Chapter 1

Introduction

1.1. Back ground

In today's highly competitive environment, manufacturing systems are struggling to operate more effectively in a profitable manner such that the continued existence of their systems could be guaranteed (Wang and Hwang, 2004). As a result, world class organizations are developing new organizational and technological paradigms in order to meet these modern challenges. These responses have led to the evolution of new approaches in managing the organization, particularly the production system (Mjema and Mweta, 2003). Some of the tested approaches with far reaching results include just in time (JIT) inventory supply systems, ISO quality systems, Six Sigma, and Kaizen manufacturing systems, etc. All these performance enhancement tools are geared towards improving the profit margin of manufacturing.

Many of the manufacturing companies in operation today were conceived in a business environment that is totally different from that which exists now. The traditional approach of functional specialism and deep management hierarchies was adequate for high volume, limited variety markets. However, customers are becoming increasingly demanding in terms of the product and service they receive, with requirements for a wide variety of high reliability, highly complex products. Competition between manufacturers is becoming increasingly strong, particularly from world class competitors such as the Japanese. All of this, on top of the inevitable swings in the economic cycle, makes the business environment hostile. Recent research has shown that product reliability is positively correlated with customer confidence and profit margins.

Global customer surveys and the recent introduction of customer satisfaction surveys show that reliability is perceived as a significant customer satisfaction factor. International standards provide advantages to industry, governments and consumers who purchase or market equipment manufactured outside their national boundaries.

Reliability is one of the most important aspects of quality as viewed by the customer. Therefore, the need for highly reliable items is obvious and this need is often reflected in high reliability requirements or goals to be attained during development. The early prototypes for complex new technology systems will invariably have significant reliability and performance deficiencies.

Improving the reliability of a product is an important part of the larger picture of improving product quality. A momentous quality characteristic, reliability is concerned with the performance of the product's function over a stated period of time. Therefore, whereas quality is defined as conformance to requirements, reliability on the other hand is defined as a failure or fault free performance in all products provided to the customer. Compared with quality which embraces the whole organization, reliability has a more product specific definition and therefore should be the main impetus to continuously improving the performance of the product's functionality.

BS 4778 (1987) defines reliability as the ability of an item to perform a required function under stated conditions for a stated period of time. The item can refer to a manufactured product or its constituent units and components, manufacturing and assembly systems (e.g. transfer lines), mechanical and electrical process systems and general mechanical, electrical and electronic systems. An expansion of the above formal definition of reliability leads to qualitative and quantitative expressions:

• Qualitatively : absence of functional failure during use or service;

• Quantitatively : the probability that an item will give failure free performance of its intended functions for the specified duration of time under stated environmental conditions.

The advantages of reliability assurance development encompassing all the relevant business functions are both qualitative and quantitative. The main benefit is that company becomes more proactive rather than reactive to reliability related problems. Other benefits include:

- Measurement of the effects of design and process changes on the reliability of the product.
- Potential reliability problems can be objectively and readily identified.
- Development of reliability objectives, setting of goals and means of achieving them.
- Overall increase in customer satisfaction, particularly for suppliers of industrial products and plants.

An extensive review of the reliability literature suggests trends towards projecting the more mathematical modelling and predictive aspects of the subject. This is a general concern, since it drastically limits the awareness, application and diffusion of the more rational reliability tools in the manufacturing industry. Although proliferation on the more rational reliability techniques developed through sensible engineering and management values are furthered, it is indicative that many journals and conference proceedings sponsored by most of the important engineering associations and institutions devote a large proportion of the literature to mathematical modeling of reliability.

Two facets of reliability which O’Connor (1993) has identified and relevant literature clearly supports the case, namely on one plane, intense effort is given on the mathematical modeling and predictive aspects, reflected by the endless flow of reliability literature in this area. The overall objective is to yield numerous behavioral characteristics of reliability which have no industrial significance or meaning. It is very difficult to find evidence that shows practitioners within the manufacturing industry making use of this material. On the other plane of reliability literature, proliferation of rational reliability methods and techniques is prominent. The overall objective of the deployment of such tools is to achieve reliability to a favorable level during the design, development and manufacturing stage.

It is not the intention to further the implications of reliability literature with respect to over utilization of mathematical modelling and prediction. O’Connor (1993) who also discusses the implications of adopting a purely “systems” approach to product reliability achievement and improvement, gives an excellent and convincing account of this view.

Although it is evident that barriers to the acceptance of such techniques will always occur, consideration must be given to the inherent problem associated with many reliability techniques in the modern concurrent engineering era which past studies failed to address. It is indicative that many tools and techniques employ lengthy procedures for successful application to product reliability improvement.

There is also a general indication from the review of the literature that new reliability tools and techniques evolve and are promoted separately as the tool for solving problems. This is representative both from an industrial and academic research perspective. In the industrial context when heavily promoted, tools and techniques come and go and distraction spreads among the people involved in product design and development improvement. On the other hand, academic researchers and most conferences and journal articles seem to concentrate on the latest tools and techniques with little emphasis given on the more contemporary ones.

In this context, reliability, like quality, requires a sound management approach and both rely on improvement through a structured method which considers the dynamics of business interaction. However, reliability goes one step further by its dependence on engineering details as a primary requirement. Therefore, optimum quality cannot exist without optimum reliability, even though optimum reliability can exist without optimum quality (Josim, 1996).

1.2. Present scenario of Reliability and availability modeling

Reliability and Availability indices are important measures of performance of engineering systems. Their values depend on the system structure as well as the component availability and reliability. Both reliability and availability decreases with respect to time and also depend on many factors such as environment, applied load, maintenance policies etc. MTTF, MTBF, MTTR, MDT etc. are other indices used in reliability analysis. Point, interval and steady state availabilities are also extensively used in the literature as important availability measures. Various analytical, mathematical and statistical techniques are used for modeling and analysis of these indices. However, several limitations such as over simplification of the system, assumption of constant failure rates etc. are reported in the literature on these techniques. Most of these techniques become extremely difficult and incapable of providing solutions when applied to complicated modern systems. Therefore, these techniques have been applied to evaluate only the steady state values of the complex systems by assuming constant failure and repair rates. Many researchers have been searching for alternate methodologies for more practical and realistic reliability and availability analysis. This research work is focused on these limitations and to develop alternate approaches for modeling complex systems having any type of failure and repair rates such as constant, increasing, decreasing and user defined functions.

