920
-2.40	.0082	.4918	.9918
-2.39	.0084	.4916	.9916
-2.38	.0087	.4913	.9913
-2.37	.0089	.4911	.9911
-2.36	.0091	.4909	.9909
-2.35	.0094	.4906	.9906
-2.34	.0096	.4904	.9904
-2.33	.0099	.4901	.9901
-2.32	.0102	.4898	.9898
-2.31	.0104	.4896	.9896

APPENDIX A-2
(Continued)

-2.30	.0107	.4893	.9893
-2.29	.0110	.4890	.9890
-2.28	.0113	.4887	.9887
-2.27	.0116	.4884	.9884
-2.26	.0119	.4881	.9881
-2.25	.0122	.4878	.9878
-2.24	.0125	.4875	.9875
-2.23	.0129	.4871	.9871
-2.22	.0132	.4868	.9868
-2.21	.0136	.4864	.9864
-2.20	.0139	.4861	.9861
-2.19	.0143	.4857	.9857
-2.18	.0146	.4854	.9854
-2.17	.0150	.4850	.9850
-2.16	.0154	.4846	.9846
-2.15	.0158	.4842	.9842
-2.14	.0162	.4838	.9838
-2.13	.0166	.4834	.9834
-2.12	.0170	.4830	.9830
-2.11	.0174	.4826	.9826
-2.10	.0179	.4821	.9821
-2.09	.0183	.4817	.9817
-2.08	.0188	.4812	.9812
-2.07	.0192	.4808	.9808
-2.06	.0197	.4803	.9803
-2.05	.0202	.4798	.9798
-2.04	.0207	.4793	.9793
-2.03	.0212	.4788	.9788
-2.02	.0217	.4783	.9783
-2.01	.0222	.4778	.9778
-2.00	.0228	.4772	.9772
-1.99	.0233	.4767	.9767
-1.98	.0239	.4761	.9761
-1.97	.0244	.4756	.9756
-1.96	.0250	.4750	.9750
-1.95	.0256	.4744	.9744
-1.94	.0262	.4738	.9738
-1.93	.0268	.4732	.9732
-1.92	.0274	.4726	.9726
-1.91	.0281	.4719	.9719
-1.90	.0287	.4713	.9713
-1.89	.0294	.4706	.9706

APPENDIX A-2
(Continued)

-1.88	.0301	.4699	.9699
-1.87	.0307	.4693	.9693
-1.86	.0314	.4686	.9686
-1.85	.0322	.4678	.9678
-1.84	.0329	.4671	.9671
-1.83	.0336	.4664	.9664
-1.82	.0344	.4656	.9656
-1.81	.0351	.4649	.9649
-1.80	.0359	.4641	.9641
-1.79	.0367	.4633	.9633
-1.78	.0375	.4625	.9625
-1.77	.0384	.4616	.9616
-1.76	.0392	.4608	.9608
-1.75	.0401	.4599	.9599
-1.74	.0409	.4591	.9591
-1.73	.0418	.4582	.9582
-1.72	.0427	.4573	.9573
-1.71	.0436	.4564	.9564
-1.70	.0446	.4554	.9554
-1.69	.0455	.4545	.9545
-1.68	.0465	.4535	.9535
-1.67	.0475	.4525	.9525
-1.66	.0485	.4515	.9515
-1.65	.0495	.4505	.9505
-1.64	.0505	.4495	.9495
-1.63	.0516	.4484	.9484
-1.62	.0526	.4474	.9474
-1.61	.0537	.4463	.9463
-1.60	.0548	.4452	.9452
-1.59	.0559	.4441	.9441
-1.58	.0571	.4429	.9429
-1.57	.0582	.4418	.9418
-1.56	.0594	.4406	.9406
-1.55	.0606	.4394	.9394
-1.54	.0618	.4382	.9382
-1.53	.0630	.4370	.9370
-1.52	.0643	.4357	.9357
-1.51	.0655	.4345	.9345
-1.50	.0668	.4332	.9332
-1.49	.0681	.4319	.9319
-1.48	.0694	.4306	.9306
-1.47	.0708	.4292	.9292

