Detection of Reliable Software Using SPRT & Pareto Type II SRGM

[1]Dr. R. Satya Prasad, [2]N Geetha Rani, [3]Dr. R. R. L. Kantam
[1,3]Dept. of CSE, Acharya Nagarjuna University, Nagarjuna Nagar, India
[2]Dept. of Computer Science, Abhinav Institute of Management. & Tech., Singarayakonda, India

Abstract
Classical Hypothesis Testing is performed with volumes of data without analysis. Nevertheless, in Sequential Analysis there should have been examination directly over each and every problem once they are accumulated. Sequential Analysis approach concedes one to infer and it can be possible to reach a final conclusion in an advance stage. The procedure, which is adopted for this is Sequential Probability Ratio test (SPRT). This paper presentation shows how to use the Wald's Sequential Probability Ratio Test (SPRT) to determine the reliability/Unreliability of software products. The well known SPRT procedure is adopted for the Pareto type II software reliability growth model (SRGM), which is based on the Non Homogenous Poisson Process (NHPP). The performance of the proposed Pareto Type II model is demonstrated by using 6 data sets.

Keywords
Software Reliability, NHPP, Pareto Type II Model, Maximum Likelihood Estimation, SPRT, Time Domain Data, Decision Lines

I. Introduction
In statistics, sequential analysis or sequential hypothesis testing is statistical analysis where the specimen size is not determined at the earlier stage. But the data are assessed, while they are being collected. When the prominent results are noticed, the next sampling is stopped in accordance with a predefined stopping rule. In this way a conclusion may be acquired in an earlier stage than it would be with more classical hypothesis testing or assessment at consequently lower financial and/or human cost.
The main aim of statistical hypothesis testing is to categorize a sequence of observations into one of possible hypothesis depending on some knowledge of statistical distribution of the observations under each of the hypothesis. For sequential testing problems, the number of observations used (sample size) is allowed to be random variable, i.e., the sample size is a function of the observations. A sequential test picks a stopping time and a final decision rule to effect a tradeoff between sample size and decision accuracy.
What Stieber [11] examines is whether the classical testing plans are utilized the application of software reliability growth models may be hard and reliability prophecies can be deluding. He notices that one can successfully apply statistical methods to the failure data. He demonstrated his observation by applying the Sequential Probability Ratio Test (SPRT) of Wald [12] for a software failure data to detect unreliable software components and compare the reliability of different software versions. Abraham Wald developed a specific sequential hypothesis test. It is known as SPRT while originally it was developed for use in quality control studies in the purview of manufacturing. Actually Abraham Wald has devised SPRT for use in computerized testing human examinees as a termination criterion.
The SPRT procedure was used in the quality control discipline to fix sequentially, the acceptance or rejection of software system. In this paper we applied SPRT for a software failure data to determine reliable/unreliable software components using Pareto type II model. The theory proposed by Stieber is presented in section II. The extension of this theory to Pareto type II SRGM is presented in section III. Section IV, discusses parameter estimation of proposed model based on time domain data. The SPRT analysis of live data sets are exhibited in section V. Section VI contains conclusions.

II. Wald's Sequential Test
The Sequential Probability Ratio Test (SPRT) was developed by Abraham Wald in 1943. He devised SPRT for use in quality control studies in the purview of manufacturing. Using SPRT methodology Stieber (1997) suggested the following procedure to reject or accept a software system.
Let $\{N(t), t \geq 0\}$ be a homogeneous Poisson process with rate 'λ'. $N(t)$ = number of failures up to time 't' and 'λ' is the failure rate (failures per unit time). For a instance that a system is kept on test (suppose a software system, where we can conduct test based on a usage lineament and where we cannot correct mistakes) and that its failure rate 'λ' will be accessed. The accurate value of 'λ' cannot be expected. But we desire not to allow the system with a high probability of the taken data suggests that the failure rate is larger than λ_1 and admit it with a high probability, if it is smaller than λ_0 $(0 < \lambda_0 < \lambda_1)$. There is always some risk to get the incorrect answers with statistical tests. So we have to specify two (small) numbers 'α' and 'β', where 'α' is the probability of falsely rejecting the system. That is rejecting the system even if $\lambda \leq \lambda_0$. This is the "producer's" risk. β is the probability of falsely accepting the system. It is accepting the system even if $\lambda \geq \lambda_1$. This is the "consumer's" risk. With specified choices of λ_0 and λ_1 such that $0 < \lambda_0 < \lambda_1$, the probability of finding $N(t)$ failures in the time span $(0,t)$ with λ_1,λ_0 as the failure rates are respectively given by

