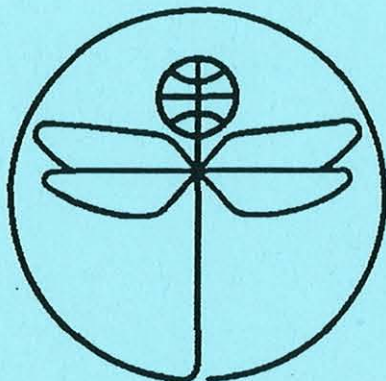


TWENTY FIRST EUROPEAN ROTORCRAFT FORUM



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**THE TOTAL FAULT-AND-FAILURE ANALYSIS AT THE DESIGN
STAGE OF A CIVIL HELICOPTER TO ENSURE SAFETY,
AVAILABILITY, AND MINIMIZED DIRECT OPERATING COSTS**

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Abstract

This paper describes the total fault-and-failure (F&F) analysis of the entire set of the reliability-dependent (RD) characteristics specified for a civil helicopter at the development stage. This technique is compared with a conventional form of the F&F used for ensuring helicopter safety. The reasons are given for the increase in the importance of expanding the analytical approach to ensuring all of the RD operating characteristics of a helicopter at the development stage. The functions, structure and benefits of the total F&F analysis are outlined.

1. Introduction

To build reliability into the design has always been one of the prime concerns of any helicopter developer. The experience have shown that this aim should be achieved in a systematic way. The fault-and-failure (F&F) analysis, combined with other means, is a generally recognized practice that helps to organize the development programme precisely in this sort of way and to produce a properly designed aircraft, as far as reliability is concerned.

Until very recently, the epithet "proper" in a reference to the outcome of a helicopter development programme in the above context would have meant, most probably, the belief on the part of a person who used it that the aircraft of interest should be expected safe to fly. The merit of a design that is worthy of such a characterization is beyond question. However, by now, the number of the reliability-dependent (RD) characteristics that are critical for the overall success of the development programme of a civil helicopter have increased significantly.

At present, ensuring safety alone does not necessarily mean that all the main objectives of the reliability segment of a civil helicopter's development programme are met. Under these circumstances a question may be raised whether there is a better

way of bringing this programme to a successful conclusion. We believe that the answer to this question is to expand the scope of the safety-oriented F&F analysis by incorporating the entire set of the RD characteristics specified for the helicopter at the design stage into the unified analytical process. The latter will be referred to below as the total F&F analysis.

In this paper, we examine the functions, structure, and benefits of the total F&F analysis at the helicopter development stage by comparing it with the conventional safety-oriented F&F analysis used by Kamov Company for its projects.

2. Conventional Approach to the Fault-and-Failure Analysis

2.1. Maturation of the F&F Analytical Practice. Kamov Company has been at the forefront of developing innovative helicopter designs for more than four decades. Dedicated to uphold high technological standards, the Company never fails to place reliability at the top of its priorities. This commitment to enhancing the reliability of the designs have grown continually over the years. The driving force behind the intention of the designer to improve reliability were the requirements aimed at ensuring safety.

The concept of reliability at the early periods of the helicopter history was understood in terms of the inherent vulnerability of the design. The cause of this vulnerability was viewed as a particular item that determined the capability of the design for continued operation. The aim of the helicopter developer was to identify this item and improve it, if necessary.

These earlier helicopter designs comprised mainly self-contained systems, so that failure of one did not influence the continued safe operation of the others. The strategy of the development process was to secure the sufficient reliability of each system. If the system was such that could result in serious hazard, the designer's course of action could be to reinforce the item or to provide an emergency system or introduce the required degree of redundancy in the primary system.

In these early projects, reliability was substantiated, by engineering judgement that took into account, mainly, the results of the performance tests, the experience with the nearest analogous designs and the calculations based on the deterministic understanding of the operating processes in both, the aircraft and its systems. However, elements of the F&F analysis as part of the development process aimed at ensuring reliability can be traced back even to this period.

