Decision Analysis in Microelectronic Reliability: Optimal Design and Packaging of a Diode Array

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This paper considers quantitative aspects in microelectronic reliability using decision analysis. In a given electronic system, a diode array (i.e., system of switches) serves as a built-in test circuit. Failure of a single component can disrupt system performance. Two failure modes are possible, short or open circuit, each resulting in different damages to the system. The decision analysis considers aspects of circuit design and packaging technology. Design involves a conventional system or one with redundancy. Important considerations are cost, total failure rate, proportion of each failure mode and malfunction costs. Three alternative packaging technologies are considered. Optimal design and packaging are determined in two alternative ways: using expected monetary costs, and using expected utility. The method and results were implemented in the Israeli electronics industry. The method has also been implemented in other areas with similar decision problems (e.g., cardiac pacemakers).

TODAY'S electronic systems are more complex, sophisticated and multipurpose than ever. Modern systems (e.g., computers, radar, medical equipment) consist of thousands of components, mostly microelectronic. Failure of a single component can disrupt system performance thus causing damages to the system or even to systems not directly related to the specific components.

Reliability has become a key word in the microelectronic industry. This paper considers quantitative aspects of microelectronic reliability using a decision-analytic approach. A rather specific system is considered, but the various considerations and methods can be and are similarly applied in other settings.

In a given electronic navigation control system, a diode array (i.e., a system of switches) serves as part of a built-in test circuit. Its reliability, especially in two failure modes—"short circuit" or "open circuit"—may reflect negatively on system performance. It is therefore important to achieve an optimal balance between the reliability of the test circuit, its

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costs and malfunction implications. Decision analysis seems an ideal methodology for attacking the problem in light of the underlying uncertainties and the need to consider multiple criteria.

The decision analysis presented in this paper considers aspects of (electronic) circuit design and packaging technology. Design may use a conventional system or one with redundancy where the important considerations are cost, total failure rate, proportion of each failure mode, and malfunction costs. Three alternative packaging technologies are considered and evaluated in terms of availability, convenience, flexibility, costs and volume.

This paper presents a quantitative analysis of the cost-reliability tradeoff of alternative designs for an electronic system. The problem arose in a routine decision making context in the Israeli electronics industry. Section 1 describes the decision problem and develops the decision tree. Section 2 presents the probability assessments. Total failure rates are calculated from standard reliability literature and the distribution of failure modes is obtained from specific professional literature. The cost calculations of Section 3 are obtained from engineering assessments. The analysis is performed twice, using first the traditional (engineering) approach of evaluating all attributes in monetary terms and employing expected costs as the decision criterion (Section 4). Then, in Section 5, utility theory is used to evaluate the multiattribute outcomes, thus allowing a simple consideration of the possible "intangibles" along with various tradeoffs to achieve a decision consistent with the decision maker's preferences.

The results have already been implemented in the Israeli electronics industry (Section 6). The decision analyses proved very beneficial as the recommendations were different from the prior intuitive inclination. A similar approach is currently being utilized in other areas with similar decision problems (e.g., selection of a cardiac pacemaker).

1. THE DECISION PROBLEM

The diode array is an electronic device consisting of 16 individual diodes ("switches"). The device is part of a built-in test circuit within a complex electronic navigation control system (see Figure 1). In this specific application, the array is a system of switches (diodes) with two possible states: "off" and "on." An ideal diode functions as a switch in an off state when the voltage across it is negative, and in an on state when the voltage is positive (Figure 2).

Two failure modes are possible: short circuit—the diode is permanently in an on state; and open circuit—the diode is permanently in an off state.

