# CHAPTER – 2

## LITERATURE SURVEY

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2.1 INTRODUCTION

The word *reliability seems to be* first coined by the English poet Samuel T. Coleridge, who along with William Wordsworth started the English Romantic Movement (Engell *et al.*, 1983):

“He inflicts none of those small pains and discomforts which irregular men scatter about them and which in the aggregate so often become formidable obstacles both to happiness and utility; while on the contrary he bestows all the pleasures, and inspires all that ease of mind on those around him or connected with him, with perfect consistency, and (if such a word might be framed) absolute reliability.”

Coleridge has written these lines in the year 1816, in praise of his friend Robert Southey. Since then the concept of reliability had grown both qualitatively and quantitatively. From 1816 to 2013 several technological developments have occurred. The world became more complicated in the late 1920s and early 1930s due to increased demand for telephone and electron vacuum tubes which spurred the early reliability services. The first generation services (1930-1960) concentrated on corrective maintenance, second generation (1960-1985) on preventive maintenance, the third generation on predictive maintenance (1985-2000) and the present on intelligent maintenance. The applications of reliability are wide and include mechanical, electrical, computers, structural etc. S. Yamada *et al* [1] has applied reliability for software testing-resource allocation problems so as to make the best use of the specified testing-resource during module
testing. J.O. Roys et al [2] presented a robust reliability based optimal design for series structural systems. The reliability of embedded systems considering both hardware and hardware cost constraints was presented by N. Wattanponsakron et al [3]. An efficient computational methodology to obtain the optimal system structure of electronic devices by using multi objective optimization approach with constraints on reliability and cost was presented by E.P. Zafiripolous and E.N. Dilalynas [4].

Reliability has become an even greater concern in the recent years because of the process time and production cost. Reliability optimization has attracted many researchers worldwide due to its critical importance in various kinds of systems. Considering the tradeoff between available resources and system performance optimal reliability design aims at determining an optimal system level configuration and takes into account of component reliability enhancement and provision for redundancy.

2.2 SYSTEM RELIABILITY MODELS WITH REDUNDANCY

Frank A.Tillman [5] has classified the optimal system reliability with redundancy into two (i) optimal system reliability models with redundancy and (ii) optimization techniques for obtaining optimal system configuration. W.Kuo [6] has presented a review on the application of the methods in [5] to various types of design problems and summarized the recent optimization techniques along with recent optimization methods. W.Kuo and R.Wan[7] presented the ‘recent
advances in optimal reliability allocation’ which contributed to reliability engineering since the publication of [6]. The following paragraphs review the literature present from [7] to [103] and discuss the recent developments in reliability engineering.

2.2.1 Classification Of Optimal System Reliability Models With Redundancy

In engineering duplication of critical components or functions of a system are done with the intention of increasing reliability of a system and this is called redundancy. For any system, modeling is necessary to evaluate the performance of the system. The various system models for which optimal system reliability has to be evaluated are classified as:

1. Series systems
2. Parallel systems
3. Series parallel systems
4. Parallel series systems
5. Stand by systems
6. General network systems
7. Consecutive and non consecutive systems.

2.2.1.1 Series systems

The components in a system are said to be in series from reliability point of view if they all must work for the success of a system or one needs to fail for system failure. Owing to its simple structure a lot of work has been done in this area. For increasing the overall reliability of a series system we introduce redundancies at each
stage which makes the system to be subjected to some linear
constraints. The optimization problem that deals with the number of
redundant components is to be introduced to get the optimum design
under the given constraints. An algorithm based on dynamic
programming for reliability maximization subjected to a single cost
constraint was introduced by Kettele et al [8]. Fan et al [9] used the
discrete maximum principle to solve reliability optimization problems.
When the number of components in a system become large the
evaluation of system reliability becomes difficult. To overcome this
problem S.K.Banerjee and K.Rajamani [10] presented a straight
forward method called parametric approach method. This method
uses a parametric operator $\Phi$ for reliability evaluation and the values
obtained by this method are in close comparison with the classical
method. The same authors have presented a computationally simple
procedure [11] for reliability optimization using the parametric
approach presented in [10]. The proposed one in conjunction with
nonlinear programming is used for either optimization of reliability or
cost with multiple linear constraints. The optimization of reliability of
a system subjected to constraints is difficult when the components fail
in just one way. It still becomes more difficult when the components
fail in several modes. To solve these problems F.A.Tillman [12]
presented an integer program for constrained reliability optimization.
2.2.1.2 **Parallel systems**

The components in a system are said to be in parallel from reliability point of view if any one among them must work for the success of a system or all must fail for system failure. The reliability of a parallel system will therefore be more than that of series system. Kneale [13] explained the theory of reliability of parallel systems with repair and switching. Moskowitz and Mclean [14] studied some reliability aspects of system design. Webster [15] explained a novel way of choosing optimum system reliability by selecting system reliability configuration. Ghare and Taylor [15] provided a fast algorithm for reliability optimization for parallel redundancy. McLeavey[16] presented extensive computational experience with several modifications of the Ghare-Taylor algorithm.