Then, the advent of individually much more complex systems

containing a much greater number of interfaces and crossconnections showed that to analyze these systems individually would be insufficient. It became clear that each function performed by the systems acting independently or in concert with other systems or parts of the aircraft should also be considered.

The above discussed was a period of accumulating hard-earned experience which was the basis of the gradual evolution of the F&F analytical methods. More recently, however, the rapid progress in technology have opened the way to the realization of even more complex functions performed concurrently with signalling and computer-aided capabilities, especially in the groups of systems responsible for flight and power-plant control and for navigation. The safety regulations and their essence for other systems have also changed significantly. Therefore, the previously used techniques have become altogether too crude, uncertain and incomplete a means for analyzing failures and meeting today's safety requirements [1 - 5].

At this stage, there was a clear need for a major change in the approach to the F&F analysis in the face of its essentially new present-day tasks. The status of the F&F analysis among other development activities aimed at ensuring helicopter safety rose. An indication of this is an increase in the number of the paragraphs of the JAR documents [4, 5] that require either explicitly or by implication to make such an analysis, as compared with the number of the related sections in the basic FAR documents [1]. The results of the F&F analysis are used for meeting the regulations cited in Table 1.

T a b l e 1

The main regulations requiring the F&F analysis

FAR29 and FAR33 sections	JAR paragraphs and a subpart
FAR29.695	JAR29.547 (b) JAR29X602 JAR29.695
FAR29.901 (c)	JAR29.901 (c) JAR29.917 (b)
FAR29.1309 (b), (c) and (d)	JAR29.1309 (b), (c) and (d)
FAR29.1529	JAR29.1529
FAR33.75	JAR-E.C4-2

As a result of these changes, it became a matter of urgency for Kamov Company to introduce into its helicopter development practice a systematic and unified analytical approach to determining failures and assessing their consequences in a way

that should cover the entire set of the relevant requirements for all helicopter systems, both traditional and of high-technology design. The effort of Kamov Company along these lines led to the development of methodologies [9, 10] for the F&F analysis that was effectively used in several projects. Results [11] obtained by applying the earlier version of methodology [9] contributed significantly to the issuance of the type certificate for the Kamov-32 helicopter by the Interstate Aviation Committee (C.I.S) in July 1993.

2.2. Functions of the F&F Analysis. Methodologies [9, 10] are designed to translate the requirements [1 - 5] and the recommendations [6 - 8] into specific sets of guidelines for making the F&F analysis in a sufficiently detailed and streamlined way. In this respect, [9, 10] may be regarded as the top-level documents, in the sense that they specify a way for carrying out the concrete tasks leading to the fulfilment of the functions of the F&F analysis in accordance with the explanations given in [7 - 9] of the intent of the requirements [1 - 5], viewed as the intermediate-level documents and the base-level documents, respectively.

Essentially, the F&F analysis described in [9, 10] is conceived as a tool that should fulfil the following functions as a part of a helicopter development project:

(a) By analyzing the design arrangement and the available test results, to provide the designer with the sufficiently complete list of the failure conditions and failure modes of the parts that are potentially expected to influence flying operations of the helicopter;

(b) Assessing the information for the crew and the effect of the failures on the continued safe flight and landing;

(c) Making qualitative, and where necessary, quantitative assessment of the expected probabilities of the failure modes and of the related failure conditions;

(d) Determining the parts that could cause a hazardous or catastrophic effect on the helicopter;

(e) Cross-checking the required measures that have to be a part of the manufacturing processes and introduced into the Flight Manual and into the Instructions for Continued Airworthiness in view of the results of the F&F analysis;

(f) Preparing the documented results of the F&F analysis for proving compliance of the helicopter with the safety requirements.