$$P_1 = \frac{e^{-\lambda_1 t}[\lambda_1 t]^{N(t)}}{N(t)!} \quad (1)$$

$$P_0 = \frac{e^{-\lambda_0 t}[\lambda_0 t]^{N(t)}}{N(t)!} \quad (2)$$

The ratio $\frac{P_1}{P_0}$ at any time 't' is considered as a measure of deciding the truth towards λ_0 or λ_1 given a sequence of time instants say $t_1<t_2<\ldots<t_k$ and the corresponding realizations $N(t_1), N(t_2)\ldots. N(t_k)$ of $N(t)$. Simplification of $\frac{P_1}{P_0}$ gives

$$\frac{P_1}{P_0} = \exp(\lambda_0 - \lambda_1)\, t + \left[\frac{\lambda_1}{\lambda_0}\right]^{N(t)}$$

The decision rule of SPRT is to decide in favor of λ_1, in favor of λ_0 or to continue by observing the number of failures at a later time than 't' according as $\frac{P_1}{P_0}$ is greater than or equal to a constant say A, less than or equal to a constant say B or in between the constants A and B. That is, we decide the given software product as unreliable, reliable or continue [7-10] the test process with one more observation in failure data, according as

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$$\frac{P_1}{P_0} \geq A \quad (3)$$

$$\frac{P_1}{P_0} \leq B \quad (4)$$

$$B < \frac{P_1}{P_0} < A \quad (5)$$

The approximate values of the constants A and B are taken as

$$A \cong \frac{1-\beta}{\alpha}, \quad B \cong \frac{\beta}{1-\alpha}$$

where 'α' and 'β' are the risk probabilities as defined earlier. A simplified version of the above decision processes is to reject the system as unreliable if N(t) falls for the first time above the line

$$N_U(t) = a\,t + b_2 \quad (6)$$

to accept the system to be reliable if N(t) falls for the first time below the line

$$N_L(t) = a\,t + b_1 \quad (7)$$

To continue the test with one more observation on (t, N(t)) as the random graph of [t, N(t)] is between the two linear boundaries given by equations (6) and (7) where

$$a = \frac{\lambda_1 - \lambda_0}{\log\left[\frac{\lambda_1}{\lambda_0}\right]} \quad (8)$$

$$b_1 = \frac{\log\left[\frac{1-\alpha}{\beta}\right]}{\log\left[\frac{\lambda_1}{\lambda_0}\right]} \quad (9)$$

$$b_2 = \frac{\log\left[\frac{1-\beta}{\alpha}\right]}{\log\left[\frac{\lambda_1}{\lambda_0}\right]} \quad (10)$$

The parameters α, β, λ_0 and λ_1 can be chosen in several ways. One way suggested by Stieber (1997) is

$$\lambda_0 = \frac{\lambda \log(q}{q-1}, \lambda_1 = q\frac{\lambda \log(q}{q-1}$$

where $q = \frac{\lambda 1}{\lambda 0}$

If we opt λ_0 and λ_1 in this way, the slope of N_U (t) and N_L (t) equals λ. There are two other ways in selecting λ_0 and λ_1. They are selecting λ_0 and λ_1 from past projects for comparison of the projects and another one is from part of the data to compare the reliability of various functional areas (components).

III. Sequential Test for Pareto Type II SRGM

In Section II, it is known that the desired value of $N(t) = \lambda_t$ called the average number of failures experienced in time 't'. It is used for the Poisson process. This is also called the mean value function of the Poisson process. On the other hand if we consider a Poisson process with a general function (not necessarily linear) m(t) as its mean value function the probability equation of a such a process is

$$P[N(t) = Y] = \frac{[m(t)]^y}{y!} e^{-m(t)}, \; y=0,1,2, \ldots.$$

Depending on the forms of m(t) we get various Poisson processes called NHPP, for our Pareto type II model the mean value function is

