# Multi-Criteria Decision-Making Approach for an Efficient Postproduction Test of Reconfigurable Hardware System

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Abstract: This paper proposes a multi-criteria decision-making approach for guiding the postproduction test of reconfigurable hardware system (RHS). The latter is a hardware device that allows to change the hardware resources at runtime in order to modify the system functions and dynamically adapt the system to its environment. The optimization of the RHS postproduction test process is a matter of concern for manufacturers since the testing activities have a significant impact on achieving manufacturing objectives in relation to quality, cost and, time control. Taking into account the fact that testing all potential faults is infeasible in practice, the testing process hence needs to be optimized by prioritizing faults according to a well-defined set of criteria. Accordingly, multi-criteria decision-making tools prove their effectiveness in selecting faults to be tested. The proposed method consists in targeting a limited number of faults that require more attention during the testing process. Two strategies are investigated through the recourse to analytic hierarchy process and Choquet Integral. This study helps to determine the most critical faults that have the highest risk priority score. A case study is provided to illustrate the application of the proposed approach and to support the discussion.



## 1 INTRODUCTION

Over the last decade, embedded systems have witnessed an outstanding growth to meet technological advancements. Due to the fact that the new generation of embedded systems is addressing new criteria such as flexibility and agility, reconfigurability has become an evolving approach in real-world applications and scientific research. Therefore, a new class of systems, which is fundamentally based on the ability to change has emerged. An RHS is a hardware device that permits to change the hardware resources at runtime in order to modify the system functions and therefore to dynamically adapt the system to its environment (Ben Ahmed et al., 2018b). As the hardware system manufacturing process is imperfect, several defects including open circuits, bridging and stuck-at faults may occur. Taking into account that these systems are increasingly fragile and safety-critical and that the actual industrial world is facing the challenge of zero defect, testing becomes an essential step for acquiring fault-free and high-quality devices (Eggersglüß, 2019). The postproduction test is a crucial phase of the hardware development process. It ensures that the system is defect-free before it is released to the customers. In industry, the most popular model is the single stuck-at line (SSL) model (Pomeranz, 2020). Given a device under test (DUT) and a fault model, it is possible to construct the initial fault set which contains all possible faults in the DUT. As the cost of the testing process is intensely influenced by the number of faults to be tested as well as the number of test vectors to be applied, many interesting academic and industrial techniques have been carried out to tackle this issue. In this context, the authors in (Eggersglüß et al., 2023) introduce a method that aims to reduce the number of automatic test pattern generation (ATPG). This issue is addressed by producing compact test sets and hence minimizing the volume of test data , test application time, and automatically the cost of testing. The study in (Yang et al., 2021) concentrates on the generation of high-speed digital test vector to accelerate the testing process and therefore allowing the detection of fault rapidly. Further approaches, so far, investigate a machine learning based fault diagnosis (Higami et al., 2022). The method does not require the performance of fault simulation or needs fault dictionaries storage for figuring out the candidate faults. The work in (Kung et al., 2018) presents a new test pattern generation flow to



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target both stuck-at and transition faults at the same time in one ATPG run without recourse to changing the ATPG tool. A compact pattern set can hence be obtained. It needs less volume of test data and shorter time of test application without affecting the fault coverage for both types of faults. The above-cited works focus in the optimization of the testing process through the reduction of the number of test vectors.

As already mentioned, the optimization of the number of faults is also worth considering. In fact, testing all faults is practically infeasible as it strongly increases the manufacturing costs and time delays. Hence, the number of faults to be targeted during the testing process crucially requires optimization. Considerable work has focused on reducing the number of faults particularly for RHS. The work in (Ben Ahmed et al., 2018b) investigates a new testing methodology using the inter-circuits relationships. Such a testing method provides an optimal fault set that can be efficiently used for testing purposes. The work in (Ben Ahmed et al., 2019) presents a new extension of the standardized boundary scan test method. The endeavor is to work on a test approach that offers the flexibility and convenience needed to test RHS based on combinational and sequential logic while ensuring an optimal time and cost. The authors in (Ben Ahmed et al., 2018a) introduce concepts of occurrence and severity ratings in the RHS testing process as a means to target the minimal necessary set of faults while ensuring an acceptable fault coverage rate that meets manufacturing quality requirements. For so doing, the authors propose an alternative for the overall fault coverage that provides guidance for ranking potential faults in terms of their occurrence and severity. However, it is possible to take into account other decision criteria such as controllability and observability. Multi-criteria decision-making (MCDM) tools are therefore helpful when considering multiple factors before making a final choice.