It is clear from the above listed functions that the purpose of the methodologies [9, 10] is not only to convince the

Aviation Authorities that the design is safe, but first and foremost, to make the F&F analysis a part of the development process that can be used effectively by the designer and management as well as by those responsible for developing required manufacturing and operating controls, procedures and checks aimed at ensuring safety.

These functions can be carried out only as a concerted effort of specialist in a variety of disciplines like systems and reliability engineering, aerodynamics, flight dynamics, structural strength, and operational aspects, to name but a few. It is obvious that the required outcome of the entire effort depends to a large extent, firstly, on the sound structuring of the F&F analytical process as concrete tasks, and second, on the effective management of the activities of the analytical process as a whole. One of the essential aims of the management is to ensure that the issues awaiting resolution be rationally scheduled, in accordance with the helicopter development programme. Therefore, conceived as a management tool for the entire development programme, the F&F analysis itself has to be properly structured and managed in order to become a help rather than a hindrance and to ensure that no important aspect of the development process is left unattended.

2.3. Structure of the F&F Analysis. According to methods [9, 10], the F&F analysis should begin from the conceptual stage of the project and continue throughout the entire helicopter development programme. The F&F analytical process is structured as a sequence of the following main tasks:

- (a) Identification of the available input material that should define the design as the object for the analysis;
- (b) Preliminary hazard analysis of the helicopter systems;
- (c) Definition of the safety objectives for the aircraft level and for the systems level;
- (d) Investigation of various types of potential failures, assessment of the degree of hazard and a qualitative or quantitative evaluation of their probabilities:
 - (1) Single active failures;
 - (2) Combinations of independent failures;
 - (3) Passive and undetected (dormant) failures;
 - (4) Common-mode failures;
 - (5) Cascade failures (zonal analysis);
 - (6) Failures produced by the environment;
 - (7) Failures resulting from human errors;
- (e) Compilation of the spreadsheets comprising the failure

conditions and their causes (i.e., the failure modes of the components), the signals and cues for the crew, the degree of hazard and the probability for different stages of flight;

(f) Identification of the critical parts;

(g) Evaluation of sensitivity of the results to variations in the failure rates that cannot be predicted with confidence;

(h) Reviewing the check periods assumed in the analysis;

(i) Preparing the documents summarizing the results of the F&F analysis that are relevant to the statement of the compliance of the helicopter systems with the safety requirements.

Each of these tasks is indispensable for achieving the safety objectives. Operating experience provides ample evidence that the safety of a modern helicopter with its assembly of complex systems can only be ensured by a thorough in-depth assessment of all the important potential failures, separately and in combinations, and of the degree of hazard resulting from such failures. In many, but not in all cases, numerical estimates of the probabilities of these occurrences are found desirable or essential. Completed faithfully to the guidelines defined in methodologies [9, 10], these tasks ensure that the F&F analysis will serve its purpose.

Although it is only one of the initial analytical steps on which the effectiveness of the F&F analysis depends, the above-cited task (d)(1) of assessing single active failures is particularly important in terms of the analytical process and of the strategic aim of the development programme in general.

Firstly, it prepares the background knowledge for several of the subsequent tasks of the F&F analysis, such as (d)(2) - (d)(5), (e) and (f). Secondly and most importantly, it allows to focus the attention of the designer on the failure conditions which can occur as a result of a single failure, and if the effect of such an event is severe, to take the appropriate measures in modifying the design arrangement, the manufacturing methods and controls as well as the operational checks (Fig. 1). One of the important products of this task is the list of the critical parts. The locations of such parts are investigated by means of the zonal analysis [task (d)(5)] in order to determine the effect of failures occurring in other systems in the vicinity of these parts (Fig. 2).

