A Tool For Design And Decision Making: Reliability

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1.0 Abstract:

As traditional engineering practices have focused more towards deterministic design it does not leave a lot to be desired in terms of performance and service life. Typically, traditional engineering practice uses a capacity approach in that one or more key failure modes are determined to be the governing mode of failure and the design was performed such that these particular failure modes would be prevented. In doing so engineers assumed that many of the parameters used in design, such as mass, ultimate strength, etc, were absolute; however, many of these parameters have a large amount of variability and should not be assumed to be absolute so quickly. From this perspective comes reliability engineering. Reliability engineering takes into account these probabilities and incorporates them into a useable form of analysis. With reliability engineering many different possible modes of failure are effectively examined giving more depth to the design. Today’s engineers are slowly beginning to realize the effectiveness of reliability engineering as a design tool and decision-making tool as well.

This paper hopes to illustrate the potential benefits that may come with incorporating reliability analysis into the engineering field. Also it will illustrate the benefits of combining commercial decision-making software with a reliability analysis of any potential design.

2.0 Introduction:

Traditionally, engineering had always taken a deterministic approach in design. An engineer’s task was to find a suitable design that would meet the design criteria. The design criteria usually consisted of a set of functions that the design must be capable of performing and used a capacity based approach to avoid failure. This capacity approach relied on one or two governing failure mechanism to base all calculations and designs and assumed that many parameters used in design were absolute such as; mass, friction coefficients, strengths of materials, and stresses. In actuality, the variability of these parameters is vital in determining the effectiveness of any design. This variability and chance should not be looked over so quickly and assigned a fixed parameter. More thought needs to be put into other possible causes of failure, the manufacturing of the product, and the maintenance and application of the product that may affect its chances of failure. Taking into consideration those probabilities defines the basis of reliability engineering.

However, in the past reliability engineering has been more of a theoretical ideal and many engineers faced the problem of how to effectively apply reliability theories into to practical applications. The aim of this paper is to illustrate the ease and effectiveness of applying reliability engineering in a practical setting and benefiting from its results.

It is also the aim of this paper to illustrate the effectiveness of reliability analysis as a decision-making tool and how such programs as DecisionPro by Vanguard Software Corporation can make the daunting task of analyzing a system’s reliability less difficult than it has to be.

3.0 Reliability Concepts and Terms:

The following terms will be used through out this report. (See USACE 2001)

(1) *Component.* A piece of equipment or portion of a system viewed as an independent entity for evaluation, i.e., its reliability does not influence the reliability of another component.
(2) *System.* An orderly arrangement of components that interact among themselves and with external components, other systems, and human operators to perform some intended function.
(3) *Failure.* Any trouble with a component that causes unsatisfactory performance of the system.
(4) *Hazard function or failure rate.* The instantaneous conditional probability of failure of an item in the next unit of time given that it has survived up to that time. It is the mean number of failures of a component per unit exposure time.
(5) *Reliability*. The probability that an item will perform its intended function under stated conditions, for either a specified interval or over its useful life.
(6) *Basic reliability*. Measure of the demand for maintenance and logistic support of a system caused by unreliability.
(7) *Mission reliability*. Measure of operational effectiveness of a system. A mission reliability prediction estimates the probability that items will perform their required functions during a mission.
(8) *Unsatisfactory performance.* Substandard operation; partial or complete shutdown of the system; operation of safety devices; unexpected de-energization of any process or equipment.

The following reliability concepts are explained below and help define a method to analyze the reliability of a system.

3.1 Reliability Function:

The first concept is the *reliability function, R(t),* which is simply the probability of a component to be still functional at time *t*. This relationship can be defined in mathematical terms as:

$$R(t) = P(T \geq t)$$

where

R(t) = the probability of success, such that $F(t) = 1 - R(t)$ = the probability of failure

T = time of component failure. A value determined statistically for that particular component using its failure rate data.

t = time at which the component is being evaluated for failure, such as the intended operational life of the component.

$P(T \geq t)$ = probability that the time of component failure is greater than the period of intended operation.

3.2 Hazard Function:

By taking the first derivative of the probability of failure function, F(t), the second reliability concept is given.

$$f(t) = \frac{-dR(t)}{dt}$$

Where *f(t)* is referred to as the probability density function. The probability density function, *f(t),* represents a curve approximation of the number of the probable occurrences of a specific variable, in this case, the failure of a component.

From the probability density function the hazard function is derived and is as follows:

$$h(t) = \frac{f(t)}{R(t)}$$

The hazard function, *h(t)*, is a measure of a component's acceptability to failure as a function its age or time in operation. This function is a reflection of a component's reliability as it changes with time during operation. There are several elements which influence a component's hazard function, some include items such as; the component's working environment, its operating conditions, its frequency of maintenance and the type of maintenance.

The hazard function is used to measure a component's instantaneous conditional probability of failure for the following unit of time providing that the component has not failed early before that given time. This instantaneous measurement gives way to the hazard being sometimes referred to as the instantaneous failure rate. A hazard function curve can consists of rising and falling peaks and plateaus; however, for most typical mechanical, structural, and electrical components the hazard function usually appears as the curve below in figure 1.

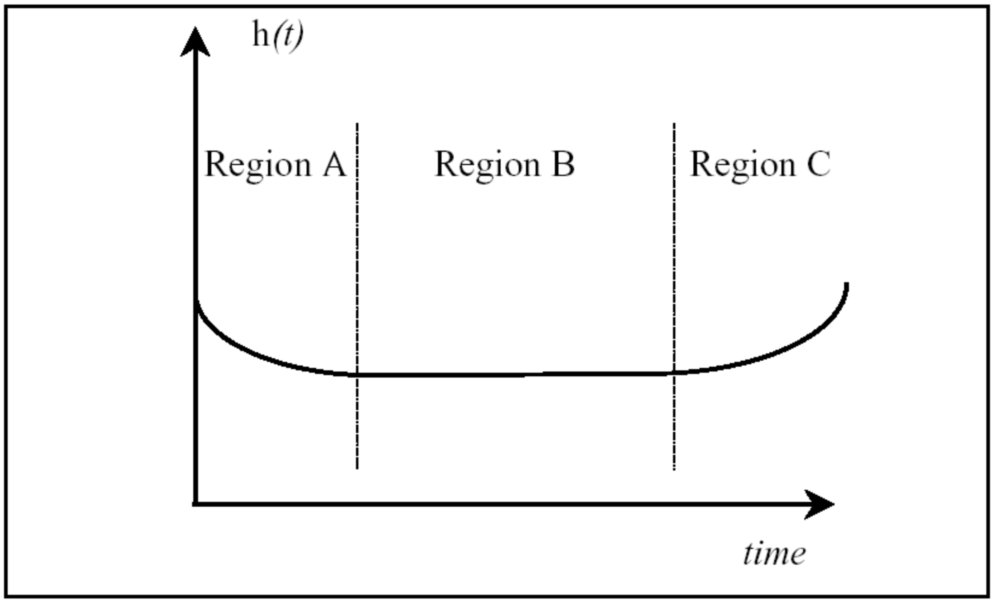


Figure 1: Bathtub Curve

A curve with this particular layout is called a *bathtub curve* where *h(t)* decreases in value as it moves with time, then plateaus, and finally increases sharply near the end of the component's life. The curve below is divided into three regions: regions A, B, and C. In region A the curve begins with a high instantaneous failure rate, which decreases as time increases. This region is referred to as the infant mortality region as it reflects such things as possible defects in the component, poor craftsmanship, improper use or application, or any other random effects that may result in premature failure. Region B is where the component proves to have no apparent defects and performs its intended function without fail; thus, its instantaneous failure rate remains constant. This region is referred to as the useful life phase. The last region, C, the component has out lived its usefulness and becomes more prone to failure as its failure rate starts to increase. The increase in failure rate at this time in its service life results from the wear and tear it has endured during is period of operation and it now approaches failure.

The bathtub curve is quite general for most components; however, depending on the component and factors such as; manufacturing, working environment, intended use, and maintenance will determine the lengths of regions A, B, and C, as well as it overall life span. Depending on the type of component will determine whether or not a component's infant mortality rate, region A, should be considered in detail. For some components region A may not be considered thoroughly as they may have a less complicated make up.

For the purposes of this case study, regions B and C will be considered.

3.3 Exponential Reliability and Hazard Functions:

In a reliability analysis it is often more convenient to employ an exponential distribution as opposed to other types of commonly used distribution curves. For an exponential distribution the reliability function is given as:

$$R(t) = e^{-\lambda t}$$

where

t = time

λ = failure rate

This distribution is commonly used to represent the constant hazard function found in region B of the bathtub curve. The hazard function is then determined to be simply λ for an exponential distribution. This relationship is outlined below:

$$f(t) = \frac{-dR(t)}{dt}$$

$$f(t) = \lambda e^{-\lambda t}$$

Thus the hazard function becomes:

$$h(t) = \frac{f(t)}{R(t)}$$

$$h(t) = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \quad \text{or simply} \quad h(t) = \lambda$$

Plotting the reliability and hazard functions with respect to an exponential distribution gives the following curves as shown:

