Proceedings of the 1993 Winter Simulation Conference
G.W. Evans, M. Mollaghasemi, E.C. Russell, W.E. Biles (eds.)

ASSESSMENT OF WAYS OF IMPROVING THE SUPPLY CONTINUITY IN ELECTRIC POWER SYSTEMS - A SIMULATION APPROACH

P. J. Nolan[1] M. E. JO'Kelly[2] C. Fahy[1]

1 Department of Mechanical Engineering
2 Department of Industrial Engineering
University College Galway
Galway, Ireland

ABSTRACT

Supply continuity is a key factor in product quality in electricity utilities. Supply outages are inevitable but a key objective of management is that these be minimised in terms of frequency and duration. The problem of supply continuity is particularly acute in rural areas which are supplied from radial tail fed lines.

Improvements can be achieved by major capital expenditure such as the addition of costly parallel lines, the inclusion of such aids as SCIs (Short Circuit Indicators) which speed up the location of faults, and additional telecommunications equipment. Also changes in the operating procedures used in locating faults and restoring supply can have a significant effect on customer down time and hence on supply continuity.

The realistic prediction of the effect of improvements in capital equipment, additional control and monitoring devices and/or of changes in operating procedures on customer down time is of fundamental importance. This paper presents a detailed simulation approach which can be used in such predictions.

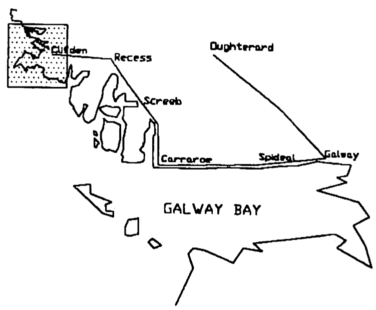
1 INTRODUCTION

The task of determining reliability and maintainability measures for large industrial systems is very difficult because of inherent complexity due to the very large number of components each with their own failure distributions. There are two general approaches based on analysis and simulation, respectively. Analytical techniques [Bazovsky (1961)] involves the repeated application of series and parallel reduction on the reliability network. The maintenance policies, which specify the procedures for repair and replacement of components vary widely. This significantly affects the overall reliability. Kapur and Lamberson [Kapur and Lamberson (1977)] used the concept of RBDs (Reliability Block Diagrams) to describe the possible combination of system components which will result in total system reliability. The components of the system are individual reliability blocks which are characterised by probability distributions for failure and repair. The connections between these reliability blocks indicate the various combinations of working components which result in an operational system. For partially redundant or other systems not amenable to structural decomposition into series and parallel blocks, general graph theoretic concepts [Dao (1974)] and generalised reliability block diagrams (RBD) can be used. Computers are of course very suitable to kind of processing in these applications.

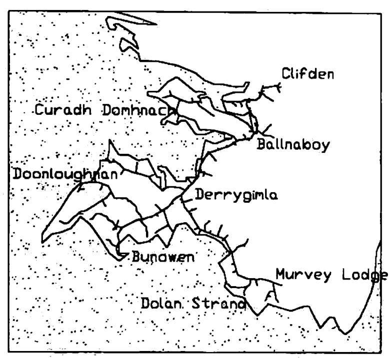
The second approach in evaluating reliability and maintainability is through simulation [Kermack, Millar & Deans (1989)][Figiel & Sule (1990)]. This is used in those situations where an analytical solution is not possible or practical. Simulating the operation of a system can include the transitions in the conditions of the components and allow the subsequent assessment of their impact on the behaviour of the overall system. This involves the use of a simulation clock which is advanced to an event such as a component failure. The effects of these component failures are subsequently propagated throughout the overall system. The simulation is continued until a specified end criterion is met.

Study System The subject of the present study is a section of the Electricity Supply Board (ESB) network. The ESB is the Irish national electricity company covering generation, transmission and distribution of electric power.The ESB's distribution system at the moment uses three main voltages, 38KV, 10KV and 220V. Most of the 38KV and 10KV systems have parallel feeds. If a fault occurs in the first line, the area can be feed from the second line (back-feeding).

The 38KV system is feed from the 110KV transmission system. There are plans to replace the 38KV and 10KV systems with a 20KV system, over the next decade or so. The Western Region due to demographic and geographic conditions has a standard of continuity lower than the national average. Figure 1 (a and b) shows the 38 kV transmission network in region being studied and an enlarged section depicting the 10 kV radial distribution lines, respectively.