The underlying principle that enables to compile the complete set of the failure conditions and their causes in the case of critical systems is based on cross-checking the results of the analysis. This is illustrated in Fig. 3 which is a simplified diagram depicting the two sources from which the data on the failure conditions and their causes (failure modes of the

parts of the system) are obtained in the course of the F&F analysis for the subsequent cross-checking. The vertical branch on the left of the flowchart shows the tasks that allow to determine a set of failure conditions and their causes on the basis of the hardware or so-called "bottom-up" method, whereas the vertical branch on the right side permits to obtain another set of similar data based on the functional or "top-down" approach [8]. By comparing these two sets as prescribed in [9, 10], it is possible to identify important features of the system design and ensure that the resulting list of failure conditions is complete.

With complex critical systems and functions, the analyst has not only to consider the effect of single failures, but also the effect of multiple failures, particularly if some of these will not be detected by the crew. The analyst also has to consider whether the design is such that it can lead unnecessarily to errors in manufacture or in maintenance or by the crew.

3. Total Fault-and-Failure Analysis.

3.1. The Need for the Total Fault-and-Failure Analysis. Safety, although important, is not the only RD characteristic to be considered at the design stage. Reliability is a multifaceted property. There are several other vital reliability-sensitive aspects of the design that have to be taken care of. Lacking reliability can undermine the practicality and the economy of the helicopter and overburden the logistics of the service operations. It is a relatively easy just to include another channel or a backup system into the design to achieve the required level of safety, but such an approach in itself may create problems of operability and spares provisioning in service. Operation of the helicopter may demand that the aircraft should take off and land safely according to the schedule, and in some cases, with various defects and shortages present. Such factors have to be integrated with the overall design of the system and the helicopter.

This is particularly important in the case of the new generation of multipurpose civil helicopters that should perform in accordance with a wider range of RD operating requirements. The success of the development programme vitally depends on each of these requirements. The helicopter developer is faced with the problem of organizing the development programme in a rational way so as to achieve these design objectives. A set of the most important of the RD operational characteristics and their typical

design levels are listed in the following table.

T a b l e 2

No.	Reliability-Dependent Characteristics	Specified Design Levels		
		Effect of failure conditions	Probability, 1 / FH	
1	Safety		event	rotocraft
		Minor	10^{-3}	-
		Major	10^{-5}	10^{-4}
		Hazardous	10^{-7}	10^{-6}
		Catastrophic	10^{-9}	10^{-8}
2	Availability, Achieved	$A_a = MTBM / (MTBM + MAMT) > 75\%$, where <i>MTBM</i> is the Mean Time Between Maintenance and <i>MAMT</i> is the Mean Active Maintenance		
3	Availability, Inherent	$A_i = MTBF / (MTBF + MTTR) > 85\%$, where <i>MTBF</i> is the Mean Time Between Failures and <i>MTTR</i> is the Maintenance Time To Replace an item		
4	Dispatch Reliability	$DR > 95\%$ - the probability of the departure on time		
5	Corrective Maintenance, Specific Workload	$CM < 0.30 \text{ MPH} / \text{FH}$, where <i>MPH</i> is the Maintenance Personnel Hours		
6	Direct Operating Costs	$DOC < 400 \text{ USD} / \text{FH}$, where <i>FH</i> is the Flying Hour		
7	Logistic Failure Rate	$\omega < 0.1, 1 / \text{FH} \text{ (} MTBF > 10, \text{FH)}$		

We propose to use the above functions and structure

(sections 2.2 and 2.3) of the conventional F&F analysis as a framework and to expand them into new forms that should encompass all the above RD characteristics, and not only the safety.

3.2. Functions of the Total F&F Analysis. The expanded F&F analysis is designed as a tool for the total management of the activities aimed at ensuring the entire set of the reliabilitydependent characteristics of a civil helicopter at the development stage. The functions of the total F&F analysis at this stage are the following:

(a) Fulfilling functions (a) - (f) cited in section 2.2 for the conventional F&F analysis;

(b) Providing the designer and management in the course of the development process with the assessed values of reliabilitydependent characteristics 2 - 7 (Table 2) that are expected during service in each of the variety of the operational roles specified for the helicopter, such as the following: transportation of passengers, materials or underslung loads as well as an ambulance, air taxi, search-and-rescue, off-shore liaison, fire fighting, etc.;

(c) Developing the documents substantiating the achievement of the design levels of the RD operational characteristics of the helicopter type design at the development stage.

