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Reliability of systems, equipment and components —

Part 2: Guide to the assessment of reliability

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Foreword

This Part of BS 5760 has been prepared under the direction of the Quality, Management and Statistics Standards Policy Committee. It supersedes BS 5760-2:1981, which is withdrawn.

This revision of BS 5760-2 has a wider scope than BS 5760-2:1981. The text has been restructured with the object of providing more guidance to the practitioner on the extensive range of techniques available for reliability assessment. Some of the important pitfalls and limitations that may be encountered are identified. Many new topics are addressed but some of the mathematical treatment of the 1981 edition has been retained in the annexes. References are given to standards that provide more detailed guidance on individual assessment techniques.

A standardized systematic approach is essential to ensure that statements are consistent and unambiguous in all communications concerning reliability programmes. As well as providing a basis for the preparation of reliability programmes this British Standard can be used in preparing documents concerned with the specification of reliability or the reporting of reliability data or tests.

It is vital that reliability is recognized and treated as an important characteristic of a system (equipment or component) from design conception to the end of its working life, and that the reliability experience of one generation of products, engineers or technology is used by the next. This means that each factor that affects reliability at any stage in the life of an item has to be identified and considered in its relationship to the other factors. This procedure can be formalized into a reliability programme. It may be necessary to divide such a programme into two parts, one of which may be the concern of the designer and manufacturer, and the other the concern of the user. It is most important that consideration be given to the reliability of items or parts that are used by one manufacturer but produced by another, i.e. subcontractor evaluation and vendor appraisal (see BS EN ISO 9000).

BS 5760 provides comprehensive guidance on many aspects of reliability management. Thirteen Parts of this standard have been published and these may be summarized as follows:

- *Part 0: Introductory guide to reliability.* This Part provides guidance for senior management and non-specialists on the importance of reliability and explains how measures to achieve reliability should be integrated with other aspects of project management.
- *Part 1: Guide to reliability and maintainability programme management.* This Part discusses the essential features of a comprehensive reliability and maintainability programme to produce reliable and maintainable products.
- *Part 2: Guide to the assessment of reliability.* This Part explains the purpose and problems of assessing reliability. A range of available assessment techniques is reviewed and the principal advantages and limitations are outlined. Sections are included on the assessment of software reliability, human reliability and one-shot devices. The extension of these techniques to the assessment of availability and to the assessment of reliability of services is considered. The use of a range of statistical distributions to analyse reliability data is described.
- *Part 3: Guide to reliability practices: examples.* This Part contains authentic practical examples illustrating the principles established in BS 5760-1 and BS 5760-2.
- *Part 4: Guide to specification clauses relating to the achievement and development of reliability in new and existing items.* This Part provides detailed guidance on the specification of reliability.
- *Part 5: Guide to failure modes, effects, and criticality analysis (FMEA and FMECA).* This Part gives guidance on the application of these techniques.

— *Part 6: Guide to programmes for reliability growth.* This Part describes procedures for exposing and removing weaknesses in hardware and software items in order to achieve acceptable reliability in a product. It explains basic concepts, management and test procedures and describes techniques for analysis and correction of failures.

— *Part 7: Guide to fault tree analysis.* This Part gives guidance on the application of fault tree analysis. This technique may be used to identify factors affecting the reliability, performance and safety characteristics of a system.

— *Part 9: Guide to the block diagram technique.* This Part describes the use of the block diagram technique for modelling and evaluating the reliability of both elementary and more complex systems. The extension of the method to calculate availability is also outlined.

— *Part 10: Guide to reliability testing.*

— *Section 10.1: General requirements.* This Section provides guidance on general principles, procedures and considerations for reliability testing in the laboratory and in the field.

— *Section 10.3: Compliance test procedures for steady-state availability.* This Section provides guidance on techniques for testing the availability performance of frequently maintained items under defined conditions.

— *Section 10.5: Compliance test plans for success ratio.* This Section gives procedures for preparing and applying compliance test plans for success ratio or failure ratio. Plans are provided for three main types of test.

NOTE 1 Further Sections of Part 10 based on other Parts of IEC 605 and related IEC standards are planned.

— *Part 12: Guide to the presentation of reliability, maintainability and availability predictions.* This Part gives guidance on the presentation of quantitative predictions of reliability, maintainability and availability. The items to be included when presenting prediction information are listed and explained with the object of facilitating comparisons between projects and reports.

— *Part 13: Guide to preferred test conditions for equipment reliability testing.*

— *Section 13.1: Indoor portable equipment; low degree of simulation.*

— *Section 13.2: Equipment for stationary use in weather protected locations; high degree of simulation.*

— *Section 13.3: Equipment for stationary use in partially weather protected locations; low degree of simulation.*

— *Section 13.4: Equipment for portable and non-stationary use; low degree of simulation.*

— *Part 14: Guide to formal design review.* This Part provides guidelines for planning and conducting design reviews. Much of the guidance given is widely applicable and relevant to the general conduct of design reviews but it also includes details of the specific contributions to be made by various specialists.

Further Parts of BS 5760 are envisaged in order to provide guidance on other techniques of reliability management. At present two further Parts are in the process of being drafted, and these are as follows:

— *Part 8: Guide to the assessment of reliability of systems containing software.* This Part will provide guidance on the assessment of reliability of systems containing software. (This is currently published as DD 198: 1991)

— *Part 11: Guide to the collection of reliability, maintainability, availability and maintenance support data from the field.*

Whilst mainly addressing system and equipment level reliability, many of the techniques described in the Parts of BS 5760 may also be applied at the component level. Further guidance on component reliability is given in CECC 00804.

Guidance on specific aspects of maintainability is provided in the various Parts of BS 6548 *Maintainability of equipment*.

NOTE 2 This Part of BS 5760 makes reference to BS 4778 *Quality vocabulary*, and in particular to BS 4778-3.1, which contains definitions relating to reliability concepts applicable to this Part of BS 5760. It is essential that these definitions and concepts should be fully understood if this guide is to be interpreted correctly. For this reason it is recommended that BS 4778 should be read in conjunction with BS 5760.

NOTE 3 BS 4778-3.2 deprecates the use of the terms “failure modes and effects analysis” and “failure modes, effects and criticality analysis”. It favours the use of “fault modes and effects analysis” and “fault modes, effects and criticality analysis”, and these terms are used throughout BS 5760-2. However, the older terms have been retained in BS 5760-5 in order to align it with the current version of IEC 812.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to viii, pages 1 to 104, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

Section 1. General

Introduction

The assessment of reliability is an important element of many reliability programmes and can be implemented during the various phases (see 3.1) of the life cycle of a product. Depending on the availability of data, the assessments may be either qualitative or quantitative.

NOTE Reliability programmes are described in BS 5760-1.

Assessments may be required during early studies to define the product and its fundamental design in order to compare the characteristics of various design options. Assessment may also be required during the design phase to provide confidence that the design will conform to customer or market requirements, or during introduction to service and throughout the life of the system in order to identify design weaknesses and to monitor reliability.

Reliability assessments may therefore be carried out at any time from original definition of the project and throughout the useful life of an equipment. Indeed, assessment of the success or otherwise of an earlier design may be used to advantage when considering the development of the design of a new product.

The party with the predominant interest in the reliability of any product is the user. However, the manufacturer or supplier also has a significant interest. Even when penalties for deficiencies in reliability are not involved, a firm's reputation and consequently its future business may suffer as a result of unreliable products. Due regard to product reliability is therefore a consideration that should be addressed by both user and supplier. The relative involvements of both tend to vary according to the type of product and the life cycle involved. In this context, products tend to fall into one of the following categories:

- a) a specialized product designed and developed for a single or small number of specialized users (e.g. a ship or a new military aircraft); and
- b) a product for which a wide potential market is perceived (e.g. an automobile).

In category a) the user normally dictates the specification of the product and is often involved to some extent in its design and development. In category b), the supplier is usually solely responsible until the useful life phase commences. In both cases the guidance given in this standard will be applicable but the balance of the complementary involvements of user and supplier will need to be adjusted according to the particular circumstances.

1.1 Scope

This Part of BS 5760 provides guidance for the practitioner on the assessment of the reliability of systems. It includes a review of the range of techniques available for performing reliability assessments. The applicability of these techniques, depending on the nature of the product and its state of development and use, is described.

1.2 References

1.2.1 Normative references

This Part of BS 5760 incorporates, by dated or undated reference, provisions from other publications. These normative references are made at the appropriate places in the text and the cited publications are listed on the inside back cover. For dated references, only the edition cited applies; any subsequent amendments to or revisions of the cited publication apply to this Part of BS 5760 only when incorporated in the reference by amendment or revision. For undated references, the latest edition of the cited publication applies, together with any amendments.

1.2.2 Informative references

This Part of BS 5760 refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on the inside back cover but reference should be made to the latest editions.

1.3 Definitions

For the purposes of this Part of BS 5760, the definitions given in BS 4778-3.1:1991 and BS 4778-3.2:1991, BS ISO 3534-1:1993 and BS 5532-3:1986 apply together with the following.

1.3.1

life cycle cost

the cost of acquisition and ownership of a product over a defined period of its life cycle

NOTE It may include the cost of development, acquisition, operation, support and disposal of the product.

1.3.2

software metric

a measure of some attribute of a software product (e.g. count of lines of code), of the software development process (e.g. time duration) or of the resources consumed (e.g. effort expended)

NOTE The term is often applied loosely to any quantified information that can be gathered regardless of whether it constitutes a well defined measure.