In this research paper, we introduce a guiding method for prioritizing potential faults according the following set of criteria: occurrence, severity, controllability and observability. To put it differently, a fault is weighted according to how frequently it can occur, how serious its consequence on system functionality, safety, etc. It is also about how controllable and observable it is. Taking into account that not all faults are worth pursuing since they do not have the same degree of the previously mentioned criteria, this paper investigates the use of analytic hierarchy process (AHP) and Choquet Integral (CI) to identify the most critical faults. First, the AHP makes it possible to assess the faults based on each criterion and therefore to provide a global risk priority score (RPS). The latter enables selecting the subset of faults that need to be targeted during the testing process. In the second phase, the CI operator is employed for the aggregation of the partial scores obtained for the different faults according to each criterion in order to deal with the preferential interactions between the criteria. Therefore, the risk assessment will be more accurate. As a consequence, targeting a limited number of faults helps the industry to optimize test resources allocation without mitigating the correctness of the system.

The originality of this research, compared to existing works, lies in considering the risk-based criteria needed for selecting faults to be targeted during the testing process. This research also differs in its use of MCDM tools allowing the reduction of the targeted fault set without affecting the correctness of the system. It is feasible to note that MCDM tools are existing concepts in the literature that are used for supporting complex decision-making processes in various domains (Oukhay et al., 2021). However, in this paper they have been coupled with hardware fault techniques for reconfigurable systems.

The remainder of this paper is organized as follows: Section II presents the decision-making framework based on risk optimization in the RHS test process. Section III introduces the proposed MCDM method for selecting the targeted faults. Section IV deals with the suggested case study and highlights some numerical results that prove the worth of the contribution. Section V concludes this paper.

## 2 DECISION-MAKING FRAMEWORK BASED ON RISK FOR OPTIMIZING THE RHS TEST PROCESS

Taking into account that testing all faults is infeasible in the practice as it strongly increases the manufacturing time and cost, the testing process need to be optimized. For a given DUT and with respect to SSL fault model, an initial set of faults that includes all potential faults is defined. This fault set can be reduced through intra-circuit fault collapsing which helps reducing faults via equivalence and dominance relationships (Prasad et al., 2002) (Venkatasubramanian et al., 2015). The application of this technique minimizes to some extent faults occurring within the same circuit. The inter-circuits fault collapsing techniques is therefore processed generating a more important reduction of faults.

As shown in Figure 1, faults generated using the inter-circuit fault collapsing present the starting point of our current approach. In fact, in order to assure efficiency, we propose in this work to focus the testing process on the critical potential faults. The latter are the faults that present the highest level of risk since their appearance would engender significant quality degradation. This is supported by the argument that pursuing faults having trivial impacts on system functionality would be a waste of resources and time. Accordingly, identifying the faults to be addressed in testing can be viewed as a decision-making task in which assessing the risks associated with the candidate faults is needed. In this work, the risk degree of a fault is assessed by calculating the RPS. The latter includes multiple criteria: the likelihood of fault occurrence, the degree of severity of the effect, the degree of controllability of the fault and, the degree of its observability. The evaluation of the RPS is based on the experts knowledge regarding the criticality of the faults and it incorporates the decision-maker preferences regarding the relative importance of the previously mentioned criteria. The experts define an acceptable level of risk (threshold) according to which a decision about the fault is made. Potential faults having RPS lower than the threshold do not need to be tested. On the other hand, critical faults with RPS that is higher than the threshold are included in the testing process. In the following part, we provide an MCDM approach for calculating the RPS.