Each failure mode results in a specific system damage. A short circuit usually causes a more severe damage than an open circuit, hence the

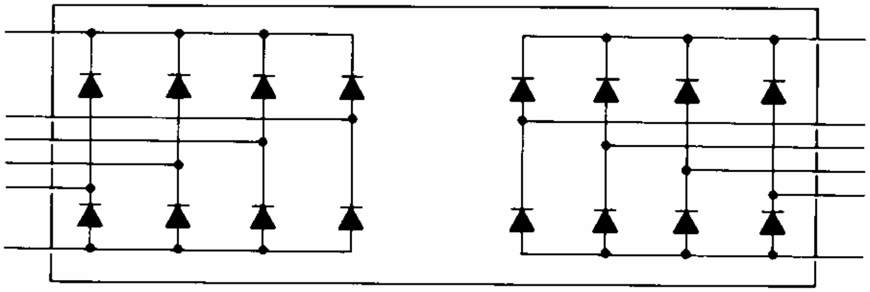

Figure 1. Diode array—schematic diagram.

motivation to consider two diodes in series instead of one to increase reliability. In such a case, if one diode fails in short circuit, the other diode within the pair will be still functioning so that the array as a whole will not be in a short circuit condition. Redundancy in a system results in fewer short circuit failures but at a higher cost. However, a redundant system will have a higher rate of (the less critical) open circuit failures, because the number of diodes is larger than in the nonredundant case, and an open circuit in any of the diodes will result in an open circuit failure for the whole system.

In addition to circuit design (redundant vs. nonredundant), three possible packaging technologies are considered: discrete, monolithic and hybrid. A discrete component refers to individual component parts (e.g., diodes), that are individually packed for use in conventional printed circuit assembly. Its main drawbacks are the rather large volume and surface area. A monolithic circuit is a semiconductor device that contains many "discrete" components and performs a relatively complete circuit function. Its main disadvantage is the inability to replace, repair or add individual components. Hybrid microcircuits are a result of the application of interconnection and packaging technology that provides the ability to combine discrete components or monolithics alone or in combination

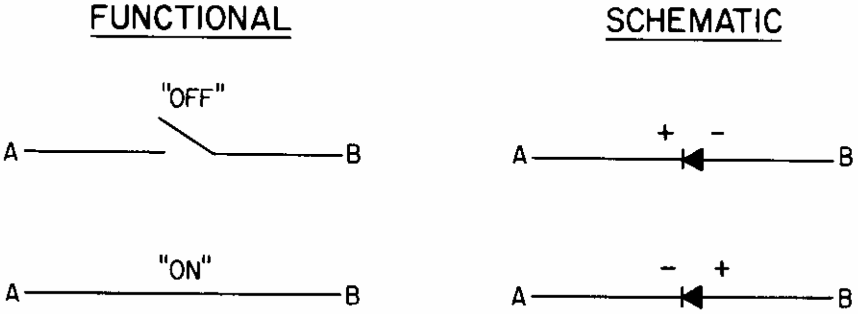

Figure 2. Functional diagram (single diode).

upon a prepared substrate. These designs differ in their cost, failure rate, availability, flexibility and convenience. Choice of circuit design must be made for each of the packaging technologies.

The objective of the decision analysis is to minimize the total life cycle cost of the system which consists of components costs and damage costs. For this purpose an optimal design-packaging combination must be determined by considering the possible malfunctions, their frequencies and implications.