1.4 Symbols

A	Availability NOTE 1 The subscripts cap, int, op, prod and sby are used to denote capability availability, intrinsic availability, operational availability, production availability and standby availability.	β	Growth factor in the AMSAA model or Customer's risk or Weibull shape parameter
A_i	Availability of unit, component or block i	$\Gamma(c)$	Gamma function
A_S	Availability of a system	γ	Weibull location parameter or minimum life
c	Shape parameter in the gamma distribution	η	Weibull scale parameter or characteristic life
D_a	Critical value in the Kolmogorov-Smirnov test for significance level α	θ	Mean time to failure (MTTF)
E	Estimated system fix effectiveness	θ_0	Reliability parameter proposed by the producer
E_i	Expected number of occurrences of failure in class i	θ_1	Minimum reliability parameter required by the customer
F_i	Probability of failure of unit or component i	λ	Numerical value of failure rate of a unit
F_S	Probability of failure of a system	$\lambda(t)$	Hazard rate
$F(t)$	Cumulative distribution function of the time to failure	λ_0	Failure rate from state 0 (similarly λ_1, λ_2 , etc.)
$f(t)$	Probability density function of the time to failure	λ_i	Failure rate of unit, component or block i (similarly λ_A etc.)
m_i	Mean order number for the i th failure	λ_S	Overall failure rate of a system
n	Total sample size or Number of data classes in the χ^2 test	μ	Numerical value of repair rate of a unit or Mean number of failures in a single trial
O_i	Number of occurrences of failure in class i	μ_0	Repair rate from state 0 (similarly μ_1 etc.)
P_0, P_1 , etc	Probability of a system being in state 0, 1, etc.	μ_i	Repair rate for unit, component or block i (similarly μ_A etc.)
p	Probability of failure in a single trial	ν	Number of degrees of freedom in the χ^2 test
$R(t)$	Reliability function	σ	Standard deviation of t or of $\ln(t)$
R_i	Reliability of unit or component i (similarly R_A, R_X, R_1 , etc.)	τ	Mean time to restoration (MTTR)
R_S	Reliability of a system	ϕ	Standard normal cumulative distribution function
T	Total test time	φ	Standard normal probability density function
t	Time	NOTE 2 A caret (^) over a symbol denotes an estimated value.	
t_i	Time to the i th failure		
t_{50}	Median of times to failure		
U	Unavailability		
U_i	Unavailability of block i		
U_S	Unavailability of a system		
α	Reliability growth factor in the Duane model or Producer's risk or Significance level in the χ^2 and Kolmogorov-Smirnov tests		

Section 2. Purposes and problems

2.1 Purposes

The principal purposes of reliability assessment or modelling include the following:

- a) to provide an early indication of the potential of a system to meet a stated reliability requirement;
- b) to reveal aspects of the design that require particular attention to reliability or that present high risks in relation to the requirements (assessment may reveal that the product specification is itself inadequate);
- c) to provide a basis for reliability apportionment (e.g. for use by subcontractors whose subsystems are required to meet reliability requirements delegated to them) and also to establish the reliability required of an item;
- d) to provide inputs to studies that may influence product design, such as design reviews, design evaluation, trade-off studies, life cycle costing, maintenance support, logistics studies and safety analyses; for example, assessment may highlight particular areas where an acceptable relaxation in performance could produce a major saving in life cycle cost;
- e) to establish whether the production process has adversely affected reliability;
- f) to establish whether an item in service has performed or is performing with the reliability required, and whether it is likely to continue performing adequately for the remainder of its operational life;
- g) to contribute to safety studies of an item (it is necessary to distinguish between the operational and the safety requirements for reliability);
- h) to estimate and control the effects of design changes on reliability;
- i) to provide input to logistic support analysis, spares ranging and scaling, hazard analysis and related maintenance studies.

2.2 Costs versus benefits

There is inevitably a cost associated with collecting and analysing data and carrying out the assessment. In order to provide data for an assessment it may be necessary to test samples, possibly in large numbers under actual or simulated environmental conditions. Arrangements may have to be made to gather field data over a long period. Such testing and monitoring is expensive and may appear difficult to justify, particularly given the pace of modern technological development.

It is therefore necessary to appreciate the gains that may follow from assessment. The results should provide information leading to better management decisions during all phases of a project. Improved reliability of the product will enhance its operational performance and may greatly reduce the costs of spares and maintenance over a long period in use. Higher reliability may improve safety and reduce risk to human life and may bring other sociological benefit. In the marketplace, poor reliability can severely damage the product image and result in loss of business.

It is important to weigh the costs of assessment against the benefits that should accrue and the risks attendant on poor reliability.

2.3 Using and presenting the results

Assessment should rarely be an end in itself. Assessment alone will do nothing to improve the reliability of a product. Vigorous and appropriate management action is necessary to ensure that maximum use is made of the information provided by assessment. Depending on the circumstances and stage of the project, this may involve, for example, the ruthless elimination of exposed design weaknesses, the improvement of production processes or better training of operators in the field. It is important that the duration and timing of assessment should be set to allow corrective action to be implemented.

Whatever use is to be made of the assessment results, it is important to ensure that they are presented in a complete and appropriate format and that any limitations and assumptions are clearly identified. General guidance is provided in BS 5760:12.

2.4 Basic concepts

During the design, development and manufacturing phases, the reliability assessment of new equipment relies upon predictive processes. Later, when actual test or service data are available, the use of statistical techniques to measure past reliability, and possibly to predict future reliability for the rest of the life of the equipment, may be possible.

Reliability assessment requires, firstly, reliability modelling of the item, and, secondly, collection of the necessary data. The techniques that should be employed will depend upon the product and the stage it has reached in its life cycle (see section 3).

2.5 Assessment problems

2.5.1 Reliability is commonly perceived as the ability of a product to give long periods of satisfactory performance without failure in use. Reliability is an important but elusive characteristic in the sense that it is often more difficult to specify than many major performance characteristics and is certainly more difficult than most to measure. Although unreliability may be readily apparent to the user, the accurate assessment of the reliability of a product in use is often difficult because of the long period needed or the large number of samples required in order to gain statistical confidence in the assessment.

NOTE In order to establish a fair degree of confidence in an assessment, it may be necessary to operate the equipment for a period up to 10 times the monitored failure time.

During design, when the product is purely conceptual, or in development, when only prototype models exist, reliability can be even more difficult to assess.

2.5.2 The assessment of reliability due to component failure can be very difficult. Systems are made up of many components and the processes that lead to their failure may be either dependent or independent of one another. The failures of a complex system are often considered to be random with respect to time (a Poisson process).

The reliability of a system as assessed throughout the various project phases is unlikely to be constant. Reliability is often described as undergoing growth during development and the early phases of introduction into use.

2.5.3 The following are some of the factors that contribute to the difficulty of assessing reliability accurately:

- a) inconsistency in manufacture;
- b) component wear-out (see **A.1**);
- c) consequential damage (or weakening) caused by failure of another component of the system;
- d) incomplete repair (particularly where the repair does not return the equipment to a state that is as good as new);
- e) poor replacement parts;
- f) failures not being reported (particularly when they are evident only through the gradual degradation of performance);
- g) the varying severity of use or environment to which the product may be exposed by different users and in different circumstances;
- h) problems due to poor maintenance, disturbance or misuse, etc.;
- i) component tolerances;

j) skill level and experience of the user in operating the item;

k) relevance, accuracy and completeness of the data used.

These factors are often ignored in theoretical calculations but may in practice have an important influence on the reliability achieved by systems operating in a working environment.

2.5.4 Certain systems or their constituent parts may be designed in such a way that their full function cannot be tested. Examples would include one-shot devices, such as a bullet, a modern drinks can or certain types of integrated circuit that may not be tested completely, either owing to their style of packaging or perhaps because their function is very complex.

Assessment of the reliability of systems containing one-shot devices requires special consideration and is covered in section **24**.

2.6 Failure classification

When the results of reliability tests and field data are assessed, it can often be difficult to decide whether or not a particular incident represents a true, countable failure. Degradation of system performance can often occur over a protracted period and even the time at which an event becomes significant can thus be difficult to assess.

In practice some kinds of failure are more important than others and it is necessary to distinguish between them. This is sometimes done by adding an adjective to the word "failure". For example, a complete failure is the complete lack of the required function. A partial failure is an event that results in one or more deviations in characteristics, but not such as to cause complete lack of the required function. A failure term applies only to the item under consideration, but if the failure is judged by its effect on another item (as in a complex system), a different term may be involved. Thus a complete failure of a particular item may cause only a partial failure of the system of which it is a part. Reports describing failures should therefore indicate which kind of failure is being considered.

Since the term partial failure is imprecise, it is preferable that the operational requirement that the system has to meet should be precisely specified. Therefore the system has failed if it is incapable of supplying these requirements in full.

The definition and classification of failures when assessing the reliability of services may cause particular difficulty (see section **23**).

2.7 Accuracy of assessment and prediction

2.7.1 It is important to appreciate that reliability predictions are subject to uncertainty. This arises from a number of factors, including the following.