APPENDIX A-2
(Continued)

-1.46	.0721	.4279	.9279
-1.45	.0735	.4265	.9265
-1.44	.0749	.4251	.9251
-1.43	.0764	.4236	.9236
-1.42	.0778	.4222	.9222
-1.41	.0793	.4207	.9207
-1.40	.0808	.4192	.9192
-1.39	.0823	.4177	.9177
-1.38	.0838	.4162	.9162
-1.37	.0853	.4147	.9147
-1.36	.0869	.4131	.9131
-1.35	.0885	.4115	.9115
-1.34	.0901	.4099	.9099
-1.33	.0918	.4082	.9082
-1.32	.0934	.4066	.9066
-1.31	.0951	.4049	.9049
-1.30	.0968	.4032	.9032
-1.29	.0985	.4015	.9015
-1.28	.1003	.3997	.8997
-1.27	.1020	.3980	.8980
-1.26	.1038	.3962	.8962
-1.25	.1056	.3944	.8944
-1.24	.1075	.3925	.8925
-1.23	.1093	.3907	.8907
-1.22	.1112	.3888	.8888
-1.21	.1131	.3869	.8869
-1.20	.1151	.3849	.8849
-1.19	.1170	.3830	.8830
-1.18	.1190	.3810	.8810
-1.17	.1210	.3790	.8790
-1.16	.1230	.3770	.8770
-1.15	.1251	.3749	.8749
-1.14	.1271	.3729	.8729
-1.13	.1292	.3708	.8708
-1.12	.1314	.3686	.8686
-1.11	.1335	.3665	.8665
-1.10	.1357	.3643	.8643
-1.09	.1379	.3621	.8621
-1.08	.1401	.3599	.8599
-1.07	.1423	.3577	.8577
-1.06	.1446	.3554	.8554
-1.05	.1469	.3531	.8531

APPENDIX A-2
(Continued)

-1.04	.1492	.3508	.8508
-1.03	.1515	.3485	.8485
-1.02	.1539	.3461	.8461
-1.01	.1562	.3438	.8438
-1.00	.1587	.3413	.8413
-.99	.1611	.3389	.8389
-.98	.1635	.3365	.8365
-.97	.1660	.3340	.8340
-.96	.1685	.3315	.8315
-.95	.1711	.3289	.8289
-.94	.1736	.3264	.8264
-.93	.1762	.3238	.8238
-.92	.1788	.3212	.8212
-.91	.1814	.3186	.8186
-.90	.1841	.3159	.8159
-.89	.1867	.3133	.8133
-.88	.1894	.3106	.8106
-.87	.1922	.3078	.8078
-.86	.1949	.3051	.8051
-.85	.1977	.3023	.8023
-.84	.2005	.2995	.7995
-.83	.2033	.2967	.7967
-.82	.2061	.2939	.7939
-.81	.2090	.2910	.7910
-.80	.2119	.2881	.7881
-.79	.2148	.2852	.7852
-.78	.2177	.2823	.7823
-.77	.2206	.2794	.7794
-.76	.2236	.2764	.7764
-.75	.2266	.2734	.7734
-.74	.2297	.2703	.7703
-.73	.2327	.2673	.7673
-.72	.2358	.2642	.7642
-.71	.2389	.2611	.7611
-.70	.2420	.2580	.7580
-.69	.2451	.2549	.7549
-.68	.2483	.2517	.7517
-.67	.2514	.2486	.7486
-.66	.2546	.2454	.7454
-.65	.2578	.2422	.7422
-.64	.2611	.2389	.7389
-.63	.2643	.2357	.7357

APPENDIX A-2
(Continued)