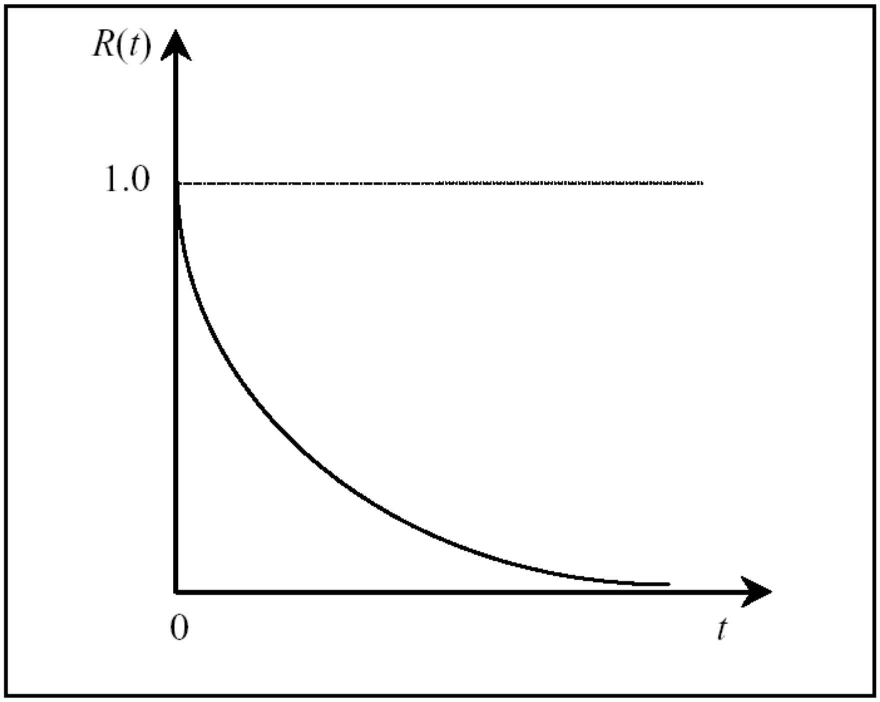


Figure 2: Reliability Function with an Exponential Distribution

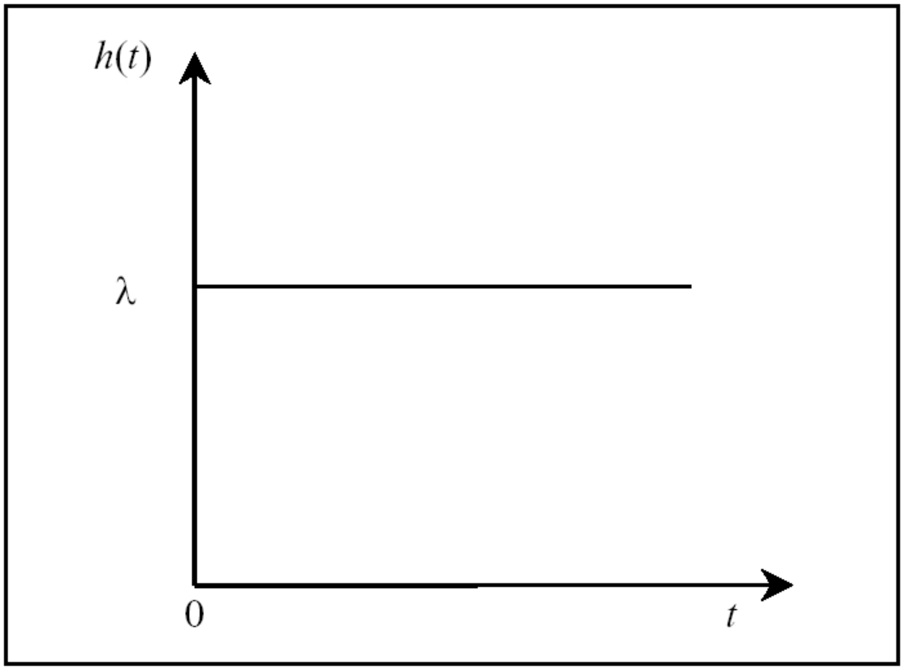


Figure 3: Hazard Function with an Exponential Distribution

3.4 Mean Time to Failure:

By taking the reciprocal of the hazard failure rate, λ, the average life expectancy of a component is given. This average or mean life expectancy is called the Mean Time to Failure (MTTF).

$$MTTF = \frac{1}{\lambda}$$

3.5 Weibull Reliability and Hazard Functions:

The Weibull Distribution is introduced to help simplify the exponential distribution. The Weibull distribution is very versatile and adaptable to many different types of curves. This important property of the Weibull distribution will make it very convenient to analyze the different regions of the bathtub curve. The Weibull distribution is very helpful for systems or complex components consisting of several parts. The Weibull reliability function is given as:

$$R(t) = \exp\left[-\left(\frac{t}{\alpha} \right)^{\beta} \right]$$

where

$\alpha =$ component characteristic life

$\beta =$ component shape factor

In instances of $0 < \beta < 1$, the Weibull distribution reflects failures that occur during the early stages of the component's life, (hazard function is decreasing). To represent the useful life phase of the component the Weibull distribution reduces the exponential distribution for cases when $\beta = 1$, (hazard function is constant). Finally, for cases where $1 < \beta < \infty$, the Weibull distribution represents the component as it reaches the end of its usefulness and begins to wear-out (hazard function is increasing). The Weibull hazard function is derived as follows:

$$f(t) = \frac{-dR(t)}{dt}$$

$$f(t) = \left(\frac{t}{\alpha} \right)^{\beta} \cdot \frac{\beta}{t} \cdot \exp\left[-\left(\frac{t}{\alpha} \right)^{\beta} \right]$$

Thus the hazard function becomes:

$$h(t) = \frac{f(t)}{R(t)}$$

$$h(t) = \left(\frac{t}{\alpha}\right)^{\beta} \cdot \frac{\beta}{t}$$

Plotting the reliability and hazard functions with respect to an exponential distribution gives the following curves as shown:

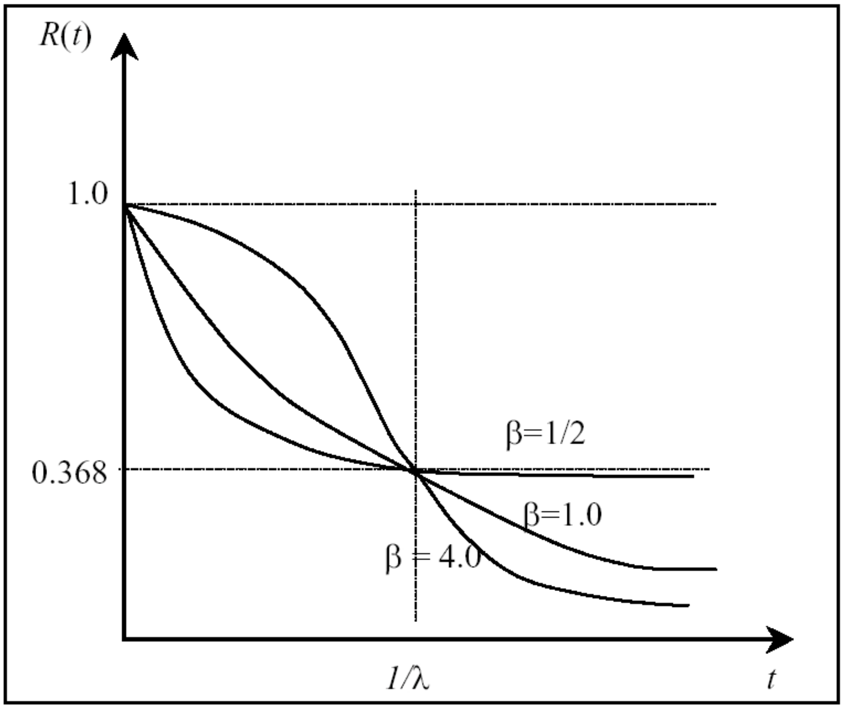


Figure 4: Reliability Function with a Weibull Distribution

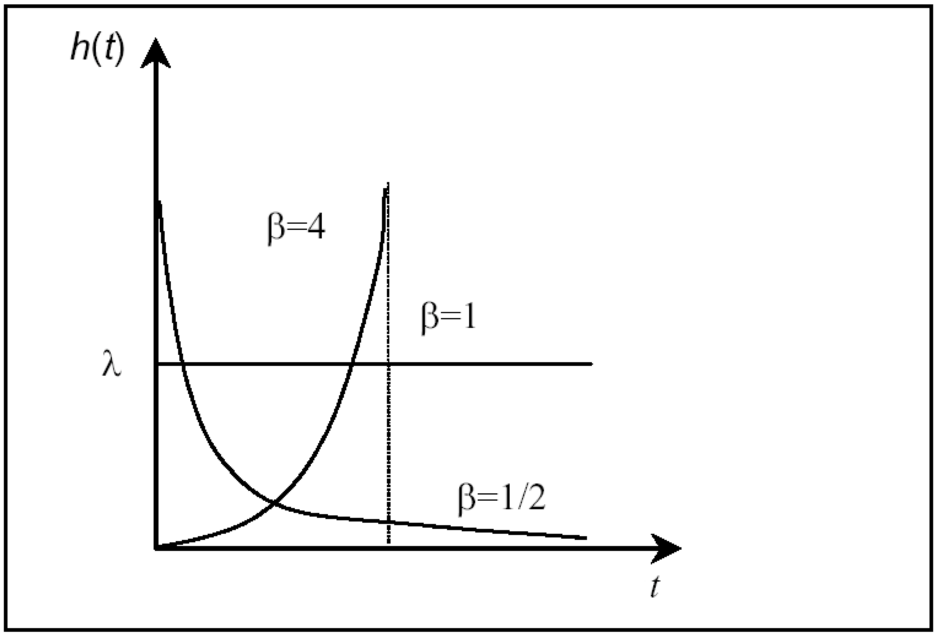


Figure 5: Hazard Function with a Weibull Distribution

3.6 Reliability Data:

As the old analogy goes, “a chain is only as strong as its weakest link.” In terms of reliability analysis the weakest link is generally the available component data. The more detailed the reliability analysis, the more detailed and in depth the data must be. Components can be very simple or complex in their make up and may have several possible modes of failure. There are many potential factors that can assist in causing a component to fail such as; friction build up, corrosion, wear-and-tear, improper use, operating conditions, etc. Having knowledge of the surrounding conditions and the factors that can lead to potential failure is important. It is also important to understand the layout of the component, such as a schematic, to understand where possible deficiencies and weakness may arise. Knowledge of a component’s layout is useful in determining the component’s system reliability, which will be explained later in this document. However, having complete knowledge of a component’s layout is only good if the appropriate failure rate data for all the pieces of the component.

Failure rate data is the historical data of a component with respect to failures, duration of use, time of failure, and mode of failure. Not only can the failure rate data be beneficial to reliability analysis, it is also beneficial in choosing the appropriate components that will make up the system and preventing any future failures.

However, failure rate data is not always an easy thing to obtain, but there are resources available. Failure rate could be found either directly from a manufacturer that properly records its own data, or indirectly by examining the manufacturer’s records, such as the repair and replacement records. Through repair and replacement records one can inadvertently determine the failure rate data of a component by seeing how often particular components are repaired or replaced. Other sources for failure rate data are organizations that create failure rate data for all types of components and mechanical systems, such organization as the Reliability Analysis Centre (RAC) and the Offshore Reliability Data group (OREDA). These organizations usually work outside of manufacturers’ influence or in cooperation with various manufacturers in order to provide reliable and unbiased data.