- a) There is an inherent uncertainty in transferring failure (or success) data to different applications, environments, etc.
- b) It may be unclear what constitutes a failure in various situations (see **2.6**).
- c) The effect of human actions and interpretation may be uncertain, for example, in manufacturing quality control, maintenance, diagnosis, etc.
- d) Predictions, by their nature, are based upon historical data. Differences in technology, changes in design team personnel and the changing specification of the product all introduce possible sources of error into predictions.
- e) The rate of occurrence of failure may not be constant with respect to time, particularly for those components that may be said to wear out or for those that undergo frequent repair.
- f) Prediction methods often have to be oversimplified in order to make problems tractable.

2.7.2 No matter what reliability may be forecast by the assessments, the actual reliability achieved will depend largely on the content of the reliability programme for the product and the effectiveness with which it is implemented. Management commitment to achieving a reliable product will be a governing factor and this may in turn be influenced not only by the resources available but by any warranties, incentives or penalties that may be invoked.

2.7.3 Reliability assessments are an aid to good engineering and consideration should be given to the following measures.

- a) Well proven engineering practices should be applied and complex, latest technology solutions addressed with great care.
- b) Previous designs and processes should be reviewed to determine the capability of the new product and also to identify any problems that can be avoided.
- c) Statistical analysis should always be tempered by engineering judgement. Parallel redundancy, for example, can be introduced to improve the overall probability of successful operation of a system, but it may not be effective if the same inherent fault exists within the parallel items.

Section 3. Assessment throughout the product life cycle

3.1 General

Reliability assessment is not a simple task that is limited to a single phase of a project. It is a continuing process that should normally extend throughout all project phases.

The generalized life cycle of a product is described in BS 5760-1, and for the purposes of this Part of BS 5760 is deemed to consist of the following principal phases:

- a) definition (including feasibility);
- b) design and development;
- c) production;
- d) installation and commissioning;
- e) function and maintenance.

NOTE A further phase, the disposal phase, is important in the life cycle of some products but is omitted from this standard since reliability assessment is rarely implemented during disposal.

Assessment contributes to the specific objectives of each project phase in turn, with the ultimate purpose of ensuring that the defined reliability requirements are met when the product is used.

Basic forms of assessment should begin during the earliest stages of conception and the results should be used to shape the fundamental definition and design of the product. The assessments should then be repeated and extended as design becomes more detailed and refined; they should be continued as the product passes through development and production, installation and commissioning and eventually enters into use.

A wide range of assessment techniques is available and it is important to select a method that is appropriate to the individual product and to the particular phase involved.

Table 1 lists a range of some commonly used assessment techniques and indicates the particular phases of the product life cycle when it is normally most appropriate to apply each technique.

The full and successful application of a particular method of assessment often depends on the availability of appropriate data, which may include, for example, historic data collected from similar equipment already in use, or data generated during development and production testing. Nevertheless it can often be useful to carry out a simplified assessment at an early stage of the project even though only limited data are available. For example, it may prove helpful to use the reliability block diagram (RBD) technique initially at system and subsystem level even during the earliest phases of a project. The analysis may reveal basic problems or suggest alternative designs that it is valuable to recognize at this early stage. Subsequently, as more information becomes available, the diagram can be extended to lower levels of detail at, for example, unit and module level.

3.2 Definition phase

The main purpose of the definition phase of a project is to permit studies to be made to establish precisely what the future product is required to do and what form it should take. This clarification involves identifying and quantifying the essential performance characteristics and deciding which of various possible design alternatives will provide the optimum solution. The selected option is then defined as a set of formal requirements which become the basis of a contract specification.

Reliability is a fundamental performance characteristic which should be included in these early considerations. Although this standard primarily addresses the assessment of reliability, it is important to appreciate the interdependence of reliability with other characteristics such as maintainability, availability, testability and safety. For example, inadequate reliability can seriously detract from the effective operation of a product and can add greatly to running costs. If maintainability is also poor the running costs will be even higher and system availability will also be undermined. The measures necessary to achieve acceptable reliability may add to the cost of developing and producing a product. These additional costs may be amply justified by improved effectiveness and reduced running costs in use. It is important that those responsible for the fundamental decisions made during the definition phase should be aware of these relationships.

Studies and assessments should be carried out to provide quantitative estimates of the reliability and maintainability of the various design options together with details of associated short and long term costs. These should preferably be presented in the form of life cycle cost studies (see BS 3843). Once the agreed option has been selected, the reliability requirements should be formally defined in quantitative terms.

Table 1 — Application of some typical assessment techniques to product life cycle phases

Section in this Part of BS 5760	Reliability assessment technique	Product life cycle phase				
		Definition/feasibility	Design and development	Production	Installation and commissioning	Function and maintenance (in use)
6	Reliability block diagram (RBD)	A	A	M	M	M
7	Reliability prediction	L	A	M	M	M
8	Fault modes and effects analysis (FMEA) and fault modes, effects and criticality analysis (FMECA)					
	Design FMEA	L	A	M	M	
	Process FMEA		A	A		
9	Fault tree analysis (FTA)	L	A	M	M	M
10	Monte-Carlo simulation	A	A	M	M	M
11	Markov techniques	L	A	A	A	A
12	Reliability growth monitoring and testing		A	A	A	A
13	Development reliability demonstration testing		A	M	M	M
14	Environmental stress screening (ESS) and burn-in			A		
15	Production reliability assurance testing			A	M	M
16	In-service reliability demonstration				A	A
17	Life data analysis: probability plotting				A	A
18	Sneak analysis (SA)		A			
19	Assessment of software reliability		A	M	M	M
20	Human reliability assessment (HRA)	A	A	A	A	A
Key A, applicable; L, only very limited data may be available during this phase; M, applicable where modifications occur.						

In order to carry out these studies and assessments, it is usually necessary to establish the intended life profile for the product, i.e. to describe how it will be used throughout the various phases of its life. The life profile is often expressed as a series of typical duty cycles and should take account of the various processes and environments that the product will encounter such as handling, packaging, storage, operations and maintenance. It is usual to identify and describe the most important phase from the viewpoint of the user, usually the operations phase, in more detail and to define individual reliability requirements for such key periods of use. Although this primary phase is normally of overriding importance, it is always advisable to be aware of the possible impact of the subsidiary phases on reliability.

Quantitative requirements for reliability should be expressed in terms of an appropriate parameter such as probability of successful operation or maximum permissible failure rate. It will be necessary to make assumptions about the relationship between the occurrence of failures and time and to select a suitable statistical model to represent this relationship (see Annex A and Annex B). Thus, for electronic devices, it may be justifiable to apply the constant failure rate model (see **A.3**) whereas for mechanical systems experiencing rough loading and high wear, only an instantaneous failure rate would be meaningful.

It may be valuable at this stage to construct RBDs (see section **6**) and to use the overall system estimate or requirement to apportion reliability values to the lower level blocks. Basic maintainability and availability block diagrams may also be constructed.

Reliability predictions may be carried out based on comparison with systems using similar technology. Alternatively, the parts count or parts stress methods may be used where detailed design data are available, subject to the limitations inherent in these methods (see section **7**). Estimates of reliability and maintainability will also be used in assessing the range and scales of spares that will be needed to support the various product options under consideration, again with the object of minimizing costs of supporting the product when it enters service.

Fault modes, effects and criticality analysis (FMECA, see section **8**) and fault tree analysis (FTA, see section **9**) can also be implemented at block level and may be used not only to estimate reliability but also to assess safety and to establish the critical items list, i.e. to identify those items whose reliable performance is critical to successful operation of the product.

Finally, it is again stressed that with the conclusion of the definition phase, the essential form and function of the product will have been decided. Thus, the principal elements that decide the potential levels of future reliability, availability and maintainability will now be fixed. From this stage onward, the project reliability and maintainability programme, and the assessments that support it, will be mainly directed at achieving this potential.

3.3 Design and development phase

During the design and development phase the main objectives of reliability assessment should be to assist those responsible for design and development of a product to ensure that defined reliability requirements are met. The results of assessment are analysed and problem areas identified. The information is fed back to the designer so that necessary changes can be made.

The assessment techniques initiated in the definition phase are carried out in greater depth as the design is refined and more information becomes available. Fully detailed assessment may be restricted to those elements which preliminary analysis shows to be critical from the viewpoints of safety, reliability and maintainability.

FMECA (see section **8**) is used to assess and classify the criticality of failures that occur. The technique is also used in maintainability studies to provide guidance on fault diagnosis and on the design of built-in test equipment (BITE), test points and facilities for continuous monitoring. FMEA and FMECA may also be implemented to resolve problems associated with the production process and human failings.

As the phase continues and development prototypes of the product become available, some prototypes may be allocated for the purpose of reliability growth testing and monitoring. This involves long term testing with appropriate environmental stresses applied (see section **12**). If failures occur, the causes are analysed and appropriate design changes introduced. Mathematical modelling techniques may be applied to assess what further test resources will be needed in order to achieve the specified reliability requirements.

Conventional reliability growth testing of this kind is acceptable for products with relatively low mean operating times between failures (MTBFs). For products where the MTBF value is high, the duration of testing required would be unacceptably long. In this case, it might be more appropriate to apply step stress testing (see **12.4.6**).

The testing of one-shot devices (see section 24) may also present problems because cost restricts the quantity that can be tested. In these cases other assessment techniques have to be used. For example, greater attention is given to the tolerance design of electronic and mechanical items, and products are manufactured with maximum (or minimum) tolerance values to select worst-case situations for testing.