2.2.1.3 **Series Parallel Systems**

The series and parallel systems form the basis for analyzing more complicated systems. The general principle used is to reduce sequentially the complicated system by combining appropriate series and parallel branches of reliability model until a single equivalent component remains. The reliability of the equivalent component then represents the reliability of the system. Nelson *et al* [17] developed a computer program which provides bounds for system reliability. The algorithms are based on the concepts of success paths and cut sets. Brown [18] developed a computerized algorithm for determining the reliability of redundant configurations. Procedure has been given for generating the reliability function directly from Boolean algebra.

2.2.1.4 Parallel Series Systems

Parallel series systems are the one in which several stages exist in series and to enhance the reliability of the system stage or overall system reliability, redundant components can be added. Redundancy can be considered at stage level as well as component level. Allocation of redundancy is one of the most important optimization problems in the designing phase of any system. Enhancement in reliability is achieved by proper allocation of redundancies to its subsystems as explained by J.H.Kim and B.J.Yum in [20]. Optimal solution to Redundancy allocation problem has been solved by various single objective optimization techniques [38, 49]. Obtaining high reliability and spending less in the designing phase of the system by aggregating the two objective functions to a unique scalar objective function and optimize the new objective function has been reported in [21]. However for single objective approaches one should design sophisticated mechanisms of combining different objectives in order to achieve better performance. On the other hand, the aggregation of two objective functions may avoid the need of finding multiple solutions. To overcome these two multi objective evolutionary algorithms have become an appropriate choice [22].
2.2.1.5 **Stand By Systems**

This is an extension of parallel system in which both branches are connected in parallel and moreover both of them are operating simultaneously. However, in some system problems one or more branches of the redundant components may not be continuously operating but remain in a normally operating mode termed as standby mode i.e. they are put into operation only when normal operating component fails. Morrison [23] suggested a method of optimum number of spare components to be present in a system. Here he has divided the system whose components have been divided into two subsystems, the lives which are exponentially distributed but with different scale parameters. Proschan and Bray [24] developed an algorithm for allocating redundancy among sub systems so as to achieve maximum system reliability without exceeding any of the several linear constraints on redundancy allocated in a system. Ir.R.N.V. Heeves *et al* [25] developed a method of optimal reliability for parallel multi component systems. Here the number and spare components will be determined for obtaining maximum reliability under the assumption that limited funds are available for the purpose.

2.2.1.6 **General Network Systems**

These include bridge networks, nonseries-nonparallel structures and other complex system configurations. For non series-parallel networks, the objective function is not generally separable into sums of terms where each term is a function of an independent variable. A direct method of reliability evaluation for any non series–non parallel
networks has been given by S.K. Banerjee and K. Rajamani [26]. The same authors [27] have presented an exact closed form of solution for star-delta and delta-star networks and the reliability of any structure can be found from this. It is desirable to evolve a method that involves evaluation rather than derivation method of optimal redundancy allocation. The three well known methods in this category are Powell’s method, Rosen-brock’s algorithm, and the Box method [28]. S.K. Rajamane et al [29] presented general algorithms for solving redundancy optimization problem for non-series parallel networks. The Box method has been employed for solving the problem.

