# ADVANCED CLASSIFIER FOR EXPERT ASSESSMENT OF DIVERSITY AND COST OF NPP INFORMATION AND CONTROL SYSTEMS

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**Abstract.** The article presents a new classifier of types of diversity (version redundancy) for information and control systems (ICS) of nuclear power plants, which significantly complements the well-known classifier according to the NUREG-7007 standard by adding subtypes of diversity, taking into account production processes and the capabilities of FPGA technologies. A method of expert evaluation of diversion metrics and the cost of implementing alternative architectural solutions at the ICS NPP based on the extended NUREG-7007 classifier is proposed. Taking into account the complexity of formalizing the concepts of divergence and value in critical systems, an adapted graph model of the classifier was proposed, which makes it possible to evaluate both individual branches (subsets of types of divergence) and complete multi-paths (for a set of subsets of types of version redundancy) of implementation. A survey of experts was conducted using the developed scale of normalized grades, the obtained data were processed taking into account ranking, normalization and correction by weight of the level. The principles of estimating cost and diversion metrics are proposed. Based on the new classifier, a method has been developed that helps detect (select) configurations with an optimal ratio of «cost/diversity», supporting engineering solutions in the early stages of design. The results can be used to build automated tools for selecting architectures of multi-version control systems for nuclear power, aviation and critical infrastructure security.Й

**Keywords:** Expert evaluation, diversity, implementation cost, graph model, information and control systems, NUREG-7007.

## 1. Introduction

Ensuring the functional safety of information and control systems (ICS), in particular emergency protection systems of NPP reactors, aircraft control systems, railway automation systems requires the use of the principle of diversity [1-3]. The essence of this principle is to use the so-called version redundancy of processes (development, verification, validation, maintenance), source and end products (electronic components, software and hardware platforms) [1,4,5].

It is clear that the use of diversity requires additional resources. To evaluate the effectiveness of the types of diversity used or chosen for use, it is necessary to have as detailed a classifier as possible.

The first classifier that summarised the types of divergence is provided in the NUREG7007 standard published in 2009 [6]. In the time since its publication, scientists and development engineers have taken substantial steps forward and provided examples of new variants of version redundancy [7-9].

## 2. Disadvantages

The development and implementation of new technologies, platform solutions, in particular, on programmatic logic (FPGA) [4,10] create opportunities for improving classification schemes of diversion and methods for assessing the impact of its types on the reduction of risks on failure by common cause (common cause failure, CCF) [7,11]. There is, however, some uncertainty in the known publications about taking into account such possibilities and creating classifiers that would integrate the kinds of divergence at different organizational, project and technological levels [12]. In addition, methods for assessing divergence, taking into account extended classifications, need to be improved [4,10,13,14].

## 3. Purpose

The purpose of the study is to increase the accuracy of the evaluation and selection of types of diversity of multi-version ICS, which take into account new possibilities, in particular, software logic technology (FPGA). Research tasks:

– development of an advanced diversion classifier that has a four-level structure with additional levels that correspond to additional types of diversion for FPGA projects;

– improvement of the method of assessing diversity using expert knowledge;

– analysis of the results of expert evaluation of diversion and value metrics.

## 4. Advanced classifier and formulation of the evaluation problem

Figure 1 provides an outline of the proposed extended classifier, in which subtypes of divergence are added at the third and fourth levels of the hierarchy in comparison with the classifier [6]. The fourth level details the possibilities of introducing diversity at the level of FPGA electronic projects, as well as diversity synchronization of various parts of backup channels. The proposed types and subspecies of diversity are highlighted in a dotted outline.