-.62	.2676	.2324	.7324
-.61	.2709	.2291	.7291
-.60	.2743	.2257	.7257
-.59	.2776	.2224	.7224
-.58	.2810	.2190	.7190
-.57	.2843	.2157	.7157
-.56	.2877	.2123	.7123
-.55	.2912	.2088	.7088
-.54	.2946	.2054	.7054
-.53	.2981	.2019	.7019
-.52	.3015	.1985	.6985
-.51	.3050	.1950	.6950
-.50	.3085	.1915	.6915
-.49	.3121	.1879	.6879
-.48	.3156	.1844	.6844
-.47	.3192	.1808	.6808
-.46	.3228	.1772	.6772
-.45	.3264	.1736	.6736
-.44	.3300	.1700	.6700
-.43	.3336	.1664	.6664
-.42	.3372	.1628	.6628
-.41	.3409	.1591	.6591
-.40	.3446	.1554	.6554
-.39	.3483	.1517	.6517
-.38	.3520	.1480	.6480
-.37	.3557	.1443	.6443
-.36	.3594	.1406	.6406
-.35	.3632	.1368	.6368
-.34	.3669	.1331	.6331
-.33	.3707	.1293	.6293
-.32	.3745	.1255	.6255
-.31	.3783	.1217	.6217
-.30	.3821	.1179	.6179
-.29	.3859	.1141	.6141
-.28	.3897	.1103	.6103
-.27	.3936	.1064	.6064
-.26	.3974	.1026	.6026
-.25	.4013	.0987	.5987
-.24	.4052	.0948	.5948
-.23	.4090	.0910	.5910
-.22	.4129	.0871	.5871
-.21	.4168	.0832	.5832

APPENDIX A-2
(Continued)

-.20	.4207	.0793	.5793
-.19	.4247	.0753	.5753
-.18	.4286	.0714	.5714
-.17	.4325	.0675	.5675
-.16	.4364	.0636	.5636
-.15	.4404	.0596	.5596
-.14	.4443	.0557	.5557
-.13	.4483	.0517	.5517
-.12	.4522	.0478	.5478
-.11	.4562	.0438	.5438
-.10	.4602	.0398	.5398
-.09	.4641	.0359	.5359
-.08	.4681	.0319	.5319
-.07	.4721	.0279	.5279
-.06	.4761	.0239	.5239
-.05	.4801	.0199	.5199
-.04	.4840	.0160	.5160
-.03	.4880	.0120	.5120
-.02	.4920	.0080	.5080
-.01	.4960	.0040	.5040
.00	.5000	.0000	.5000
.01	.5040	.0040	.4960
.02	.5080	.0080	.4920
.03	.5120	.0120	.4880
.04	.5160	.0160	.4840
.05	.5199	.0199	.4801
.06	.5239	.0239	.4761
.07	.5279	.0279	.4721
.08	.5319	.0319	.4681
.09	.5359	.0359	.4641
.10	.5398	.0398	.4602
.11	.5438	.0438	.4562
.12	.5478	.0478	.4522
.13	.5517	.0517	.4483
.14	.5557	.0557	.4443
.15	.5596	.0596	.4404
.16	.5636	.0636	.4364
.17	.5675	.0675	.4325
.18	.5714	.0714	.4286
.19	.5753	.0753	.4247
.20	.5793	.0793	.4207
.21	.5832	.0832	.4168

APPENDIX A-2
(Continued)

.22	.5871	.0871	.4129
.23	.5910	.0910	.4090
.24	.5948	.0948	.4052
.25	.5987	.0987	.4013
.26	.6026	.1026	.3974
.27	.6064	.1064	.3936
.28	.6103	.1103	.3897
.29	.6141	.1141	.3859
.30	.6179	.1179	.3821
.31	.6217	.1217	.3783
.32	.6255	.1255	.3745
.33	.6293	.1293	.3707
.34	.6331	.1331	.3669
.35	.6368	.1368	.3632
.36	.6406	.1406	.3594
.37	.6443	.1443	.3557
.38	.6480	.1480	.3520
.39	.6517	.1517	.3483
.40	.6554	.1554	.3446
.41	.6591	.1591	.3409
.42	.6628	.1628	.3372
.43	.6664	.1664	.3336
.44	.6700	.1700	.3300
.45	.6736	.1736	.3264
.46	.6772	.1772	.3228
.47	.6808	.1808	.3192
.48	.6844	.1844	.3156
.49	.6879	.1879	.3121
.50	.6915	.1915	.3085
.51	.6950	.1950	.3050
.52	.6985	.1985	.3015
.53	.7019	.2019	.2981
.54	.7054	.2054	.2946
.55	.7088	.2088	.2912
.56	.7123	.2123	.2877
.57	.7157	.2157	.2843
.58	.7190	.2190	.2810
.59	.7224	.2224	.2776
.60	.7257	.2257	.2743
.61	.7291	.2291	.2709
.62	.7324	.2324	.2676
.63	.7357	.2357	.2643