2.2.1.7 Consecutive and Non Consecutive Systems

It consists of k-out of n systems i.e., F and G systems. If k out of n system fails, that is when k units fail it is called an F-system. A G-system is operational if and only if at least k out of n units are operational. Pham [30] has described an optimal method for k-out-of-n redundant systems. Here the optimization problem was formulated and solved to minimize the total cost of k-out-of-n systems. The same author [31] has presented methods for optimal determination of most economical number of components in k-out-of-n subsystems. Here the methods described determine the optimal values of k for fixed n and n for fixed k for minimizing the mean total cost of k-out-of-n subsystems. Suich and Patterson [32] have also derived several cost models for single k-out-of-n systems. Pham and Malon [33] have solved the problem of achieving optimal system size n and a threshold k for k-
out-of-n subsystem with competing failure modes. Bai et al [34] has presented the problem of finding the optimal number of redundant units \( k \)-out-of-\( n \) subsystems with common cause failures. In each of the above cases only one subsystem was considered. D.W. Coit and Jiachen Liu [35] has presented a new method which addresses the problems of the above methods. Individual systems can be either active or cold standby redundancy or no redundancy. D.W. Coit [36] presented cold standby redundancy optimization for non-repairable systems. It employs the more flexible and realistic Erlang distributed component time to-failure. V.C. Bueno [37] investigates the problem of allocation of spares in a \( k \)-out-of-\( n \): \( F \) system of components which are dependent through minimal standby redundancy; and R. Romera et al [38] studied the allocation of one active redundancy when it varies based on the component with which it is to be allocated. Prasad VR et al [39] considered the problem of optimally allocating a predetermined number of \( s \)-similar multi-functional spares for a stochastic or deterministic mission time. Inspite of few sufficiency conditions for optimality, the presented algorithm can be implemented even for large systems. S.V. Amari et al [40] maximized the reliability of systems which are subjected to imperfect fault coverage. He generalized that the reliability of such a system reduces with an increase in redundancy beyond a particular limit because of common-cause failures and the maximum allowable spare limit. The various types of models considered here include parallel, parallel-series, \( k \)-out-of-\( n \) and \( k \)-out-of-(\( 2k-1 \)) systems.
2.2.2 Classification Of System Reliability Models With Redundancy (By Optimization Techniques)

2.2.2.1 Integer Programming

When all the variables in an optimization problem are constrained to take only integers, it is called an integer programming problem. The cutting plane algorithm proposed by Gomory [41] and the branch and bound algorithm of Land and Doig [42] are most popular integer programming techniques among the researchers. As described previously in section 1.6, the reliability of a system can be increased by utilizing redundancies at various stages. Integer programming has been widely used to attain solutions to the redundancy allocation problem and to find an optimal solution to this allocation under various constraints such as cost, weight and volume. Many researchers [43-47] have applied integer programming for maximizing reliability or minimizing cost subjected to various constraints. There are several drawbacks which include no guarantee of convergence and accuracy of the solution, cannot obtain optimal solutions in a reasonable time, restriction on the number of constraints, transformation of the nonlinear objective functions into a linear form. Lawler and Bell [48] proposed an algorithm for solving discrete optimization problem with a monotone objective function and arbitrary constraints. K.B. Mishra [49] used this algorithm and formulated redundancy optimization problem as an integer programming problem of zero-one type variables. This is simple and not affected by number of constraints and, moreover, it can compete
with earlier methods of redundancy allocation. When the elements fail in one mode the problem of optimization of reliability for a system with nonlinear constraints is difficult to solve. Tillman and Liittschwager [50] solved this problem using integer programming based on cutting plane algorithm. Henin used Branch and bound method for optimizing the system reliability subjected to linear constraints. Tillman [51] solved the optimal redundant allocation problem when the system is subjected to nonlinear constraints and when the elements fail in two different modes. K. Nam and Hyun [52] proposed a zero-one linear programming, ZOLP and is identical with the one proposed by Tillman. The proposed ZOLP decreases the computational time.

2.2.2.2 Dynamic Programming:

The reliability of a multi component series system can be improved by adding parallel redundancies at each stage. Integer programming does not provide a solution to multistage decision process. Richard Bellman introduced the dynamic programming in the early 50’s to solve multistage decision problems. Bellman and Drefyus [53] solved the problem of allocating parallel redundancy under constraints by using dynamic programming. Moreover it reduced the dimensionality of the problem from sequences of two variables to a sequence of functions of one variable using Lagrange multiplier technique. A dynamic programming approach to the one constraint problem was presented by Kettele [54]. Nadamuni et al[55] applied the stochastic dynamic programming for optimizing the redundancy
of components in a series system. Santosh et al [56] developed a package for a two constraints reliability problem using Stochastic dynamic programming technique for particular configuration of a complex system. The constraints included in this optimization problem are on space and cost.

2.2.2.3 Maximum Principle

This principle is used to determine the system design which maximizes the minimum subsystem reliability as system time to failure is equal to the minimum subsystem time to failure. Thus this principle increases the system reliability by enhancing the subsystem reliability. Fan et al [59] presented a simple computational procedure for the optimum design of multistage parallel systems to maximize system profit. Tillman et al [60] formulated a set of nonlinear transcendental equations for solving system reliability using Newton’s method. There is no guarantee of getting a solution through the formulation of above methods due to non-convergence or convergence to an absurd solution. Misra [61] presented a simple algorithm which uses the Maximum principle to arrive at an optimal solution.