Traditional analytical techniques represent the system by a mathematical model and evaluate the reliability and availability indices from this model using direct mathematical solutions. The practicing engineers feel that this type of analysis is mostly of academic nature that does not give accurate results when applied to their systems. The disadvantage with the analytical approach is that the model used in the analysis is usually a simplification of the system. In addition, the output of the analytical methods is usually limited to expected values only. The complexity of the modern engineering systems besides the need for realistic considerations when modeling their availability/reliability renders analytical methods very difficult to be used. Analyses that involve repairable systems with multiple additional events and/or other maintainability information are very difficult (if not impossible) to solve analytically.

1.3. System modeling

The reliability indices such as Availability, Mean Time between Failure (MTBF), Failure frequency, etc. provide measures of system effectiveness (Misra, 1992; Modarres et al., 1999). Reliability indices evaluation can be done by direct analytical techniques or stochastic simulation approaches (Billinton and Allan, 1992; Marquez et al., 2005). Reliability Block Diagram (RBD), Fault Tree Analysis (FTA), and Markov models fall under analytical techniques. Traditional analytical techniques represent the system by a mathematical model and evaluate the reliability indices from this model using direct mathematical solutions. As pointed out by Landers et al. (1991) the trend toward concurrent engineering raises the need for reliability modeling tools that are simple to use and can be easily integrated in the production process.

In general the techniques such as binomial theorem to evaluate network reliability, network reduction technique, decomposition method, minimal cutest method, delta star techniques, Reliability block diagrams, Fault tree analysis, state space approach (Markov processes) are widely used for reliability/availability analysis. The failure or success logic of system can be obtained from developing Reliability Block Diagram (RBD) or Qualitative Fault Tree Analysis. RBD is a diagram which is used to show the functional relationships between components of a system. Once the RBD of a system is prepared, appropriate laws of probability can be applied to evaluate the system reliability as a function of component reliabilities. The interaction between failure of components and their impact on system success state is depicted with FTA. The FTA method is suitable when there is complex configuration. However, both the approaches can be adopted to give the list of minimal cut sets. There can be dependency between the cut sets and this must be properly accounted in the analysis. Time to failure and time to repair are generally assumed as exponential distribution from the operating experience. However, the actual distributions may be different. Although fault trees provide a reasonable qualitative evaluation, it can also be quantified if basic event probabilities are known.

Reliability block diagrams resemble schematic representations of systems where the connections symbolize the interdependency and functioning of systems. Buzacott (1970) examines the computation of reliability measures based on successive reduction of complex models and the determination of estimate intervals based on parallel and series sets referred to as cut and path sets. In his study, Buzacott (1970) like many other researchers uses the exponential distribution to model system failure and repair distributions to study the effect of redundancy. Henley and Gandhi (1975) develop a unified approach to obtain reliability parameters based on reliability block diagrams for process industries and provide a means to automate the task. McCluer and Whittle (1992) review three petroleum refineries with reliability block diagrams to identify potential effects of single failures. Although reliability block diagrams provide useful reliability information, they do not reveal availability or fault characterization information.

The Universal Generating Function (UGF) Method (UGFM) was introduced in Ushakov (1986) and it has proved to be very effective in evaluating the reliability of different types of multi-state networks (Levitin, 2001, 2005; Lisnianski and Levitin, 2003; Yeh. 2006a), and it does not require a great computational effort. The UGFM is straightforward, effective and universal (Levitin, 2005). It involves intuitively simple recursive procedures combined with simplification techniques. The best known UGFM for the one-to-all Multi-state Arc Network (MNN) reliability evaluation problem was proposed by Yeh (2006a), however, it is only effective for Acylic MNN problems. MNNs are more practical and reasonable than AMNNs. In real-life cases, many networks such as computer and telecommunications networks include cycles for redundancy and overload prevention. Thus, there is a need for a new UGFM to evaluate the reliability of one-to-all MNNs.

An alternative approach for reliability and availability analysis could be based on Markov models. These models can take into account wide range of dependencies; however, they are restrictive in terms of number of components, preventive maintenance and failure/repair time distributions. Furthermore it is not possible to take into account any trends or seasonal effects. Derman (1963) introduces the basic Markov maintenance model. Cafaro et al. (1986) explains the use of Markov models in evaluating the reliability and availability of a system with time dependent transition rates using analytical matrix based methods. Markov chain models provide accurate long run availability and failure characterization calculations, and can sometimes be solved analytically, but are hard to formulate and involve high computational effort particularly as the number of states grows large.

Among the above mentioned reliability analysis techniques the state space approach or Markov analysis is a very general approach. It can be used when the components are independent as well as for systems involving dependent failure and repair modes. There is no conceptual difficulty in incorporating multistate components and modeling common cause failures. Therefore, Markov analysis is studied in more details.

1.4. Markov analysis

Markov analysis or state space approach looks at a sequence of events, defined as transitions between states, and calculates the relative probability of encountering these events in both the short run and the long run. A Markov chain is useful for analyzing dependent random events that is, events whose likelihood depends on what happened last. Markov analysis proceeds by the enumeration of system states. The state probabilities are then calculated and the steady state reliability and availability measures can be calculated using the frequency balancing approach.