4.0 Reliability Analysis:

From the component reliability analysis and data the reliability of a system may be determined. Reliability analyses are becoming a more intricate part in the design of any system as it can be used to represent a system's service life and functionality, in addition to its use as a tool to prevent any foreseen failures; thus, increasing the service life of a system. By having knowledge of all the components in the system and their relationship with one another reliability analysis becomes more valuable. The reliability block diagram (RBD) approach is a common method for determining a system's reliability and will be used in this report.

5.0 System Reduction:

Many times a system may have a very complex make up of the components, in reliability analysis it is important to clarify which components are essential to the operation of the system and which components have less influence. To facilitate the reliability analysis, it is good practice to reduce the larger complex system into smaller systems that when combined together will represent the complex system. In each reliability group that will make up the complex system, it is best to identify the critical components and leave out the non-essential components as they may skew the data. Non-essential are those components that their failure has a minimal impact on the operation of the entire system and they may also be components that can be easily replaced and monitored.

6.0 System Reliability Analysis Using Block Diagrams:

The Reliability Block Diagram (RBD) method is a very useful method that presents a complicated system as a simplified system that can be easily visualized. In the RBD method components are represented by labelled blocks and ordered in a fashion that reflects their importance within the system, such that their individual failure will reflect the system's failure. There are four possible types of basic reliability systems; they are series, parallel, standby, and complex systems. A system may include all of these systems and sometimes it is better to break the overall system into smaller system reliabilities and later in the analysis sum up all the smaller system reliabilities.

6.1 Series System Reliability Model:

In a series system model all the components are ordered so that if one component fails the system will fail. Therefore, all components are dependent on each other and the system failure is dependent on only one component failing. It should be noted that the overall reliability of the system is inversely proportional to the number of components within the system, consequently, the more components present the overall system reliability will be reduced. The RBD of a series system is represented in the following figure:

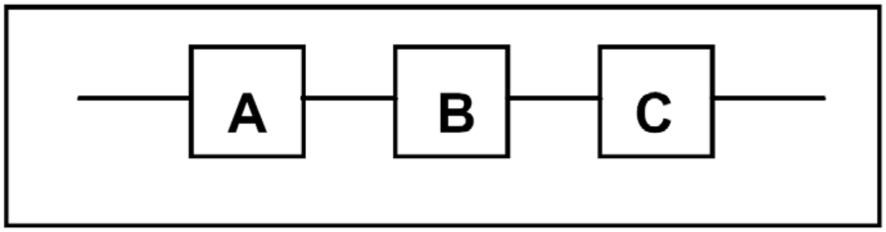


Figure 6: Series System RBD

Series systems that have *N* mutually independent components have a system reliability that is represented:

$$R_S(t) = R_A(t) \cdot R_B(t) \cdot R_C(t) \cdot \ldots \cdot R_N(t)$$

And the corresponding hazard function for the series system is:

$$h_s(t) = \sum_{i=1}^{N} h_i(t)$$

It is evident that the series system's reliability is equal to the sum of the failure rates of its components, regardless of their failure distribution.

6.2 Parallel System Reliability Model:

Unlike the series system model, the failure of a component in a parallel system does not mean system failure; rather system failure depends upon all components failing. In such a system, the system is able to perform after one or more component failures. A parallel RBD appears as follows:

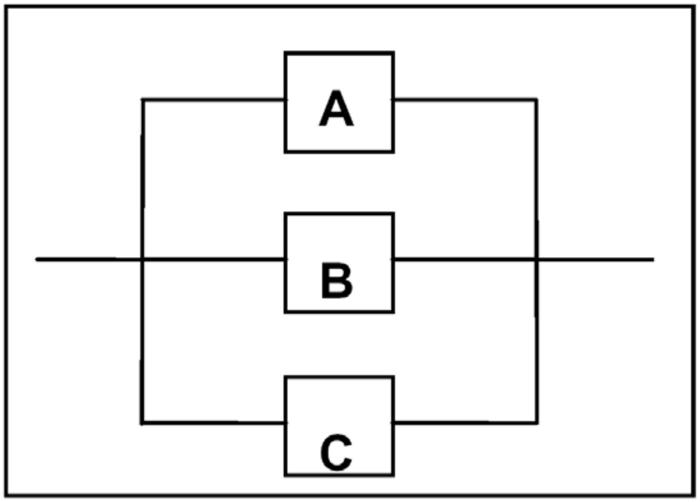


Figure 7: Parallel System RBD

And its reliability is given as:

$$R_S(t) = 1 - \left[1 - R_A(t)\right] \cdot \left[1 - R_B(t)\right] \cdot \left[1 - R_C(t)\right]$$

or can be written as:

$$R_S(t) = 1 - \prod_{i=1}^{N} \left[1 - R_i(t)\right]$$

for a system with *N* components in parallel.

The hazard function of the parallel system is written as:

$$h_S(t) = \frac{-d \ln R_S(t)}{dt}$$

or

$$h_S(t) = \frac{-d \ln \left\{1 - \prod_{i=1}^{N} \left[1 - R_i(t)\right]\right\}}{dt}$$

6.3 Standby Redundant Reliability System Model:

In a standby redundant system model two or more components are capable of performing the desired task, but only one component is active and the other components may only become active when either a switch is flipped or the other component fails and then the system switches to the other component that was previously idle. The primary function of a standby system is to have a back up solution in the event that one component may fail, or the other component is desired to be used, to facilitate this “switch” an additional component referred to a switching device (SS) is used. The switching device can either be operated manually or automatically.

A two component standby redundant system RBD appears as:

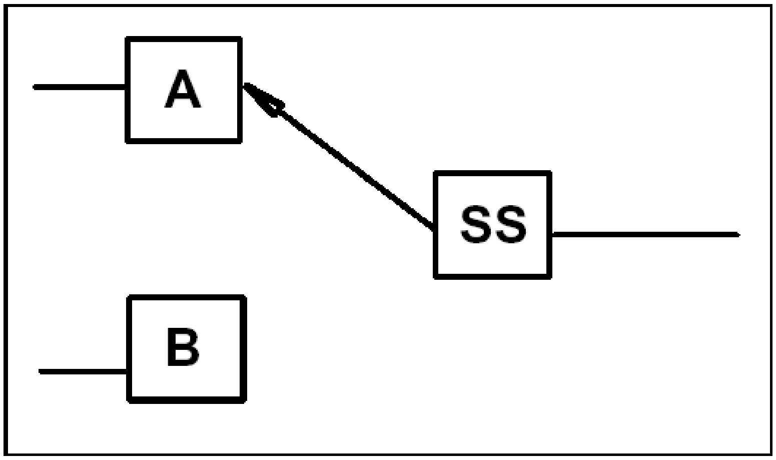


Figure 8: Standby Redundant System RBD

The system reliability of the two component standby redundant system is written as an exponential distribution and given as:

$$R_S(t) = R_A(t) + \frac{\left[\lambda_A R_B(t)\right]}{\left(\lambda_A + \lambda_{SS} + \lambda_B^{'} - \lambda_B\right)} \cdot \left\{1 - \exp\left[-\left(\lambda_A + \lambda_{SS} + \lambda_B^{'} - \lambda_B\right) d_i t\right]\right\}$$

where

λ_A = *hazard rate of A*

λ_{SS} = *hazard rate of switching device*

λ_B’ = *hazard rate of the standby equipment while not in use*

λ_B = *hazard rate of B*

d_i = *duty factor for respective failure rate*

6.4 Complex System Reliability Models:

More often than not the reliability of a system cannot be properly represented by the simpler systems shown above. It is usually better to represent a complex system as a system of smaller simpler systems and to determine the reliability of the smaller systems and then finally combine all their reliabilities into the final complex system. Complex systems may then appear as a system of both series and parallel systems to form the series-parallel system or they may not have any direct series or parallel systems and would be represented best by a non-series-parallel system.

In a series-parallel system the smaller series and parallel systems are analyzed as modules and then the reliability of the system is found by combining the reliabilities of the individual modules. An example is presented below:

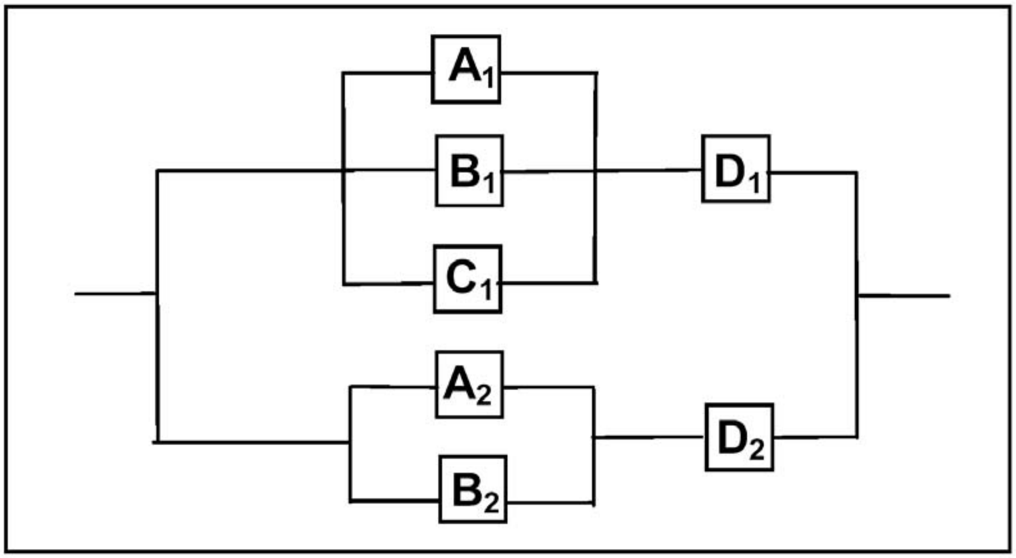


Figure 9: Series-parallel System RBD

Here the complex system is divided up into to modules, where the upper portion is module 1 and the lower portion is module 2, as denoted by the subscript for each component. Firstly the reliability of module 1 is determined as:

$$R_1(t) = \left(1 - \left\{\left[1 - R_{A1}(t)\right] \cdot \left[1 - R_{B1}(t)\right] \cdot \left[1 - R_{C1}(t)\right] \cdot\right\}\right) \cdot R_{D1}(t)$$

and module 2 is given as:

$$R_2(t) = \left(1 - \left\{\left[1 - R_{A2}(t)\right] \cdot \left[1 - R_{B2}(t)\right]\right\}\right) \cdot R_{D2}(t)$$

Thus the final system reliability can be determined as:

$$R_S(t) = \left(1 - \left\{\left[1 - R_1(t)\right] \cdot \left[1 - R_2(t)\right]\right\}\right)$$

A non-series-parallel system may appear as something similar to figure 10.