$$m(t) = a\left[1 - \frac{c^b}{(t+c)^b}\right]$$

We may write

$$P_1 = \frac{e^{-m_1(t)}[m_1(t)]^{N(t)}}{N(t)!}$$

$$P_0 = \frac{e^{-m_0(t)}[m_0(t)]^{N(t)}}{N(t)!}$$

where $m_1(t)$, $m_0(t)$ are values of the mean value function at mentioned sets of its parameters pointing reliable software and unreliable software respectively. The mean value function m(t) contains the parameters 'a', 'b' and 'c'. Let P_0, P_1 be values of the NHPP at two specifications of b say b_0,b_1 where (b_0<b_1) and two specifications of c say c_0, c_1 where (c_0<c_1). It can be shown that for our model m(t) at b_1 is greater than that at b_0. and m(t) at c_1 is greater than that at c_0. Symbolically $m_0(t) < m_1(t)$. Then the SPRT procedure is as follows:

Accept the system to be reliable

$$\frac{P_1}{P_0} \leq B$$

i.e., $$\frac{e^{-m_1(t)}[m_1(t)]^{N(t)}}{e^{-m_0(t)}[m_0(t)]^{N(t)}} \leq B$$

$$\text{i.e., } N(t) \leq \frac{\log\left(\frac{\beta}{1-\alpha}\right) + m_1(t) - m_0(t)}{\log m_1(t) - \log m_0(t)} \quad (11)$$

Decide the system to be unreliable and reject if

$$\frac{P_1}{P_0} \geq A$$

i.e., $$\frac{e^{-m_1(t)}[m_1(t)]^{N(t)}}{e^{-m_0(t)}[m_0(t)]^{N(t)}} \geq A$$

$$\text{i.e., } N(t) \geq \frac{\log\left(\frac{1-\beta}{\alpha}\right) + m_1(t) - m_0(t)}{\log m_1(t) - \log m_0(t)} \quad (12)$$

Continue the test procedure as long as

$$\frac{\log\left(\frac{\beta}{1-\alpha}\right) + m_1(t) - m_0(t)}{\log m_1(t) - \log m_0(t)} < N(t) < \frac{\log\left(\frac{1-\beta}{\alpha}\right) + m_1(t) - m_0(t)}{\log m_1(t) - \log m_0(t)} \quad (13)$$

substituting the appropriate expressions of the mean value function, we get the respective decision rules and are given in followings lines

Acceptance region:

$$N(t) \leq \frac{\log\left(\frac{\beta}{1-\alpha}\right) + a\left[\frac{c_0^{b_0}}{(t+c_0)^{b_0}} - \frac{c_1^{b_1}}{(t+c_1)^{b_1}}\right]}{\log\left[\frac{1-\frac{c_1^{b_1}}{(t+c_1)^{b_1}}}{1-\frac{c_0^{b_0}}{(t+c_0)^{b_0}}}\right]} \quad (14)$$

Rejection region:

$$N(t) \geq \frac{\log\left(\frac{1-\beta}{\alpha}\right) + a\left[\frac{c_0^{b_0}}{(t+c_0)^{b_0}} - \frac{c_1^{b_1}}{(t+c_1)^{b_1}}\right]}{\log\left[\frac{1-\frac{c_1^{b_1}}{(t+c_1)^{b_1}}}{1-\frac{c_0^{b_0}}{(t+c_0)^{b_0}}}\right]} \quad (15)$$

Continuation region:

$$\frac{\log\left(\frac{\beta}{1-\alpha}\right) + a\left[\frac{c_0^{b_0}}{(t+c_0)^{b_0}} - \frac{c_1^{b_1}}{(t+c_1)^{b_1}}\right]}{\log\left[\frac{1-\frac{c_1^{b_1}}{(t+c_1)^{b_1}}}{1-\frac{c_0^{b_0}}{(t+c_0)^{b_0}}}\right]} < N(t) < \frac{\log\left(\frac{1-\beta}{\alpha}\right) + a\left[\frac{c_0^{b_0}}{(t+c_0)^{b_0}} - \frac{c_1^{b_1}}{(t+c_1)^{b_1}}\right]}{\log\left[\frac{1-\frac{c_1^{b_1}}{(t+c_1)^{b_1}}}{1-\frac{c_0^{b_0}}{(t+c_0)^{b_0}}}\right]} \quad (16)$$

What we may note in the above model is the decision rules are exclusively based on the strength of the sequential process (α,β) and the value of the mean value function namely, $m_0(t), m_1(t)$. The decision rules become decision lines as described by Stieber (1997), if the mean value function is linear in 't' passing through origin that is $m(t) = \lambda_t$. In that sense equations (11), (12) , (13) can be regarded as generalizations to the decision procedure of Stieber (1997). The applications of these results for live software failure data are presented with analysis in Section V.