2.2.2.4 Linear Programming

Linear programming problem arises whenever two or more candidates or activities are competing for limited resources and when it can be assumed that all relationships within the problem are linear. Since the reliability optimization problem usually has nonlinear objective function and/or nonlinear constraint functions, unless we
linearize the objective and/or constraint functions or we do encounter specific case, linear programming is not applicable. It is an optimization technique applied for the solution of the problems in which the objective function and the constraints are linear functions of the decision variables. Linear programming has sometimes been included in reliability optimization techniques for solving (a) an optimization problem with a linear form of non-negative variables subject to a system of linear inequalities [62,63], or (b) an original nonlinear optimization problem having been transformed to a standard linear form which can be solved by linear programming. Separable programming [64,65] is a typical technique to handle this formulation.

2.2.2.5 Geometric Programming

Geometric Programming developed by Richard Duffin is used to minimize functions that are in the form of polynomials subjected to the constraints of the same type. The non-linear optimization problems have been solved by different nonlinear optimization techniques. Geometric Programming (GP) is an effective method among those to solve a meticulous type of non-linear programming problem. Zener [66] introduced GP technique, and Duffin et al [67] further developed the GP method. There are various mathematical programming and heuristic methods being developed to solve the single and multi-objective reliability optimization problem. GP method is rarely used to solve the reliability optimization problem. Federowicz
and Mazumdar [55] first used GP on reliability optimization problem. Govil [68] used GP for a 3-stage series reliability system. Now-a-days GP in fuzzy environments, a competent optimization method, is used to solve a typical fuzzy optimization problem which is called Fuzzy Geometric Programming (FGP). In 1987, Cao [69] first introduced FGP. Mahapatra and Roy [70] used FGP with cost constraint to find optimal reliability for a series system. Fuzzy reliability optimization models with redundancy through FGP are very rare in literature [71].

### 2.2.2.6 Unconstrained Minimization Technique

It is a technique by which the basic optimization problem is transformed into alternative formulations such that numerical solutions are obtained by solving a sequence of unconstrained minimization problems. This technique is mainly employed in optimizing the reliability of a complex system where the redundant units of the system cannot be reduced to purely series or parallel configurations. McCormick et al [72] developed computer program for sequential unconstrained minimization technique (SUMT) which employs a second-order gradient method. Obtaining the first and order partial derivatives of complicated non linear functions is the difficult task in the employment of this method. Hook and Jeeves [73] employed a pattern search technique to carry out a sequence of unconstrained minimizations. Though this technique eliminates the need for taking derivatives it suffers from the disadvantage that it goes outside the feasible region when bounded by inequality constraints.
and the search may be prematurely terminated at a point near the boundary which may not be optimum. Paviani and Himmelblau [74] employed a heuristic programming technique to avoid this difficulty which forces the search back into the feasible region near the boundary of the inequality constraints. With the aid of Hook and Jeeves method and heuristic programming, C.L Hwang et al [75] presented a new approach for implementing SUMT to optimize the reliability of a complex system.

2.2.2.7 Modified Sequential Simplex Pattern Search

Sequential pattern search is the simplest method and most efficient method among the search techniques and the same has been applied for solving the problems arising in production control and planning by LT.Fan et al [76]. MJ Box [77] compared several optimization methods and the use of transformations in constrained problems. Here he has discussed the transformations used for eliminating the inequality constraints in the formulation of an optimization problem. A simplex method for function minimization was presented by J.A. Nelder and R. Mead [78]. The proposed method adapts itself to the local environment and contracts in the neighborhood of a minimum. A new technique called Sequential Weight increasing factor Technique (SWIFT) was presented by B.V. Sheela and P. Ramamoorthy [79] for constrained optimization problems. This uses a polyhedron method for uncontrolled
optimization. It penalizes the objective function and thus making it simple and fast convergence method.

### 2.2.2.8 Lagrangian Multipliers and Kuhn–Tucker Conditions

Lagrange multipliers are used to solve a multivariable optimization problem with equality constraints. R.E. Barlow et al [80] and H. Everett III [81] attempted to solve the reliability optimization problem through the use of Lagrangian multipliers with single constraint. With multiple constraints it was difficult to use Lagrangian multipliers. K.B. Misra [82] found a new way for transforming the constrained optimization problem to a saddle point problem with the use of Lagrange multipliers. He used Newton’s method for rapid convergence. The limitations of this method are requirement of large number of iterations and longer computer time for convergence and moreover the values of Lagrange multipliers and the initial points are to be carefully select for the program to converge.