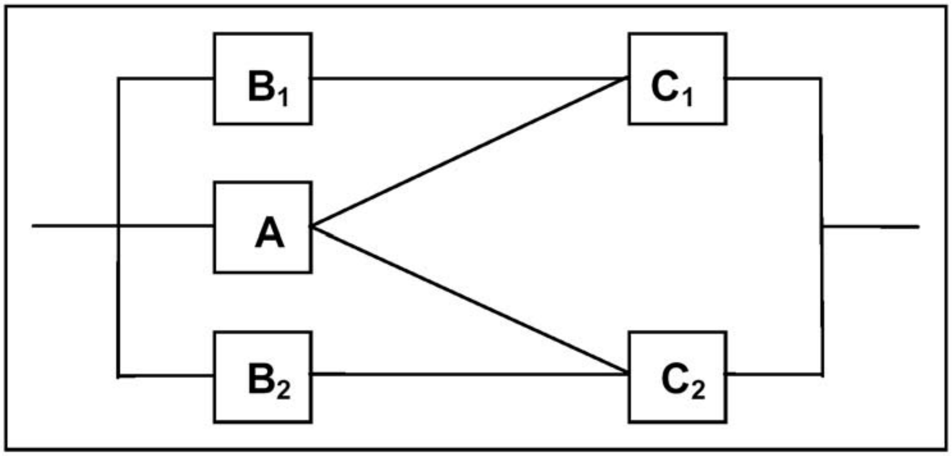


Figure 10: Non-series-parallel System RBD

A generalized theorem for dealing with a non-series-parallel system is given below:

$$R_S(t) = R_S(if\ X\ is\ working) \cdot R_X(t) + R_S(if\ X\ \ fails)\left[1 - R_X(t)\right]$$

In this theorem a critical component, such as X, is selected and the conditional reliability of the system working with and without that component is found.

7.0 Component Reliability:

The failure distribution of different types of components is not always known or is easy to represent in a mathematical model, it is for this reason that distributions like an exponential or Weibull distributions are employed. For the Weibull distribution the α and β parameters represent empirical data from controlled test data or values determined in the field. The α value is the characteristic life of the component and is determined by the overall failure rate data and the MTTF values for that particular component. The β values represent the failure mode of the component and were determined previously through years of data collection. If the mode of failure is unknown or the appropriate β value is not known, then it is suggested that a value of 1.0 be given to the β parameter. A list of possible failure modes and their corresponding β value are given in tables found in appendix C.

7.1 Overview of Reliability Analysis:

In the following paragraphs is a brief introduction into the component reliability analysis that is to be performed in order to provide adequate values for the system reliability analysis.

7.2 Define System Layout:

The first step in performing a system reliability analysis is to define the system layout by identifying all the mechanical components and their relation to one another. By analyzing a schematic of the mechanical piece one can form the *reliability block diagram* (RBD) that is a series, parallel and/ or complex system of nodes. In figures 11 and 12 an example from USACE 2001 of converting a simple schematic into a RBD, which will aid in the reliability analysis, is shown. Since failure of any component results in system failure the winch has an inherent series system.

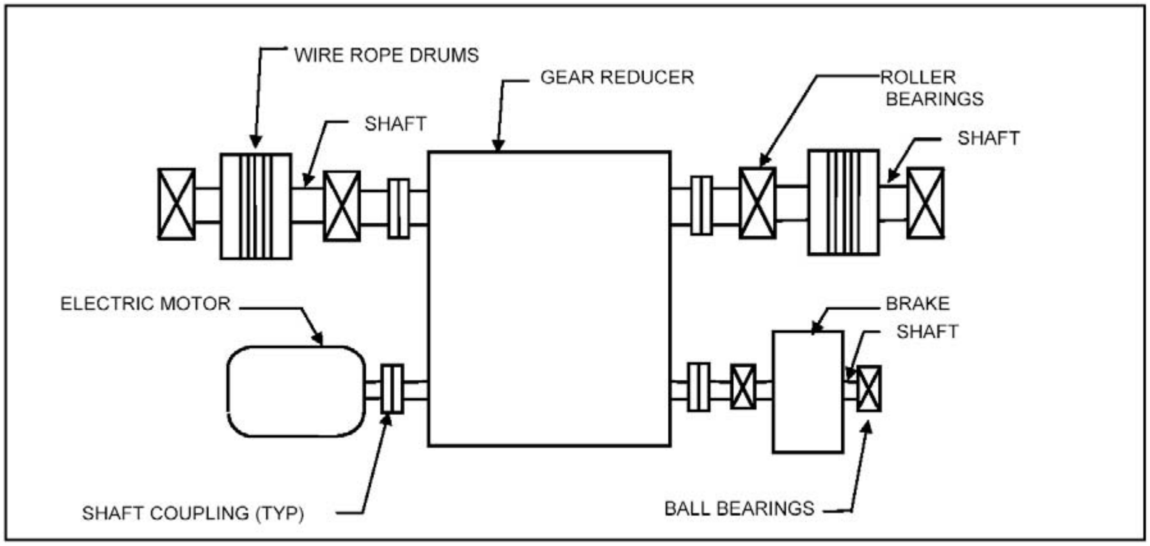


Figure 11: Simple Schematic of a Winch System

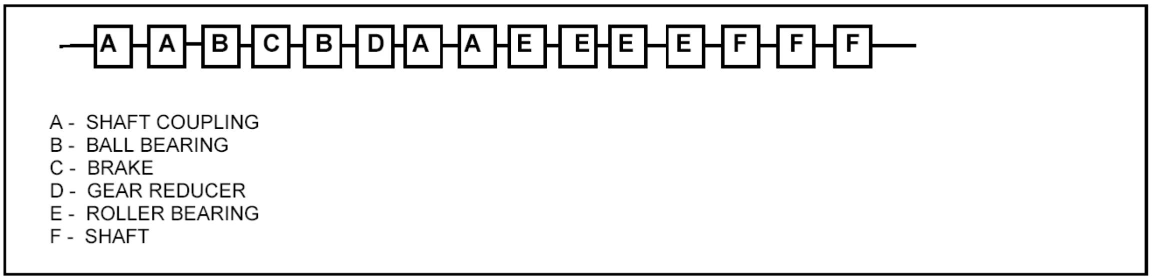


Figure 12: RBD of a Winch System

7.3 Determining Component Reliability:

In order to determine the reliability of a component several key factors must be established. These factors include the duty cycle of the system, environmental conditions, the failure rate of the component, the characteristic life of the component and the mode of failure for that particular component.

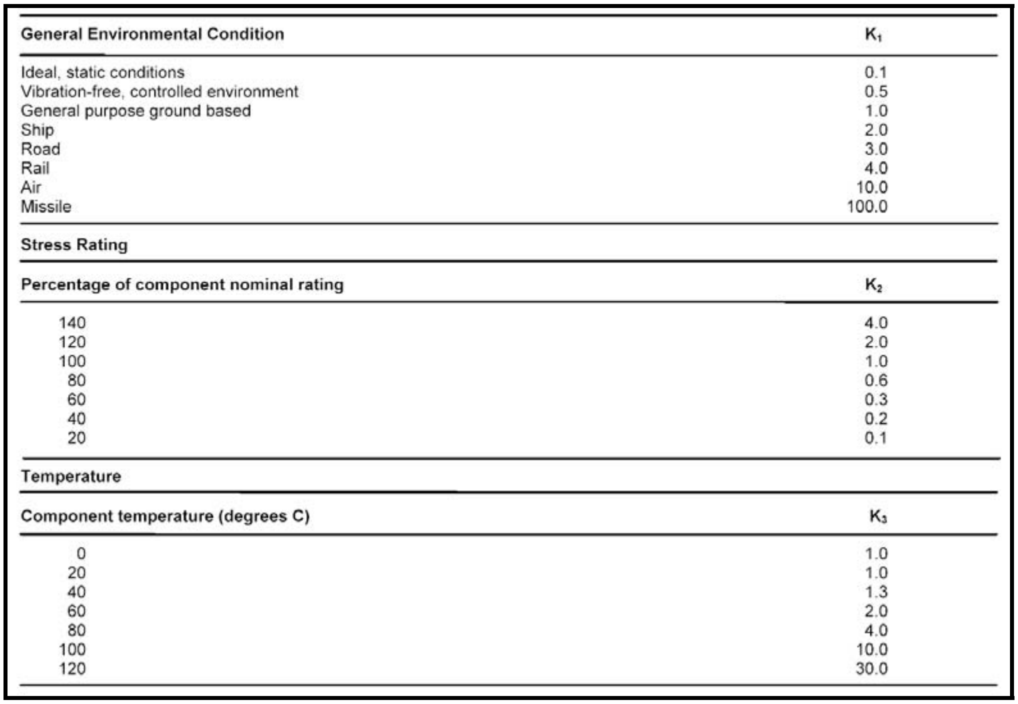
7.3.1 *Duty Cycle*

The duty cycle refers to the number of cycles the system is expected to perform each year. By knowing the number of cycles that the system performs per year the duty factor *d* can be calculated. To calculate the duty factor *d* of a component or system the following formula is generally used:

$$d = \left(\frac{no.\ cycles}{year}\right)(duration\ of\ cycle\ [\text{sec}])\left(\frac{1hr}{3600\,\text{sec}}\right)\left(\frac{1year}{8760hr}\right)$$

7.3.2 *Environmental Conditions*

The surrounding environmental conditions will have an effect a component's useful life span. To determine the extent that the surrounding environmental conditions will have on the component, the *environmental factor adjustment coefficient K* is introduced. There are three *K* factors; K_1, K_2, and K_3. K_1 corresponds to the general environment, K_2 to the specific rating or stress of the component, and K_3 to the general effect of temperature. The various values for the environmental factors *K* are given in the table below:



General Environmental Condition	K_1
Ideal, static conditions	0.1
Vibration-free, controlled environment	0.5
General purpose ground based	1.0
Ship	2.0
Road	3.0
Rail	4.0
Air	10.0
Missile	100.0

Stress Rating

Percentage of component nominal rating	K_2
140	4.0
120	2.0
100	1.0
80	0.6
60	0.3
40	0.2
20	0.1

Temperature

Component temperature (degrees C)	K_3
0	1.0
20	1.0
40	1.3
60	2.0
80	4.0
100	10.0
120	30.0

Figure 13: Overall Environmental Component Stress Levels (data from USACE 2001)

7.3.3 *Failure Mode (Weibull Index, β)*

The Weibull index β is introduced in order to account for the influence that the type of failure will have on a component's reliability. β values for their corresponding mode of failure are given in appendix C, these values were determined previously through years of data collection and are given in USACE 2001. The values of β can either be equal to or greater than 1.0 and no greater than 3.0. If the value of β is not known for a certain component, then a value of 1.0 is assigned.