IV. Parameter Estimation of Pareto Type II Model

Parameter estimation is of primary importance in software reliability prediction. Once the analytical solution for m(t) is known for a given model, parameter estimation is achieved by applying a well known technique of Maximum Likelihood Estimation (MLE).

The main idea behind maximum likelihood parameter assessment is to decide the parameters that maximize the probability (likelihood) of the specimen data. The method of maximum likelihood is contemplated to be more robust (with some exceptions) and relinquishes estimators with good statistical properties. In the other words, MLE methods are versatile and applicable to most models and to different types of data. Though the methodology for maximum likelihood estimation is simple, the implementation is mathematically vehement.

The mean value function of Pareto type II model is given by

$$m(t) = a\left[1-\frac{c^b}{(t+c)^b}\right] \quad , t \geq 0 \tag{17}$$

The values of a, b and c which would maximize L are called maximum likelihood estimators (MLEs) and the process is called Maximum Likelihood (ML) method of estimation.

The required likelihood function is given by

$$L = e^{-m(x_n)} \cdot \prod_{i=1}^{n} m'(x_i) \tag{18}$$

$$L = e^{-a\left[1-\frac{c^b}{(x_n+c)^b}\right]} \cdot \prod_{i=1}^{n} \frac{abc^b}{(x_i+c)^{b+1}} \tag{19}$$

Then the log likelihood equation to estimate the unknown parameters a, b and c are given by

$$\text{Log } L = -a\left[1-\frac{c^b}{(x_n+c)^b}\right] + \sum_{i=1}^{n}\left[\log a + \log b + b\log c - (b+1)\log(x_i + c)\right] \tag{20}$$

Accordingly parameters ‘a’, ‘b’ and ‘c’ would be solutions of the equations

$$\frac{\partial LogL}{\partial a} = 0 , \frac{\partial LogL}{\partial b} = 0 , \frac{\partial^2 LogL}{\partial b^2} = 0 , \frac{\partial LogL}{\partial c} = 0 , \frac{\partial^2 LogL}{\partial c^2} = 0$$

Substituting the expressions for m(t) (17) in the above equations, taking logarithms, differentiating with respect to ‘a’, ‘b’, ‘c’ and equating to zero, after some joint simplications we get

$$a = \frac{n(x_n+c)^b}{(x_n+c)^b - c^b} \tag{21}$$

$$g(b) = \frac{n\log\frac{1}{x_n+1}}{(x_n+1)^b - 1} + \frac{n}{b} - \sum_{i=1}^{n}\log(x_i+1) \tag{22}$$

$$g'(b) = -n\log\frac{1}{x_n+1}\left[\frac{(x_n+1)^b\log(x_n+1)}{\left[(x_n+1)^b-1\right]^2}\right] - \frac{n}{b^2} \tag{23}$$

$$g(c) = \frac{n}{x_n+c} + \frac{n}{c} - \sum_{i=1}^{n}\frac{2}{x_i+c} \tag{24}$$

$$g'(c) = -\frac{n}{(x_n+c)^2} - \frac{n}{c^2} + \sum_{i=1}^{n}\frac{2}{(x_i+c)^2} \tag{25}$$

By using the Newton Raphson Method, we can acquire the values of ‘b’ and ‘c’ mentioned in the above equations. The point estimates of the parameters ‘b’ and ‘c’ yields after solving the above equations simultaneously. The above extracted equations should be solved iteratively and their solutions in turn when substituted in the log likelihood equation of ‘a’ would give analytical solution for the MLE of ‘a’

For the present model of Pareto type II, the parameters are estimated from [6].

V. SPRT Analysis of Live Data Sets

In this section we evaluate the decision rules based on the considered mean value function for six different data sets, borrowed from [2, 4-5, 13] and SONATA software services. Based on the estimates of the parameter ‘b’ and ‘c’ in mean value function, we have chosen the specifications of b_0, b_1 such that $b_0 < b < b_1$ and c_0, c_1 such that $c_0 < c < c_1$. The estimates are given in the below table.