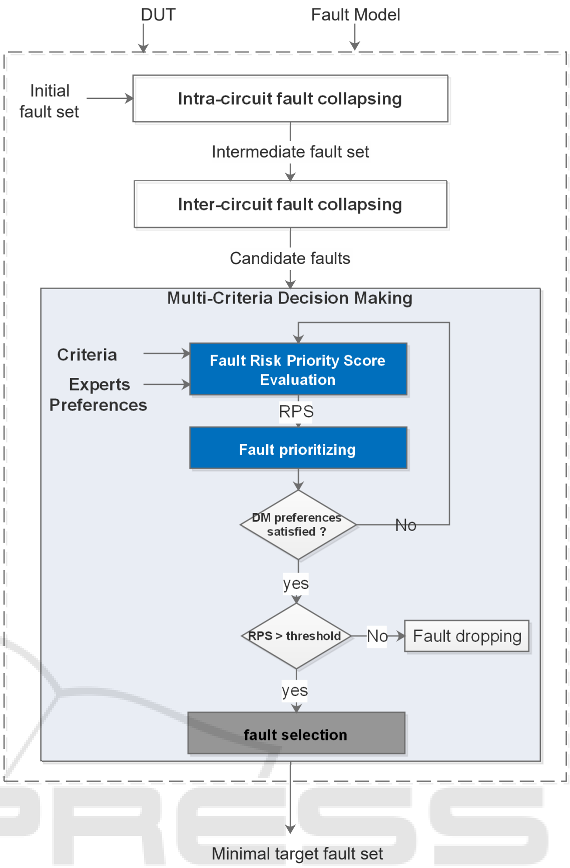


Figure 1: Decision-making framework based on risk for RHS test process optimization.



# 3 PROPOSED MCDM METHOD FOR SELECTING THE TARGETED FAULTS

## 3.1 Method Description

The proposed MCDM method, consisting of five steps is explained in the following:

**Step1:** Specify the objective. The goal defined in this study is to evaluate and prioritize the different faults occurring within the RHS. The evaluation is done according to a finite set of criteria in order to select faults that require more attention during the testing process and therefore to reduce testing workload and allow better resource allocation.

**Step 2:** Specify the criteria. Let D be a finite set of criteria denoted by $D = \{d_1, d_2, ..., d_p\}$. To address and test faults in a circuit, the concepts of occurrence, severity controllability and observability play a major role for so doing. Each criterion is defined as follows:

- Occurrence: It gives us an idea about how often faults can occur. Occurrence can provide information that help estimate or foreshadow future frequency. Given that faults are not likely to occur with the same frequency, they need to be weighted by an occurrence rate. The latter estimates the occurrence frequency of a fault. Faults with the highest occurrence rate need to be addressed in priority.
- Severity: It means the degree of seriousness of a fault measured by its impact on system functionality, performance, safety, or other critical factors. It is basically measured on a scale, with higher levels determining more critical issues that need immediate attention. Poor severity, however, indicates that faults do not affect the functionality of the system and therefore can be ignored.
- Controllability: It refers to the quickness of setting 0 or 1 values at any point within a system through its inputs. Good controllability is defined by the direct manipulation of the system allowing to excitation of the fault as well as the observation of its effects. However, poor controllability problematizes the quick isolation of the fault due

to the fact that the application of inputs might not activate it. Thus, faults having poor controllability present high risk level and require the highest attention during testing.

- Observability: It indicates the ability to determine the value at any point within a system by observing its outputs. It permits the understanding of the impact of the fault on the system outputs. Low observability, on the contrary, makes it hard to differentiate the fault from normal system behavior which problematizes the pinpointing of faults. Therefore, it is mandatory to focus on faults having low observability during the testing process.

The faults are then assessed according to each criterion based on the experts judgement using the AHP method as described in details in the following steps.
**Step 3:** Specify the candidate faults set. Let F be a finite set of potantial faults denoted by $F = \{f_1, f2, ..., f_n\}$.
**Step 4:** Employ AHP method to assess and prioritize faults. This step is explained in details in Subsection 3.2.
**Step 5:** Employ the CI to prioritize faults. This step is explained in details in Subsection 3.3.