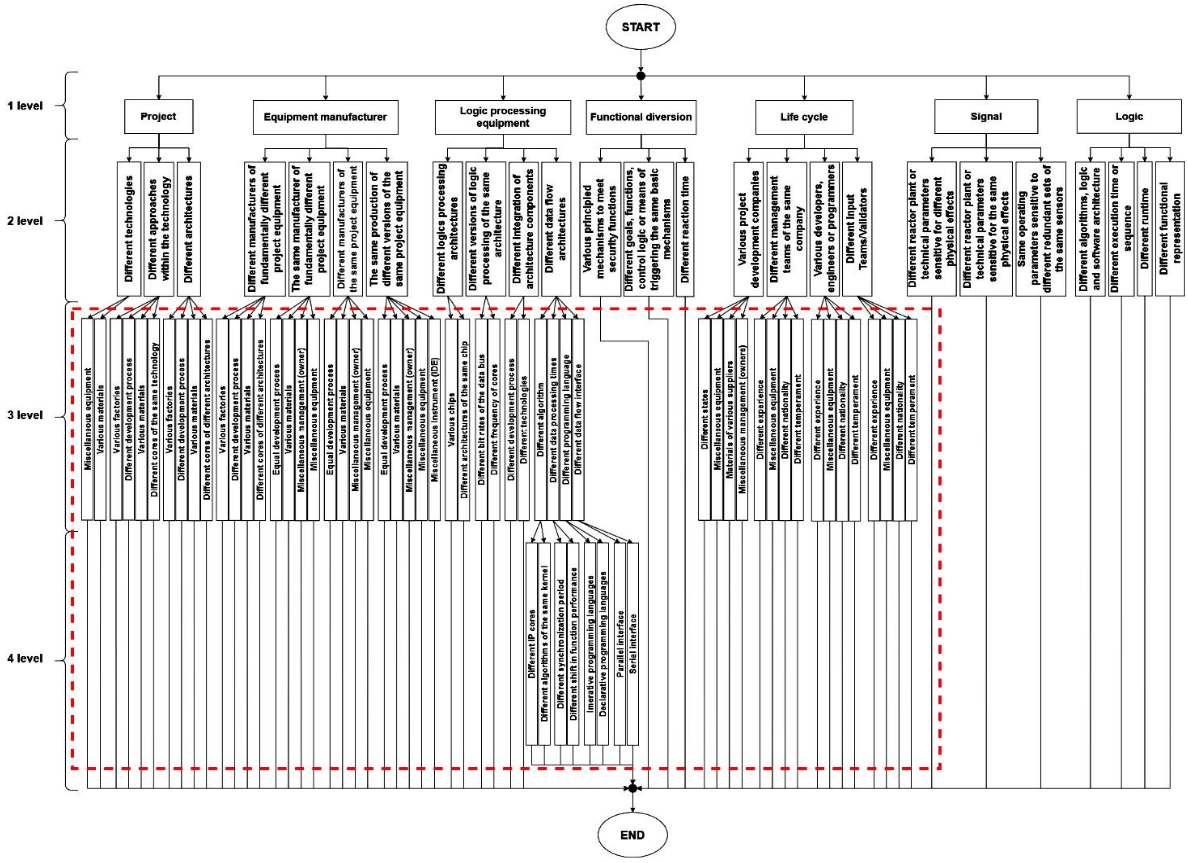


*Fig. 1. Advanced classifier of species and subspecies of diversion*

## 5. Method of expert assessment of diversity

The advanced classifier is the basis for assessing diversity for specific ICS projects. An expert method is proposed for evaluation, taking into account the impossibility of analytical determination of diversion and cost metrics. Tasks of expert evaluation:

– build a complete list of possible classifier branches, including all hierarchy levels (functional, software, hardware, organizational, etc.);

– formulate key issues for evaluating each branch based on the cost of implementation, the level of heterogeneity of components, the independence of sources, the degree of influence on the overall security of the system, and more;

– develop an evaluation scale that allows you to normalize results in the interval from 0 to 1;

– define criteria for the selection of experts who are able to provide reasonable assessments;

– provide a methodology for processing results, including calculating averages and general graph path metrics.