Table 1: Estimates of a, b, c & Specifications of b_0, b_1, c_0, c_1,

Data Set	Estimate of ‘a’	Estimate of ‘b’	b_0	b_1	Estimate of ‘c’	c_0	c_1
NTDS	55.018710	0.998899	0.648899	1.348899	278.610091	273	283
AT & T	34.636895	0.999859	0.649859	1.349859	390.507674	385	395
IBM	36.914829	0.999530	0.649530	1.349530	432.191666	427	437
Xie	44.834192	0.999825	0.649825	1.349825	365.151781	360	370
Lyu	50.196811	0.992935	0.642935	1.342935	75.673305	70	80
Sonata	338.720949	0.999958	0.649958	1.349958	18851.722242	18846	18856

Using the selected b_0, b_1 and c_0, c_1 and subsequently the $m_0(t)$, $m_1(t)$ for the model we calculated the decision rules given by equations (14), (15), sequentially at each ‘t’ of the data set taking the strength (α, β) as (0.05, 0.2). Application of SPRT for the six data sets and the related calculations are given in the following table.

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Table 2: SPRT Analysis for 6 Data Sets

Data set	t	N(t)	R.H.S of equation (14) Acceptance Region(≤)	R.H.S of equation (1)5 Rejection Region (≥)	Decision
NTDS	9	1	-0.625494	5.689154	Accept
	21	2	1.370656	7.804387	
	32	3	**3.060550**	9.601969	
AT & T	5.5	1	-1.762828	4.416667	Continuous
	7.33	2	-1.617226	4.575441	
	10.08	3	-1.401039	4.811382	
	80.97	4	3.265448	9.971477	
	84.91	5	3.482139	10.214789	
	99.89	6	4.272655	11.105808	
	103.36	7	4.448588	11.304863	
	113.32	8	4.939423	11.861747	
	124.71	9	5.476276	12.473563	
	144.59	10	6.355699	13.482420	
	152.4	11	6.682622	13.859720	
	167	12	7.267859	14.538445	
	178.41	13	7.703148	15.046188	
	197.35	14	8.386277	15.848453	
	262.65	15	10.420503	18.283354	
	262.69	16	10.421617	18.284709	
	388.36	17	13.319395	21.915640	
	471.05	18	14.731926	23.787736	
	471.51	19	14.738957	23.797297	
	503.12	20	15.203084	24.432892	
	632.43	21	16.773601	26.683790	
	680.03	22	17.245247	27.398149	
IBM	10	1	-1.425715	4.755247	Continuous
	19	2	-0.759069	5.480016	
	32	3	0.156309	6.478616	
	43	4	0.890075	7.282146	
	58	5	1.835309	8.321581	
	70	6	2.549062	9.109948	
	88	7	3.555208	10.226823	
	103	8	4.339626	11.102466	
	125	9	5.410192	12.305183	
	150	10	6.523917	13.566826	
	169	11	7.305376	14.459184	
	199	12	8.438666	15.765056	
	231	13	9.528640	17.035912	
	256	14	10.305800	17.952224	
	296	15	11.431953	19.297328	
Data set	**t**	**N(t)**	**R.H.S of equation (14) Acceptance Region(≤)**	**R.H.S of equation (15) Rejection Region (≥)**	**Decision**
Xie	30.02	1	0.956814	7.340516	Accept
	31.46	2	1.096422	7.490942	
	53.93	3	**3.145993**	9.707533	

Lyu	0.5	1	-2.275757	4.923078	Continuous
	1.7	2	-1.553076	5.687195	
	4.5	3	0.046772	7.383206	
	7.2	4	1.484286	8.912756	
	10	5	2.876639	10.399839	
	13	6	4.268044	11.891940	
	14.8	7	5.057271	12.741189	
	15.7	8	5.439864	13.153684	
	17.1	9	6.019794	13.779983	
	20.6	10	7.393523	15.268872	
	24	11	8.632679	16.618871	
	25.2	12	9.049422	17.074498	
	26.1	13	9.355309	17.409468	
	27.8	14	9.918079	18.026986	
	29.2	15	10.367361	18.521173	
	31.9	16	11.199645	19.439604	
	35.1	17	12.131641	20.472935	
	37.6	18	12.821775	21.241672	
	39.6	19	13.351511	21.833941	
	44.1	20	14.476245	23.098259	
	47.6	21	15.292014	24.021555	
	52.8	22	16.418567	25.306236	
	60	23	17.829777	26.933313	
	70.7	24	19.659042	29.077140	
Sonata	52.5	1	-1.235305	4.701932	Continuous
	105	2	-0.342398	5.602728	
	131.25	3	0.102160	6.051227	
	183.75	4	0.987512	6.944455	
	201.25	5	1.281519	7.241086	
	306.25	6	3.034022	9.009312	
	411.25	7	4.766978	10.757959	
	432.25	8	5.111252	11.105367	
	467.25	9	5.683340	11.682677	
	502.25	10	6.253312	12.257866	
	554.75	11	7.104327	13.116700	
	607.25	12	7.950644	13.970829	
	712.25	13	9.629343	15.665127	
	747.25	14	10.184821	16.225799	
	799.75	15	11.014244	17.063005	
	852.25	16	11.839148	17.895684	
	887.25	17	12.386591	18.448306	
	939.75	18	13.204044	19.273521	
	1044.75	19	14.825719	20.910698	
	1149.75	20	16.429991	22.530440	
	1254.75	21	18.017137	24.133026	