1.4.1. Literature survey and review on Markov analysis

Several authors have used the state space approach for various applications in reliability engineering and availability modeling. The state space approach has been extensively discussed in the paper (e.g. Johnson, 1986; Islamov, 1994). However, Traditional Markov analysis methods have several limitations when applied for reliability and availability modeling and analysis of systems. Many researchers have pinpointed the limitations of this approach as follows:

- The number of states of Markov diagrams is exceptionally high; the actual solution of relevant equations is practically impossible and is tied to many numerical problems (Zoran *et al*. 1989; Dimitris, 1995; Sandra V. Howell et al. 1990).
- Markov models require extensive numerical inputs that are often unknown during conceptual system designs (Gerard *et al*. 1994).
- Assumption of independent components with independent failure modes, assumption of each component can be characterized by two states (Andrea *et al*. 1980)
- Assumption of exponential distribution for modeling the failure process of many systems (Gohary, 2004; Aldo Cumani, 1982; Endrenyi, 1978, IEEE Std. 1997, M. H. J. Bollen, 1999; Jasper *et al*., 2000; Jose A, 2001; Long *et al*, 1991; Quintas, 1998).
- Difficulty in solving the Kolmogorov system of differential equations in Markov models used for reliability and availability analysis (Shooman, 1968, Billing ton et al, I983, Dhillon *et al*, 1981, Gnedenko et al, 1969; Johnson, 1986; Islamov, 1994).
- In addition, work has been published on semi Markov models in reliability analysis (Carravetta *et al.* 1981; Brahim *et al.* 1997) and on non Markov analysis with time varying failure and repair rates (Thomas *et al*. 1995; Tieling *et al*. 2001).

- However, these analysis methods consists rigorous mathematical treatment and are very difficult to handle when the number of system possible states increases in many cases.

These limitations have motivated the author to search for other methods which can eliminate or minimize the major limitations of the state space approach, viz., the mathematical complexity in the traditional solution procedure, restriction of exponential time assumption etc. It was felt that simulation could be effectively used in conjunction with the state space approach to eliminate some of these limitations. Simulation has been used as a powerful tool for system reliability and availability analysis. It is used to represent the dynamic behavior of systems in the most realistic sense. Simulation has also been used as an approximation tool to remedy the limitations of analytical Markov chains. Therefore further literature has been collected on simulation methodologies in general and its applications in reliability engineering in particular. These are presented in the following sections.

1.5. Simulation in reliability and availability analysis

1.5.1. Background

Simulation is the imitation of the operation of a real world process or system over time. Whether done by hand or on a computer, simulation involves the generation of an artificial history of a system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system. In the simplest form of the basic simulation, each random variable in a problem is sampled several times to represent its real distribution according to its probabilistic characteristics. Considering each realization of all the random variables in the problem produces a set of numbers that indicates one realization of the problem itself. Solving the problem deterministically for each realization is known as a simulation cycle, trial, or run. Using many simulation cycles gives the overall probabilistic characteristics of the problem, particularly when the number of cycles tends to infinity. The simulation technique using a computer is an inexpensive way (compared to laboratory testing) to study the uncertainty in the problem.

The behavior of a system as it evolves over time is studied by developing a simulation model. This model usually takes the form of a set of assumptions concerning the operation of the system. These assumptions are expressed in mathematical, logical, and symbolic relationships between the entities, or objects of interest, of the system. Once developed and validated, a model can be used to investigate a wide variety of “what if” questions about the real world system. Potential changes to the system can first be simulated in order to predict their impact on system performance.

Simulation can also be used to study systems in the design stage, before such systems are built. Thus simulation modeling can be used both as an analysis tool for predicting the effect of changes to existing systems, and as a design tool to predict the performance of new systems under varying sets of circumstances. With a simple simulation technique, it is possible to calculate the probability of failure for both the explicit or implicit limit state functions without knowing the analytical techniques and with only a little background in probability and statistics. The availability of personnel computers and software makes the process very simple.

Simulation can be used for the following purposes:

- Simulation can be used as a pedagogical device to reinforce analytic solution methodologies.
- Simulation enables the study of, and experimentation with, the internal interactions of a complex system, or of a subsystem within a complex system.
- The knowledge gained in designing a simulation model may be of great value towards suggesting improvement in the system under investigation.
- By changing simulation inputs and observing the resulting outputs, valuable insight may be obtained into which variables are most important and how variables interact.
- Simulation can be used to experiment with new designs or policies prior to implementation, so as to prepare for what may happen.
- Informational, organizational, and environmental changes can be simulated, and the effect of these alterations on the model’s behavior can be observed.
- By simulating different capabilities for a machine, requirements can be determined.
- Simulation models designed for training allow learning without the cost and disruption of on the job learning.

- Animation shows a system in simulated operation so that the plan can be visualized.
- The modern system (factory, wafer fabrication plant, service organization, etc.) is so complex that the interactions can be treated only through simulation.
- Simulation can be used to verify analytic solutions.

Advantages of Simulation:

Simulation has many advantages. These are listed by Pegden *et al*., 1995. The advantages are as follows.

- Insight can be obtained about the importance of variables to the performance of the system.
- A Simulation study can help in understanding how the system operates rather than how individuals think the system operates.
- New policies, operating procedures, decision rules, information flows, organizational procedures, and so on can be explored without disrupting ongoing operations of the real system.
- Hypotheses about how or why certain phenomena occur can be tested for feasibility.
- "What if" questions can be answered. This is particularly useful in the design of new systems.
- Bottleneck analysis can be performed indicating where work in process, information, materials, and so on is being excessively delayed.
- New hardware designs, physical layouts, transportation systems, and so on, can be tested without committing resources for their acquisition.
- Time can be compressed or expanded allowing for a speedup or slowdown of the phenomena under investigation.
- Insight can be obtained about the interaction of variables.

Limitations:

However, there are several limitations to using simulation models. They typically take much longer to run than analytic models and the results from a simulation model can be difficult to interpret. For these reasons, simulation can be an expensive option. And the expertise is required for developing credible models. However the effect of many of these limitations can be minimized by using powerful modern computational facilities and software.

1.6. General scenario of simulation in reliability and availability studies

Several works have been published on representing the use of simulation in reliability and availability studies as described below.