3.3. Structure of the Total F&F Analysis. In its expanded form, the total F&F analysis retains the structural ordering and the content of tasks (a) - (f) cited in section 2.3 for the conventional F&F analysis, except that some of these tasks are supplemented with additional responsibilities aimed at assessing RD operational characteristics 2 - 7 (Table 2) of the helicopter. As a result, the structure of the total F&F analysis takes the following form.

The scope of task (a) of section 2.3 increases in order to provide the initial data needed for determining the RD operating characteristics (a) - (h). To achieve this, the original database of the component failure rates used in the safety assessment should be expanded substantially. In its new form, this database for every system of the helicopter includes also the following data:

(1) The failure rate per cycle of operation, if the item is involved in performing the starting cycle of the system;

(2) The maintenance time required for replacing the item;
and

(3) The cost of the item.

Task (b) remains the same as in section 2.3.

Task (c), apart from safety, defines the objectives in terms of each of the rest RD operational characteristics 2 - 6 (Table 5) for the aircraft and its systems.

In addition to investigating failures as described in section 2.3, task (d) analyzes the effect of potential single failures on RD operational characteristics 2 - 7 of Table 2. In this case, the analyst has to consider each stages of the entire operational cycle of the helicopter, including the following: preventive and corrective maintenance, preflight starting of the engines and other systems, taxiing, the departure and the flight stage.

Task (e) is for summarizing the results of the investigation of the failures described in task (d) and for developing the complete list of the potential failure conditions that can be encountered at any stage of the helicopter operations. For better accuracy of assessing the achieved and inherent availability and the dispatch reliability, the concept of the failure condition from the safety-oriented F&F analysis has been generalized. This new concept can be applied to the operational stages other than flight. As a result, task (e) for the total F&F analysis also involves the development of the spreadsheet containing the failure conditions that can occur at the stages of the preflight starting the engines and other systems as well as during taxiing. The analysis of the data from the live service experience shows that a significant part of the delays and cancellations of scheduled and planned flights should be expected to occur during these operational stages. In particular, it is essential for the accurate assessment of the expected availability and dispatch reliability of the helicopter that the failure to start an engine or any other system before the flight as well as the detection of the latent failures during maintenance are taken into account. The above-discussed data from this task can be used as inputs for assessing the RD operational characteristics of the helicopter by either approximate deterministic formulas of the type shown in Table 2 or by simulation techniques like the one described in [11].

Tasks (f) - (h) remain the same as in section 2.3.

To include the results of analyzing characteristics (2) - (7) of Table 2, task (i) is expanded accordingly.

3.4. Benefits of the Total F&F Analysis. It is obvious that fulfilling the significantly broader set of functions within the more complex structure of the reliability-related analytical activities will inevitably result in an increase in the volume of

the required work. When a specialized self-contained database is developed and updated for the purposes of the total F&F analysis, the volume of work for completing tasks (a), (c) - (e) and (i) may increase by 100% in comparison with the corresponding volume of work in the case of the conventional safety-dedicated F&F analysis. However, if integrated with any of the flexible CAD/CAM/CAE systems, such as CATIA or CADDs, the total F&F analysis can be realized at its full potential while resulting only in a half of the above-cited increase.

In either case the benefits of adopting the total approach to the F&F analysis outweigh the associated workload penalty, simply because such a penalty would be inevitably even greater if one chooses to discard the systematic approach and to consider inherently related RD characteristics 1 - 7 of Table 2 as disparate entities. Therefore, the first of the benefits is that the F&F analysis minimizes the effort in dealing with the RD characteristics of the helicopter at the development stage.