## 3.2 Prioritizing Faults Using the AHP Technique

The AHP, also known as Saaty method, is a versatile tool for MCDM that can be applied in different contexts (Saaty, 1990). In this research paper, the recourse to AHP is justified by the fact that this method allows the organization of the problem of selecting a limited number of faults which require more attention into a hierarchical structure of objective, criteria, and alternatives. Furthermore, the AHP facilitates the extraction of the relative performance scores of the alternatives associated with each individual criterion as well as the relevance weights of the criteria through a series of pairwise comparisons. In addition, it provides a mechanism for checking and improving the evaluations consistency, which differentiate AHP from other multi-criteria tools. The application of this method for selecting a subset of faults is carried out through five major steps:

1. Identify the problem and determine the main objective: selecting a limited number of faults which require more attention during the testing process.

2. Organize the problem into a hierarchy of levels that comprise the objective, the criteria, the subcriteria, and the alternatives as described in Figure 2.

3. Make pairwise comparison matrices for each element using the Saaty 9-point scale to determine the relative weights of the criteria and alternatives (candidate faults).

4. Determine the weighted average for each candidate fault according to the following Equation.

$$X_i = \sum_{j=1}^{p} (x_{ij}.w_j) \quad (1)$$

where $w_j$ is the weight of criterion $j$ with $w_j >= 0$, $sum(w_j) = 1$ and $x_{ij}$ is the partial score of the alternative $i$ according to the criterion $j$.

5. Based on the obtained risk priority scores of the faults represented by $X_i$ , the target faults are selected. A risk threshold is defined and the faults with RPS higher than the threshold are chosen to be included in the testing process.

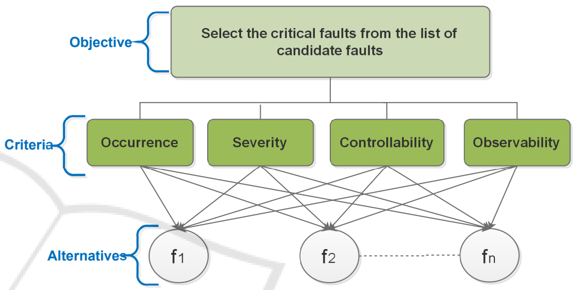


Figure 2: Hierarchy scheme for faults selection.

## 3.3 Prioritizing Faults Using the CI

As part of the AHP technique, the weighted average (equation (1)) is used to aggregate these partial scores of the candidate faults in order to calculate the global scores $X_i$. Since it assumes the criteria's independence, this operator cannot represent preferential relationships between the criteria. As a result, it is unreliable because the interactions frequently occur (Mandic et al., 2015). We suggest utilizing the CI to address the aggregation problem in order to be able to consider interaction phenomena among criteria. The CI operator allows to model not only the significance of each criterion but also the weighting of each subset of criteria, based on a monotone set function known as the Choquet capacity or fuzzy measure (Marichal, 2000). Fuzzy measurement can describe three different kinds of criteria interactions (Grabisch et al., 2008): (1) Negative synergy or negative interaction: When two criteria $i$ and $j$ are viewed by the DM as redundant, they interact negatively; that is, the significance of the pair $\{i, j\}$ is nearly equal to the significance of the individual criterion $i$ and $j$. (2) Positive interaction, also known as positive synergy, is the presence of an interaction between criteria that are deemed complementary, meaning that while the significance of a single criterion is negligible, the significance of the pair is considerable. (3) Independence: When there is no interaction between two criteria, $i$ and $j$ are said to be independent. The fuzzy measure is additive in this instance: $\mu(i,j) = \mu(i) + \mu(j)$.

Some numerical indices, including the Shapley value (Shapley, 1953) and the interaction index (Murofushi and Soneda, 1993), can be computed to help describe the interaction phenomena more fully. A criterion's overall relevance is measured by its Shapley value, and the average interaction between two criteria, $i$ and $j$, is measured by its interaction index.

Let $F$ be the set of faults and $f_i \in S$ ,the global score $X_i$ given by the CI according to a fuzzy measure $\mu$ and a set $C$ of criteria, is defined by:

$$CI_\mu(x_{i1}, \cdots, x_{ip}) = \sum_{j=1}^{p} (x_{i(j)}[\mu(A_{(j)} - \mu(A_{(j-1)}]) \quad (2)$$

Where the notation $_{(.)}$ indicates a permutation on $C$ such as $x_{i(1)} \leq \cdots \leq x_{i(p)}$. Also, $A_{(j)} = \{(1) \cdots (p)\}$ , for all $j \in \{1, \ldots n, p\}$ and $A_{(p-1)} = \phi$.