### 2.2.2.9 Generalized Lagrangian Function

A generalized mathematical programming problem subjected to constraints which form a subset of Euclidean space can be solved by methods which are based on transformation of a given constrained problem into a sequence of unconstrained problems. There are two classes of such methods, namely, the penalty and Lagrangian methods. The penalty methods (e.g., sequential unconstrained minimization technique) have been studied extensively and applied to many practical problems [83], [84]. However, they suffer from
numerical instabilities. The Lagrange multipliers method has been used mostly for the analysis of economic systems [85]. Recently, augmented Lagrangian functions have been proposed to solve the problems with equality [86, 87, 88] and inequality constraints [89, 90]. In this section a new type of the generalized or augmented Lagrangian function proposed by Sayama et al [89, 90] for finding the solution of a non-linear programming problem with inequality constraints is applied to optimal systems reliability problems. The function is twice continuously differentiable and closely related to the generalized penalty function which includes the interior and exterior penalty functions as special cases.

2.2.2.10 Generalized Reduced Gradient:

The Generalized Reduced Gradient Method (GRG) was proposed by Abadie and Carpentier [91, 92]. The method is a generalization of the Kolfe reduced gradient method [93, 94], which solves problems having a nonlinear objective function and linear equality constraints. It classifies the variables as dependent and independent ones, and substitutes into the objective function the expressions obtained from the linear equality constraints for the dependent variables, in terms of the independent variables. Thus the original problem reduces to an unconstrained one with reduced dimension. A variety of optimization techniques may now be used. Applying the same concept to a problem with a set of non-linear constraints, complications may be added, but it is possible by using numerical methods to obtain the solution.
2.2.2.11 Heuristic Approach

Sharma and Venkateswaran [95] developed an intuitive procedure for allocating redundancy among subsystems. To improve the system reliability at each step of the algorithm, the procedure is to add a redundancy in the stage which has the highest stage unreliability. The algorithm was applied for solving multistage system problems subject to multiple nonlinear constraints. In this approach, the constraints are never in active. Misra [96] then introduced an approach for redundancy optimization problem with multiple linear constraints. In the process of solving a problem, the problem with r constraints is decoupled into r-problems, each has one constraint. "Desirability factor", i.e. ratio of the percentage increase in the system reliability to the percentage increase of the corresponding cost, is introduced to determine a stage which a redundancy, is to be added. Aggarwal et al [97] improved Sharma- Venkateswam approach by introducing a relative increment in reliability versus decrement in slacks (the balance of the resources) as a criterion to select the stage to which a redundancy is to be added for solving series system problems with multiple nonlinear constraints. Aggarwal [98] extended the approach to a problem of complex systems. Nakagawa and Nakashima [99] presented the fourth approach to solve a different type of series system. In this approach a thorough consideration of the balance between the objective function and the constraints is especially emphasized. Lee et al [100] compared this method with the max-min approach presented by Ramirez-Marquez [101].
comparison was based on solution quality and computational complexity. Comparison infers that this Max-Min approach is superior to the one presented by Nakagawa and Nakashima with respect to quality of the solution. But it is computationally inferior to Nakagawa and Nakashima method.

2.2.2.12 Parametric Approach

Parametric approach was originally used in evaluating system reliability, especially when the number of components in a system was large or the system configuration complex. A straightforward method of evaluating the reliability of complex system was presented by S.K. Banerjee and K. Rajamani [10]. Here probability is treated as a point in a Cartesian frame and formulas are derived to evaluate the reliability of simple and complex systems. The same authors [11] developed a novel method for optimization of system reliability with linear constraints using the parametric approach. The classical nonlinear programming technique is used for this solution.

2.2.2.13 Pseudo-Boolean Programming

For reliability optimization of process systems the problem formulation based on r-out-of-n configurations is more suitable than that based on a conventional parallel redundancy (1-out-of-n) configuration. The formulated reliability optimization problems (r-out-of-n configurations) can be solved by using integer gradient method proposed by Reiter and Rice [102] and by using pseudo-Boolean
programming method proposed Lawler and Bell [103]. The extreme ease of programming and true optimal solution provided by Lawler and Bell is preferred over Reiter and Rice method.

2.3 Conclusions

In this chapter, reliability models with redundancy and optimization techniques developed for obtaining the optimal solution for the redundancy models have been reviewed. The works/research contributions of few researchers are mentioned in the form of survey. The merits and demerits of different techniques used for reliability optimization have been presented in this chapter.