7.3.4 *Failure Rate λ*

Failure rates are calculated from years of data collection on individual components. The values used in this report are the values presented in the USACE 2001 technical letter. The USACE obtained their failure rate values by comparing values from many different sources and then calculated a combined failure rate value.

From the combined failure rate λ value am adjusted failure rate value is calculated. This new adjusted λ accounts for the environmental factors *K* and is given as follows:

$$\lambda' = \lambda \cdot K_n$$

where

$$K_n = K_1 \cdot K_2 \cdot K_3$$

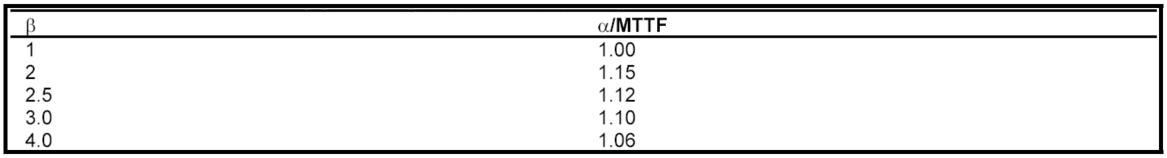
7.3.5 *Mean Time to Failure*

From the adjusted failure rate λ’ the Mean Time to Failure (MTTF) is determined as:

$$MTTF = {}^{1}\!/_{\lambda'}$$

7.3.6 *Characteristic Life Parameter α*

The final value needed in order to calculate the reliability of the component is the characteristic life parameter α. The value of α is determined by using a ratio of $\alpha/MTTF$ based on the Weibull index β. The value of the ratio $\alpha/MTTF$ with the corresponding β value are given in the table below:



β	α/MTTF
1	1.00
2	1.15
2.5	1.12
3.0	1.10
4.0	1.06

Figure 14: α/MTTF Ratio as a Function of β (USACE 2001)

7.3.7 *Component Reliability*

Finally the reliability of the component can be calculated, it is expressed as:

$$R(t) = \exp\left[-\left(\frac{td}{\alpha} \right)^{\beta} \right]$$

where *t* is the time in years

And the hazard rate, which is the instantaneous probability of failure at time *t*, is given as:

$$h(t) = \frac{\beta}{\alpha} \left(\frac{td}{\alpha} \right)^{\beta - 1}$$

8.0 Reliability's Role In Decision-making:

As reliability is becoming a more and more useful tool in the design of engineering systems it can also be used as an excellent decision-making tool. By analyzing the reliability of several potential solutions and comparing their long-term functionality with possible maintenance costs engineers have more to consider than before. In traditional engineering practice it was very common for an engineer to create a design that would only meet the design criteria and not consider the performance life of that design. Quite often designs from this approach would never see through their intended service life, as their system and component reliabilities were never examined for potential sources of failure. However, engineers of today are beginning to see the value behind reliability analyses and are starting to incorporate them more frequently into everyday practice. Manufacturers also see the importance of providing the reliability data of their systems and components as a selling point of their products.

8.1 Applying DecisionPro

By comparing the reliability of several potential design solutions engineers can narrow in on the most appropriate solution that meets both the initial design criteria and the performance criteria. However, sometimes analyzing the reliability of a system can become complicated as many components can be involved. For these types of systems a great software package, such as DecisionPro by Vanguard Software Corporation, provides a logical illustration of all the system's components and their dependence on one another.

By incorporating DecisionPro's decision trees into a reliability analysis it is quite possible to see which components and/set of components are problematic. A complex system as shown in the figure 15 can be simplified by using the tree structure available in DecisionPro.

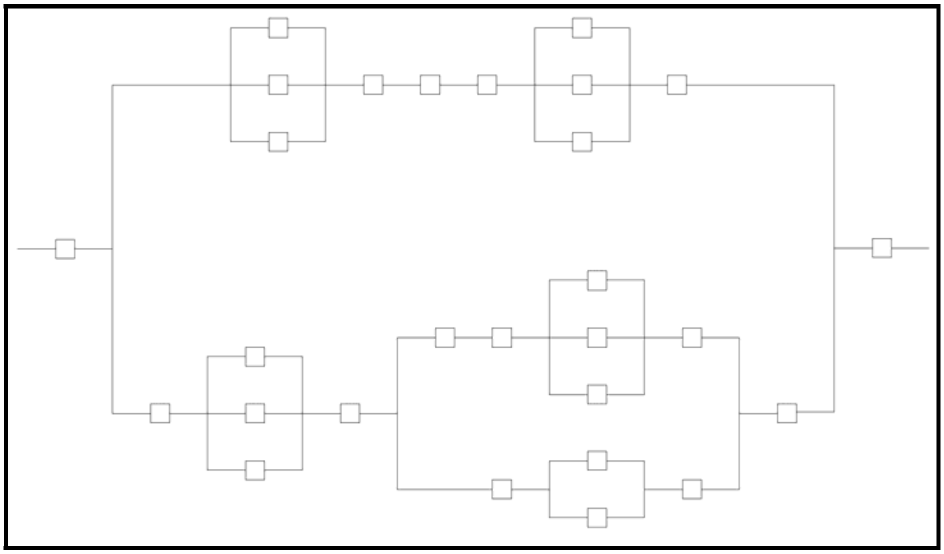


Figure 15: Example of a Complex System Layout

In this complex examples there are several components that act in series and parallel. In order to better analyze this system it is best to break the complex system into smaller subsystems that are either a series or a parallel system. Then by determining the reliability of all the smaller subsystems the reliability of the entire system can be found. A possible grouping may appear as shown in figure 16:

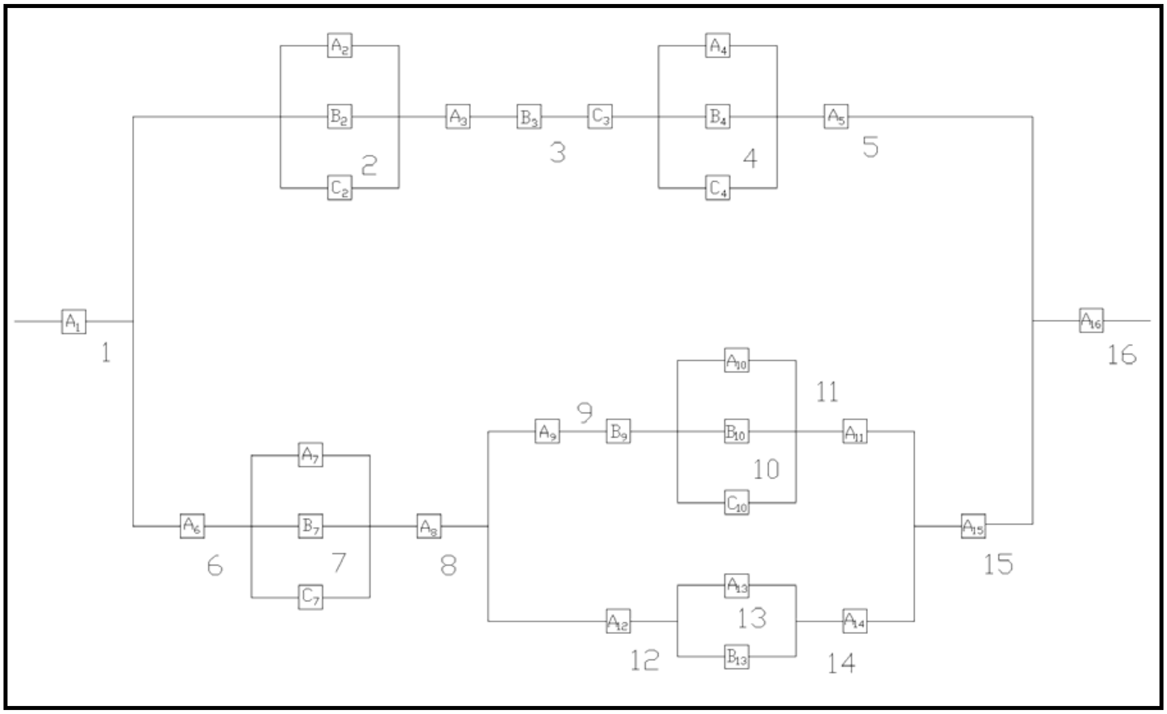


Figure 16: Grouping of Components

In the above figure components were grouped into single, series or parallel subsystems and designated a group identification number. By using the smaller, simpler subsystems the system reliability can be determined easily. The reliability of each subsystem is calculated according to the type of system it is, i.e. single, series, or parallel. For example:

For single components:

$$R_i = A_i$$

where

A_i = reliability of component A in component group i.

For a series system:

$$R_i = A_i \cdot B_i \cdot C_i \cdot \ldots \cdot N_i$$

where

N = A, B, C… (Number of components)

i = component group number

And similarly for a parallel system:

$$R_i = 1-(1-A_i)\cdot(1-B_i)\cdot(1-C_i)\cdot\ldots(1-N_i)$$

Once the reliability of the initial group of subsystems (R_1, R_2, R_3……R_{16}) was determined the next step is to again simplify the system a step further.