The identification of capacities is the main difficulty while working with aggregation using the CI based on fuzzy measurements. A survey of techniques for capacity identification in multi-attribute utility theory based on CI is provided by the authors in (Grabisch et al., 2008). The least squares approach, which is the most popular optimization technique for this purpose in the literature, is what we employ in our work (Grabisch et al., 2008). Further understanding of the intended overall evaluations $Y_i$ of the accessible items $S_i \in S$ is necessary. Minimizing the overall quadratic error $E^2$ between the global scores determined by the CI and the targeted scores $Y_i$ supplied for each scenario is the aim of the least squares technique. To further enhance the outcomes, the heuristic least squares approach may be applied. An initial capacity must be defined in order to use the heuristic approach. The uniform capacity might be utilized because it is challenging to determine the beginning capacity (Grabisch et al., 2008). The definition of the uniform capacity in this instance is as follows:

$\mu(1) = 0.333333$ ; $\mu(2) = 0.333333$;
$\mu(3) = 0.333333$ ; $\mu(1,2) = 0.666667$;
$\mu(1,3) = 0.666667$ ; $\mu(2,3) = 0.666667$;
$\mu(1,2,3) = 1.000000$

## 4 CASE STUDY

In this section, we provide a case study using an RHS circuit to demonstrate the proposed contribution.

### 4.1 Presentation

To further illustrate the proposed contribution, we present a case study where hardware components can be added, removed or updated to ensure the adequate functionality of the system when needed. The system presents two units that can perform addition and subtraction operations. These units are designed using lower-level components such as logic gates, including AND, OR, XOR gates and multiplexers and they are also constructed using reconfigurable hardware as shown in Figure 3. At a given time, the selection of the unit is controlled by a multiplexer MUX as shown in Figure 4.

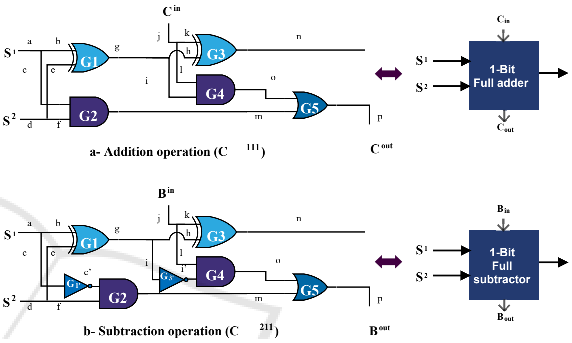


Figure 3: Different reconfigurations implementing the proposed RHS.

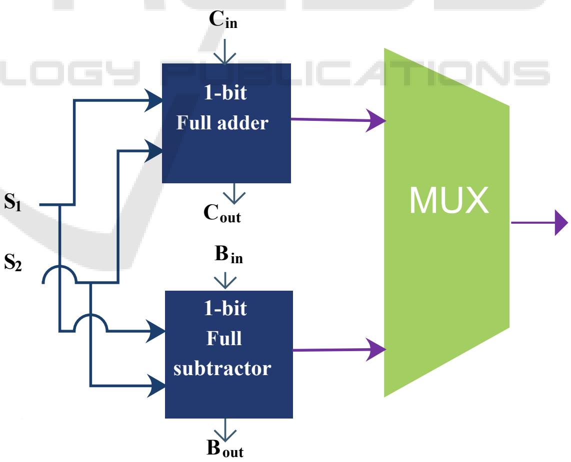


Figure 4: The proposed RHS.