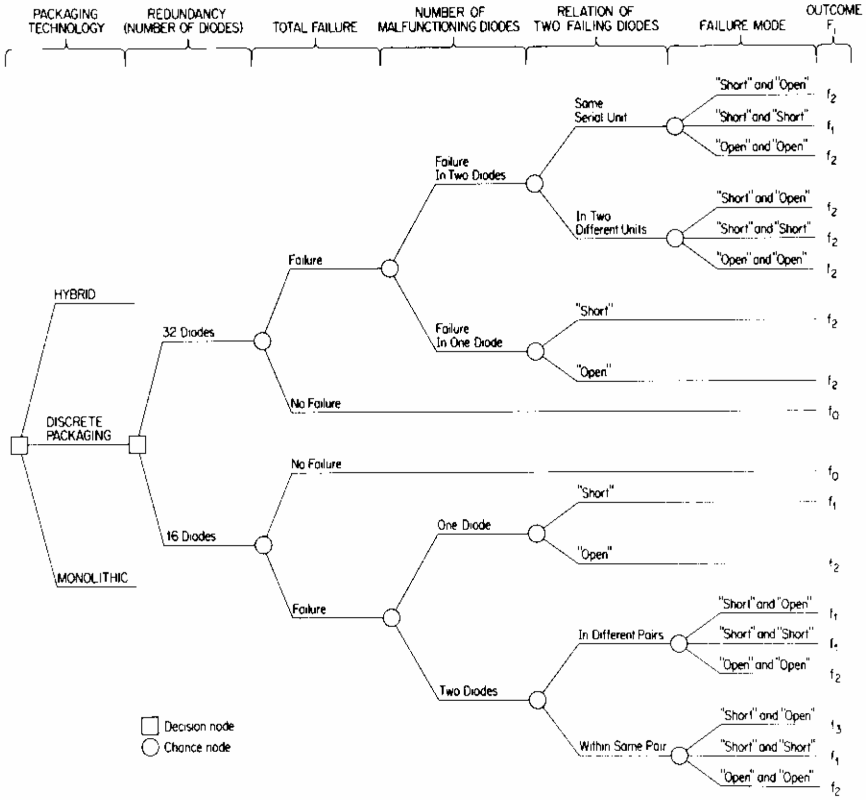

Figure 3. Decision tree.

The decision problem is depicted in the decision tree of Figure 3. The branching following the hybrid and monolithic packagings is identical to the detailed branching outlined for discrete packaging. The six alternatives differ in the total failure rate, the proportion of each failure mode, the damages resulting from each failure mode, and component costs. This results in different probability assessments and different end-consequences for each of the six basic alternatives. Also invoked is the (reasonable) assumption that the probability of failure in three or more diodes during mission time is negligible as compared to the other possibilities. It should be noted that in the nonredundant setting (i.e., 16 diodes), the diodes are arranged in eight pairs. A malfunction of two diodes within the same pair has different implications from a malfunction of two diodes in different pairs; hence the consideration of two malfunctions in the lower branching in Figure 3, resulting in different damage distributions.

The malfunction coded "f_1" functionally affects the whole (navigation control) system in certain operating modes. The system interprets the malfunction f_1 in the built-in test equipment as instructions to perform operations that disrupt the full functional performance of the system. This malfunction can be easily detected during maintenance. The malfunction coded "f_2" partially disconnects the diode array from other parts of the system. When f_2 occurs, full information on the state of the system is unavailable. This bars the detection of certain malfunctions of the system itself. However, in many systems, f_2 does not create serious complications because they contain built-in test circuits to control the original test circuits and malfunctions can be easily detected and repaired. Failure mode "f_3" is similar to f_1 but is very difficult to detect because it results from two simultaneous malfunctions that are of a contradicting nature. The normal condition is coded by f_0.

Before determining an optimal decision, all chance forks must be quantified by assessing the relevant probabilities. Preferences for end-consequences must also be quantified (see Raiffa [1968]).

2. PROBABILITY ASSESSMENTS

Two sets of assessments are needed for each alternative: (a) total failure probabilities (i.e., failure of one or more diodes within the circuit), and (b) the distribution of the various failure modes.

Total Failure Probabilities

Generally, the failure rate of microelectronic components follows the well-known (Anderson [1976]) "bathtub" curve. Early failures are screened out after several hundred hours of operation. When used in military and other high reliability applications, the components are well beyond the early failure stage. The period of useful life extends for millions of hours and covers the time the components are expected to function. During the period of useful life, diode failures are assumed to occur randomly according to a stationary Poisson process with failure rate $\lambda = \lambda^*$ (a constant). The value of λ can be obtained from the *Military Standardization Handbook 217B* (MIL-HDBK 217B) (1974) which is the standard reference used for reliability prediction. It includes models for predicting reliability of circuits and systems as functions of environmental conditions. The failure rates obtained from this source, for a single diode, in each of the alternatives are presented in Table I.