As the development phase nears completion, there may be a requirement for further development prototypes to be allocated for demonstrations of reliability, maintainability and testability. Such demonstrations represent a form of qualification testing in which the prototypes are tested and reliability and other characteristics are assessed under formal conditions. The object of the tests is to prove, before transition to the production phase is authorized, that the development samples are capable of meeting the defined requirements for reliability and maintainability. The tests do not in themselves enhance the reliability of a product but their inclusion as a formal qualification requirement is intended to encourage management to allocate appropriate priority to reliability and maintainability throughout the development programme. If the product were to fail these tests, urgent action would be needed to effect the necessary improvements and the project schedule would be jeopardized.

3.4 Production phase

The transition to the production phase provides many opportunities for the reliability of the product to be degraded below the levels achieved during development. Assessment is necessary to indicate whether required reliability levels are being maintained or whether such degradation is occurring.

For example, the production version of a product may incorporate modifications which significantly change the design and it is important to assess the effect of these on reliability. Environmental stress screening (ESS) and conditioning (see section 14) may be implemented to eliminate early life failures and monitoring is necessary to establish whether these measures are effective or whether levels need to be adjusted. Reliability assessments carried out in early phases as a basis for spares forecasting and other logistics support analysis activities need to be reviewed and revised.

FMEA and FMECA may be continued and can be useful in establishing whether any reliability weaknesses detected are inherent in the design or have been introduced during the manufacturing process (see section 8). FMEA used for this purpose is often known as a process FMEA.

Production reliability assurance testing may be initiated on a batch basis (see section 15) to provide formal assurance that defined reliability levels are being achieved on the production line.

3.5 Installation and commissioning

During the installation and commissioning phase it is important to continue to collect data and to assess whether any problems that occur relate to installation difficulties or arise from problems which should have been eliminated earlier.

Reliability and maintainability qualification tests may be carried out to demonstrate formally that requirements have been met. The results may be used to establish whether the contractor should receive bonus payments for exceeding defined reliability requirements or whether penalties for falling short of them will be invoked.

3.6 Function and maintenance

It is important to continue to assess reliability and maintainability of the product during the function and maintenance phase.

Such in-use assessments may again be part of contractually required formal tests to establish whether defined reliability, availability and maintainability requirements have been met. Assessments should also be used by management to draw attention to problem areas. Subsequent detailed investigation may show that belated design modifications or changes to the production process are needed. If major modifications are introduced, their effect on reliability will need to be assessed since such changes can in themselves introduce new reliability problems.

Section 4. Fundamentals of reliability assessment

4.1 General

Reliability is normally expressed as the probability that an item can perform a required function under given conditions, for a given time interval.

When assessing the reliability of a product there are thus four important elements to be considered, as follows:

- a) function;
- b) conditions of use;
- c) time interval;
- d) probability.

4.2 Function

It is always necessary to define the function or functions of the product in terms of the performance required. For complex systems this can be difficult, particularly where the performance gradually degrades (see 2.7). Nevertheless, in order for an assessment to be provided it is essential to define specific pass and fail criteria in terms that can be measured.

It may also be necessary to recognize that an item may have distinct phases of use in which different functions are required and in which the definitions of failure vary accordingly. For example, a video recorder has recording, playback and standby as major modes of operation. Different functions are required in each of these modes (and different electrical and mechanical components are employed to provide them). It may be helpful in the project definition stage (see 3.2) to generate RBDs (see section 6) as these can provide an effective method of visually representing a complex mathematical relationship.

4.3 Conditions of use

The conditions of use (or environment) to which a product is subjected throughout all phases of its life can have a significant impact on the reliability of the product. This includes not only the obvious physical conditions (temperature, pressure, vibration, humidity, etc.) but also other elements such as dust, chemicals and the effects of use and the user, together with the available maintenance resources.

In considering the conditions that the product will encounter, it is important to take account of all phases of use. These can include packaging, transportation and storage as well as the principal in-use phase. It is necessary to define the environmental boundaries to which the product will be exposed in each of these phases. The resulting range of conditions is often referred to as the life profile of the product. It can be very complex.

In practice, it may be possible to make some simplification by assuming a typical, representative life profile for use in reliability assessments. It may nevertheless be advisable in some circumstances (e.g. when considering warranty conditions) to take note of the worst possible environmental conditions likely to be encountered.

4.4 Time interval

The nature of the time interval selected to measure reliability is determined by the way the product is used. In practice it may be appropriate to employ some measure other than time, as the pattern of use may not be directly related to time itself. Some examples of suitable measures include the following:

- a) number of operations, e.g. repetitions of use of a mechanical device;
- b) time (calendar or duration of operation);
- c) distance travelled;
- d) number of successful operations within a sample set (this example applies particularly to one-shot devices, see section 24).

4.5 Probability

Although normally stated as a mathematical probability, reliability can also be expressed as a hazard rate or as the expected time to failure. For repairable systems, reliability may be expressed as a failure rate or as the MTBF or some other appropriate unit (see 4.4).

When analysing reliability data, it is necessary to determine the statistical technique to be employed. The following two stages are normally involved.

- a) The type of period has to be established. The period may be a series of discrete events (number of operations) or a continuum (time).
- b) The statistical distribution has to be determined.

Annex B describes several important failure distributions.

4.6 Reliability and safety

Many of the techniques used for the assessment of reliability are also used for the assessment of safety. Sometimes, however, safety and reliability can appear to conflict. This may occur where design for safety introduces additional complexity which reduces reliability. For example, for a bomb to explode when required, a detonator is needed. A simple detonator with few components may have failure modes which could cause premature detonation and it is necessary to introduce additional safety devices to inhibit such failure modes. These devices, by introducing greater complexity, add to the probability that the bomb may fail to operate when required, even though it is made safer to handle by incorporating them.

4.7 Principles of reliability modelling

When assessing reliability it is necessary to express mathematically the relationship between the four elements discussed in 4.1 to 4.5, i.e. between function, time interval, conditions of use and probability. This process is known as reliability modelling. The precise way in which the model is developed will depend on the circumstances surrounding an item and the stage it has reached in its life cycle.

In order to evaluate the model, it is necessary to insert data. Data may be derived from experience of the item itself or from a related item.

When a model is to be developed the outputs required from the model and the input data available should be clearly identified. The quantity and accuracy of the input data is of major importance in determining the model. If the input data are imprecise then nothing will be gained by developing a highly complex model. When a complex model is used, it is usual to construct it as a series of submodules so that the functions of each submodule can be clearly identified and defined together with their associated inputs.

During model development it is necessary to establish the sensitivity of the results to the assumptions and approximations made. In this way the most critical areas of the model, and assumptions on which it is based, can be identified and the model can be refined.

As the development of an item progresses, the type of reliability model employed also tends to evolve. Initial qualitative models based on deductive and inductive techniques give way to quantitative models derived from analytical and simulation techniques.

The most useful models are those which strike a good balance between an accurate representation of the real life situation and the need to provide results in a reasonable time with due regard to the quantity of the input data and the required accuracy of the results.

4.8 Redundancy

4.8.1 General

A redundant system contains more items than are strictly necessary for the function of the system, the objective being to increase reliability.

NOTE 4.8.2 to 4.8.4 apply only to open-circuit failures. The application is to pneumatic and hydraulic systems as well as to electrical systems.

4.8.2 Series systems

In a series system, failure of any component constitutes system failure.

$$R_S = \prod_{i=1}^n R_i \quad (1)$$

i.e. the reliability of the system R_S is the product of the reliabilities R_i of the component parts.

Alternatively this may be expressed in terms of the failure probabilities, which are additive.

$$F_S = \sum_{i=1}^n F_i \leq 1 \text{ provided } F_i \ll 1 \quad (2)$$

where

$$F_S = 1 - R_S$$

Availabilities, particularly steady state availabilities, can be dealt with in the same way.

$$A_S = \prod_{i=1}^n A_i \quad (3)$$

4.8.3 Active parallel redundancy

In this case n identical items share provision of the function, which can be sustained by as few as m items. Systems failure occurs at the $(n - m + 1)$ th overlapping failure.

4.8.4 Switched standby (redundant) systems

In switched standby redundant systems, one or more items sustain the function until one fails, when its duty is taken over by a standby unit. There may be several standby units and these may fail in the passive state. In this case, failures may not become apparent until the unit is required.

Standby redundancy is theoretically more efficient at raising reliability than active parallel redundancy. This generalization may not apply because of the following factors:

- a) the switch reliability may be important;
- b) the reduced stresses when operating in the active parallel mode may lower the unit failure rate;
- c) standby equipment may have a probability of not starting when needed;
- d) there may be common cause failures.

Four types of failure are possible:

- 1) failure to switch when required;
- 2) spurious switching to a failed unit;
- 3) failure of switch to make contact;
- 4) failure of both (all) elements.

NOTE The switch may be manual or automatic and need not be electrical: it could be a pneumatic or hydraulic valve system.

4.9 Computer tools for reliability assessment

The assessment of reliability can be greatly facilitated and rationalized by the use of computer tools. These tools are readily available for the majority of techniques used by the reliability analyst. Many major companies have developed their own software (often under licence) and many consultancies exist where the supply of software is an integral part of their business. In some cases software may also be freely supplied by the contractor for use on a specific project.

Such proliferation can be confusing but a potential user should ensure the following.