(a) 38 kV Transmission Line



(b) 10 kV Lines in target area
Figure 1 Electric Network in Study Region

Faults are categorised as follows: (i) Fault rural, (ii) Fault urban (iii) Voluntary rural and (iv) Voluntary urban. Voluntary faults are prearranged outages of which the customers are given advance notice. These outages are required for line maintenance, repair, and system improvements.

There is a continuity target associated with each of the fault types. Faults are classified as being caused as follows: (i) Non-Weather, (ii) Lightening and (iii) Other Weather. Figure 2 shows the customer outage hours (whole country) due to each of these over an eight year period. Similar patterns are evident for the study region in which the "Other weather" and Lightening categories constitute an even larger proportion of the fault causes. In assessing reliability, the three characteristic types of failure i.e. burn-in, wearout-failures and chance failures must generally be considered [Bazovsky (1961)].

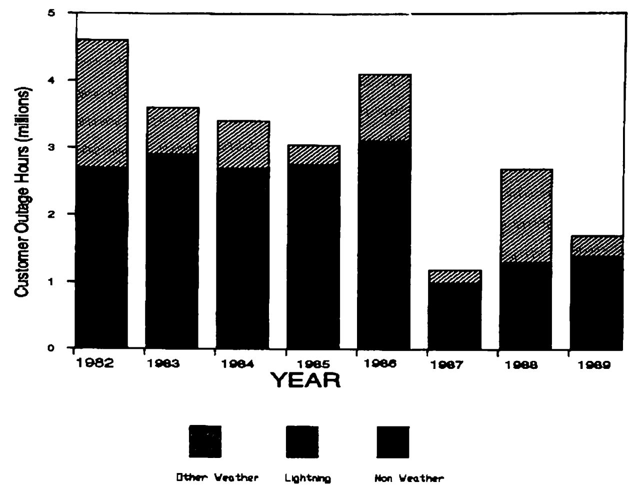


Figure 2 Fault Causes 1982-1989

In our case, the failure can be considered to be caused by the improper operating environment due to the weather conditions. Based on operational statistics from the electricity utility company, it can be seen that the majority of outages (failures) are due to lightning or windstorms. Consequential, in limiting the scope of the present study, the random failures of individual components were neglected. All failures are considered to be caused by externally applied stress levels considerably in excess of the normal operational values. Thus, since the wearout and chance failures need not be included, prohibitively expensive simulations involving special purpose algorithms, such as that used in the Reliability Simulation Workstation [Kermack, Millar & Deans (1989)], are not necessary.

It is worth noting that we are primarily interested in reliability assessment at the operational rather than at the design stage. Considerable effort at the design stage goes into increasing reliability by using parallel combinations of generators, transformers and transmission lines.

As part of an overall programme undertaken by the ESB aimed at improving continuity of supply, it was decided to build a simulation model which could be used to investigate the impact both of proposed changes of operating/maintenance procedures and of additional plant on supply continuity. It was agreed that initially a model should be developed for the non clustered sparsely populated tail fed area representing the Western Region of the ESB. A feature of this system is the small ratio of customers served to line length.

Questions relating to operational procedures such as the number and disbursement of electricians, whether all electricians cover all faults or if dedicated electricians respond to specific faults, the equipment available, transport and communications delays, may be significant in determining the overall outage time. Similarly, improvements in plant (e.g. addition of parallel lines), increased of use SCIs (Short Circuit Indicators) and general improvements in monitoring and telecommunications equipment will impact on supply continuity.

A previous paper [Fahy, O'Kelly & Nolan] described a preliminary simulation model used to investigate operational aspects. This paper presents a more comprehensive model, organised in a modular way which allows alternative subsystem models to be included. This permits alternative network configurations and/or additional equipment installations (e.g. supplementary short circuit indicators) to be also evaluated thus extending the scope of our investigations.

The next section discusses the overall modelling scope, algorithm used and the hierarchical modelling concepts employed in representing the system. Then the process interaction model for the overall system and the main subsystem models is presented. Sample results, verification and validation issues are subsequently presented.

2 MODELLING APPROACH

2.1 Model Description

Following detailed study of the supply continuity problem and the scope of the investigations of interest to the utility, the overall model evolved to include the effects of:

* Travel time within the region
* Sectionalising
* Line Patrolling
* Repair and Restoration

It should accommodate:

* Variety of fault types including earth faults and short circuits
* Any network location (on backbone, spur etc.)
* Day or night faults
* Variable number of electricians
* Selectable base location for electricians

2.2 Algorithm

There are a number of approaches in the simulation modelling of discrete event systems: Event-Based, Activity Scan and Process Interaction. For a general discussion Reference [Pritsker (1984)] is recommended. While each approach has its own advantages and disadvantages, in the opinion of the authors, the choice ultimately is dictated by the subjective preference of the modeller. Reference [Banks & Carson] contrasts the approaches.