In order to obtain quantitative information on the degree of diversity and the expected cost of implementation of each individual branch of the classifier, a special list of questions submitted for expert evaluation was developed. The formulation of questions was based on generally accepted principles of expert methods, and also took into account the specifics of building two-version ICS architectures. The survey was divided into blocks of questions, each of which provided a list of 2 to 7 diversionary components, which must be assigned a priority value (rank) of 1 to n within the current block to assess diversion and cost. Thus, a questionnaire was formed (Figure 2), which was filled out by independent experts answering the same questions. Therefore, a full-fledged response matrix was constructed for the set of branches to calculate the average values of the metrics.

The list of questions is formed in the form of a questionnaire table. An example of the process of processing one block of questions of section “divergence of fundamental criteria”, which consists of 7 points, is as follows:

Estimate the importance (priority) of diversion and cost between 1 and 7, where 1 – is the highest cost (diversity) and 7 – is the lowest cost (diversity):

– project development process (various technologies, architectures, etc.);

– diversified project equipment manufacturers;

– logical processing of equipment (transmission and processing of architecture data);

– various functions to achieve security;

– life cycle (different manufacturers, programmers, marketers, etc. during project development);

– signals (measuring equipment);

– logic and algorithms.

**Test survey on the topic of the extended diversity classification according to NUREG-7007.**

Provide priorities in each survey item for the diversity types (from 1 to k, where 1 is the highest diversity and k is the number of items in the criterion) according to the extended classifier of NUREG-7007, and the relative implementation cost for the corresponding type of diversity (from 1 to k, where 1 is the highest cost). The level and relative priority of a diversity type are determined by the risk level of common-cause failure (CCF), i.e., the probability of coincident failures of both subsystems – the main and the diverse one. The assessment is performed within the group 1–26.

| № | Question | Priority | | Comments |
|---|---|---|---|---|
| | | Diversity | Cost | |
| **0.** | **Example:** | | | |
| a. | Lowest CCF risk in the group, highest cost | 1 | 1 | |
| b. | Medium CCF risk, lowest cost | 2 | 3 | |
| c. | Highest CCF risk, medium cost | 3 | 2 | |
| **1.** | **Diversity of fundamental criteria (7 items):** | | | |
| a. | Project development process (different technologies, architectures, etc.) | | | |
| b. | Diverse manufacturers of project equipment | | | |
| c. | Logical processing of equipment (data transmission and architectural processing) | | | |
| d. | Different functions to achieve safety | | | |
| e. | Lifecycle (different manufacturers, programmers, marketers, etc. in the project development) | | | |
| f. | Signals (measuring equipment) | | | |
| g. | Logic and algorithms | | | |
| **2.** | **Diversity in the development process (3 items):** | | | |
| a. | Use of different technologies (for example, microcontroller and FPGA) | | | |
| b. | Use of different approaches within a single technology (for example, FPGA and CPLD) | | | |
| c. | Use of different architectures (Atmel microcontroller and ARM) | | | |
| **3.** | **Diversity of project equipment manufacturers (4 items):** | | | |
| a. | Different manufacturer of fundamentally different implementations of the project equipment | | | |
| b. | Single manufacturer of fundamentally different implementations of the project equipment | | | |
| c. | Different manufacturers of identical project equipment | | | |
| d. | Single manufacturer of different versions of an identical implementation of the project equipment | | | |

*Fig. 2. Extended classifier questionnaire illustration*

Experts assessed the extent to which these elements actually perform different functions, are based on different construction principles, or belong to different vendors, platforms, or paradigms. A high degree of independence is a guarantee of the system's resilience to CCF failures.

Example of working through the block of questions in the "diversity in the development process" section, which consists of 3 items:

Rate the importance (priority) of diversity and cost on a scale of 1 to 3, where 1 is the highest cost (diversity), and 3 is the lowest cost (diversity):

– use of different technologies (e.g. microcontroller and FPGA);

– using different approaches within the same technology (e.g. FPGA and CPLD);

– use of different architectures (Atmel and ARM microcontroller).