A more important advantage becomes obvious if one compares the conditions for fulfilling the safety-dedicated tasks of the conventional F&F analysis with the conditions for investigating the entire set of the RD operational characteristics concurrently with the safety by means of the total F&F analysis. Figure 4 makes it clear that the total F&F analysis, for the purposes of the safety analysis, investigates the occurrences (set in bold italics in the figure) of the failure conditions during the flight stage and the dormant failures and defects detected by the maintenance at the scheduled intervals specified as a part of the helicopter's operational profile, and then for the purposes of analyzing other RD operational characteristics, takes this investigation a step further. As a result, the F&F analysis creates an additional margin of assurance that all the safety-related features of the helicopter system and of the operational profile have really been considered.

And last but not least, the benefit of the total F&F analysis is that it has the potential to improve the efficiency of the development process by applying simulation techniques to calculating the expected reliability-dependent characteristics of the helicopter.

4. Conclusions

For over four decades now, various forms of the fault-and-failure (F&F) analysis have been used as an effective development tool for building safety into the helicopter design.

At present however, the success of the development

programme of a multirole civil helicopter is also based on several other reliability-dependent operating characteristics that are closely linked with safety. The conventional F&F analysis does not provide for the needs of the helicopter development programme in ensuring these RD characteristics.

By rationally incorporating some additional functions and properly structured tasks into the conventional F&F analysis, it is possible to upgrade this technique to the level of a tool for the total management of the entire set of the RD characteristics of the helicopter in the course of development.

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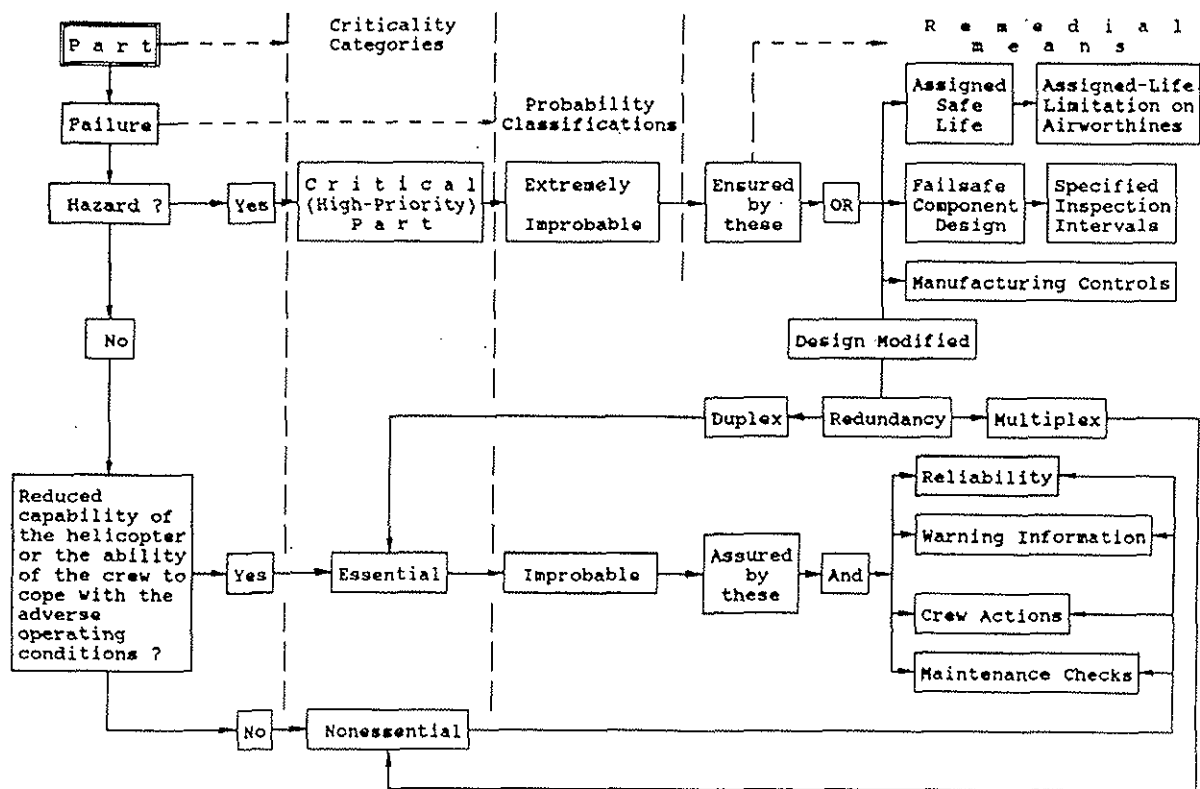