Data set	t	N(t)	R.H.S of equation (14) Acceptance Region(≤)	R.H.S of equation (15) Rejection Region (≥)	Decision
Sonata	1359.75	22	19.587431	25.718731	Continuous
	1412.25	23	20.366342	26.505336	
	1464.75	24	21.141140	27.287820	
	1517.25	25	21.911857	28.066217	
	1569.75	26	22.678526	28.840557	
	1674.75	27	24.199845	30.377198	
	1727.25	28	24.954558	31.139561	
	1779.75	29	25.705348	31.897993	
	1832.25	30	26.452245	32.652526	

We can see from the above table that a decision either to accept or reject the system is reached in earlier stage for the last time instant of the data (the testing time).

VI. Conclusion

We applied SPRT procedure on the proposed model to detect reliable/unreliable software products. The result of the present study shows that Pareto type II SRGM as exemplified for 6 Data Sets indicates that the model is performing well in arriving at a decision. The proposed model has given a decision of acceptance for 2 data sets and inconclusive for 4 data sets. NTDS and Xie Data Sets are accepted at 3rd instant of time. We can come to an early conclusion of reliable/unreliable software products by applying SPRT procedure on data sets.

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Dr. R Satya Prasad received Ph.D. degree in Computer Science in the faculty of Engineering in 2007 from Acharya Nagarjuna University, Guntur, Andhra Pradesh, India. He have a satisfactory consistent academic track of record and received gold medal from Acharya Nagarjuna University for his outstanding performance in a first rank in Masters Degree. He is currently working as Associate Professor in the Department of Computer Science & Engineering, Acharya Nagarjuna University. He has occupied various academic responsibilities like practical examiner, project adjudicator, external member of board of examiners for various Universities and Colleges in and around in Andhra Pradesh. His current research is focused on Software Engineering, Image Processing & Database Management System. He has published several papers in National & International Journals.

Mrs.N.Geetha Rani received M.C.A. and M.Tech degrees from Acharya Nagarjuna University. She is currently pursing Ph.D at Department of Computer Science and Engineering, Acharya Nagarjuna University, Guntur, Andhra Pradesh, India. She is currently working as Associate Professor and Head of the Department, in the Department of Computer Science, Abhinav Institute of Management and Technology, Singarayakonda, Andhra Pradesh. Her research include on Software Engineering.

R.R.L. Kantam is professor of statistics at Acharya Nagarjuna University, Guntur, India. He has 31 years of teaching experience in statistics at Under Graduate and Post Graduate programs. As researcher in Statistics, he has successfully guided many students for M.Phil and Ph.D in statistics. He has authored more than 60 research publications appeared various statistics and computer science journals published in India and other countries like US, UK, Germany, Pakistan, Srilanka and Bangladesh. He has been a referee for Journal of Applied Statistics (U.K.), METRON (Italy), Pakistan Journal of Statistics (Pakistan), IAPQR - Transactions (India), Assam Statistical Review (India) and Gujarat Statistical Review (India). He has been a special speaker in technical sessions of number of Seminars and Conferences. His areas of research interest are Statistical Inference, Reliability Studies, Quality Control Methods and Actuarial Statistics. As a teacher his present teaching areas are Probability Theory, Reliability and Actuarial Statistics. His earlier teaching topics include Statistical Inference, Mathematical Analysis, Operations Research, Econometrics, Statistical Quality control, Measure theory.