The particular approach adopted in this study was to initially develop the model in terms of the process interaction approach i.e. to model the progress of the simulation entities (e.g. electricians) as they progress through the process. In this way we can show the entry, various operations, queues, delays, branch points and so on associated with the entities. The process interaction approach is widely used in the available general purpose simulation languages. This approach is particularly amenable to hierarchical modelling which is important in a large scale study such as this. It also forms a suitable basis upon which to build animated displays (described later).

In implementing the simulation, we subsequently converted this model into the ABC or three-phase representation [Mathewson (1990)]. The term three-phase refers to three phases in the simulation algorithm and has nothing to do with three phase electric supply. The nomenclature is thus unfortunate in the context of this electricity utility application. The ABC or three-phase representation is an adaptation of the pure activity scan approach referenced above. The approach is significantly more computationally efficient than the activity scan method and has been used extensively in simulation studies - particularly in the UK.The phases are defined as follows:

A-phase Time is advanced during this phase. An event calendar is used to hold the scheduled events. Entries are made to the calendar due to the creation of entities and also in response to events scheduled within the simulation model e.g. if a time delay is encountered then a event is scheduled to reflect its ending.

B-phase This are scheduled events bound to occur i.e. once scheduled these always happen. They do not depend on the cooperation of entities within the simulation model. As an example if a service activity has started (e.g. a repair operation) then its conclusion will be scheduled as a B-phase event.

C-phase C-phase activities involve the evaluation of a test head and if this is true the activity can take place. As an example, in order for a particular operation to begin a workpiece may be required (non empty queue) and certain resources may be required to be free.

The pseudocode for the basic algorithm is:

```
INITIALISATION
A-phase (Time Advance)
Exit Criterion
B-phase
C-phase
go to A-phase
EXIT
```

Translating a process interaction model into the three-phase representation is straightforward. It can be performed manually or if an appropriate graph theoretic data representation is used for the process iteration model, an automatic conversion can be employed.

2.3 Hierarchical Modelling

In modelling large systems such as that under consideration here, it is useful if we use a 'divide et impera' (divide and conquer) approach. Submodels can be used effectively to help reduce the complexity of the overall model. This allows us to replicate repeated sections and to simplify the task of including variability in the number of model elements.

The overall system is considered to comprise, at the top-level, a number of interacting subsystems. The subsystems are defined first at an abstract level. Subsequently, the subsystems are refined by adding detail. It should be emphasised that it is not always possible, apriori, to decide if a particular effect is important. It is important to compare results from models with different levels of detail to establish what the significant issues are, and thus establish the level of modelling required.

In many practical systems, the overall system model contains sections which are similar. Also different systems may have sections which are quite similar. For example, a simulation model used in studying the emergency operation of ambulances, and the model for investigating the repair of rural electric utility systems would have sections dealing with travel. Correspondingly, in a large model a section may be replicated a number of times. By storing in a library such a generic submodel, it may be used repeatedly in the same system model or in different applications. Obviously, this will reduce duplication of effort. Also, the possibility of errors is reduced as a centrally maintained version would be rigourously tested.

The above advantages of hierarchical decomposition is fully consistent with modern OOP (Object Oriented Programming) philosophy. In the context of simulation modelling another important advantage is that often a subsystem model will be amenable to analytical solution even though the overall system model may not be. Even when the subsystem model can not be solved analytically, a separate simulation of the subsystem can often be used to characterise an equivalent model.

3 IMPLEMENTATION

3.1 Process Interaction Representation

The model is constructed by depicting the system as a series of successive process functions (known as activities) such as time delays and service operations. The model may be viewed as a flowchart which describes the movement of entities (see below) through the system. The particular process functions available to the modeller depend on the simulation language being used. Most simulation languages provide a similar set of basic simulation elements. The basic set of blocks used in the present study are depicted in Figure 3

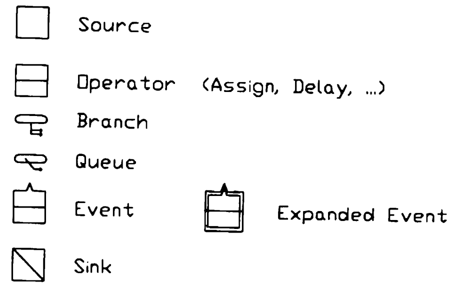


Figure 3 Simulation Blocks Description

The objects of concern in our simulation study such as faults, alarms, electricians or information are known as entities. An entity may carry information which allows the modeller to distinguish between entities of different types (travel time, alarm sequence, etc.). This information is stored as attributes of the entity, which it carries with it through the model. As the entities move from block to block, they may be delayed, destroyed, combined with other entities, etc. depending on the element types encountered. In a simulation model, the physical resources of the system being modelled (workers, machines, tools, etc.) are represented by resources. A resource is a number of units which may be allocated to the entities flowing through a model.