Fig. 1. A typical flowchart for analyzing single active failures.

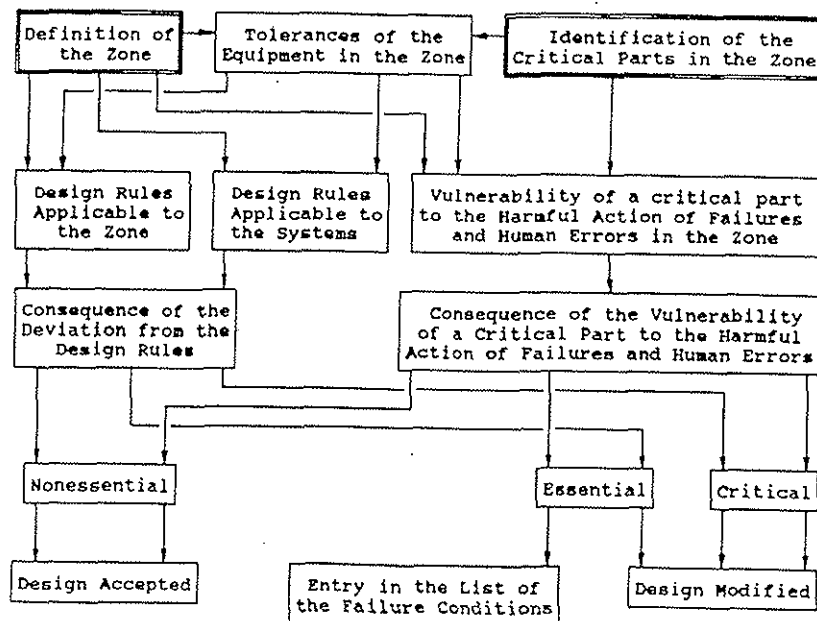


Fig. 2. A typical flowchart for the zonal analysis of a critical part.