- a) The tool should conform to any standard invoked by the contract.
- b) The algorithms should be visible to ensure that the assumptions and the mathematics are valid.
- c) The degree of training necessary should be appreciated as an untrained user can produce misleading results.
- d) The tool should fulfil the requirements without special tailoring (which may be expensive).
- e) The tool should be supported and updated to the latest standards, methods and data. This is particularly important when quantifying reliability.
- f) The tool should not be too complex for the task in that the tool requires more input data than the user has available.

Section 5. Assessment techniques

5.1 Outlines of techniques

Many techniques are available for the assessment of reliability. A range of the more important techniques and associated methodology is reviewed in sections 6 to 25. Each technique is briefly introduced and its practical applications are explained. The advantages and limitations of each technique are summarized and reference is made to British Standards that describe the detailed procedures to be followed to implement the techniques.

5.2 Assumptions

5.2.1 Awareness of assumptions

It is important to be aware that the assessment techniques described in this standard are only valid if certain basic assumptions are true. It is often the case that these assumptions are not specifically identified by the practitioner when assessing reliability; they are simply taken for granted.

It is important to appreciate that the non-specialist may be unaware of the assessor's formal interpretation of the data. The non-specialist's expectation of the reliability likely to be achieved in service may therefore differ from that of the assessor.

5.2.2 Definition of failure

Many techniques assume that the system is functioning or not functioning. There may in practice be many gradations of partial failure as explained in 2.6. It is necessary to define precisely what constitutes failure in the particular system and circumstances under consideration.

5.2.3 Operating and environmental conditions

It is important to establish whether realistic operating and environmental conditions have been assumed. Many techniques apply a simplified set of conditions. For example, reliability growth modelling (see section 12) predicts reliability using data that are often derived from development trials in which relatively simple operating and environmental conditions are applied; the resulting prediction could be seriously in error when compared with the performance in customer use.

5.2.4 Component failure rate data

The validity of component failure rate data is often questionable particularly for advanced technology components. This is largely due to the small amount of data available. Any calculation of system reliability based on such component failure data will be similarly suspect (see 2.5 to 2.7).

5.2.5 Assumption of constant failure rate

Many assessment techniques assume that the components employed in the systems concerned fail at a constant rate (i.e. the constant failure rate assumption described in Annex A is adopted). The mathematical relationships involved are then easier to handle. However, the assumption is often untrue in practice. The failure rate of an electronic component such as a capacitor may vary over a range of values and may be influenced by such factors as the following:

- a) the nature of the component and the method of construction and technology employed;
- b) the electrical stress ratio, i.e. the ratio of operating to rated voltage;
- c) the temperature at which the component operates;
- d) the age of the item;
- e) the manufacturing quality of the item.

5.2.6 Maintenance

The assessment techniques described in this standard assume that correct preventive maintenance is carried out. Poor maintenance will generally lead to poor reliability. Similarly, when repair is necessary equipment is sometimes not returned to use in a good-as-new condition.

5.2.7 Common cause failures

The classical formulae used when calculating the reliability of a system from the reliability of its components assume that all failures that occur are independent of each other.

NOTE The methods of calculating system reliability from components may be briefly summarized as follows:

- a) the reliability of a series system may be derived by multiplying the reliabilities of the individual components;
- b) the reliability of a parallel system may be derived by multiplying the individual failure probabilities or, for a system with redundancy, by use of the binomial distribution.

In a reliability analysis, it is not sufficient to consider only random and independent failures; some common cause (or common mode) failures can occur. Common cause failures lead to system performance degradation or failure through simultaneous deficiency in several system components, due to the occurrence of a single event such as design error or human error.

A common cause failure is the result of an event that, because of logical dependences, causes a coincidence of failure states in two or more components (excluding secondary failures caused by the effects of a primary failure).

Where a system contains redundant elements and where common cause failures exist, the classical formulae overestimate the system reliability. Underestimation of reliability is not particularly serious, in that the system will turn out to be more reliable than estimated, but overestimated reliability can have serious consequences particularly where safety is a consideration.

The use of FMEA to analyse common cause failures is described in **2.4.1.4** of BS 5760-5:1991. Fault tree analysis (see section **9**), block diagram techniques (see section **6**) and Markov techniques (see section **11**) can also be used to deal with the problem.

Section 6. Reliability block diagram (RBD) technique

6.1 Application

Before any form of reliability analysis is attempted, it is generally advisable to represent the system under consideration as a block diagram.

Various forms of block diagram can be drawn for a system. Often, a functional block diagram is drawn to show how a system is partitioned and describe how the system is expected to operate. For reliability assessment it is often more useful to draw a reliability block diagram (RBD).

The purpose of the RBD technique is to represent failure and success criteria pictorially and to use the resulting diagram to evaluate system reliability parameters. It should be noted that in many cases the RBD will bear no resemblance to the functional block diagram. Under certain conditions (see 6.6) the method can also be used to calculate system availability.

The RBD method is primarily intended to apply to systems in which the redundant units are not repaired when failures occur and where the order of the occurrence of failure does not matter. In this method individual units are represented by blocks that are considered to exist in one of only two possible states, operational or failed.

In order to proceed, the analyst will need to understand the way in which the system operates and the corresponding environmental conditions, including an understanding of the modes of equipment operation (e.g. in a radio transceiver, the receive mode and the transmit mode). To this end, it is desirable that the analyst works closely with the design team or as a member of it.

For any system there may be a number of system failure or success definitions and each of these may be modelled by a separate RBD. Each relevant system failure or success definition should be clearly stated and the corresponding RBD should be referenced (e.g. by labelling) to the associated system failure or success definition. In turn, the reliability parameters to be calculated should also be clearly stated.

NOTE Where possible the terminology and symbols used should be in accordance with BS 4778-3.

6.2 Benefits

The principal benefits of the RBD technique are as follows.

- a) The pictorial representation means that models are easily understood and therefore readily checked.

- b) Block diagrams are used to identify the relationship between elements in the system. The overall system reliability can then be calculated from the reliabilities of the blocks using the laws of probability.

- c) The block diagrams can readily be interpreted in the case of elements that are, in reliability terms, in series.

- d) Block diagrams can be used for the evaluation of system availability provided that both the repair of blocks and failures are independent events, i.e. provided the time taken to repair a block is dependent only on the block concerned and is independent of repair to any other block (see 6.6).

6.3 Limitations

The main limitations of the RBD technique are as follows.

- a) The method cannot model systems in which the sequence of failures affects the outcome (i.e. order-dependent failures).

- b) In general the method cannot be used to model maintenance strategies for systems that can be repaired.

- c) For a given system, each failure or success definition needs a separate block diagram.

6.4 Elementary models

Before beginning the model construction, consideration should be given as to the best way of dividing the system into blocks. It is particularly important that each block should be statistically independent of all other blocks (i.e. no unit or component should be common to a number of blocks). The most elementary models are the following:

- a) series;
- b) active parallel;
- c) m -out-of- n ;
- d) standby models.

Details of all these models, along with corresponding formulae for the reliability parameters, are given in 6.7.2 to 6.7.6.

6.5 More complex models

Although fairly widely applicable, the procedures described above have the limitation that they cannot, as described, cope with RBDs in which the same block appears more than once in the diagram. This is easily overcome by using an appropriate analytical procedure. Examples of such procedures include the following:

- a) the use of the theorem of total probability

- b) the use of Boolean truth tables;
- c) the use of Boolean algebra to give Boolean expressions which have then to be suitably treated before probabilities can be substituted for the variables (i.e. the expressions have to be disjointed prior to substitutions).

NOTE Details of procedures using the theorem of total probability and Boolean truth tables are given in BS 5760-9.

By regarding a group of blocks as a “super block”, and treating such blocks as block diagrams in their own right, it is possible to simplify block diagrams considerably by reducing the number of blocks. However, the way in which the individual blocks are selected to form a super block has to be carefully considered. Further details of this approach are given in BS 5760-9. Although *m*-out-of-*n* systems can be easily analysed when all units have the same reliabilities, the analytical procedure can become more tedious when the units have different reliabilities. An indication of a method to use under these circumstances is given in BS 5760-9.

6.6 Extension to calculations of system availability

Under certain conditions it is possible to use the block diagram technique to carry out steady state system availability calculations. This can be done simply by replacing the quantity $R_X(t)$ for a block X, with the corresponding value for the steady state availability A_X of block X. The certain conditions referred to above are that failure and repair of any block have to be totally independent events. In other words the failure of one block should in no way bring about the failure of any other. Similarly the mean down time of a block needs to be a characteristic of that block alone and should not depend on how many other blocks are also failed and in need of repair. This latter requirement implies that an infinite pool of repairmen has to be available for work on failed blocks as the need arises.

It should also be noted that the block diagram technique can be readily extended to system safety analysis.

6.7 Typical RBD configurations and related formulae

6.7.1 General

Figure 1 to Figure 13 depict a number of typical RBD configurations. The formulae from which the reliability of these configurations can be derived are discussed in 6.7.2 to 6.7.7. In these figures I represents the input and O represents the output.

6.7.2 Simple series and parallel systems

For systems where system success requires that every unit comprising the system has to be working in order for the system to be fully operational, the system success or failure definition is modelled by Figure 1a) where A, B, C,...Z are the units constituting the system. The interpretation of Figure 1a) can also be stated as “any unit failing causes the system as a whole to fail”, and the system is referred to as a series system. Under these conditions, the reliability R_S of the system (usually a function of time *t*) is given by

$$R_S = R_A \times R_B \times R_C \times \dots \times R_Z \quad (4)$$

where

R_S is the reliability of the system; and

R_A, R_B , etc. are the reliabilities of the individual units.