Top-Level Model. The overall process model is depicted in Figure 4.

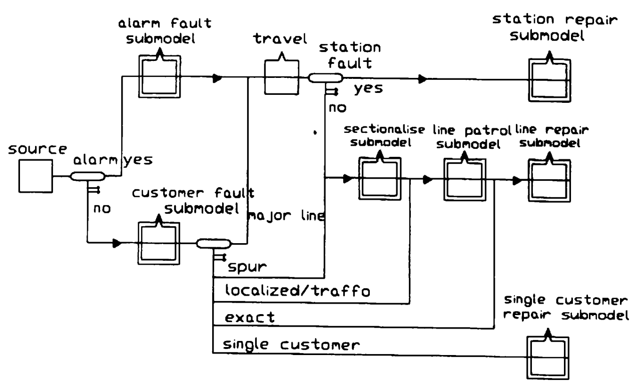


Figure 4 Overall Process Interaction Model

It is based on the hierarchical submodelling concepts described already and its operation is largely self evident. The mainstream entity in our simulation model is a fault. It has a number of attributes with information on whether it was automatically detected or reported by customers, details supplied by neighbours as to whether neighbours are out, type (earthfault or short circuit), its location in the network (line and pole number) and so on. A brief explanation of the operation is given below. The first block after a fault is generated represents the decision whether it is reported by a customer (case 1) or automatically detected (case 2). Appropriate submodels (described later) are used to represent the processes involving alarm and customer reported faults, respectively.

Both in the case of alarm faults and major line faults which have been reported through customer complaints, an electrician travels to the station. In the case of a station fault, a station repair submodel is invoked.

In the case of either (i) an alarm fault other than a station fault or (ii) of a spur fault (reported by customer complaint), the electrician(s) proceed to perform sectionalisation, line patrol and repair. Each of these is represented as a separate submodel.

For those situations involving customer reported faults, sectionalisation is necessary in the case of spur faults but is not in the case of localised and transformer faults. Line patrol is not required when exact fault location information is available. In the particular circumstance of a single customer outage, special procedures are followed and this is again represented by a specific submodel.

Customer Fault Classification Submodel. The submodel, shown in Figure 5, mimics the query session conducted and the rules of thumb used in attempting to glean as much information as possible from customer(s) reporting a fault.

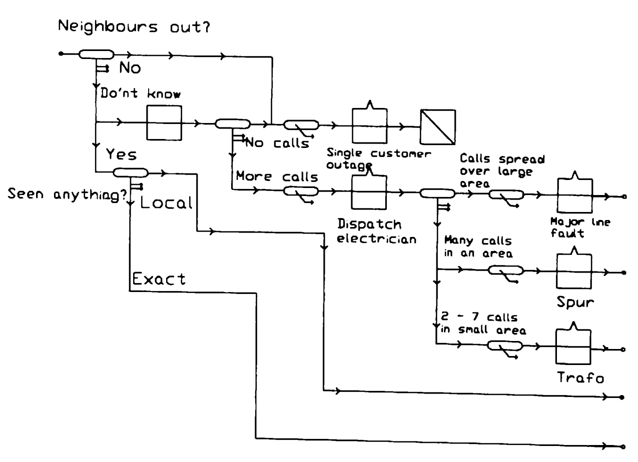


Figure 5 Submodel for Fault Classification

In particular it can be seen that if a customer is sure his neighbours are not out or if he is not sure and there are subsequently no further calls, then the likelihood is that it is a single customer outage. Similarly, customers reporting a fault may be able to provide very useful information such as identifying the general and often the exact location.

Alarm Fault Classification Submodel. This submodel represent the steps followed when a fault is automatically detected as distinct to being reported by customers. Three different alarms are possible. The first, designated as Alarm-1, indicates an earth fault. Alarm-2 represents the case of a short circuit on a line which is not equipped with a short circuit indicator. Correspondingly, Alarm-3 represents the case of a short circuit on a line equipped with a short circuit indicator.

Following the alarm submodels, the submodel of the electrician's travel to the station is processed. The coordinates of the electricians original location (usually, though not always, the base location) and those of the station are used. The season and time of day are also factored in. The possibility that the fault is within the station is taken into account.