APPENDIX A-2
(Continued)

.64	.7389	.2389	.2611
.65	.7422	.2422	.2578
.66	.7454	.2454	.2546
.67	.7486	.2486	.2514
.68	.7517	.2517	.2483
.69	.7549	.2549	.2451
.70	.7580	.2580	.2420
.71	.7611	.2611	.2389
.72	.7642	.2642	.2358
.73	.7673	.2673	.2327
.74	.7703	.2703	.2297
.75	.7734	.2734	.2266
.76	.7764	.2764	.2236
.77	.7794	.2794	.2206
.78	.7823	.2823	.2177
.79	.7852	.2852	.2148
.80	.7881	.2881	.2119
.81	.7910	.2910	.2090
.82	.7939	.2939	.2061
.83	.7967	.2967	.2033
.84	.7995	.2995	.2005
.85	.8023	.3023	.1977
.86	.8051	.3051	.1949
.87	.8078	.3078	.1922
.88	.8106	.3106	.1894
.89	.8133	.3133	.1867
.90	.8159	.3159	.1841
.91	.8186	.3186	.1814
.92	.8212	.3212	.1788
.93	.8238	.3238	.1762
.94	.8264	.3264	.1736
.95	.8289	.3289	.1711
.96	.8315	.3315	.1685
.97	.8340	.3340	.1660
.98	.8365	.3365	.1635
.99	.8389	.3389	.1611
1.00	.8413	.3413	.1587
1.01	.8438	.3438	.1562
1.02	.8461	.3461	.1539
1.03	.8485	.3485	.1515
1.04	.8508	.3508	.1492
1.05	.8531	.3531	.1469

APPENDIX A-2
(Continued)

1.06	.8554	.3554	.1446
1.07	.8577	.3577	.1423
1.08	.8599	.3599	.1401
1.09	.8621	.3621	.1379
1.10	.8643	.3643	.1357
1.11	.8665	.3665	.1335
1.12	.8686	.3686	.1314
1.13	.8708	.3708	.1292
1.14	.8729	.3729	.1271
1.15	.8749	.3749	.1251
1.16	.8770	.3770	.1230
1.17	.8790	.3790	.1210
1.18	.8810	.3810	.1190
1.19	.8830	.3830	.1170
1.20	.8849	.3849	.1151
1.21	.8869	.3869	.1131
1.22	.8888	.3888	.1112
1.23	.8907	.3907	.1093
1.24	.8925	.3925	.1075
1.25	.8944	.3944	.1056
1.26	.8962	.3962	.1038
1.27	.8980	.3980	.1020
1.28	.8997	.3997	.1003
1.29	.9015	.4015	.0985
1.30	.9032	.4032	.0968
1.31	.9049	.4049	.0951
1.32	.9066	.4066	.0934
1.33	.9082	.4082	.0918
1.34	.9099	.4099	.0901
1.35	.9115	.4115	.0885
1.36	.9131	.4131	.0869
1.37	.9147	.4147	.0853
1.38	.9162	.4162	.0838
1.39	.9177	.4177	.0823
1.40	.9192	.4192	.0808
1.41	.9207	.4207	.0793
1.42	.9222	.4222	.0778
1.43	.9236	.4236	.0764
1.44	.9251	.4251	.0749
1.45	.9265	.4265	.0735
1.46	.9279	.4279	.0721
1.47	.9292	.4292	.0708

APPENDIX A-2
(Continued)