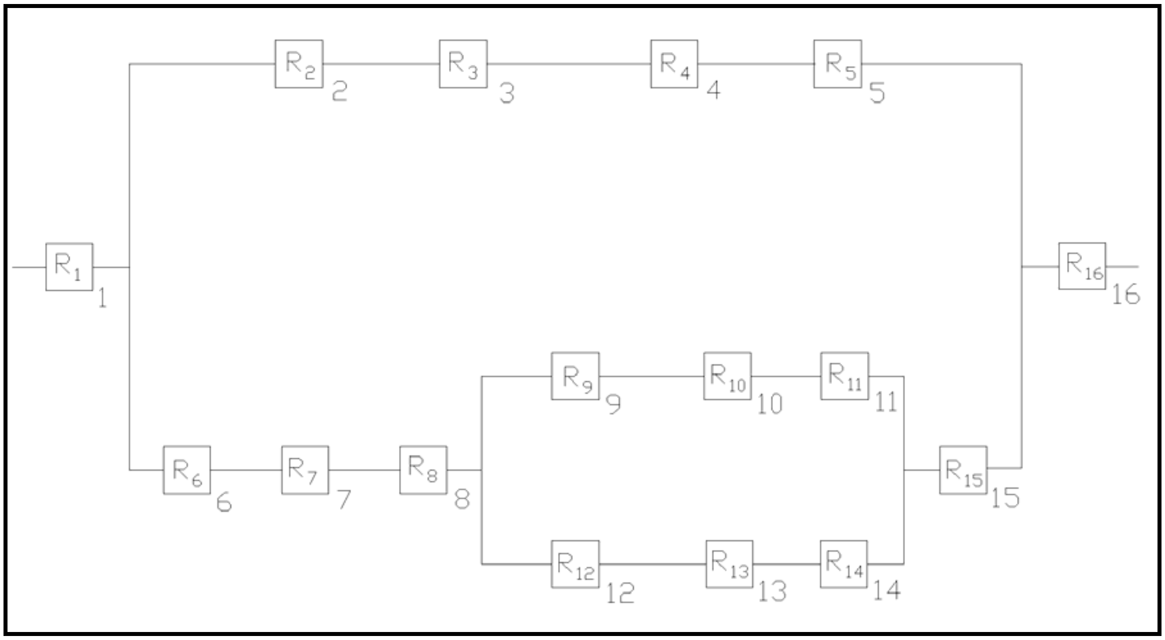


Figure 17: Simplifying the Complex System

Again the complex system, which has been simplified, can again be broken into subsystems and simplified. For an example the reliabilities of groups 9, 10, and 11 are combined into a series system with a corresponding reliability, R_{17}. The simplifying process is continued until finally the complex system represents a simple series or parallel system and cannot be simplified any further.

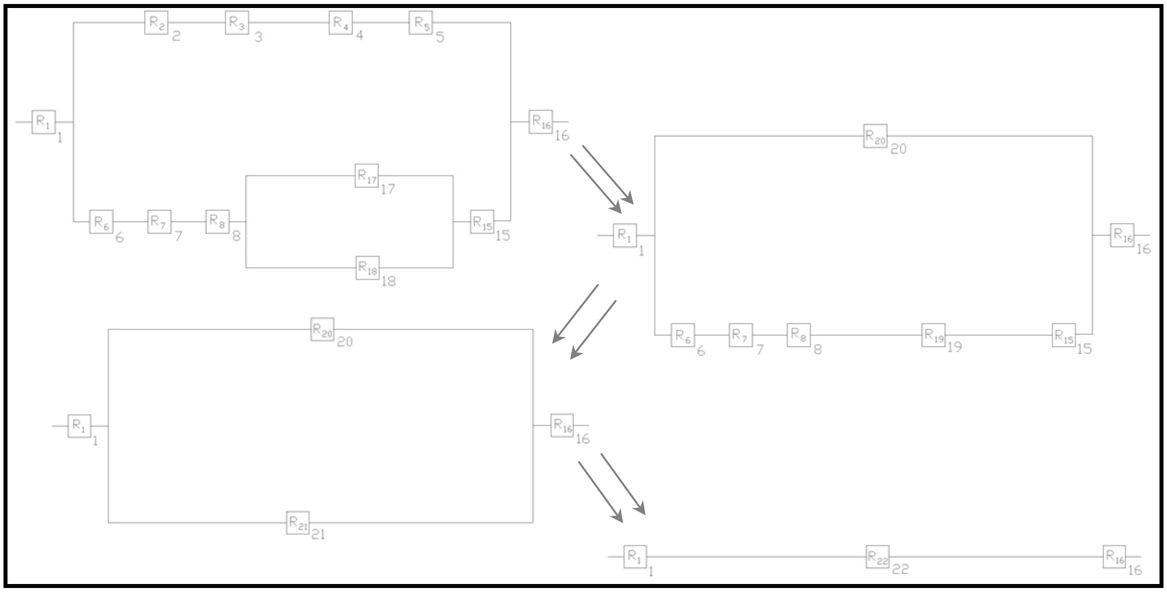


Figure 18: Further Simplifying the Complex System

The entire simplifying process can be shown in a tree diagram as in figure 19 (arbitrary component reliability values have been assigned). With the benefit of the tree diagrams constructed in Decision Pro one can examine the tree in detail and determine the degree of influence each component or subsystem (i.e. the branches of the tree) has on the system reliability. Additional subsystems may be added into the existing tree diagram and evaluated; furthermore, components or subsystems may me removed from the system tree diagram. In each case the system reliability can be determined almost instantly. Of course, it would depend on the actual design itself on which components and subsystems can or cannot be added or removed.

Each node in the tree diagram in figure 19 is labelled as either Reliability Group or Component Reliability. The reliability groups are located at the beginning of each new branch and defined either as a single, series, or parallel system. Depending upon the type of system that that reliability group represents determines which equation is used at that junction. The values used to determine the reliability at a particular node are the values in the nodes that immediately follow towards the right of the tree.

In figure 20 reliability group 19, R_{19}, is set to null to illustrate the level of influence that particular subsystem had on the overall system reliability. It can be seen that by removing that subsystem the reliability of the hypothetical system is reduced from a value of 0.45903 to 0.37951. This subsystem appears to have a large effect on the reliability of the system; therefore, failure of this subsystem could prove to be critical. With the ability to easily add and remove subsystems engineers can analyze many different possible scenarios of failure.