Several authors have used the simulation approach for analysis and evaluation of reliability and availability parameters of systems. They have focused on utilizing the simulation approach in various purposes such as understanding the system processes, model formulation activities, estimating the importance measures of the components of systems, estimating the system availability, in systems safety analysis, reengineering activities, early reliability prediction at the conceptual stage of systems, large scale as well as small to medium scale enterprises. Simulation programs, especially if well structured, are in general very comprehensive and known for the ease with which modifications and additions can be made. Perhaps their main benefit arises from the fact that it is possible to analyze output information about subsystems to gain more understanding of the whole system processes (Windebank, 1983). Simulation methodology which is used to construct the model includes model formulation, model translation, verification and validation, experimentation and reporting of results.

A survey by Baldwin *et al*. (2000) looked at the perceptions of simulation usage from both academic and industry specialists and their findings indicated that simulation tools make modeling easier and faster. Luca podofillini *et al* (2003), presented a simulation approach which allows estimating all of the importance measures of the components at a given performance level in a single simulation, provided that the components are independent. He has also a generalized concept of importance measures for multi state systems (MSS) considered. The generalized measures allow the quantification of the relevance of the fact that a component achieves a given level of performance with respect to a measure of system performance such as the mean system unavailability. The computation of the importance measures associated with the components of a system provides useful information to system analysts and design engineers.

The large scale systems have been analyzed by either approximate empirical methods or by mathematical reliability/availability analysis, which requires severely limiting assumptions about component failure and repair time distributions and about component linkages. The simulation modeling approach is very accurate for determining time between failure and time to repair distributions without any limiting assumptions. Discrete simulation modeling is shown to be of value in determining the time between failure and time to repair distributions at various points in series/parallel and non series/parallel, cross linked systems. Most real world systems, such as power, telephone, gas, water, and electro/mechanical systems, are extremely large and have cross linked components that are not "well behaved" statistically, which make them impossible to analyze accurately and efficiently using mathematical reliability/availability analysis (Chisman, 1998).

During the early stages of conceptual design, the ability to predict reliability is very limited. Without a prototype to test in a lab environment or field data, component failure rates and system reliability performance are usually unknown. A popular method for early reliability prediction is to develop a computer model for the system. However, most of these models are extremely specific to an individual system or industry. Stephen W *et al*, (2001) proposed a generic simulation model for predicting system reliability without knowing the exact failure rate for the components in the system at the conceptual design of the systems.

Kolarik *et al*. (1988) presented a simulation model, as well as the technique for its development which demonstrates a method for studying possible reliability characteristics of a system in the early design stages. It was compatible with methods of sensitivity analysis and provides life cycle reliability outputs in a distributional form. Lambros *et al*. (2005) presented a simulation method for reliability analysis of linear dynamical systems based on simple additive rules of probability.

Landers *et al*. (1991) reported a simulation model for use in the engineering design process. This simulation model facilitates reliability modeling by design engineers and reliability analysts early in the design process. The model applied to preliminary feasibility and design tradeoff studies. This model focused on applications to mission reliability analysis.

Rotab Khan (1995) performed availability simulation which is a useful tool not only on evaluating plant performances but also in indicating possible ways of improving plant performance. Plant availability has estimated using the plant configuration and actual failure and repair time distributions. Thomas *et al*. (1984) described modeling techniques for simulating the production availability of continuous process plants based on the configuration, throughput capabilities and downtime distributions of its component process units and the capacities of any intermediate buffer storage between process units. Labeau (1996) presented a biased simulation which gives the marginals and compares different ways of speeding up the integration of the equations of the dynamics and quoted that simulation seems to be the only practical way of dealing with the size of realistic problems of probabilistic dynamics.

O' Kane (2004) shown that simulation technology can be used to help support re-engineering activities and the modeling studies allowed the case study companies to analyze system performance and to potentially achieve maximum productivity in a cost effective manner. The use of simulation methodology in the small to medium sized enterprise (SME) sector is somewhat overlooked and most simulation studies tend to focus on larger organizations. There is a strong argument to make more use of simulation in organizations and to maximize the benefits that can be accrued through it use. This is even more important within the small business sector as simulation has not been widely applied to SME's to enable these types of organizations to reap the benefits from adopting and embracing this technique (Greasley, 2004).

The simulation approach overcomes the disadvantages of the analytical method by incorporating and simulating any system characteristic that can be recognized. It can provide a wide range of output parameters including all moments and complete probability density functions. It can handle very complex scenarios like non-constant transition rate, multi state systems and time dependent reliability problems. However, the solution time is usually large and there is uncertainty from one simulation to another. But as indicated by Yanez *et al*. (1997) the demerits of simulation can be easily overcome with few modifications in the simulation. It is to be noted that the experimentation required is different for different types of problems and it is not possible to precisely define a general procedure that is applicable in all circumstances. However, the simulation technique provides considerable flexibility in solving any type of complex problems.

1.6.1. Types of Simulation methods for system reliability and availability analysis

Following simulation methodologies are used for system reliability and availability analysis.

Monte Carlo simulation

Discrete event (DE) simulation

Subset simulation

Hybrid subset simulation

Simulated annealing

Stochastic simulation approach

Digital simulation methods

These are briefly discussed in this section.

1.6.1.1. Monte Carlo simulation in Reliability and availability studies

Monte Carlo simulation approach is obvious choice for complex environments as this method allows considering various relevant aspects of system operations which can not be easily captured by analytical methods. The method commonly used to solve the given problem deterministically and to obtain its overall probabilistic characteristics and also to study the uncertainty in it is called the Monte Carlo simulation technique. The name itself has no significance, except that it was used first by Von Neumann during World War II as a code word for nuclear weapons work at the Los Alamos National Laboratory in New Mexico. Most commonly the name Monte Carlo is associated with a place where gamblers take risks. This technique has evolved as a very powerful tool for engineers with only a basic working knowledge of probability and statistics for evaluating the risk or reliability of complicated engineering systems.

The Monte Carlo simulation technique has six essential elements; defining the problem in terms of all the random variables; quantifying the probabilistic characteristics of all the random variables in terms of their PDFs of PMFs and the corresponding parameters; generating the values of these random variables; evaluating the problem deterministically for each set of realizations; extracting probabilistic information from such realizations; and determining the accuracy and efficiency of the simulation. This technique is used for uncorrelated as well as for correlated random variables.