Sectionalisation Submodel. This submodel (see Figure 6) essentially involves an iterative procedure of switching out various sections of network and checking when the faulted section of line is isolated thus identifying the section of line which is faulted. Somewhat different procedures are used in the case of earth faults as distinct to short circuits. If the lines are equipped with SCIs (Short Circuit Indicators) they are used to further narrow down the area of the fault. This subsequently affects the amount of work to be done in line patrolling. This submodel essentially models travel by foot along the line.

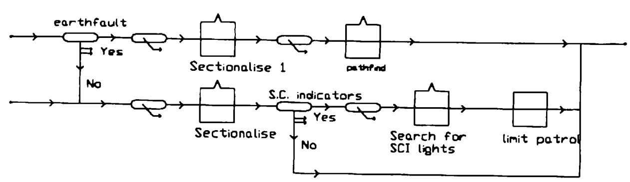


Figure 6 Submodel for Sectionalisation

Line Repair Submodel. This submodel is depicted in Figure 7. In the present study a relatively simple model is used - more detailed submodels can be included.

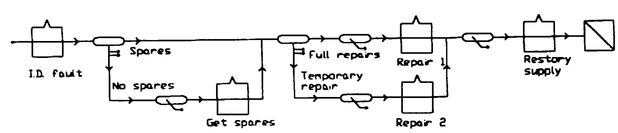


Figure 7 Submodel for Line Repair

A noteworthy feature is the situation when the required spares are not at hand is accommodated. Also differentiation is made between permanent and temporary repairs.

3.2 Stochastic Aspects

When modelling real situations such as the present system, some activities are essentially stochastic (probabilistic) in nature. Examples include duration of repair time, or number of occurrences of events (e.g. faults) in a period of time. As well as activity duration, the routing and resource requirements of entities may be governed by rules which cannot be expressed deterministically.

In characterizing such situations, three separate approaches may be adopted. Firstly, data collected from the real system may be fed directly into the simulation model (trace driven approach). Secondly, observed data may be grouped and fed into the model. Finally, data may be approximated by a theoretical distribution and values obtained by sampling from the chosen distribution employed.

Some of the advantages of using statistical distributions are that they extend the range of data beyond values observed, smooth the input data, and provide insight into the nature of the input data. UniFit [Vincent & Law (1990)] was used to fit a distribution to data. The result is a list of distributions and a heuristic evaluation of which distribution most accurately represents the data.

3.3 Hardware/Software System

The selection of the software and hardware platform for this study followed detailed discussions on the both the project scope and projected future use of the model. It was decided that the model should ideally be PC based. Because of the problem,s complexity it was decided that graphical animation [Earle, Brunner & Henriksen (1990)] would be very important. The approach used in general purpose simulation languages e.g. SIMAN [Pegden (1984)] and SLAM [Pritsker (1984)] would be applicable. However it was decided to initially develop the system using AutoLISP [AutoCAD/LISP (1991)] because of the suitability of AutoCAD [AutoCAD/LISP (1991)] as a front end, its suitability in implementing the animation and its general acceptance among engineers.

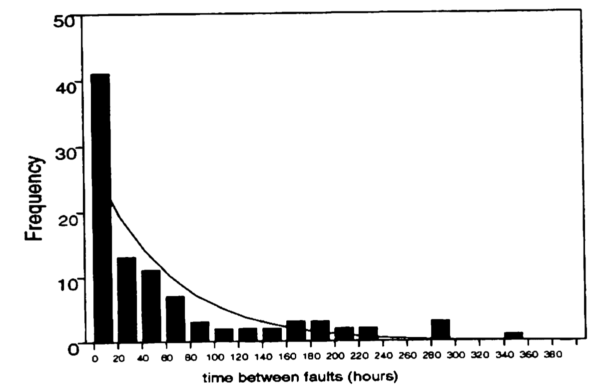
4 SAMPLE RESULTS

4.1 General

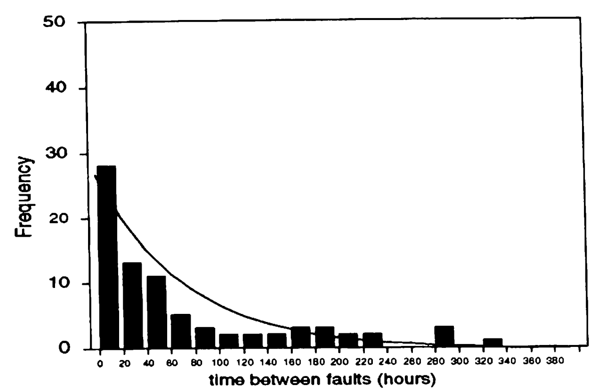
The primary purpose of this paper was to show the use of simulation in the present application by outlining the overall simulation model, discussing the verification and validation of the model and to presenting sample results. The design of comprehensive simulation experiments, subsequent exercising the model, interpretation of the results, drawing the relevant conclusions therefrom and making the appropriate management decisions is the subject of further work at the utility. The verification procedure and validation results as well as typical experiments which might be carried out are presented here.