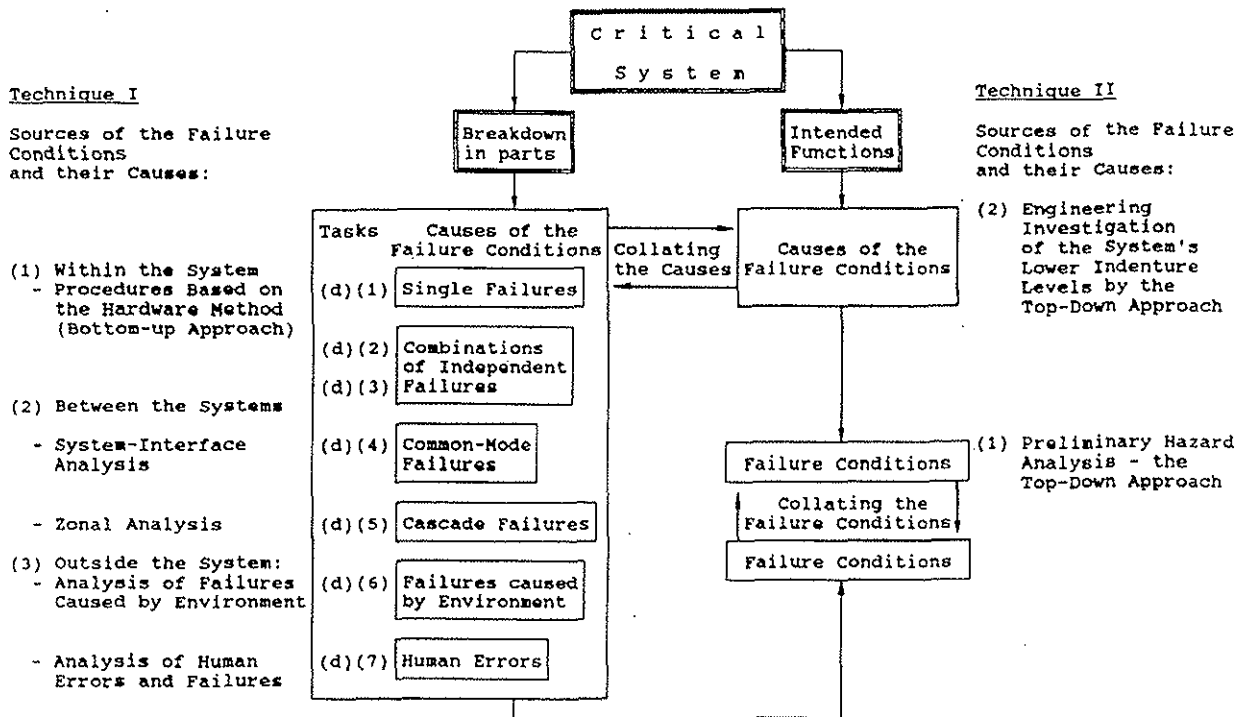


Fig. 3. Collating two sets of analytically obtained data for a critical system.

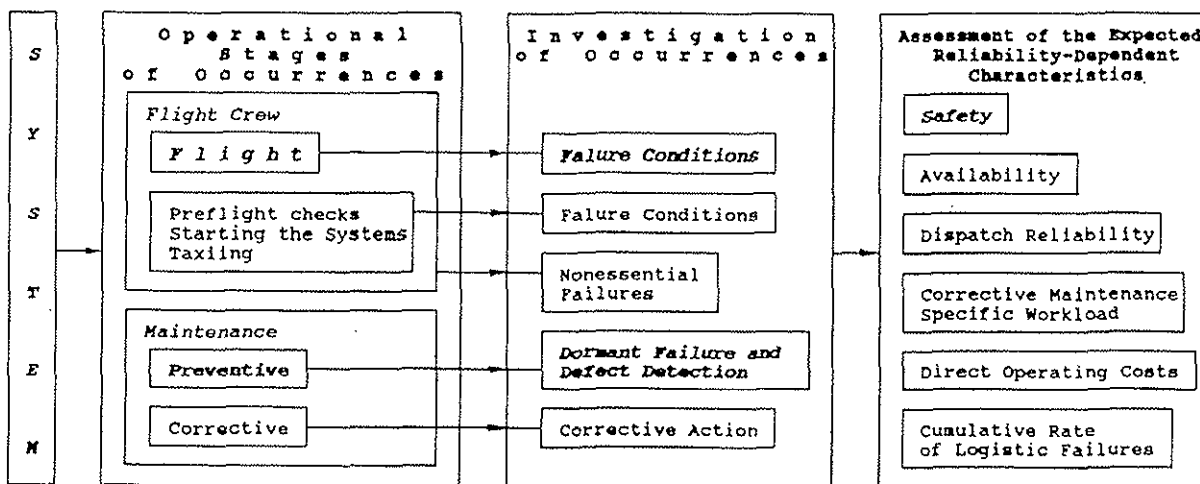


Fig. 4. The scope of the total fault-and-failure analysis of a multirole civil helicopter. The *Italicized Bold-Typed* are the items that are also a part of the conventional safety-dedicated analysis.