1.48	.9306	.4306	.0694
1.49	.9319	.4319	.0681
1.50	.9332	.4332	.0668
1.51	.9345	.4345	.0655
1.52	.9357	.4357	.0643
1.53	.9370	.4370	.0630
1.54	.9382	.4382	.0618
1.55	.9394	.4394	.0606
1.56	.9406	.4406	.0594
1.57	.9418	.4418	.0582
1.58	.9429	.4429	.0571
1.59	.9441	.4441	.0559
1.60	.9452	.4452	.0548
1.61	.9463	.4463	.0537
1.62	.9474	.4474	.0526
1.63	.9484	.4484	.0516
1.64	.9495	.4495	.0505
1.65	.9505	.4505	.0495
1.66	.9515	.4515	.0485
1.67	.9525	.4525	.0475
1.68	.9535	.4535	.0465
1.69	.9545	.4545	.0455
1.70	.9554	.4554	.0446
1.71	.9564	.4564	.0436
1.72	.9573	.4573	.0427
1.73	.9582	.4582	.0418
1.74	.9591	.4591	.0409
1.75	.9599	.4599	.0401
1.76	.9608	.4608	.0392
1.77	.9616	.4616	.0384
1.78	.9625	.4625	.0375
1.79	.9633	.4633	.0367
1.80	.9641	.4641	.0359
1.81	.9649	.4649	.0351
1.82	.9656	.4656	.0344
1.83	.9664	.4664	.0336
1.84	.9671	.4671	.0329
1.85	.9678	.4678	.0322
1.86	.9686	.4686	.0314
1.87	.9693	.4693	.0307
1.88	.9699	.4699	.0301
1.89	.9706	.4706	.0294

APPENDIX A-2
(Continued)

1.90	.9713	.4713	.0287
1.91	.9719	.4719	.0281
1.92	.9726	.4726	.0274
1.93	.9732	.4732	.0268
1.94	.9738	.4738	.0262
1.95	.9744	.4744	.0256
1.96	.9750	.4750	.0250
1.97	.9756	.4756	.0244
1.98	.9761	.4761	.0239
1.99	.9767	.4767	.0233
2.00	.9772	.4772	.0228
2.01	.9778	.4778	.0222
2.02	.9783	.4783	.0217
2.03	.9788	.4788	.0212
2.04	.9793	.4793	.0207
2.05	.9798	.4798	.0202
2.06	.9803	.4803	.0197
2.07	.9808	.4808	.0192
2.08	.9812	.4812	.0188
2.09	.9817	.4817	.0183
2.10	.9821	.4821	.0179
2.11	.9826	.4826	.0174
2.12	.9830	.4830	.0170
2.13	.9834	.4834	.0166
2.14	.9838	.4838	.0162
2.15	.9842	.4842	.0158
2.16	.9846	.4846	.0154
2.17	.9850	.4850	.0150
2.18	.9854	.4854	.0146
2.19	.9857	.4857	.0143
2.20	.9861	.4861	.0139
2.21	.9864	.4864	.0136
2.22	.9868	.4868	.0132
2.23	.9871	.4871	.0129
2.24	.9875	.4875	.0125
2.25	.9878	.4878	.0122
2.26	.9881	.4881	.0119
2.27	.9884	.4884	.0116
2.28	.9887	.4887	.0113
2.29	.9890	.4890	.0110
2.30	.9893	.4893	.0107
2.31	.9896	.4896	.0104

APPENDIX A-2
(Continued)