4.2 Typical Simulation Results

Routine Lightening Faults. As a typical example, we considered the routine repair of the network due to lightning faults over a one year period. The histogram in Figure 8(a) shows the frequency of all lightning faults for interval width of twenty hours. Experienced utility engineers helped to identify the data associated with lightning storms. The diagram in Figure 8(b) is the corresponding case when the storm contributions are removed. Also shown superimposed on the histograms are trial theoretical distribution fits (exponential in this case) to the data. UniFit [Earle Brunner & Henriksen] was used to provide graphical and appropriate statistical tests to verify that proper distribution functions with realistic parameters.



(a) All Lightening Faults



(b) Lightening Fault (exc. Storms)

Figure 8 Faults due to routine lightning

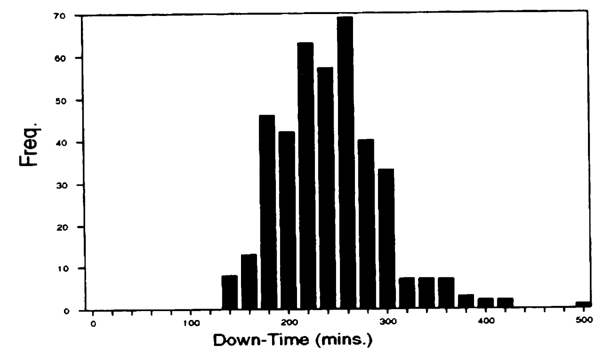
An exponential distribution was used to model the interarrival time of incoming faults. The system was simulated for 365 days. No significant change in output statistics was found for longer runs. Processing time on 386 PC was approximately 5 minutes. During this time the simulation shows that 1361 faults were repaired in the Clifden area. The minimum and maximum times between faults was 20 hours and 17 days, respectively. The average time between faults was 2.67 days.

Table 1 shows the down time due to routine lightning for the cases of three and four electricians on call. In the case of three electricians, the effect of adding additional short circuit indicators (which reduces the line patrol time) is also shown.

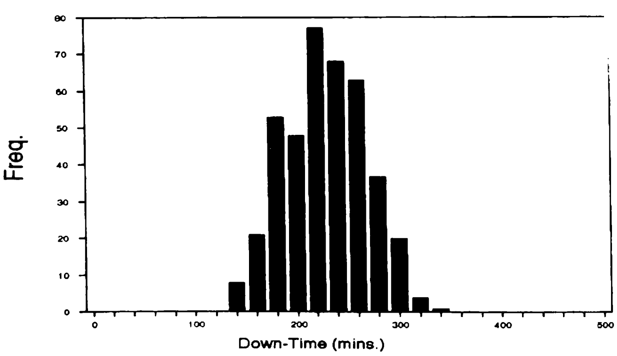
Table 1 Down time (mins) due to Routine Lightening (RL)

case	elecs	min	max	mean	stdev
RL	3	125.8	485.3	232.2	51.1
RL	4	125.8	335.0	218.0	39.6
New patrol	3	103.4	324.3	192.6	39.0

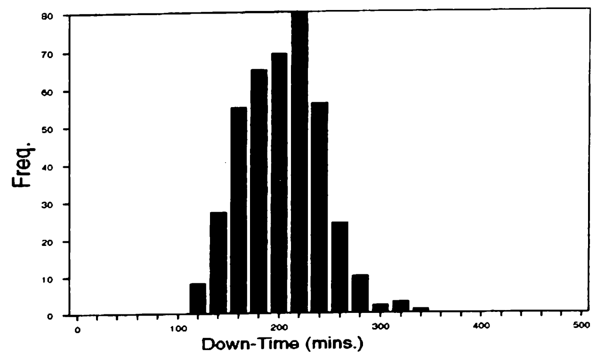
The histograms in Figures 9 show the distributions. In particular the outlying results above 400 minutes (Figure 9a) is noteworthy.