In order to compute failure probabilities the mission time t is defined in this application as the interval between two successive tests of the diode array, which occur within 168 hours (i.e., one week).

Distribution of Failures

Diode failures are assumed to be independent. The latter assumption requires some explanation. The MIL-HDBK-217B models are of the "parts count" type (see Anderson). The parts count method provides an estimate of the reliability based on a count by part type (e.g., resistor, capacitor, transistor, diode). This method is applicable during proposal and early design studies where the degree of design detail is limited. It involves counting the number of parts of each type, multiplying this number by a generic failure rate for each part type and summing up the products to obtain the failure rate of each functional circuit, subassembly, etc. Thus, the accepted parts count method provides estimates for system reliability by assuming the components are independently distributed with a constant failure rate (Barlow and Prochan [1975]). The probabilities for the two failure modes of individual diodes were obtained from the Centre de Fiabilite (1972):

TABLE I

FAILURE RATE λ PER DIODE (PER 10^8 HOURS)

Design	Packaging Technology		
	Discrete	Hybrid	Mono-lithic
16 diodes	7.487	1.118	1.606
32 diodes (redundant case)	7.487	0.944	1.606

$$P(\text{open circuit}|\text{failure}) = 0.35$$

$$P(\text{short circuit}|\text{failure}) = 0.65.$$

These probabilities depend on the current in the diode, its voltage and its environmental conditions. It is assumed that changes in these factors will influence the failure rate, λ, but will not produce statistical dependence of one component on the other. Such conditions as vibration or heat will be known at the planning stage and will relate to the environment in which the components will function; the same environmental, stress and thermal conditions are assumed to exist in the three packaging technologies.

It should be noted that the parts count method is employed in the analysis of thousands of systems annually, some of which do involve interdependencies. However, this is the method used by engineers as there are no superior comparative models. The diode array considered in our analysis provides perhaps the best example for using the parts count method because component failures are indeed independent. Because of the separate physical location of the diodes and due to the low current and voltage of the system it is unlikely that events leading to a "caused" failure of one diode will be contributory to the failure of another diode. This independence is very obvious with the discrete and hybrid realizations although somewhat less so with the monolithic realization.

The probability of failure in k diodes in an array with n (16 or 32) diodes during time t is given by:

$$P_{n,k} = \binom{n}{k} p^k (1-p)^{n-k} \tag{1}$$

where p is the probability of failure in a single diode and equals $1 - e^{-\lambda t}$.

TABLE II

UNCONDITIONAL PROBABILITIES OF FAILURE IN ONE AND TWO DIODES

	Discrete Packaging		Hybrid Packaging		Monolithic Packaging	
	1 Failure	2 Failures	1 Failure	2 Failures	1 Failure	2 Failures
16 diodes	1.2×10^{-4}	1.84×10^{-8}	2.88×10^{-5}	3.89×10^{-10}	4.16×10^{-5}	8.11×10^{-10}
32 diodes	3.96×10^{-4}	7.62×10^{-8}	4.48×10^{-5}	9.72×10^{-8}	8.32×10^{-5}	3.35×10^{-9}

Table II gives the unconditional probabilities of failures in one or two diodes.

The conditional probabilities of failure are obtained by using Bayes' rule. Given that 2 diodes fail in the nonredundant case, the probability of both being within the same pair is obtained by simple combinatorial reasoning. The number of possibilities for "drawing" two diodes from among 16 is $\binom{16}{2} = 120$. Of these 120 possibilities, only 8 (pairs) are from within the same pair. Thus, the desired probability is $8/120 = 0.0666$. Similar arguments hold for the redundant case.