In the reliability community the two main categories of evaluation techniques are analytical and simulation. Monte Carlo simulation techniques have been used to evaluate the reliability of real engineering systems (Rocco, 2003). In the Monte Carlo simulation approach, system reliability evaluation is performed by randomly determining the rate of each component and by the application of an appropriate evaluation function, assessing if the system succeeded or failed. A single simulation run generates either a system success or failure, and multiple simulation runs (replications) can be used to determine a reliability estimator (Pereira *et al*. 1991). Monte Carlo simulation is recognized as a proper evaluation technique if complex operating conditions are considered or the number of events is relatively large (Billinton *et al*. 1994). Monte Carlo simulation method has its ability in handling sequential operations reliability problems and wide applications to human error analysis (Paolo *et al*. 1991). The Monte Carlo simulation method can be applied to predict or study the performance and response of a large system and to analyze complex probability problems, that is, its major usefulness and advantage over analytical methods would be most apparent in problems where analytical models are mathematically intractable (Zhao, 1990). The Monte Carlo approach is a natural one to the problem of parameter estimation in the presence of uncertain data, and may be the only practical formal approach when considering many parameters at once. Applications to realistic common cause failures data indicate that this approach is accurate and quick when advantage can be taken of intermediate analytical results (i.e., when employing conjugate prior distributions and likelihood functions), even when analyzing highly redundant systems(N.Siu, 1990). Monte Carlo simulation a technique that repeatedly generates random values for uncertain variables to simulate a model accounts for the effects on risk factors such as vehicle position and consumption of propellants, weather uncertainties, vehicle guidance, and vehicle performance deviations. Monte Carlo simulation is also used to determine the launch decisions (Luis *et al*. 2006).

Lewis *et al*. (1984) formulated the evaluation of fault trees for the unreliability of repairable systems as a Markov process suitable for effective simulation by Monte Carlo methods. A variety of variance reduction techniques beyond those discussed may lead to further improvements in computational efficiency; these may include Russian Roulette and splitting, correlated sampling, and number of importance sampling techniques.

Lewis *et al*. (1986) demonstrated inhomogeneous Markov Monte Carlo simulation to treat wear, preventive maintenances and combinations of revealed and unrevealed failures for multi component systems. They allow wear and preventive maintenance to be modeled within the simulation of large systems. Moreover, a limited class of repair models can also be included for both revealed and unrevealed failures. This method can be easily extended to account for fixed component downtimes for testing and repair of unrevealed failures as well as for imperfect repair.

Heung *et al*. (1985) stated that the Monte Carlo simulation method has been widely used for the analysis of uncertainty propagation in fault tree analysis and developed the Monte Carlo method without sorting by using the segmentation between the sufficient upper bound and the sufficient lower bound of the evaluated top event frequencies into meshes and interpolation within the mesh.

Celeux *et al*., (1999) proposed a Bayesian methodology which makes use of Markov chain Monte Carlo algorithms which allows the analyst to discard limitations on the parametric flaw distribution function, on the flaw probability of detection function, and on the flaw sizing error distribution functions. Monte Carlo simulation techniques having intrinsic potentialities which allow taking into account many relevant aspects involved in a probabilistic safety assessment (PSA) analysis (Marseguerra et al., 1996). The Monte Carlo simulation technique in which experiments are conducted on a digital computer is a very powerful technique for power system reliability evaluation. Monte Carlo simulation methods estimate the reliability indices by simulating the actual process and random behavior of the system. The method therefore treats the problem as a series of real experiments. Monte Carlo simulation may be preferable if non exponential time distributions have to be modeled, the basic characteristics of peaking units have to be considered or the distributions associated with the output indices are required. Simulation methods based on the Monte Carlo technique permit the system reliability to be quantitatively evaluated, even in the most complex cases (Ghajar *et al*., 1988).

Zio (2004), utilized the Monte Carlo simulation method for modeling the multi state system reliability and for the estimation of the importance measures of multi state elements which entails evaluating the system output performance under restrictions on the performance levels of its multi state elements.

1.6.1.2. Discrete event (DE) simulation in Reliability and availability studies

A good discrete event simulation model can replicate the performance of an existing system very closely and provide decision maker insights into how that system might perform if modified, or how a completely new system might perform. To achieve this fidelity to the performance of a real world process, a DES model requires accurate data on how the system operated in the past or accurate estimates on the operating characteristics of a proposed system. DES models can represent a system in a computer animation that can provide a decision maker an excellent overview of how a process operates, where backlogs and queues form, and how proposed improvements to the system might alter the system's performance.

DES also gives the decision maker the capability to model and compare the performance of a system over a range of alternatives. DES has capabilities that make it more appropriate to the detailed analysis of a specific, well defined system or linear process, such as a production line or call center. These systems change at specific points in time: resources fail, operators take breaks, shifts change, and so forth. DES can provide statistically valid estimates of performance measures associated with these systems, such as number of entities waiting in a particular queue or the longest waiting time a particular customer might experience.

DES modelers often invest a great deal of effort analyzing historical data to capture process means, variances, and distributions, but once entered into the model these parameters often remain fixed. There is less emphasis in DES models on identifying events that might trigger changes in the model's parameters. Simulation modeling in the form of discrete event (DE) simulation has been used for many years to analyze different types of organizations and the benefits of adopting simulation are well known.

In one of the leading textbooks on discrete event simulation (DES), Law and Kelton (2000) defined a system as a collection of entities that interact together towards the accomplishment of some logical end. DES concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. DES is used to gain an understanding of how an existing system behaves, and how it might behave if changes are made in the system.

Warrington et al (2003) described that system reliability can be achieved by a combination of component reliability, system architecture and maintenance. DES is an important tool to assess the combined influence of these factors. DES of safety and reliability does not need to model component reliability, system architecture and maintenance using a single methodology. Rather, DES may adopt the most appropriate methodology for each. And the authors proposed a method that integrates DES with path sets to allow dynamic system modeling

Thara Angskun *et al* (2007) analyzed the reliability of a self healing network for parallel runtime environments using discrete event simulation. This network is designed to support transmission of messages across multiple nodes and at the same time, to protect against node and process failures. Results demonstrated the flexibility of a discrete event simulation approach for studying the network behavior under failure conditions and various protocol parameters, message types, and routing algorithms. The authors studied the influence of various factors on the network behavior in failure circumstances. Kim J *et al* (1995) presented an enhanced reliability modeling and evaluation methodology using discrete event simulation techniques. This simulation methodology has the capability of estimating reliability, mean time to failure, and probability density function of time to failure for a complex network system.