(a) 3 electricians



(b) 4 electricians



3 electricians- improved patrol times
Figure 9 Histogram for down times in routine lightning

Electric Storm Situation. As part of the experimentation carried out in validating the simulation model the response to a two day summer electric storm was considered. Based on analysis of the ESB's fault data the average time between faults was two hours and the minimum and maximum times between faults was 20 and 270 mins, respectively. The base case scenario assumes that there are three electricians on call in the Clifden Area (see Figure 1) during the storm. It is further assumed that operating policy requires that at night two electricians respond to a fault. During day time a single electrician suffices - he may, however, depending on the severity of the fault require back up assistance from another electrician.

The system was assumed to be "empty and idle" initially. Replications of the simulations using different streams of random numbers and different end times were used to insure convergence in the output statistics. The results showing the minimum, maximum and average outage times in the above fault scenario are summarised in Table 2. The target mean down time is achieved with 4 electricians.

It should be pointed out that the results presented above are for the specific cases of storm response and routine repair to lightning outages. Further studies are planned where the normal long term mix of faults due to wind, lightning, equipment ageing are considered together.

Table 2 Down time (mins) during lightning storm

case	elecs	min	max	mean	stdev
Lightning	2	132.7	647.1	259.0	86.5
(as above)	3	124.0	466.8	223.3	47.3
(as above)	4	124.0	337.3	217.3	40.0

4.3 Verification & Validating

Verification. This is concerned with determining if the simulation program works as intended. The animation facility available with our AutoCAD interface provides a visual means to verify that the model correctly represents the system. By monitoring the movement of the entities and the state of the resources (e.g. Electricians) errors in logic can be readily determined. Such errors might be very difficult to detect otherwise. Experienced engineers verified our model.

Statistical Aspects. As our simulation model is stochastic, different results will be obtained during each run due to the inherent randomness. Consequential, we are faced with the issue of showing that the different results obtained between two simulation runs are due to a parameter change and not to the above inherent randomness. The factors used in estimating the required length of a simulation run and in deciding the number of repetitions of the simulation experiment is discussed in [Pritsker (1984)]

In order to determine confidence intervals for the results obtained, the individual simulation runs were subdivided into batches. The mean down times from each batch was calculated. The t-test, described in Reference [Pritsker (1984)], was used to establish the confidence intervals for our results.

If $t_{\alpha,d}$ represents the t statistic for given degrees of freedom, d and significance level α Statistics tables are available with the values e.g. $t_{0.05,8} = 2.262$.

If a simulation experiment has been replicated K times, i.e., a lengthy simulation broken into K batches, then for the stochastic variable X with mean m_x and variance R_{XX}, the confidence interval for the 'true' mean can be calculated from the following equation:

$$m_x \pm t_{\alpha,d}\sqrt{\frac{R_{xx}}{K}}$$

where $t_{\alpha,d}$ is the t-statistic for confidence level α and d degrees of freedom, and R_{XX} is the variance.

Applying the above formula to the simulation experiments arranged into 8 batches, we obtain the following 96% confidence intervals for the mean down times for the routine lightning fault cases:

3 electricians: 210.9 min < mean down time < 225.6 min

4 electricians: 183.6 min < mean down time < 201.7 min

It can be seen from the above that, as there is a clear separation between the 95% confidence intervals, the simulation experiments yield definite results

Validation. Validation ensures that the results from the simulation are correct and faithfully represent the behaviour of the real system. The process involves comparing the statistical outputs from the real system and model. Confidence intervals can then be constructed to guide us in applying the simulation results. Fortunately, in the present application, a wealth of data is available for validation purposes.

Statistics on the behaviour of the real system such as the mean down times can be calculated from the data base derived from the computerised fault outage reports. The t-test used above in determining the confidence intervals on the simulation results can be used to test the hypothesis that the simulated and real mean down times are acceptably close.

5 DISCUSSION

The purpose of developing the simulation was to provide a tool which could be used by engineers in the utility in performing "WHAT-IF" experiments to ascertain the effect of procedural and equipment changes on the down time in electricity supply. The overall objective function is to reach target down times within financial constraints. The simulation implemented includes realistic modelling of the main processes including initiation of fault alarms (customer phone in or automatic), travel to station, travel to fault, line sectionalisation and patrol and repair. Various changes in procedure can be readily investigated via parameter changes (e.g. change number of on call electricians). Similarly appropriate infrastructural changes which might be made to the network can be implemented in the model and their effects investigated. As a specific example the effect of adding further SCIs (short circuit indicators) would be expected to reduce the time required to locate faults. The extent to which a given investment in SCIs would reduce the down-time can be determined within specified confidence limits.