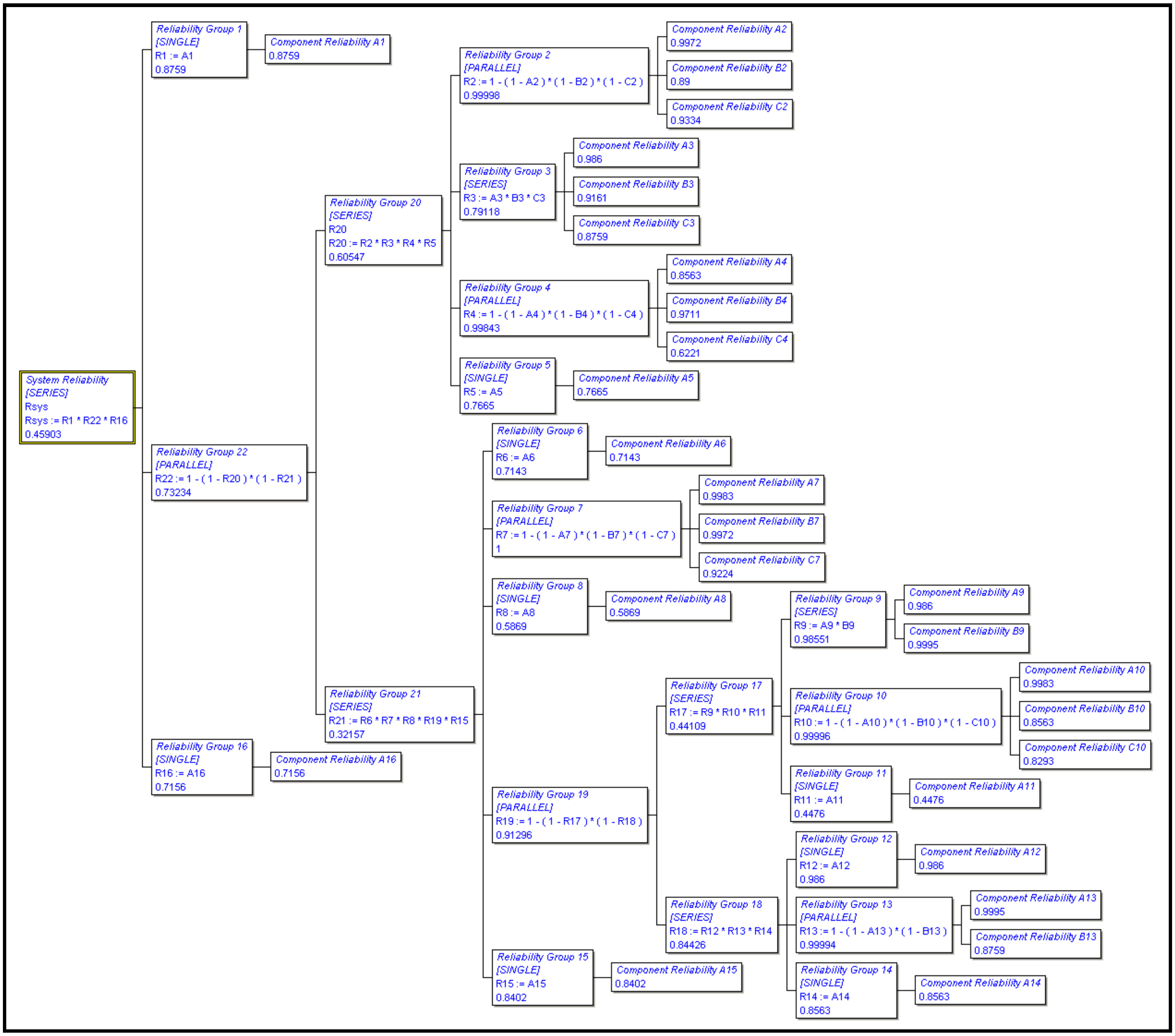


Figure 19: Reliability Tree of Complex System

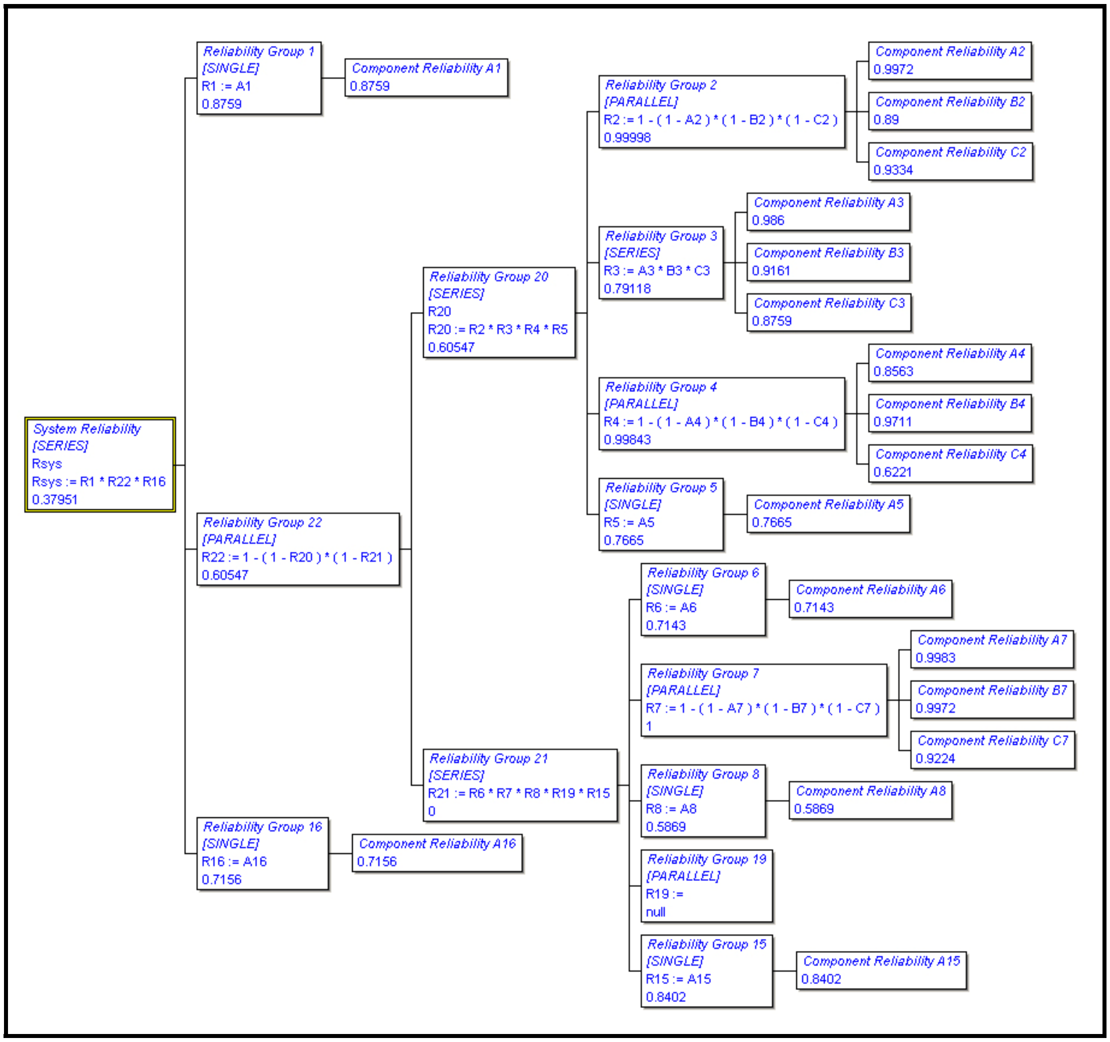


Figure 20: Reliability of Complex System with Reliability Group 19 Removed

Subsystems can be inspected and refined by isolating the subsystem using a built in function that comes equipped with DecisionPro as seen in figure 21.

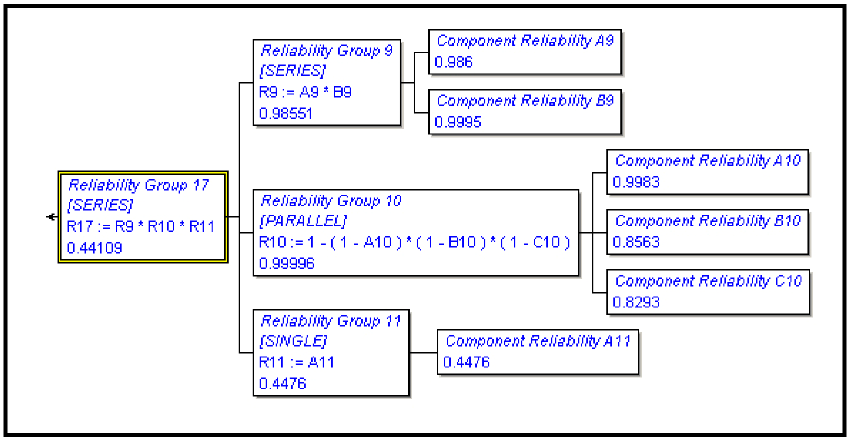


Figure 21: Isolation of Reliability Group 17

So far the advantages of DecisionPro have only been displayed with one particular complex model, but DecisionPro is capable of analyzing many different models at once. Therefore, engineers can modify and evaluate many different systems and determine which system with which components have the best optimal reliability that is required for a particular design.

9.0 Summary:

It is evident that the extra time and efforts put into performing a reliability analysis of any potential engineering solution has many advantages. A reliability analysis can give engineers a glimpse into a design's future and find and fix any potential flaws it may have that may have been overlooked during traditional design practice. Reliability engineering can also give project managers a better idea of the total production costs and long-term maintenance costs involved in potential designs, allowing them to provide a more accurate bid. In the future, with the aid of reliability analysis, designs may become even more efficient and cost effective.

Programs, such as DecisionPro, have great potential in the field of engineering, not just as decision-making tools, but also as effective tools for design. With their easy-to-use interfaces and ability for user configuration they provide a valuable asset. These programs are able to present complex problems in a better light allowing engineers to clearly identify any and all potential flaws and benefits of a design.

It is hoped that in the future reliability engineering will become more widely used as a tool for design and critical decision-making.

Appendix A: References

USACE 2001 - U.S. Army Corps of Engineers, *Reliability Analysis of Navigation Lock and Dam Mechanical and Electrical Equipment*, U.S. Army Corps of Engineers, June 30th, 2001, ETL 1110-2-560.

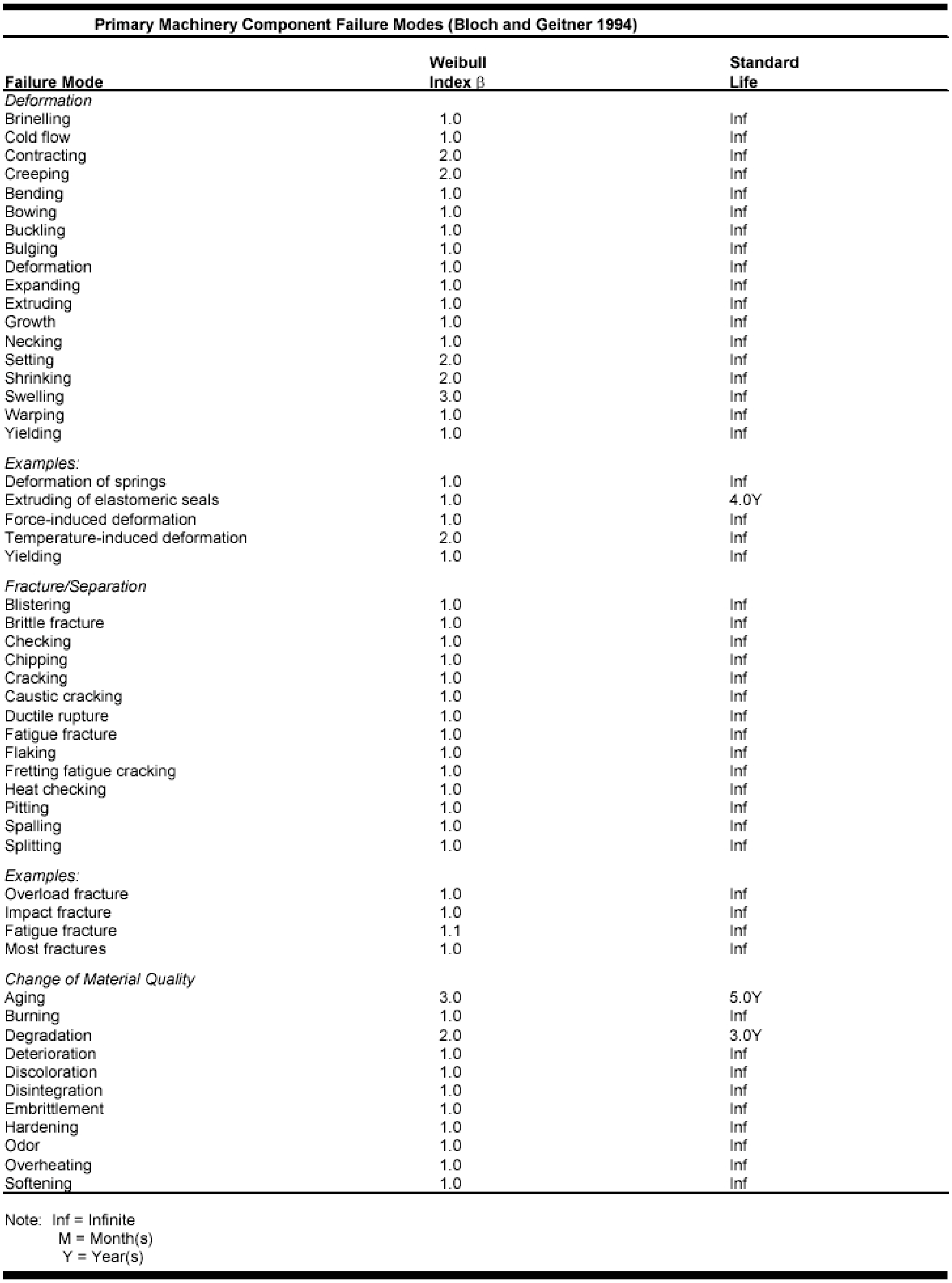
Appendix B: Software

DecisionPro, *Vanguard Software Corporation*, 2003.