Leemis L M, *et al* (2005) noted that discrete event simulation (DES) can be treated as a method to model the behavior of a system in response to designated events as time progresses. It offers an alternative to traditional analytical models as it can capture details of the system and illustrate the influence of various factors. Bargueño *et al* (2008) proposed the use of discrete event simulation (DES) as an efficient methodology to obtain estimates of both survival and availability functions in time dependent real systems such as telecommunication networks or distributed computer systems and discussed the use of DES in reliability and availability studies.

Petri nets based discrete event simulation

Petri nets (PN), developed by Carl Petri and is a useful tool for analyzing and modeling the complex systems with concurrent discrete events (Brams, 1985). First, PN research was mainly focused on performance analysis of discrete systems, such as communication protocols, computer architecture, hardware and software systems, for example to model microprocessor architecture (Ajmone Marsan*et al.*, 1994). Various PN applications in several industrial engineering fields are described in scientific literature, such as Flexible Manufacturing System (FMS) modeling (Yan *et al.*, 1998) and just in time systems modeling (Song and Lee, 1998).

It is only in the last few years that PN have been introduced in the field of maintenance and reliability analysis. Schneeweiss (1999) describes several Petri nets application for this maintenance and reliability modeling. Most of this recent research work still concentrated on the reliability analysis of fault tolerant computer systems and communication networks (Malhotra and Trivedi, 1995).

Rouvroye et al. ((1999); (2002)), described that the multitude of existing variations of Petri net formalism might have excellent modeling capabilities, but lack a unified standard; as a result, what is referred to as SPNs can vary drastically from one application or paper to another and indicated that such ambiguity can be quite confusing for reliability practitioners, and by and large SPNs are perceived as a technique that is perhaps powerful but cumbersome and somewhat arcane. It is quite characteristic that SPNs are often absent from the list of compared techniques for system dependability (a measure of system performance that includes reliability, availability, and safety). Similarly, SPNs are only briefly mentioned (if at all) in books on the subject.

Vitali Volovoi (2004), described that in the previously existing stochastic Petri net formulations, memory was associated solely with transitions, which resulted in certain difficulties in modeling the changes in the system configuration while preserving the memory and introduced the concept of aging tokens and demonstrated that these aging tokens significantly improve the dependability modeling flexibility and clarity of stochastic Petri nets.

Salvatore et al. (2009), explained that although the Petri Nets can theoretically model the behavior of the systems, the main drawback of the approach is the ‘‘distance from modelers'' or ''user friendly ness'': the syntax elements (places, transitions, arcs and tokens) are not directly representing or do not have any logic correspondence with the part of the system being modeled.

Currently, the major drawback of Petri Nets is the lack of readily available software packages. While Markov Chain analysis appears in most of the major reliability software tools such as those from Relex Software, Petri Net software applications are obscure and difficult to integrate with existing software tools. The underlying structure of all Petri Net software is a code-based architecture. Different programmers use different languages for each software package and the learning curve associated with each package can be steep.

1.6.1.3. Subset simulation in Reliability and availability studies

Subset simulation (Au *et al.*, 2001) has been recently developed as an efficient simulation method for computing small failure probabilities for general reliability problems with no special regard to any characteristics of the system. Its efficiency stems from the observation that a small failure probability can be expressed as a product of larger conditional failure probabilities that can be estimated with much less computational effort. By estimating the larger conditional failure probabilities to obtain an estimate for the failure probability, the problem of simulating rare events in the original probability space is replaced by a sequence of simulations of more frequent events in the conditional probability spaces. However, generating samples in the conditional spaces is not a simple task.

Subset simulation makes use of Markov Chain Monte Carlo (MCMC) simulation to generate conditional samples from a specially designed Markov chain with limiting stationary distribution equal to the target conditional distribution. An essential aspect of the implementation of subset simulation is the choice of proposal distribution, which governs the generation of the next sample from the current one in the MCMC algorithm and which influences the efficiency of the algorithm. The choice should depend on the nature of the uncertain parameters as well as the sensitivity of the failure probability to each of these parameters (Au *et al.*, 2003), requiring the proposal distribution to be tailored to each particular class of reliability problems.

A new subset simulation approach proposed by Ching *et al*. (2005) for reliability estimation for dynamical systems subject to stochastic excitation and it is applicable to general causal dynamical systems and it is robust with respect to the dimension of the uncertain input variables.

1.6.1.4. Hybrid subset simulation in Reliability and availability studies

Au *et al.* (2005) proposed a hybrid subset simulation method for dynamic reliability problems that combines subset simulation with Markov Chain Monte Carlo algorithm and subset simulation with splitting and also this hybrid subset simulation approach performs satisfactorily compared with the subset simulation methods. Moreover, the new approach is more robust in the sense that it is less sensitive to the choices of proposed probability density function for the Markov Chain Monte Carlo algorithm and to the selection of the intermediate threshold levels.

1.6.1.5. Simulated annealing in Reliability and availability studies

Simulated annealing (SA) introduced by Kirkpatrick *et al*. (1983) and Cerny (1985) as an alternative of the local search, is a general probabilistic method for solving combinatorial optimization problems. SA is an approach to search the global optimal solution that attempts to avoid entrapment in poor local optima by allowing an occasional uphill move to inferior solutions. Simulated annealing is a technique, which was developed to help solve large combinatorial optimization problems. It is based on probabilistic methods that avoid being stuck at local minima. It has proven to be a simple but powerful method for large scale combinatorial optimization.