Given that two failures occur, and assuming them to be independent, the probabilities of the various failure modes (e.g., open and short) follow the binomial distribution with $P(\text{short}) = 0.65$.

3. COST CALCULATIONS

There are two main elements of total cost: component costs and damage costs. Component costs are obtained from engineering assessments. The system is planned for eight years of operation (416 weeks).

Thus, the weekly cost (i.e., mission time) is total cost/416. Table III presents the component costs. (Redundancy in a monolithic packaging is not considered because of the extremely higher component costs.)

Every malfunction causes some damage which can be generally expressed as

$$C_T(f_i) = C_M(f_i) + C_F(f_i), \qquad i = 0, \cdots, 3 \qquad (2)$$

where f_i is the damage (outcome), $C_T(f_i)$ is the total damage cost, $C_M(f_i)$ are the maintenance costs incurred after damage f_i, and $C_F(f_i)$ are the costs of mission failure as result of damage f_i. Maintenance costs are relatively easy to obtain in monetary terms. It is very difficult to assess the monetary costs $C_F(f_i)$.

Table IV presents the various costs as they were assessed by the design and reliability engineers involved in the project.

4. EXPECTED COST CRITERION

The conventional approach is to calculate the expected monetary cost of each alternative. Table V presents the expected monetary costs for producing 1000 units with an 8-year life cycle. The costs were obtained by averaging out and folding back the decision tree (see Raiffa). The table shows that a monolithic packaging with 16 diodes is the preferred choice with the hybrid packaging with 16 diodes a close contender.

TABLE III

COMPONENT COSTS

Packaging Technology	No. of Diodes	Component Cost ($)	Weekly Cost ($ × 10^{-2})
Discrete	16	20	4.8
	32	23	5.5
Hybrid	16	22	5.3
	32	27	6.5
Monolithic	16	20	4.8

The expected cost criterion considered only component costs and damage costs. Such issues as availability or convenience have not been introduced because of the near impossibility of assigning monetary values to them. This major drawback of the conventional approach was avoided in the utility analysis where these issues do not have to be expressed in monetary terms (Section 5).

Uncertainty also was not taken into account in cost estimates. The component costs are fixed and therefore deterministic both for components purchased outside the plant (e.g., discrete or monolithic) and the hybrid module purchased from another department in the plant on a purely customer-subcontractor commercial basis. The uncertain costs are the damage costs of Equation 2. Uncertainty underlies both the mainte-

TABLE IV

DAMAGE COSTS

A. For Nonredundant Design (16 Diodes)

No. of Failing Diodes	Failure Mode	Failure Code	Existence of C_F	Existence of C_M	Total Damage Cost, C_T ($)
1	Short circuit	f_1	√	√	300
1	Open circuit	f_2	—	√	100
2	Short circuit and open circuit in the same pair	f_3	√	√	1000
2	Short circuit and open circuit in different pairs	f_1	√	√	300
2	Two open circuits (in the same pair or in different pairs)	f_2	—	√	100
2	Two short circuits (in the same pair or in different pairs)	f_1	√	√	300

B. For a Redundant Design

No. of Failing Diodes	Failure Mode	Failure Code	C_F	C_M	Cost, C_T ($)
1	Short circuit	f_2	—	√	100
1	Open circuit	f_2	—	√	100
2	Short circuit and open circuit (in the same serial unit or in different serial units)	f_2	—	√	100
2	Two open circuits (in the same serial unit or in different serial units)	f_2	—	√	100
2	Two short circuits in the same serial unit	f_1	√	√	300
2	Two short circuits in different serial units	f_2	—	√	100

nance and damage costs. Since the analysis relates to the planning phase of the system, the repair time of a possible malfunction and the resulting maintenance costs, $C_M(f_i)$, as well as the damage costs $C_F(f_i)$, are difficult to assess and especially difficult to express in monetary terms. However, the expected cost criterion assumed all costs to be deterministic and expressed in monetary terms. Because of the underlying uncertainties

TABLE V

EXPECTED MONETARY COSTS (EMC)

Ranking	Packaging and Design	EMC ($)	% Component Cost	% Damage Cost
1	Monolithic, 16 diodes	24,544	81	19
2	Hybrid, 16 diodes	25,738	87	13
3	Hybrid, 32 diodes	29,536	92	8
4	Discrete, 32 diodes	40,255	57	43
5	Discrete, 16 diodes	40,060	50	50

which were not explicitly considered, a sensitivity analysis was performed over a wide range of total damage costs.