Appendix C: Weilbull Index, β Values

Presented below are the β values for their corresponding mode of failure taken from USACE 2001:

Table C-1

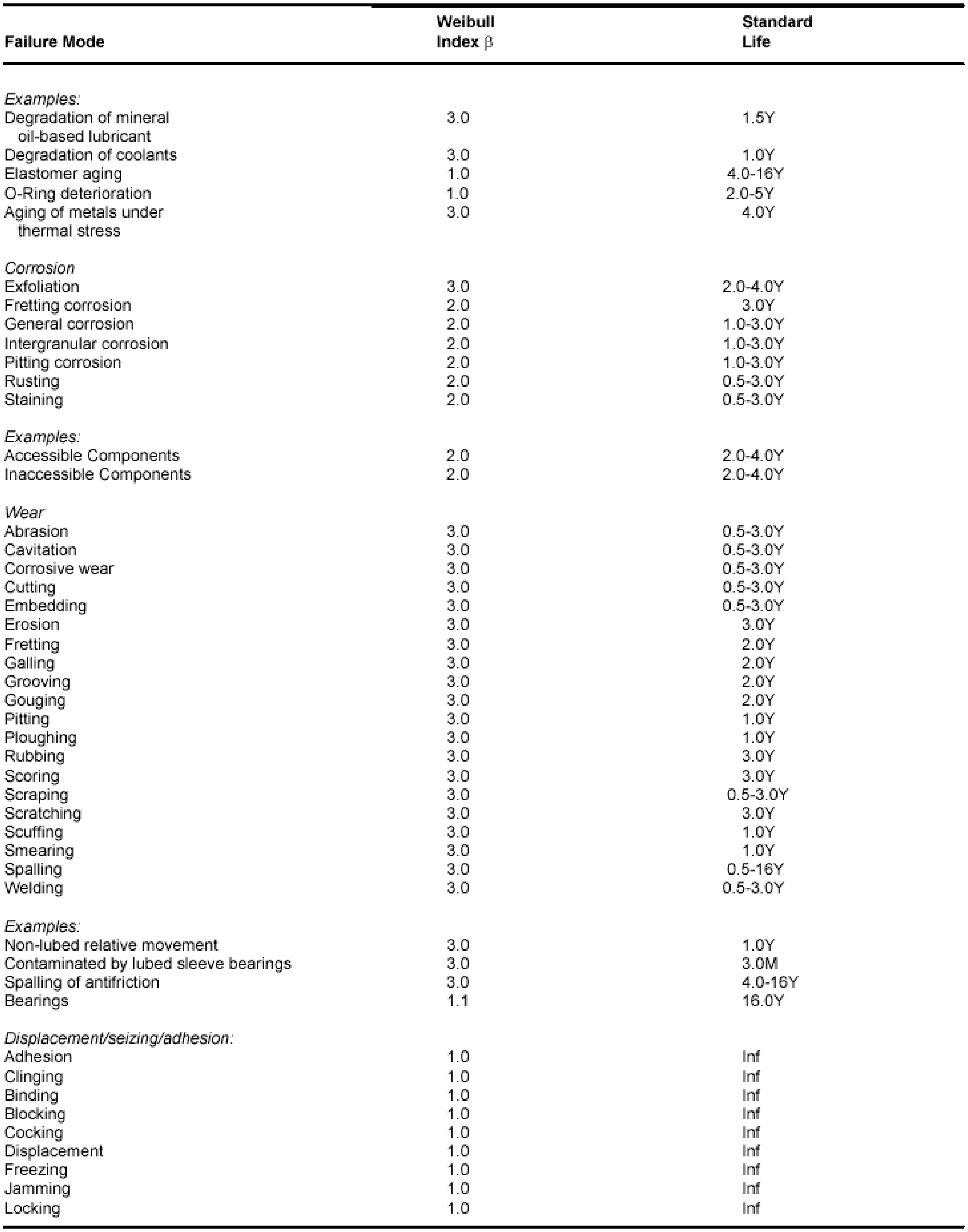


Primary Machinery Component Failure Modes (Bloch and Geitner 1994)

Failure Mode	Weibull Index β	Standard Life
Deformation		
Brinelling	1.0	Inf
Cold flow	1.0	Inf
Contracting	2.0	Inf
Creeping	2.0	Inf
Bending	1.0	Inf
Bowing	1.0	Inf
Buckling	1.0	Inf
Bulging	1.0	Inf
Deformation	1.0	Inf
Expanding	1.0	Inf
Extruding	1.0	Inf
Growth	1.0	Inf
Necking	1.0	Inf
Setting	2.0	Inf
Shrinking	2.0	Inf
Swelling	3.0	Inf
Warping	1.0	Inf
Yielding	1.0	Inf
Examples:		
Deformation of springs	1.0	Inf
Extruding of elastomeric seals	1.0	4.0Y
Force-induced deformation	1.0	Inf
Temperature-induced deformation	2.0	Inf
Yielding	1.0	Inf
Fracture/Separation		
Blistering	1.0	Inf
Brittle fracture	1.0	Inf
Checking	1.0	Inf
Chipping	1.0	Inf
Cracking	1.0	Inf
Caustic cracking	1.0	Inf
Ductile rupture	1.0	Inf
Fatigue fracture	1.0	Inf
Flaking	1.0	Inf
Fretting fatigue cracking	1.0	Inf
Heat checking	1.0	Inf
Pitting	1.0	Inf
Spalling	1.0	Inf
Splitting	1.0	Inf
Examples:		
Overload fracture	1.0	Inf
Impact fracture	1.0	Inf
Fatigue fracture	1.1	Inf
Most fractures	1.0	Inf
Change of Material Quality		
Aging	3.0	5.0Y
Burning	1.0	Inf
Degradation	2.0	3.0Y
Deterioration	1.0	Inf
Discoloration	1.0	Inf
Disintegration	1.0	Inf
Embrittlement	1.0	Inf
Hardening	1.0	Inf
Odor	1.0	Inf
Overheating	1.0	Inf
Softening	1.0	Inf

Note: Inf = Infinite
M = Month(s)
Y = Year(s)

Table C-1 cont'd



Failure Mode	Weibull Index β	Standard Life
Examples:		
Degradation of mineral oil-based lubricant	3.0	1.5Y
Degradation of coolants	3.0	1.0Y
Elastomer aging	1.0	4.0-16Y
O-Ring deterioration	1.0	2.0-5Y
Aging of metals under thermal stress	3.0	4.0Y
Corrosion		
Exfoliation	3.0	2.0-4.0Y
Fretting corrosion	2.0	3.0Y
General corrosion	2.0	1.0-3.0Y
Intergranular corrosion	2.0	1.0-3.0Y
Pitting corrosion	2.0	1.0-3.0Y
Rusting	2.0	0.5-3.0Y
Staining	2.0	0.5-3.0Y
Examples:		
Accessible Components	2.0	2.0-4.0Y
Inaccessible Components	2.0	2.0-4.0Y
Wear		
Abrasion	3.0	0.5-3.0Y
Cavitation	3.0	0.5-3.0Y
Corrosive wear	3.0	0.5-3.0Y
Cutting	3.0	0.5-3.0Y
Embedding	3.0	0.5-3.0Y
Erosion	3.0	3.0Y
Fretting	3.0	2.0Y
Galling	3.0	2.0Y
Grooving	3.0	2.0Y
Gouging	3.0	2.0Y
Pitting	3.0	1.0Y
Ploughing	3.0	1.0Y
Rubbing	3.0	3.0Y
Scoring	3.0	3.0Y
Scraping	3.0	0.5-3.0Y
Scratching	3.0	3.0Y
Scuffing	3.0	1.0Y
Smearing	3.0	1.0Y
Spalling	3.0	0.5-16Y
Welding	3.0	0.5-3.0Y
Examples:		
Non-lubed relative movement	3.0	1.0Y
Contaminated by lubed sleeve bearings	3.0	3.0M
Spalling of antifriction	3.0	4.0-16Y
Bearings	1.1	16.0Y
Displacement/seizing/adhesion:		
Adhesion	1.0	Inf
Clinging	1.0	Inf
Binding	1.0	Inf
Blocking	1.0	Inf
Cocking	1.0	Inf
Displacement	1.0	Inf
Freezing	1.0	Inf
Jamming	1.0	Inf
Locking	1.0	Inf

Table C-1 cont'd

Failure Mode	Weibull Index β	Standard Life
Displacement/seizing/adhesion:		
Loosening	1.0	Inf
Misalignment	1.0	Inf
Seizing	1.0	Inf
Setting	1.0	Inf
Sticking	1.0	Inf
Shifting	1.0	Inf
Turning	1.0	Inf
Examples:		
Loosening (locking fasteners)	1.0	Inf
Loosening (bolts)	1.0	Inf
Loosening	1.0	Inf
Misalignment (process pump set)	2.0	1.5-3.0Y
Seizing (linkages)	1.0	Inf
Seizing (components subject to contamination or corrosion)	1.0	Inf
Shifting (unstable design)	1.0	Inf
Leakage:		
Joints with relative movement	1.5	3.0M-4.0Y
Joints without relative movement	1.0	16.0Y
Mechanical seal faces	0.7-1.1	0.5-1.5Y
Contamination		
Clogging	1.0	Inf
Coking	2.0	0.5-3.0Y
Dirt accumulation	2.0	0.5M-3.0Y
Fouling	1.0	Inf
Plugging	1.0	Inf
Examples:		
Fouling gas compressor	3.0	1.5-5.0Y
Plugging of passages with moving medium	1.0	Inf
Plugging of passages with nonmoving medium	1.0	Inf
Conductor Interruption		
Flexible cable	1.0	Inf
Solid cable	1.0	Inf
Burning through Insulation		
Motor windings	1.0	16Y
Transformer windings	1.0	16Y