Angus and Ames (1997) proposed a simulated annealing algorithm to find the minimum cost redundancy allocation subject to meeting a minimal reliability requirement for a coherent system of components. It is assumed that components are independent of one another, and that the form of the nominal system reliability function is available for input to the algorithm. In one of the leading texts on reliability, Kuo *et al.* (2001) were concerned with great potentials for simulated annealing application in the reliability design problem.

Lash Kari (2006) developed a simulated annealing based algorithm to solve the multi objective, multiple process plan model and this algorithm solves the multi objective cellular manufacturing systems design model and generates near optimal solutions for medium to large sized problems. Kim *et al*. (2006) proposed a simulated annealing algorithm to search the optimal solution of reliability redundancy allocation problems with nonlinear resource constraints and several test problems are investigated to show its effectiveness. The application of the simulated annealing is expanded to the reliability redundancy allocation problems, which can help reliability engineers design the system reliability.

1.6.1.6. Stochastic simulation in Reliability and availability studies

Stochastic simulation, also known as kinetic Monte Carlo, is a numerical procedure for determining the dynamics of a continuous time Markov process. A continuous time Markov process is a memory less stochastic process that is used to describe all sorts of systems. The solution of a Markov process includes two equivalent parts: a time dependent probability distribution of states in state space or trajectories of the state moving in state space over time. By computing an ensemble of trajectories, one can generate the distribution. Or, by computing the distribution, one can sample it to obtain trajectories. If the state space of the Markov process is discrete, it is called a jump Markov process and its probability distribution is governed by the Master equation. If the state space is continuous, it is called a continuous Markov process and its distribution is governed by the Fokker Planck equation. For all but the most trivial systems, the Master equation is analytically unsolvable. For large dimensional systems (i.e. many chemical species), the Fokker Planck equation is impractical to solve. Stochastic simulation is a way to generate trajectories of a Markov process and then to compute the distribution of all possible trajectories, effectively sidestepping the problems with solving either the Master or Fokker Planck equations. Of course, for some systems, stochastic simulation can be as impractical, motivating the usage of hybrid stochastic simulation methods.

Verma *et al*. (2007) proposed a stochastic simulation approach applied to availability evaluation of AC Power supply system of Indian Nuclear Power Plant (INPP) and emphasizes the importance of realistic reliability modeling in complex operational scenario with Monte Carlo simulation approach and simulation procedure for evaluating the availability/reliability of repairable complex engineering systems having stand by tested components. The same simulation model finds application in importance measures calculation, technical specification optimization and uncertainty quantification.

Arthur *et al*. (1994) proposed a stochastic production cost simulator which gives a method of simulating the annual operational cost of an electrical power system. The significant aspects of this simulation method are; the method of simulation was chronological, the uncertainty of unit availability was modeled and fuel/emission constraints were adoptively met. The purpose of their work is to describe a method of stochastic simulation. The first part of their work is a summary of the method used for chronological simulation, while the last part of the work describes a Monte Carlo type of sampling that is applicable for an annual simulation. Such a sampling method is necessary because of the emission constraints and the fuel constraints which are adaptively met in actual system operation. Thus, the annual stochastic production cost simulation should reflect the adaptive operational decisions.

1.6.1.7. Digital simulation methods in Reliability and availability studies

According to Shannon (1975), digital computer simulation is the process of designing a model of a real system and conducting experiments with this model on a digital computer for a specific purpose of experimentation. Digital simulation methods, widely used in many fields, can in some cases be a good tool to use to avoid methodological problems in studies of typical control room operations and also for efficient reliability evaluation processes (Sikorski, 1991).

As the complexity of engineering systems increases and the demands on designers and operators to carry out reliability studies intensify, much attention is being directed towards the development of reliability assessment tools. Recent advances in digital processor design, the developments in simulation methodologies and the advances in special purpose simulation languages have made the technique of system simulation one of the most widely used and accepted tools in the analysis of system performance in general, and reliability assessment in particular (Miller *et al*., 1986).

Yue et al., (2004) has performed circuit fault injection and testing by simulation using PSPICE 9 software based on digital simulation methods and discussed about automatic fault injection, fault mode simulation model of semiconductor integrate digital circuits.

Chenming Hu, (1992) has described motivation and challenges of IC reliability simulation process using BERT simulator which can be used either SPICE 2 or 3 in circuit analysis by indicating that a reasonable goal is to simulate circuit reliability and failure rate with CPU time twice that of typical SPICE simulations so that design for reliability adds only a moderate effort to the routine process of design for performance. And also indicated that the reliability models must be simple, yet accurate and general enough to pin point major reliability weak spots in a circuit and to always correctly predict at least the relative changes in “what if” design procedures.

Luo et al., (2006) described that as billions of transistors are integrated into a high end chip, traditional circuit simulators such as SPICE are inefficient for VLSI signal analyses owing to its intolerable complexity. As a result, a number of methods are proposed recently for efficient signal analysis, for instance the wavelet analysis method and S domain circuit reduction simulation methods.

1.6.1.8. Rare event simulation in system reliability and availability analysis

Rare event is an event that is deemed to be rare with very low probability and is the occurrence of large delay dispersions among the items. For example, the simulation of a network or even a single switch to estimate the probability of occurrence of such rare events would require a very large simulation time if accomplished through a traditional Monte Carlo technique. This has stimulated the application of existing, and the creation of new, advanced simulation techniques to estimate these very low probabilities to reduce the simulation time down to reasonable values as follows.

Cancela, H *et al* (2005) studied the robustness measures, the standard ones in the literature being bounded relative error and bounded normal approximation. By considering the problem of estimating the reliability of a static model for which simulation time per run is the critical issue, in this work, it has been defined bounded relative efficiency and generalized bounded normal approximation properties of the two previous measures in order to encompass the simulation time with an illustration which gives how a user can have a look at the coverage of the resulting confidence interval by using the so called coverage function. Altamirano (2007) derived efficient importance functions for networks with two stages and different nodes in each stage. Some approximations were used to derive the formulas. The goodness of such approximations was supported by the simulation results obtained; very low values of the inefficient factor and thus efficiencies close to the optimal REpetitive Simulation Trials after Reaching Thresholds (RESTART) efficiency were obtained with the importance functions. This methodology can be extended to other networks. Dupuis. P *et al* (2008) discussed the issues like how sub solutions of the HJB equations associated with a variety of rare event problems could be used to construct and rigorously analyze efficient importance sampling schemes, the characterization via sub solutions of a PDE for the purposes of practical construction of importance functions.