The relation of the expected costs to the values assigned to the total damage costs ($C_T(f_i)$) is presented in Figure 4. From the figure it can be seen that the hybrid packaging with 16 diodes should be preferred in case the damage costs are in reality larger than assessed. Because this alternative was such a close contender to the similar monolithic packaging, the recommendation for the optimal choice was a hybrid packaging with 16 diodes. Additionally considering such attributes as availability, design flexibility or volume (included in the utility analysis below), showed that the preference for the 16-diode hybrid packaging is even stronger.

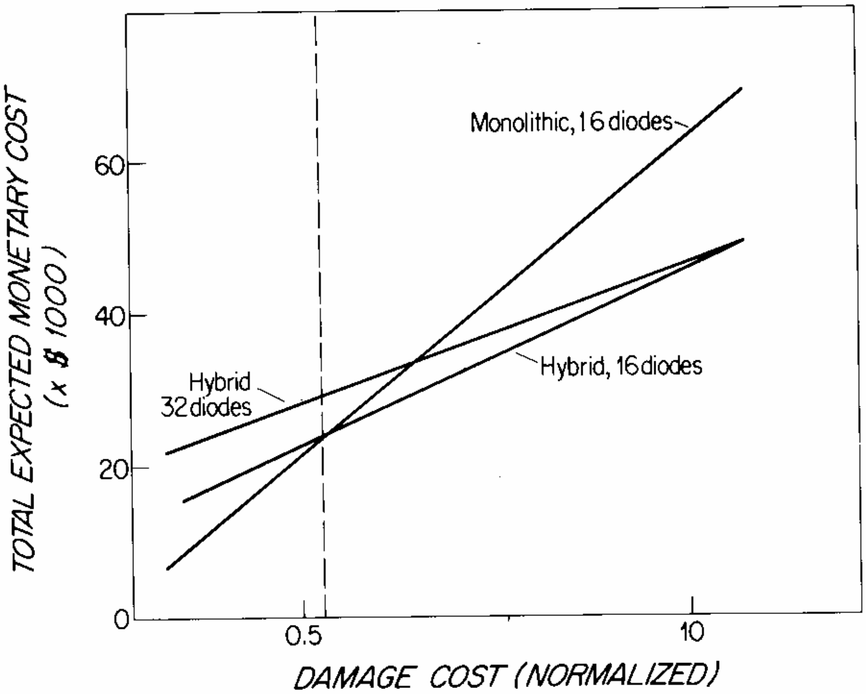

Figure 4. Sensitivity analysis.

Additional analysis also indicated that both discrete realizations (inferior choices by the expected cost criterion) are not made more attractive even by emphasizing other advantages they may have. Hence, the discrete packagings were not included in the utility analysis of Section 5.

It should be noted that all consideration of failures in two diodes could have been neglected. The probabilities of failure in two diodes are in the range 10^{-10}-10^{-8}, while the probabilities for one failure are in the 10^{-5}-10^{-4} range. Thus, there is at least a four-magnitude difference in probabilities. At the same time, there is only a one-magnitude difference in damage costs (\$1000 for damage f_3), so that damages cannot outweigh the probabilities. This is important for future applications and use of our model because a much simpler decision tree can be employed as in the expected utility calculations of the following section. The simplified, more practical decision tree is given in Figure 5.