**Assumptions:** Let's assume that stuck-at 1 faults occur more frequently than stuck-at 0 faults. Additionally, we assume that the faults in NOT gate are of high occurrence and faults in AND gate are of a less higher occurrence. However, faults in XOR and OR gates are almost non-existent. The severity of faults in OR gate is much higher than those in AND gate. Faults in XOR and NOT gates are however of a very low severity. Let's assume also that a stuck-at fault, in a digital circuit, might be easily controllable only if an input has a direct impact on the faulty node. Nevertheless, if the fault is hidden deep within the circuit, controllability might be low. Moreover, determining the observability of a faulty circuit output is less apparent when the degree of similarity between a fault-free circuit output and a faulty one is very high.

According to the case study, the application of previous fault collapsing techniques (Ben Ahmed et al., 2018b) reduces the number of faults from 34 to 11 faults. Therefore, the list of candidate faults are as follows:

F={d/0_C111, d/1_C111, e/0_C111, e/1_C111, e/1_C111, g/0_C111, g/1_C111, i/1_C111, f/1_C211, i/1_C211, p/0_C211}

where d/0_C111 means that the signal d is stuck-at 0 in the circuit C111 (addition operation).

## 4.2 Numerical Results

The results of the AHP approach for ranking the faults based on their risk priority score are shown in Table 1. Based on the obtained AHP results, the faults to be included in the test process are those that have an RPS higher than the risk threshold defined by the expert. In this case, the threshold is the mean between all the scores ($threshold = 0.091$). Accordingly, the selected faults are;

p/0_C211 ; i/1_C211 ; d/1_C111 ; i/1_C111 ; f/1_C211 ; f/1_C111

To enhance incorporating the expert's preferences into the decision process, the CI is employed in the second part of the approach to calculate the RPS instead of the weighted average used in AHP. Initially, the decision maker is asked to provide a preference order for a pertinent subset of faults, meaning a subset that is thought to be especially helpful in representing his preferences regarding the criticality of faults:

p/0_C211 $\succ$ i/1_C211 $\succ$ f/1_C111 $\succ$ f/1_C211 $\succ$ e/0_C111 $\succ$ e/1_C111

The desired total scores that are associated with this are $Y_i = [0.2230.1300.1040.1020.0260.025)]$. Next, the heuristic least squares method is used to calculate the Choquet capacity. Above are the capacities attained:

$\mu(\{d_1\}) = 0.163; \mu(\{d_2\}) = 0.267; \mu(\{d_3\}) = 0;$
$\mu(\{d_4\}) = 0.207; \mu(\{d_1,d_2\}) = 0.527;$
$\mu(\{d_1,d_3\}) = 0.488; \mu(\{d_1,d_4\}) = 0.452;$
$\mu(\{d_2,d_3\}) = 0.606; \mu(\{d_2,d_4\}) = 0.548;$
$\mu(\{d_3,d_4\}) = 0.400; \mu(\{d_1,d_2,d_3\}) = 0.803$ ;
$\mu(\{d_1,d_2,d_4\}) = 0.788, \mu(\{d_1,d_3,d_4\}) = 0.697;$
$\mu(\{d_2,d_3,d_4\}) = 0.606, \mu(\{d_1,d_2,d_3,d_4\}) = 1$

The obtained faults RPS using the CI are represented in Table 1. Accordingly, the faults that have RPS higher than the threshold ($threshold = 0.086$) are:

$p/0_C211; i/1_C211; i/1_C111; f/1_C211; f/1_C111$

We notice that when using the weighted average the faults to be tested are reduced to 6 faults. However, when using the CI operator the faults are reduced to 5 faults. This result can be explained by taking into account the decision maker's preferences with regard to the relative weight of the criteria, particularly the way they interact. This can be analyzed more thoroughly by computing the Shapley Values $\phi_\mu$ and the interactions indices $I_\mu$ parameters.

$\phi_\mu(d_1) = 0.283$ ; $\phi_\mu(d_2) = 0.323$ ; $\phi_\mu(d_3) = 0.173$ ; $\phi_\mu(d_4) = 0.221$ ; $I_\mu(d_1,d_2) = 0.015$ ; $I_\mu(d_1,d_3) = 0.157$ ; $I_\mu(d_1,d_4) = 0.057$ ; $I_\mu(d_2,d_3) = 0.071$ ; $I_\mu(d_2,d_4) = -0.05$ ; $I_\mu(d_3,d_4) = -0.017$ ;

The severity criterion $d_2$ in this instance is the most important, followed by the occurrence, observability, and controllability criteria. The criteria {severity, observability} and {observability, controllability} interact negatively, i.e., they present some redundancy, whereas the criteria {occurrence, severity} {occurrence, controllability }, {occurrence, observability }and, {severity, controllability} have positive interactions.