2.32	.9898	.4898	.0102
2.33	.9901	.4901	.0099
2.34	.9904	.4904	.0096
2.35	.9906	.4906	.0094
2.36	.9909	.4909	.0091
2.37	.9911	.4911	.0089
2.38	.9913	.4913	.0087
2.39	.9916	.4916	.0084
2.40	.9918	.4918	.0082
2.41	.9920	.4920	.0080
2.42	.9922	.4922	.0078
2.43	.9925	.4925	.0075
2.44	.9927	.4927	.0073
2.45	.9929	.4929	.0071
2.46	.9931	.4931	.0069
2.47	.9932	.4932	.0068
2.48	.9934	.4934	.0066
2.49	.9936	.4936	.0064
2.50	.9938	.4938	.0062
2.51	.9940	.4940	.0060
2.52	.9941	.4941	.0059
2.53	.9943	.4943	.0057
2.54	.9945	.4945	.0055
2.55	.9946	.4946	.0054
2.56	.9948	.4948	.0052
2.57	.9949	.4949	.0051
2.58	.9951	.4951	.0049
2.59	.9952	.4952	.0048
2.60	.9953	.4953	.0047
2.61	.9955	.4955	.0045
2.62	.9956	.4956	.0044
2.63	.9957	.4957	.0043
2.64	.9959	.4959	.0041
2.65	.9960	.4960	.0040
2.66	.9961	.4961	.0039
2.67	.9962	.4962	.0038
2.68	.9963	.4963	.0037
2.69	.9964	.4964	.0036
2.70	.9965	.4965	.0035
2.71	.9966	.4966	.0034
2.72	.9967	.4967	.0033
2.73	.9968	.4968	.0032

APPENDIX A-2
(Continued)

2.74	.9969	.4969	.0031
2.75	.9970	.4970	.0030
2.76	.9971	.4971	.0029
2.77	.9972	.4972	.0028
2.78	.9973	.4973	.0027
2.79	.9974	.4974	.0026
2.80	.9974	.4974	.0026
2.81	.9975	.4975	.0025
2.82	.9976	.4976	.0024
2.83	.9977	.4977	.0023
2.84	.9977	.4977	.0023
2.85	.9978	.4978	.0022
2.86	.9979	.4979	.0021
2.87	.9979	.4979	.0021
2.88	.9980	.4980	.0020
2.89	.9981	.4981	.0019
2.90	.9981	.4981	.0019
2.91	.9982	.4982	.0018
2.92	.9982	.4982	.0018
2.93	.9983	.4983	.0017
2.94	.9984	.4984	.0016
2.95	.9984	.4984	.0016
2.96	.9985	.4985	.0015
2.97	.9985	.4985	.0015
2.98	.9986	.4986	.0014
2.99	.9986	.4986	.0014
3.00	.9987	.4987	.0013
3.01	.9987	.4987	.0013
3.02	.9987	.4987	.0013
3.03	.9988	.4988	.0012
3.04	.9988	.4988	.0012
3.05	.9989	.4989	.0011
3.06	.9989	.4989	.0011
3.07	.9989	.4989	.0011
3.08	.9990	.4990	.0010
3.09	.9990	.4990	.0010
3.10	.9990	.4990	.0010
3.11	.9991	.4991	.0009
3.12	.9991	.4991	.0009
3.13	.9991	.4991	.0009
3.14	.9992	.4992	.0008
3.15	.9992	.4992	.0008

APPENDIX A-2
(Continued)

3.16	.9992	.4992	.0008
3.17	.9992	.4992	.0008
3.18	.9993	.4993	.0007
3.19	.9993	.4993	.0007
3.20	.9993	.4993	.0007
3.21	.9993	.4993	.0007
3.22	.9994	.4994	.0006
3.23	.9994	.4994	.0006
3.24	.9994	.4994	.0006
3.25	.9994	.4994	.0006
3.26	.9994	.4994	.0006
3.27	.9995	.4995	.0005
3.28	.9995	.4995	.0005
3.29	.9995	.4995	.0005
3.30	.9995	.4995	.0005
3.31	.9995	.4995	.0005
3.32	.9995	.4995	.0005
3.33	.9996	.4996	.0004
3.34	.9996	.4996	.0004
3.35	.9996	.4996	.0004
3.36	.9996	.4996	.0004
3.37	.9996	.4996	.0004
3.38	.9996	.4996	.0004
3.39	.9997	.4997	.0003
3.40	.9997	.4997	.0003
3.41	.9997	.4997	.0003
3.42	.9997	.4997	.0003
3.43	.9997	.4997	.0003
3.44	.9997	.4997	.0003
3.45	.9997	.4997	.0003
3.46	.9997	.4997	.0003
3.47	.9997	.4997	.0003
3.48	.9997	.4997	.0003
3.49	.9998	.4998	.0002
3.50	.9998	.4998	.0002