Several authors have applied the rare event simulation technique in evaluating and analysis of reliability parameters of systems. They have focused on utilizing this simulation approach in various purposes like in approximating the continuous time model by a discrete parameter semi Markov process for a reliability model of a two unit parallel system; in the estimation of probabilities of rare but potentially damaging events in Markovian systems; in the optimization involving rare events on discrete event simulation systems based on likelihood ratio and importance sampling methods; in the context of the estimation of rare events in Asynchronous Transfer Mode (ATM) networks; in developing a splitting based importance sampling technique for a very general class of models including reliability models with general repair policies

The literature analysis on various types of simulation methods in reliability studies shows that by using simulation methodologies, various types of reliability problems can be solved very easily when compared with complex analytical methods. But so far, the simulation methodologies are only used to speed up the solution processes or used partly in the total analysis of reliability studies of systems. The kinetic Monte Carlo simulation method used as a numerical procedure for determining the dynamics of a continuous time Markov process, a simulated annealing algorithm used to search the optimal solution of reliability redundancy allocation problems, subset simulation used for computing small failure probabilities for general reliability problems and to generate conditional samples from a specially designed Markov chain with limiting stationary distribution equal to the target conditional distribution, and Monte Carlo simulation used to generate random values for uncertain variables are some of the examples for this.

Even though the simulation methodology is a powerful tool, so far it was used in limited areas and for limited purposes in the reliability and availability modeling and analysis of systems. Therefore the author feels that there is still a lot of scope for tapping the full potential of simulation methodology in reliability and availability modeling and analysis of engineering systems.

1.7. Critical observations from the above literature survey

The following observations can be made from the literature survey covered in the earlier sections.

* As the systems become more complex, the analytical techniques become more difficult to apply.
* Simulation techniques can be used to perform the reliability and availability analysis of systems.
* Simulation approach overcomes certain disadvantages of the analytical method by incorporating and simulating any system characteristic that can be recognized.
* Simulation can provide a wide range of output parameters including all moments and complete probability density functions.
* Simulation can handle very complex scenarios like non-constant transition rate, multi state systems and time dependent reliability problems.
* The simulation techniques are conceptually simpler for calculating the reliability measures but consume considerable computer time, especially when performing sensitivity studies.
* Sometimes it may be possible to apply a hybrid approach, that is, part solution by analytical methods and part by simulation. For example, the system base probabilities may be calculated by analytical models and the probabilities of delays by specific system deficiencies calculated by simulation and the two results combined to yield demand based measures.
* Simulation has been used as a powerful tool for modeling and analysis of system reliability and availability. It is used to represent the dynamic behavior of systems in the most realistic sense.

* There is a need for further development of the analytical and simulation methods for application to more complex systems in deriving suitable measures of reliability and availability modeling and analysis.

1.8. Aim & Scope of the work

The literature collected on this topic indicates that simulation is a powerful tool for the reliability/ availability analysis of systems. However, it appears that the full potential of simulation is not yet effectively used in reliability modeling and analysis. Therefore, to capture the full potential of this powerful tool, this work proposes a system dynamics simulation based framework for the reliability/ availability modeling and analysis of systems and to study the dynamic behavior of systems. The present work also aims at developing models for all types of failure and repair time distributions including user defined functions.

1.9. Objectives

* To study the present methods of reliability and availability modeling and propose alternative approaches such as simulation to mitigate any limitations.
* To develop alternative approaches for reliability modeling and analysis of non repairable systems.
* To propose alternative approaches for reliability/availability modeling and analysis of complex repairable systems. The research also aims at developing a methodology to find out the exact time at which a system reaches its steady state point, and to evaluate its point, steady state as well as interval availabilities.
* To perform Reliability and Availability analysis of complex systems with time varying and also user defined failure and repair rates.
* To develop an alternative approach for modeling and analysis of reliability/ availability indices for multistage degraded systems.
* To develop an integrated approach for the availability analysis of serial manufacturing processes in industries.

To fulfill the above objectives, a system dynamics approach has been chosen as one of the tools and the respective literature survey has been done. About this approach and its applications has been discussed in the next chapter.

1.10. Overview of the thesis

The thesis establishes an alternative approach for time dependent reliability / availability modeling and analysis of non repairable as well as repairable systems of different configurations using Markov system dynamics simulation approach. There are nine chapters in this thesis. The main topics of each chapter are as follows.

Chapter 1 describes the various reliability and availability modeling and analysis techniques available in the literature with their advantages and limitations and also discusses various simulation methodologies in general and their applications in reliability engineering in particular. Chapter 2 describes the system dynamics simulation approach by considering it as a tool in this proposed methodology. This chapter also describes the origin of system dynamics simulation, its characteristics, applicability, similarities and differences in relation to the Markov analysis. Chapter 3 presents the system dynamics representation of systems for reliability and availability modeling and analysis and proposes a hybrid approach called as Markov System Dynamics simulation approach as an alternative approach for time dependent reliability and availability modeling and analysis of systems. This chapter also validates the proposed approach in comparison with the traditional approach. Chapter 4 proposes Markov system dynamics models for reliability modeling and analysis of various non repairable systems. Chapter 5 develops Markov system dynamics models for reliability/availability modeling and analysis of various repairable complex systems. Chapter 6 presents Markov system dynamics models for reliability/availability modeling and analysis of various non repairable as well as repairable complex systems with time varying failure and repair rates. This chapter also describes the user defined failure and repair rate case of systems Chapter 7 presents a method for the multi stage degraded systems analysis by using the proposed approach. Chapter 8 proposes a method for serial processes time dependent and long run availability analysis in a process industry. Chapter 9 provides the summary, conclusion and limitations of this research work with scope for further investigations.