For systems comprising two units (X and Y) that are operating in such a way that the system will survive as long as at least one of the units survives, the system success or failure definition is represented by Figure 1 b). This type of system is referred to as an active parallel system. The corresponding expression for system reliability is

$$R_S = 1 - (1 - R_X)(1 - R_Y) \quad (5)$$

NOTE For three blocks X, Y and Z (i.e. at least one out of three is needed for system success), the corresponding reliability expression is

$$R_S = 1 - (1 - R_X)(1 - R_Y)(1 - R_Z) \quad (6)$$

Similar expressions can be derived for more than three blocks.

6.7.3 A series/parallel system

When blocks such as X and Y themselves comprise sub-blocks in series, block diagrams of the type illustrated by Figure 2 are obtained. The corresponding reliability expression is then obtained by calculating

$$R_X = R_{A1} \times R_{B1} \times R_{C1} \times \dots \times R_{Z1} \quad (7)$$

and

$$R_Y = R_{A2} \times R_{B2} \times R_{C2} \times \dots \times R_{Z2} \quad (8)$$

and substituting these values for R_X and R_Y in equation (5).

6.7.4 Other series/parallel systems

RBDs that are in effect a series of super blocks, where each super block is itself an arrangement like Figure 1b), may take the form illustrated in Figure 3. Once again the system reliability expression R_S corresponding to this block diagram can be evaluated by repeated use of equations (4) and (5). Thus:

$$R_A = 1 - (1 - R_{A1})(1 - R_{A2}) \quad (9)$$

$$R_B = 1 - (1 - R_{B1})(1 - R_{B2}) \quad (10)$$

and so on. By making the necessary substitutions in equation (4), the equation for R_S is obtained.

$$R_S = \{1 - (1 - R_{A1})(1 - R_{A2})\} \times \\ \times \{1 - R_{B1}(1 - R_{B2})\} \times \dots \times \\ \times \{1 - (1 - R_{Z1})(1 - R_{Z2})\} \quad (11)$$

Using this procedure, it is possible to write down system reliability expressions corresponding to Figure 4 and Figure 5.

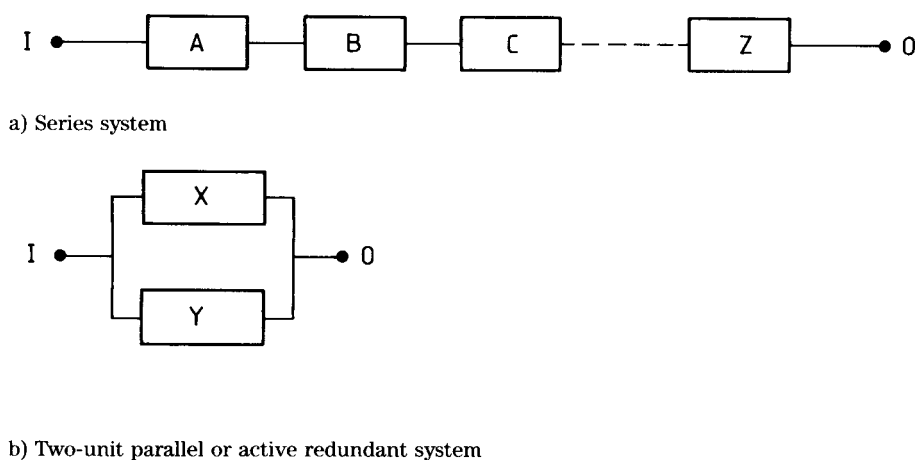


Figure 1 — Block diagrams of simple systems

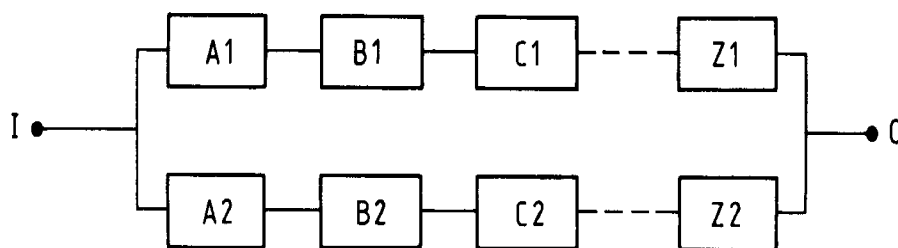


Figure 2 — A series/parallel arrangement

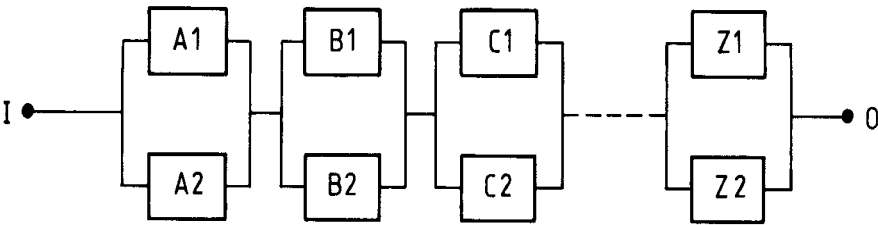


Figure 3 — Another type of series/parallel arrangement

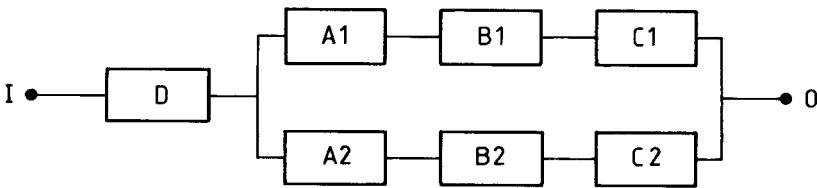


Figure 4 — A series/parallel arrangement with a common block (D)

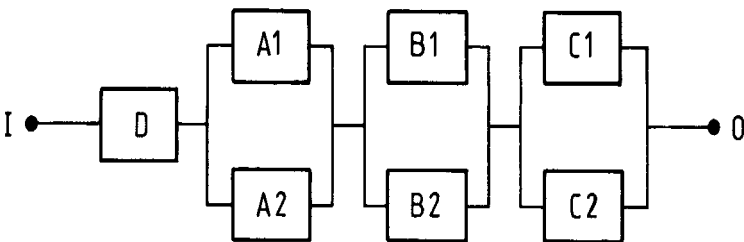


Figure 5 — Another type of series/parallel arrangement with a common block (D)

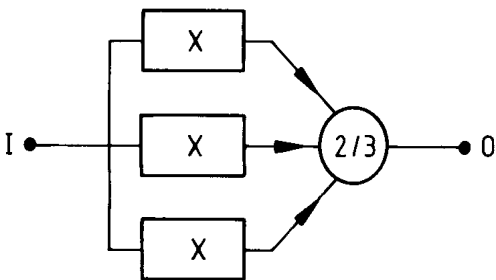


Figure 6 — A two-out-of-three system (at least two needed for system success)

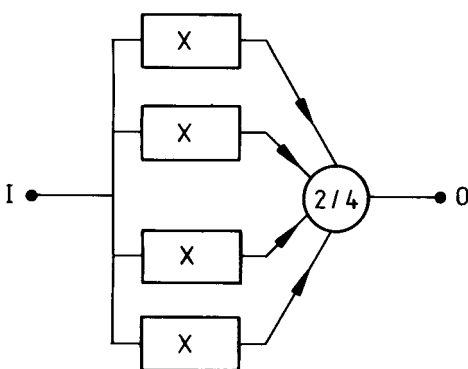


Figure 7 — A two-out-of-four system

6.7.5 m -out-of- n units required

Reliability expressions corresponding to Figure 6 and Figure 7 are best evaluated using an alternative approach. These diagrams represent instances where system success is assured whenever at least m of n identical units are in an operational state. In figure 6 $m = 2$ and $n = 3$, while in Figure 7 $m = 2$ and $n = 4$. One such alternative approach is pick out the system success terms in the expansion of $(R_X + F_X)^3$ (where $F_X = 1 - R_X$) with reference to Figure 6, and $(R_X + F_X)^4$ with reference to Figure 7. The binomial distribution (see B.9.1) may also be used to evaluate such expressions.

Thus, for Figure 6:

$$R_S = (R_X)^3 + 3(R_X)^2 F_X \quad (12)$$

and for Figure 7:

$$R_S = (R_X)^4 + 4(R_X)^3 F_X + 6(R_X)^2 (F_X)^2 \quad (13)$$

6.7.6 Standby

Figure 8 represents a standby arrangement of units in which one unit (unit A) is working and the other (unit B) is not used until the working unit fails, when it takes over from unit A for the duration of the mission or until failure. If it can be assumed that unit B does not fail or deteriorate in storage, then the reliability R_S of the system given by

$$R_S(t) = R_A(t) + \int_0^t f(u) R_B(t-u) du \quad (14)$$

where

t is the mission time;

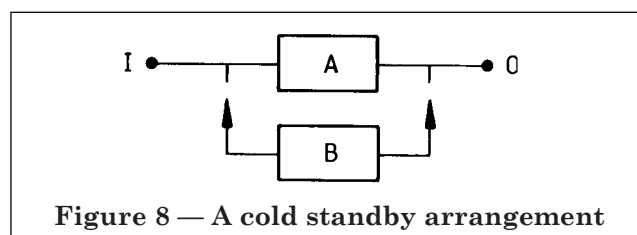
$R_A(t)$ is the probability of unit A surviving the entire mission; and

the integral is the probability that unit A fails before the end of the mission but unit B then survives for the remainder of the mission. In this context $f(t)$ is the probability density function (p.d.f.) of the time to failure of the working unit.