This question elaborates on the first one, and focuses on whether there is a noticeable difference in the means of implementation between the components. For example, two components can be functionally independent, but at the same time built on the same platform, or developed by the same supplier - then the level of heterogeneity will be low.

All answers (priorities) had to be normalized on a scale from 0 to 1, with a step of 0.01, where 0 is the minimum value (for example, complete similarity or minimal costs), and 1 is the maximum (maximum difference or the highest expected costs).

The assessment was carried out separately for each branch of the classifier, and independently of each other, without prompts or leading factors. Also, before conducting the survey, the experts were provided with a brief explanation of the terms, examples from real systems, as well as a unified instruction describing the procedure. This significantly reduced the spread of assessments and improved consistency between respondents.

After completing the expert questionnaire stage, comprehensive processing of the collected data was carried out, which included preliminary verification, systematization, numerical processing, and statistical analysis of the obtained estimates. The goal of the processing was to convert individual expert judgments into aggregated quantitative metrics that could be directly used within the framework of the classifier graph model.

Each expert provided ratings in the form of a spreadsheet, in which each branch of the current classifier vertex was a separate row, and two evaluation parameters (diversity and implementation cost) were columns.

After receiving the results from the experts, a matrix of size M × N × I was formed, where M is the number of branches (objects of evaluation, in our case 28), N is the number of experts (in our case 10), and I is the number of evaluation criteria (in our case 2: diversity and cost). Each cell contains a numerical priority value in the range 1…n, where n is the number of branches to the vertex of the current level (Figure 3).

Based on the collected data, partial diversity and cost metrics are calculated for each component considered.

Calculation steps:

1. Calculation of the arithmetic average between all experts for each question separately.

2. Ranking of average scores within one block with prioritization, which returns the same ranking, but taking into account the scores of all experts.

3. The normalized sum of the reciprocal numbers of the components of the current level allows us to obtain the metrics of the current block with a sum of 1.

4. This algorithm is calculated the same way to obtain the diversity and cost metrics separately.

In several cases, abnormally high variances were recorded, when one or two experts significantly differed in their assessments from the others. In such cases, a cross-analysis of the explanations provided by the experts (in the comments to the questionnaires) and a check of the clarity of the branch formulation were carried out. All the identified anomalies had explanations related to the interpretation or specificity of the experience of a particular expert, so the assessments were left unchanged.