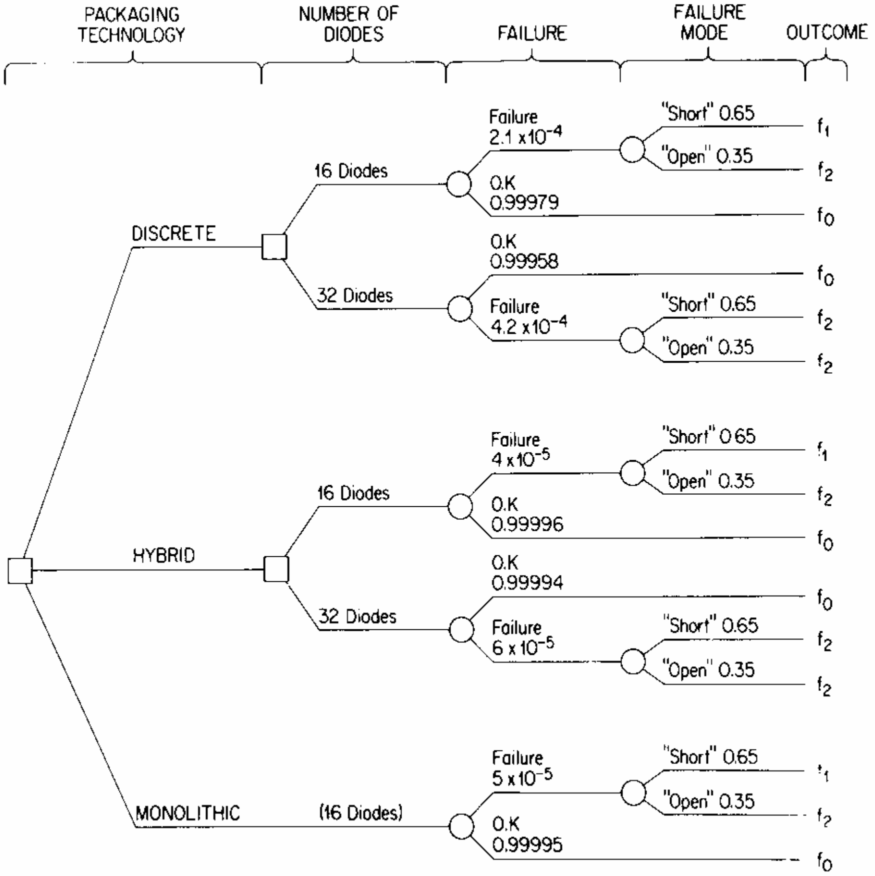

Figure 5. A simplified, practical decision tree.

5. UTILITY ANALYSIS

The expected cost calculations performed in Section 4 can be used as rough guidelines in practical decision making. However, even if costs were the only attribute, expected costs would not necessarily reflect the decision maker's preferences for monetary outcomes. Because of this and the multiplicity of outcomes, not all of which are expressable in monetary terms, it is natural to turn to utility theory which enables a systematic evaluation of preferences for outcomes (see Raiffa).

At this point in the analysis only three alternatives are considered: (a) hybrid packaging with 16 diodes, (b) hybrid packaging with 32 diodes, and (c) a monolithic packaging with 16 diodes.

Each outcome can be characterized by three attributes: unit cost, damage, and flexibility. The flexibility attribute can be further subdivided into three: (1) design flexibility, (2) availability and (3) ease of design change. The design flexibility relates to the range of component functions and characteristics. It is good for the hybrid module (and discrete) but poor for the monolithic packaging. Availability and ease of design change are both good for the hybrid packaging (in-house facility, all components in warehouse) and very poor for the monolithic one (special specifications, special order). The three subattributes are not considered separately because they are fixed for a given packaging technology. Hence only flexibility, the general attribute, which encompasses the above three features is examined. It can take on two values: "good" (for the hybrid module) or "poor" (in the monolithic case). Three damage outcomes are considered: f_0, f_1, f_2. The damage outcome f_3 is no longer relevant as it does not appear on the decision tree of Figure 5. Units costs are \$20 for a monolithic packaging (16 diodes), \$22 for a hybrid packaging with 16 diodes, and \$27 for a hybrid packaging with 32 diodes.