NOTE 1 For the particular instance when the failure rate of the units is constant (equal to λ , say), $f(t) = \lambda \exp(-\lambda t)$, so that equation (14) becomes

$$R_S(t) = \exp(-\lambda t) + \lambda t \exp(-\lambda t) \\ = (1 + \lambda t) \exp(-\lambda t) \quad (15)$$

NOTE 2 In equations (14) and (15), the reliabilities of the individual units have been written as a function of t rather than in the shorthand notation omitting the (t) .



6.7.7 More complex block diagrams

The evaluation of system reliability when the system failure or success definitions are modelled by diagrams of the type illustrated by Figure 9, Figure 10, Figure 11 and Figure 12 cannot readily be obtained by the methods described above. BS 5760-9 describes methods for dealing with these types of block diagram.

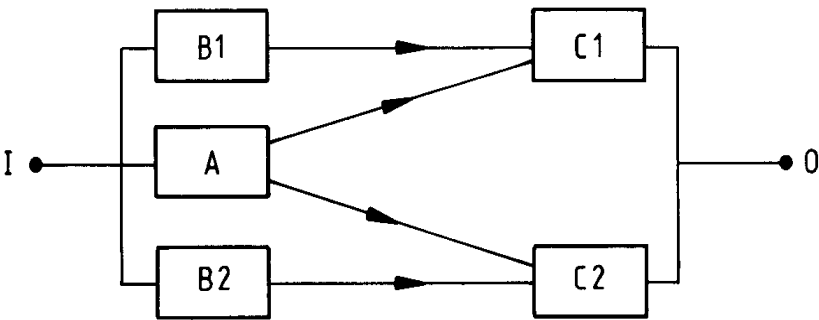


Figure 9 — Complex form of RBD

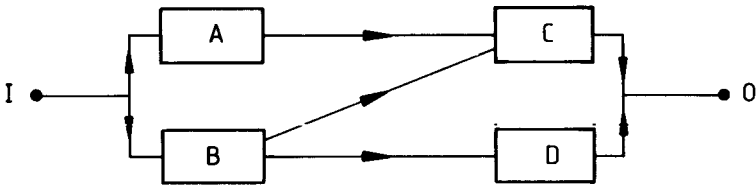


Figure 10 — Another type of complex RBD

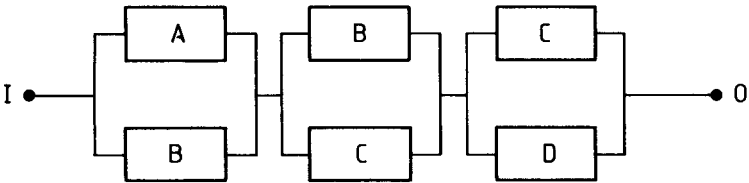


Figure 11 — Alternative representation of the RBD shown in Figure 10

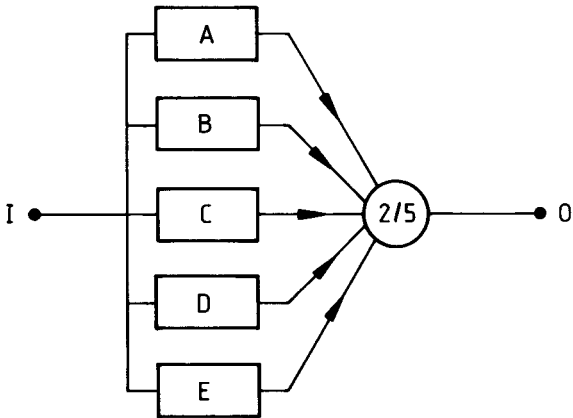


Figure 12 — A two-out-of-five system

6.8 Example of a block diagram analysis

6.8.1 System description

Consider a hi-fi stereo system consisting of the following components:

- a) two speakers (units Spk1 and Spk2, each having reliability R_{Spk});
- b) a pre-amplifier (unit A1 of reliability R_{A1});
- c) a power amplifier (unit A2 of reliability R_{A2});
- d) a turntable (unit T of reliability R_{T});
- e) a stylus (unit Sty of reliability R_{Sty});
- f) a standby for the stylus (unit Spare sty also having a reliability of R_{Sty} when in use).

6.8.2 Success definitions

Consider that, for this hi-fi system, there are two system success definitions as follows:

- a) the system is regarded as working, i.e. operating successfully, only as long as it is possible to listen to stereo;
- b) the system is regarded as working provided either stereo or mono can be heard.

For success definition a), the block diagram is illustrated by Figure 13 a), from which the expression for system reliability $R_{\text{S}}(t)$ is

$$R_{\text{S}}(t) = \{R_{\text{Spk}}(t)\}^2 R_{\text{A1}}(t) R_{\text{A2}}(t) R_{\text{T}}(t) \times [R_{\text{Sty}}(t) + \int_0^t f(u) R_{\text{Sty}}(t-u) du] \quad (16)$$

For success definition b), the RBD is illustrated by Figure 13 b), from which, using the formulae given in 6.7, the expression for system reliability, $R_{\text{S}}(t)$ is

$$R_{\text{S}}(t) = [1 - \{1 - R_{\text{Spk}}(t)\}^2] R_{\text{A1}}(t) R_{\text{A2}}(t) R_{\text{T}}(t) \times [R_{\text{Sty}}(t) + \int_0^t f(u) R_{\text{Sty}}(t-u) du] \quad (17)$$

NOTE In equations (16) and (17), the reliabilities of the individual units have been written as functions of t rather than in the shorthand notation omitting the (t) .

6.8.3 Insertion of numerical values for reliability parameters

The next stage in the analysis is to obtain numerical values from some suitable data source and insert these in the equations. The following values are assumed in this example.

- a) The times to failure of the speakers follow a Weibull distribution (see B.8.4) with scale parameter $\eta = 2$ years, shape parameter $\beta = 2$ and location parameter $\gamma = 0$, and are given by

$$R_{\text{Spk}}(t) = \exp\{-(t/2)^2\} \quad (18)$$

- b) The failure rate of the pre-amplifier is constant with time, and takes a value of 10 000 fits where the number of fits is the number of failures per component (or unit) per 10^9 h. If t is measured in years and the number of hours in one year is taken as 8 760 then there are 0.0876 failures per unit per year and the reliability (see B.8.2) is given by

$$R_{\text{A1}}(t) = \exp(-0.0876t) \quad (19)$$

- c) The failure rate of the power amplifier is constant with time, being 100 000 fits so that the reliability is given by

$$R_{\text{A2}}(t) = \exp(-0.876t) \quad (20)$$

- d) The times to failure of the turntable follow a Weibull distribution with $\eta = 15$ years, $\beta = 2.5$ and $\gamma = 0$, i.e. the reliability is given by

$$R_{\text{T}}(t) = \exp\{-(t/15)^{2.5}\} \quad (21)$$

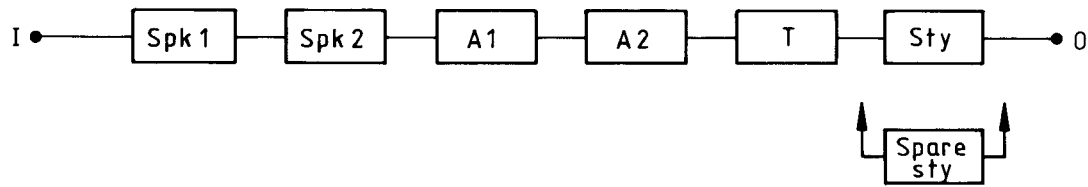
- e) The times to failure of the stylus follow a Weibull distribution with $\eta = 2$ years, $\beta = 3$ and $\gamma = 0$, i.e. the reliability is given by

$$R_{\text{Sty}}(t) = \exp\{-(t/2)^3\} \quad (22)$$

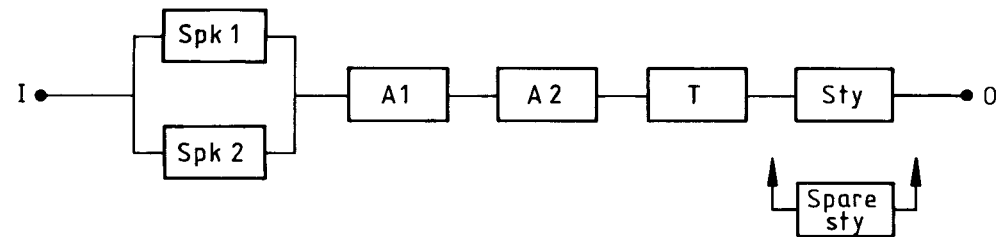
which means that $f(t)$ is given by

$$f(t) = (3/8)t^2 \exp\{-(t/2)^3\} \quad (23)$$

On substituting these reliability expressions in equations (16) and (17) and plotting the results for a range of values of t , Figure 14 is obtained.



a) Success definition as in 6.8.2a



b) Success definition as in 6.8.2b

Figure 13 — Examples of RBDs corresponding to a hi-fi system

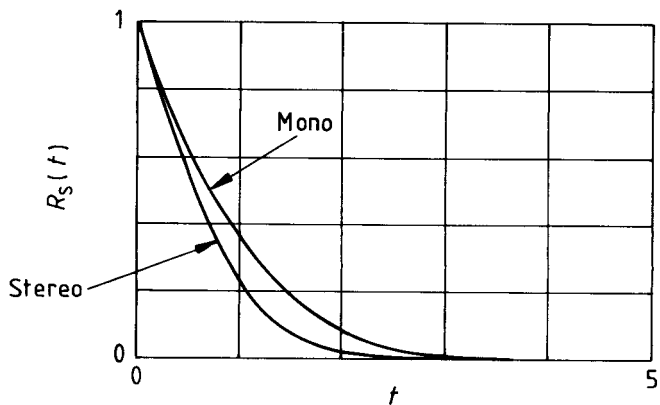


Figure 14 — Evaluation of system reliability following RBD analysis

Section 7. Reliability prediction

7.1 Application

Reliability predictions are particularly useful when preparing product proposals and during the early stages of design and development. Predictions can be refined as development progresses by the analysis of test and trial data. Predictions can be used for many purposes including the following.