The model was developed and the simulation implemented in such as way that users are easily able to follow the decision logic. The model can be trace driven from historic data to prove that it produces the same results as the real system as well as the more usual case of using statistical distributions. The animated displays assist in verifying that the model correctly reflects the decisions made in practice. The decomposition of the overall model into interacting submodels each representing clearly identifiable processes and the subsequent facility for using models of varying detail for each of these, greatly simplifies the task of producing an overall model which is sufficiently accurate .

6 CONCLUSIONS

The general problem of predicting the effect of capital investment and procedural changes in an electricity distribution network has been presented and a simulation approach proposed. A detailed model developed in terms of a hierarchical decomposition of a top-level model has been presented. Detailed submodels represent the effects of travel, sectionalisation, line patrolling, repair and restoration. The model can accommodate a variety of faults including earth faults, and short circuits. The faults (both day and night time faults) can occur at any location in the network. The model was validated against operational records of outages available from the utility company. The usefulness of the model in investigating operating procedures on supply continuity has been exhibited by presenting output results and calculations on the confidence measure for the mean down time which is a main indicator in supply continuity.

7 ACKNOWLEDGEMENTS

This project was sponsored by the Distribution Department of the ESB. The assistance of Mr K. O'Hara (Director, Customer Services), Mr T. Stefanazzi (Computer Applications), Mr T. Martin (Galway Branch Manager), Mr K O'Shea (Customer Service Engineer Galway), Mr. J Kirby (Systems Division Manager) and the other engineers and area supervisor electricians at the Galway Branch, is gratefully acknowledged.

REFERENCES

AutoCAD/LISP 1991 "AutoCAD Reference Manual, & AutoLISP Programmers Reference", AutoDesk LTD, Surrey, England.

Banks, J., Carson, J.S.," Process-interaction Simulation Languages" Simulation 44

Bazovsky I. 1961. Reliability theory and Practice, Prentice Hall, Englewood Cliffs, New Jersey.

Dao N., 1974. Graph Theory with Applications to Engineering & Computer Science.Prentice-Hall, Englewood Cliffs, New Jersey,

Earle, N.J., Brunner, D.T. Henriksen, J.O., "Proof - The General Propose Animator", 1990 Winter Simulation Conference Proceedings, pg 106 - 108.

Fahy, C., O'Kelly M.E.J., and Nolan ,P.J. 1992. Simulation Modelling of the Repair Operations in Electric Power Systems, Proceedings of the Ninth Conference of the Irish Manufacturing Committee, pp 373-389 Editor J. Brown, Dublin. ISBN 1-870089-79-0

Kermack C.S, Millar A.J and Deans N.D. 1989. A Reliability Simulation Workstation p 750-753, Proceedings of the Third Simulation Congress, Edinburgh, Scotland.

Kigiel K.D and Sule D.R. 1990. "A Generalised Reliability Block Diagram (RBD) Simulation". pp 551 - 556, 1990 Winter Simulation Conference Proceedings, Society for Computer Simulation, International, San Diago California.

Kapur K.C and Lamberson L.R. 1977. Reliability in Engineering Design, John Wiley , New York.

Mathewson S.C, "Simulation Modelling Support via Network Based Concepts", pp 459 - 467, 1990 Winter Simulation Conference Proceedings, Society for Computer Simulation, International, San Diago California.

Pegden, D.D.,1984. " Introduction to SIMAN", Systems Modelling Corporation, state College, Pennsylvania 16805, April

Pritsker, A.A.B. 1984 "Introduction to Simulation and SLAM", 2nd edition, Halsted Press, West Lafayette, Indiana, USA.

Vincent, S.G., Law, A.M., "A Tutorial in UniFit II - A System for Total Support of Simulation Input Modeling", 1990 Winter Simulation Conference Proceedings, pg 180 - 185

AUTHORS BIOGRAPHIES

Paul J. Nolan is a Statutory Lecturer in Mechanical Engineering at University College, Galway. He received the BE degree from University College Dublin and the M.Eng and PhD degrees from McMaster University (Canada) in Electrical Engineering. His research interests include discrete and continuous time simulation and control systems.

MEJ O'Kelly is Professor of Industrial Engineering at University College Galway. He holds a PhD degree in Applied Mechanics, Electrical Engineering and Economics from the Californian Institute of Technology. His research interests are in the areas of operations, reliability and manufacturing strategy.

Cathal L. Fahy received the BE and M.Eng Sc degrees in Mechanical Engineering at University College Galway. He is currently working as research engineer at University College Galway.