To sum up, with respect to the proposed RHS the application of this approach decreases the number of faults from 11 to 6 and 5 (almost the half) using the AHP technique and the AHP combined with CI, respectively. The obtained fault set presents the critical faults posing the greatest risk. These faults have to be targeted during the testing process. The proposed system can be part of a more complex digital circuit such as the commonly used reconfigurable arithmetic and logic unit (R-ALU) (Ben Ahmed et al., 2018b). The n-bit R-ALU can be constructed by chaining n 1-bit R-ALU. For instance, in a 256 R-ALU, we obtain 256*11=2816 candidate faults. The application of AHP approach decreases drastically the number of faults to 1536. This reduction reaches 1280 faults when using AHP combined with CI.

For mass production, supposing that for each targeted fault we need on average two test vectors, and

Table 1: Priority rankings derived using the AHP technique and CI.

| Criteria Weights | $d_1$: Occurrence $w_1 = 0.319$ | $d_2$: Severity $w_2 = 0.53$ | $d_3$: Controllability $w_3 = 0.044$ | $d_4$: Observability $w_4 = 0.106$ | RPS with AHP | RPS with CI |
|---|---|---|---|---|---|---|
| d/0_C111 | 0.117 | 0.072 | 0.021 | 0.026 | 0.0.79 | 0.057 |
| d/1_C111 | 0.196 | 0.072 | 0.021 | 0.026 | 0.104 | 0.069 |
| e/0_C111 | 0.016 | 0.026 | 0.032 | 0.041 | 0.025 | 0.026 |
| e/1_C111 | 0.024 | 0.026 | 0.032 | 0.026 | 0.026 | 0.025 |
| f/1_C111 | 0.066 | 0.109 | 0.032 | 0.203 | 0.102 | 0.102 |
| g/0_C111 | 0.04 | 0.055 | 0.1 | 0.031 | 0.050 | 0.047 |
| g/1_C111 | 0.052 | 0.055 | 0.1 | 0.045 | 0.055 | 0.052 |
| i/1_C111 | 0.102 | 0.082 | 0.146 | 0.203 | 0.104 | 0.125 |
| f/1_C211 | 0.057 | 0.118 | 0.032 | 0.203 | 0.104 | 0.103 |
| i/1_C211 | 0.317 | 0.018 | 0.145 | 0.123 | 0.130 | 0.130 |
| p/0_C211 | 0.014 | 0.37 | 0.34 | 0.075 | 0.223 | 0.220 |

that the test application time of a test vector takes 1s and one working hour costs $10, then for a 256-bit R-ALU the total cost of 1000 256-bit R-ALU devices will be about $15600 using the existing techniques (Ben Ahmed et al., 2018b) (Prasad et al., 2002) and about $8500 and $7100 using AHP approach and AHP coupled with CI, respectively. We notice that the difference between the costs is considered tremendous in mass production industry.

This study is important in a way that (1) it guides experts to identify faults that necessitate immediate attention due to their criticality score (2) it supports allocating resources and efforts more efficiently and (3) it helps to save the scarcest resource in the industry, which is time and cost.

## 5 CONCLUSIONS

This study presents a MCDM approach to prioritize faults that require more attention during the testing process. This approach is based on a well-defined set of criteria: occurrence, severity, controllability and observability and is implemented using the AHP and CI. The effectiveness of the proposed approach lies in helping prioritize resources and efforts towards addressing the most critical faults posing the greatest risk. It is feasible to note as a conclusion that two major results of our study can be signaled. First, it introduces a MCDM approach that allows the reduction of the targeted fault set without affecting the correctness of the system. Second, it implies that resources are allocated in an efficient manner. In future work, we plan to add other criteria such as fault coverage and to incorporate the proposed approach in the software tool TnTest [1].

[1]https://lisi-lab-projects.wixsite.com/demo/demonstration

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