- a) To provide an early indication of the potential of the product to meet the required reliability.
- b) To reveal design weakness.
- c) To provide inputs for associated activities such as:
 - 1) trade-off studies to enable compromises to be made between the various aspects of product design;
 - 2) estimating the number of spares needed to support the equipment in use.
- d) To compare design alternatives.

7.2 Methods

There are five main methods that can be used to predict the reliability of a product:

- a) system models (see 7.3);
- b) similar equipment method (see 7.4);
- c) extrapolation of reliability data from tests and trials (see 7.5);
- d) reliability modelling (see 7.6);
- e) generic parts methods (parts count and parts stress) (see 7.7).

Irrespective of the method selected, reliability predictions can only be estimates since even the most recent data are inevitably out of date. It is important to be aware of the degree of uncertainty involved.

Whilst computer programs are available to assist in predicting reliability, dependence upon complex computer programs to produce accurate predictions is dangerous when the accuracy of the input data is unknown. Many computer methods are based on assumptions that are not clearly defined.

7.3 System models

A range of models including computer models are commercially available for estimating the reliability of large, complex systems. They include parametric cost and rapid prototyping models. The input data used by these models include parameters such as weight, volume and cost, many of which may appear at first sight to have little obvious connection with reliability. However, experience has shown they can be useful in providing empirical estimates of reliability.

These methods are particularly useful during the very early stages when the design is in its infancy. An advantage of this approach is that the reliability prediction forms only a small part of the total output from such a model and the cost of prediction is proportionately low.

The disadvantages of such system models are that they require careful refinement and calibration for each specific company, and different models may be required for different types of product. The functional structure, such as lower levels of system redundancy, is often omitted from consideration at the early stage of design.

For simple system models, given these limitations, the accuracy of the prediction can be as good as any other method employed during the concept and very early design phases.

7.4 Similar equipment method

In the similar equipment method, the proposed design is compared with similar designs for which the achieved reliability is known. The estimated reliability for the new design is then changed to take into account any differences between the designs and any areas of risk.

The ability of the method to accurately predict the eventual reliability of the design being analysed is dependent on many factors including the following:

- a) function of the design;
- b) operating environments;
- c) definition of failure;
- d) operational requirements;
- e) development timescales;
- f) design organization;
- g) manufacturing organization;
- h) maturity of the designs.

Any differences between the new and the similar equipment, as they relate to these various areas, should be considered and judgement used to modify the predictions accordingly; this is inevitably a weakness of the method.

The similar equipment method can produce accurate predictions very early in the design phase if suitable data are available. However, if different technology is being used or if there are other significant differences between the new and related equipment, comparison becomes difficult and uncertainty in the prediction increases.

7.5 Extrapolation of reliability data from tests and trials

When a product is undergoing development, it may be possible to use data from testing or other activities to develop reliability growth models to predict the reliability as described (see section 12).

7.6 Reliability modelling

RBDs (see section 6), FTA (see section 9) and Markov techniques (see section 11) can be used to estimate reliability. These methods address redundancy and the effects of multiple failures. They can be applied in the design phase and developed further as the design progresses. These methods often incorporate predictions obtained from other methods such as those described in 7.3, 7.4 and 7.7.

7.7 Generic parts methods

7.7.1 General

In generic parts methods, the reliability of a system is predicted from the reliabilities of the individual components comprising it. For a simple series system in which all components are required to operate, the overall failure rate λ_S is given by the sum of the component failure rates. This is expressed by

$$\lambda_S = \lambda_1 + \lambda_2 + \lambda_3 + \dots + \lambda_n \quad (24)$$

where λ_1 to λ_n are the failure rates of components 1 to n , etc.

It should be noted that this expression is only true where the failure rates are considered to be constant, i.e. exponentially distributed.

The two principal generic parts methods are parts count analysis (see 7.7.2) and parts stress analysis (see 7.7.3).

7.7.2 Application of parts count analysis

Parts count analysis is applicable in the early design phase of a product when a parts list becomes available. This technique involves multiplying the base failure rate for each component by the appropriate environmental, quality and complexity factors, and then summing to give a total failure rate for the product. There are a number of publications that detail failure rates for components and that also specify a particular model to be used to derive the failure rate of a system. These publications are based upon historic data gathered for a specific industry such as defence, telecommunications or off-shore oil. The most widely used international methodology and failure data are probably those given in US Military Handbook 217 [1] but other methods are also in use including those described in *Handbook of reliability* (HRD4) [2] and *Off-shore reliability handbook* (OREDA) [3].

Failure rate data relating to specific types of components are available from some professional institutions.

This method is concerned with the behaviour of the components themselves and the effects of environmental, quality and complexity factors. The method assumes that all components are connected in series. It does not take into account the effects of interaction of one part with another. It also assumes that the failure rate is constant during the useful life period of the product.

The following information is generally required to apply parts count analysis:

- a) a parts list;
- b) the base failure rates of all generic parts;
- c) the quality factors of parts;
- d) detailed knowledge of the environmental factors to which the system (and all its parts) are subjected;
- e) the component and part complexity factors;
- f) the numbers of different generic types of parts;
- g) other information that may have a bearing on failure rates, such as the year of manufacture of integrated circuits.

Although parts count analysis can be applied to mechanical parts the data should be treated with caution. The use of a mean failure rate may be questionable as the variance can be quite large. Some publications provide a range of failure rates. This large variance is usually due to the variations in load and environment to which a mechanical item can be subjected.

These models also assume that the failure rates are constant and hence can be summed to determine the failure rate of the system. However, a mechanical system can sometimes be regarded as a collection of parts which is only as strong as the weakest link and hence only the highest failure rate need be considered instead of the sum of the failure rates.

Parts count and parts stress analysis assume that failure rates are dependent on the stress to which the components are exposed. In parts count analysis the stress values can be fixed at some arbitrary level (e.g. 50 % of the maximum).

7.7.3 Application of parts stress analysis

Parts stress analysis may be regarded as an extension of parts count analysis. It requires additional information about the components including stress levels, temperature weighting factors, power dissipation thermal resistance, ambient temperature, the number of pins and, in the case of integrated circuits, the type of package. Parts stress analysis requires more time and effort to carry out and is more suitable for use in the later stages of the design process when the detailed information needed becomes available. Parts stress analysis assists the designer by drawing attention to highly stressed components and marginal stress levels. Parts stress analysis for mechanical parts is inhibited by the lack of data available.

7.7.4 Benefits

The principal benefits of the parts count analysis and parts stress analysis techniques are as follows.

- a) Provided they are prudently applied and interpreted, the methods can be useful in predicting the reliability of a system to provide a basis for reliability apportionment.
- b) The rigorous application of the methods, particularly in the case of parts stress analysis, imposes a disciplined review of design which may reveal potential reliability weakness such as highly stressed components.
- c) The parts count analysis and parts stress analysis techniques enable comparisons to be made of the reliability of competing systems, for example when assessing competitive tenders or alternative designs.

7.7.5 Limitations

The main limitations of the parts count analysis and parts stress analysis techniques are as follows.

- a) They rely on the failure rate data gathered from a variety of sources representing average conditions. The accuracy and validity of such data may be questionable.

b) For new technology devices failure rate data may not be available, and for all devices even the most recently published data are inevitably out of date.

c) Without the use of a computer, calculation in both methods is very tedious and time consuming.

d) The methods provide only broad estimates of reliability.

e) The prediction inaccuracies can be several times worse or several times better than the achieved failure rate of the system. For this reason, it is strongly recommended that comparisons are made of previous predictions and achievements. Experience has indicated that failure rates also vary according to the designer and manufacturer involved. It may therefore be appropriate to modify the prediction on the basis of previous experience of, for example, a given manufacturer. Any such assumption should be clearly identified and justified (see 7.6).

f) Unless common mode and common cause failures are previously identified, the results of the prediction are questionable.

g) The assumption of constant failure rate during the useful life period of an item is not always valid.

h) The methods do not take account of errors in design and manufacture that may be generated by the assembly of individual components into systems. Systems may fail because of causes other than the time-based failure of components.

i) Most models assume that any component failure causes system failure.

j) It is difficult to apply the methods entirely consistently and different practitioners assessing the same systems are likely to arrive at different conclusions.

7.7.6 Software for computation of generic parts prediction

Software packages are available to process the input data and to compute the system reliability prediction. The software may include generalized data which are often accepted in the absence of more accurate specific data and the accuracy of the resulting analysis should be judged accordingly.