APPENDIX B-1

Sales Data for Color and Black & White Televisions

[Source 29]

Year	Black and White Television Units (thousands)	Color Television Units (thousands)
1946	6	-NA-
1947	179	-NA-
1948	970	-NA-
1949	2,970	-NA-
1950	7,355	-NA-
1951	5,312	-NA-
1952	6,194	-NA-
1953	6,870	-NA-
1954	7405	5
1955	7738	20
1956	7351	100
1957	6388	85
1958	5051	80
1959	6278	90
1960	5707	120
1961	6155	147
1962	6558	438
1963	7019	747
1964	8028	1404
1965	8409	2694
1966	7189	5012
1967	5290	5563
1968	5778	6215
1969	5191	6191
1970	4707	5320
1971	4941	7274
1972	5512	8845
1973	7242	10071
1974	6318	8411
1975	4955	6485
1976	5561	7700
1977	-NA-	9107
1978	-NA-	10236
1979	-NA-	9846
1980	-NA-	10897

APPENDIX B-1
(Continued)

Year	Black and White Television Units (thousands)	Color Television Units (thousands)
1981	-NA-	11157
1982	-NA-	11366
1983	-NA-	13986
1984	-NA-	16083
1985	-NA-	16995
1986	-NA-	18204
1987	-NA-	19330
1988	-NA-	20216
1989	-NA-	21706
1990	-NA-	20384
1991	-NA-	19474
1992	-NA-	21056
1993	-NA-	23005
1994	-NA-	24715
1995	-NA-	23231
1996	-NA-	22384
1997	-NA-	21900
1998	-NA-	21700

APPENDIX B-2

Current Situation – Color Television Failure

Data generated by the forecasting software using both the models. Parameters supplied for the models are as follows:

Bath-tub model:

A = 1.5% T_1 = 1 year
B = 0.5% T_2 = 9 years
C = 1% T_3 = 11 years
D = 11%

Standard Normal Distribution Model:

MTTF = 11 years
Standard Distribution = 2 years

A storage factor was added in the computation for both the models. Storage is also modelled as a standard normal distribution.

MTTF = 1 year
Standard Distribution = 6 months

Years	Bath-tub model (thousand units)	Standard Normal Distribution model (thousand units)
1954	0	0
1955	0	0
1956	1	0
1957	2	0
1958	2	0
1959	3	0
1960	4	0
1961	4	1
1962	8	3
1963	15	9
1964	30	19

APPENDIX B-2
(Continued)

Years	Bath-tub model (thousand units)	Standard Normal Distribution model (thousand units)
1965	59	32
1966	111	47
1967	166	68
1968	223	89
1969	290	123
1970	340	193
1971	422	334
1972	590	583
1973	839	1019
1974	1249	1655
1975	1881	2492
1976	2722	3456
1977	3756	4378
1978	4821	5161
1979	5735	5793
1980	6229	6369
1981	6687	6936
1982	7089	7526
1983	7613	7967
1984	8419	8190
1985	8827	8284
1986	8841	8397
1987	8563	8737
1988	8746	9230
1989	9607	9812
1990	10439	10454
1991	11050	11201
1992	11625	12111
1993	12567	13229
1994	13592	14560
1995	14911	15894
1996	16522	17162
1997	17849	18303
1998	18824	19214
1999	19480	19902
2000	19898	20398
2001	20316	20813
2002	20472	21297
2003	20358	21885

APPENDIX B-2
(Continued)

Years	Bath-tub model (thousand units)	Standard Normal Distribution model (thousand units)
2004	20824	22206
2005	21476	22275
2006	21805	21294
2007	20983	19263
2008	18768	15950
2009	15510	11737
2010	11536	7305
2011	6458	3999
2012	882	1845
2013	38	614
2014	0	257
2015	0	33
2016	0	1
2017	0	0
2018	0	0

APPENDIX B-3

United States Census Data
[Source 32]

Year	United States	State of Massachusetts
1940	132,164,569	4,316,721
1950	151,325,798	4,690,514
1960	179,323,175	5,148,578
1970	203,302,031	5,689,170
1980	226,542,203	5,737,093
1990	248,718,301	6,016,425
1996	265,283,783	6,092,352

APPENDIX B-4

Effect of CRT Disposal Ban in Massachusetts

Data generated by both the forecasting models. The parameters supplied to the models are as described in Appendix B-2.