As mentioned earlier, there is a fourth attribute that relates to volume and surface area. But since it is identical for all the alternatives examined in this section there is no need to introduce it explicitly.

Because the number of possible outcomes is rather small (only 9), the utility function is assessed directly as a discrete 9-point function rather than decomposed (see Keeney and Raiffa [1976]) into the 3-attribute function U (unit cost, damage, flexibility). The 9 outcomes were ranked and a utility function scaled between 0 and 1 was assessed using the standard lottery method with certainty equivalents (Raiffa). Because of the discrete nature of outcomes, certainty equivalents for a given lottery could not be directly assessed but rather a given outcome was taken with certainty and the probabilities of a lottery with given outcomes were varied to achieve indifference between the lottery and the outcome. Some examples will follow. The best and worst outcomes were assigned utility values of 1 and 0 respectively. (Two values can be assigned arbitrarily; they simply determine the origin and unit of measurement.) The outcome (\$20, f_2, poor) was compared to a lottery yielding (\$22, f_0, good) with probability p and (\$27, f_1, good) with probability $1 - p$. The project decision maker was asked to assess the value of p such that he would be indifferent between the lottery and the first outcome for certain. After some thought he settled on a value of $p = 0.7$. This yielded U (\$20, f_2, poor) = 0.7. He was then asked to compare (\$27, f_0, good) with a lottery yielding (\$22, f_0, good) with probability p and a complimentary chance at (\$20, f_2, poor). For a value of $p = 0.6$ he was indifferent between the two alternatives. This yielded U (\$27, f_0, good) = 0.88. Assessment of utility values for all outcomes was made in a similar manner. After several consistency checks the values presented in Table VI were obtained.

Using the utility values of Table VI with the relevant probabilities on the "practical" decision tree of Figure 5, the highest expected utility (0.999) was achieved for a hybrid packaging with 16 diodes. The 16 diode monolithic packaging ranked second (0.899) and the 32-diode hybrid module ranked third (0.879).

It should be noted that the utility analysis was initially made using only two attributes: unit cost and damages, since the decision maker stressed these as important. As in the expected cost analysis, the 16 diode monolithic packaging ranked first with the 16-diode hybrid a close second. But when flexibility, availability, convenience, and logistics were introduced as an additional attribute the 16-diode hybrid packaging became the obvious choice.

TABLE VI

UTILITY VALUES FOR OUTCOMES

Ranking	Outcome (Component Cost (\$), Failure Code, Flexibility)	Utility
1	(22, f_0, good)	1.00
2	(20, f_0, poor)	0.90
3	(27, f_0, good)	0.88
4	(22, f_2, good)	0.79
5	(20, f_2, poor)	0.70
6	(27, f_2, good)	0.50
7	(22, f_1, good)	0.30
8	(20, f_1, poor)	0.15
9	(27, f_1, good)	0.00

Some sensitivity analyses were performed on the utility assessments of Table VI. They did not alter the ranking of the three alternatives. The final recommendation was for the hybrid packaging with 16 diodes.

6. IMPLEMENTATION

Both analyses (expected monetary cost criterion and expected utility criterion) yielded evidence against introducing redundancy. The above recommendation was accepted and implemented at the Israeli Aircraft Industry. The decision analyses were very beneficial. The initial intuitive inclination was not to consider the discrete and monolithic packagings because of availability and logistic considerations. However the redundant (32 diodes) design with the hybrid packaging incurred much higher costs. The analysis clearly demonstrated that the higher costs of redundancy are not offset by the benefits in terms of lower failure rates. The preanalysis intuitive choice ranked a rather distant third in both analyses.

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