Years	Bath-tub model (thousand units)	Standard Normal Distribution model (thousand units)
1954	0	0
1955	0	0
1956	0	0
1957	0	0
1958	0	0
1959	0	0
1960	0	0
1961	0	0
1962	0	0
1963	0	0
1964	0	0
1965	1	0
1966	2	1
1967	4	1
1968	6	0
1969	7	2
1970	9	6
1971	14	10
1972	19	17
1973	24	29
1974	35	48
1975	53	69
1976	76	99
1977	106	124
1978	134	143
1979	164	162
1980	175	177
1981	185	194
1982	197	205
1983	209	217

APPENDIX B-4
(Continued)

Years	**Bath-tub model** (thousand units)	**Standard Normal Distribution model** (thousand units)
1984	227	223
1985	239	221
1986	235	222
1987	223	231
1988	228	239
1989	247	250
1990	264	266
1991	280	282
1992	293	302
1993	313	330
1994	339	364
1995	369	394
1996	410	424
1997	434	450
1998	453	472
1999	469	481
2000	481	495
2001	482	501
2002	488	501
2003	481	509
2004	485	496
2005	482	456
2006	456	385
2007	386	284
2008	281	178
2009	155	97
2010	21	44
2011	1	14
2012	0	6
2013	0	1
2014	0	0
2015	0	0
2016	0	0
2017	0	0
2018	0	0

APPENDIX B-5

Estimated Color Television Failure after the Introduction of Flat Panel Televisions

Data generated by both the forecasting models. The parameters supplied to the models are as described in Appendix B-2.

Years	Bath-tub Model (thousand units)	Standard Normal Distribution Model (thousand units)
1954	0	0
1955	0	0
1956	1	0
1957	2	0
1958	2	0
1959	3	0
1960	4	0
1961	4	1
1962	8	3
1963	15	9
1964	30	19
1965	59	32
1966	111	47
1967	166	68
1968	223	89
1969	290	123
1970	340	193
1971	422	334
1972	590	583
1973	839	1019
1974	1249	1655
1975	1881	2492
1976	2722	3456
1977	3756	4378
1978	4821	5161
1979	5735	5793
1980	6229	6369

APPENDIX B-5
(Continued)

Years	Bath-tub Model (thousand units)	Standard Normal Distribution Model (thousand units)
1981	6687	6936
1982	7089	7526
1983	7613	7967
1984	8419	8190
1985	8827	8284
1986	8841	8397
1987	8563	8737
1988	8746	9230
1989	9607	9812
1990	10439	10454
1991	11050	11201
1992	11625	12111
1993	12567	13229
1994	13592	14560
1995	14911	15894
1996	16522	17162
1997	17849	18303
1998	18825	19214
1999	19667	19902
2000	20298	20398
2001	20746	20813
2002	21089	21297
2003	21188	21886
2004	21683	22393
2005	22520	22680
2006	23057	22655
2007	22992	22442
2008	22358	22172
2009	21892	21919
2010	21599	21748
2011	21418	21612
2012	21271	21516
2013	21119	21399
2014	20972	21216
2015	20775	20885
2016	20456	20349
2017	19944	19504

APPENDIX B-5
(Continued)

Years	Bath-tub Model (thousand units)	Standard Normal Distribution Model (thousand units)
2018	19066	18312
2019	17744	16797
2020	16240	15070
2021	14408	13394
2022	12452	11984
2023	10780	10857
2024	9789	10015
2025	9299	9109
2026	8643	7990
2027	7713	6509
2028	6194	4782
2029	4616	2960
2030	2681	1629
2031	369	759
2032	16	249
2033	0	108
2034	0	0
2035	0	0

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