| Test survey on the topic of expanded diversity classification Nureg-7007 | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *In each survey item, assign diversity priorities (1-X, where 1 is the highest diversity) for different diversity factors according to Nureg-7007, which has been expanded, and their costs (1-X, where 1 is the highest cost) to achieve the current diversity. The number of priorities for each question is equal to the number of items for that question. | | Exp. 1 | | Exp. 2 | | Exp. 3 | | Exp. 4 | | Exp. 5 | | Exp. 6 | | Exp. 7 | | Exp. 8 | | Exp. 9 | | Exp. 10 | |
| № | Question | Div. | Cost. | Div. | Cost. | Div. | Cost. | Div. | Cost. | Div. | Cost. | Div. | Cost. | Div. | Cost. | Div. | Cost. | Div. | Cost. | Div. | Cost. |
| a. | The highest priority and most expensive priority | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| b. | Normal but cheap priority | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 |
| c. | Low priority with average cost | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 |
| 1. | Diversity of fundamental criteria (7 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Project development process (different technologies, architectures, etc.) | 1 | 1 | 4 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 5 | 6 | 4 | 3 | 2 | 1 | 1 |
| b. | Different manufacturers of project equipment | 2 | 3 | 6 | 4 | 3 | 2 | 1 | 1 | 6 | 7 | 1 | 1 | 6 | 7 | 7 | 7 | 2 | 4 | 2 | 2 |
| c. | Logical processing of equipment (data transmission and processing architecture) | 5 | 6 | 5 | 6 | 2 | 2 | 1 | 1 | 4 | 6 | 3 | 4 | 3 | 4 | 4 | 2 | 6 | 7 | 2 | 2 |
| d. | Different functions to achieve safety | 4 | 4 | 1 | 3 | 1 | 3 | 1 | 1 | 2 | 4 | 5 | 5 | 7 | 3 | 3 | 4 | 4 | 5 | 2 | 2 |
| e. | Life cycle (different manufacturers, programmers, marketers, etc. during project development) | 3 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 7 | 2 | 4 | 2 | 5 | 6 | 5 | 6 | 1 | 1 | 1 | 1 |
| f. | Signals (measuring equipment) | 7 | 5 | 7 | 5 | 2 | 2 | 1 | 1 | 3 | 5 | 7 | 6 | 4 | 2 | 1 | 1 | 7 | 3 | 2 | 3 |
| g. | Logic and algorithms | 6 | 7 | 3 | 7 | 1 | 3 | 1 | 1 | 5 | 3 | 6 | 7 | 2 | 1 | 2 | 1 | 5 | 6 | 1 | 2 |
| 2. | Diversity in the development process (3 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Use of different technologies (e.g., microcontroller and FPGA) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| b. | Use of different approaches within the same technology (e.g., FPGA and CPLD) | 3 | 3 | 3 | 3 | 1 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 3 | 3 | 2 | 2 |
| c. | Use of different architectures (Atmel microcontroller and ARM) | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 3 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3. | Diversity of project equipment manufacturers (4 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different manufacturer of fundamentally different implementation of project equipment | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 1 | 3 | 2 | 2 |
| b. | One manufacturer fundamentally different implementations of the project equipment | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | 3 | 3 |
| c. | Different manufacturers of the same project equipment | 3 | 3 | 4 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 1 | 2 | 2 |
| d. | One manufacturer of different versions of the same implementation of the project equipment | 4 | 4 | 3 | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 1 | 1 | 1 | 1 | 4 | 4 | 2 | 2 |
| 4. | Diversity of logical processing of the equipment (4 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different logical processing of the architecture (data processing using a vhdl function or a Nios core) | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 4 | 4 | 4 | 3 | 1 | 2 | 1 | 2 |
| b. | Different logical processing versions of the same architecture (for example, different data bit depth of a megafunction) | 4 | 4 | 3 | 4 | 2 | 2 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 1 | 1 | 2 | 1 | 3 | 3 |
| c. | Different integrations of architecture components | 2 | 2 | 2 | 2- | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 4 | 3 | 2 | 2 |
| d. | Different data flows of the architecture (serial and parallel data transfer interface) | 3 | 3 | 4 | 3 | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 1 | 1 | 3 | 4 | 3 | 4 | 2 | 2 |
| 5. | Diversity of functions for achieving safety (3 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different basic mechanisms for achieving safety | 1 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 2 | 3 | 2 | 1 | 2 | 2 |
| b. | Different goals, functions, control logic or means of triggering the same basic mechanisms | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 1 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 1 | 2 | 1 | 1 |
| c. | Different response time | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 |
| 6. | Diversity of the project development life cycle (4 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different project development companies | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 3 | 1 | 1 | 1 |
| b. | Different managers within the same company | 4 | 4 | 4 | 4 | 2 | 3 | 3 | 1 | 4 | 4 | 4 | 4 | 3 | 3 | 1 | 1 | 4 | 3 | 2 | 2 |
| c. | Different engineers, circuit designers and programmers | 2 | 3 | 2 | 2 | 2 | 3 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 1 | 2 | 2 | 2 |
| d. | Different testers, verifiers and executors | 3 | 2 | 3 | 3 | 2 | 3 | 1 | 1 | 3 | 3 | 3 | 2 | 1 | 1 | 2 | 3 | 2 | 4 | 2 | 2 |
| 7. | Diversity of measuring devices (3 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different reactor or process parameters sensitive to different physical influences | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 1 | 1 | 2 | 2 |
| b. | Different reactor or process parameters sensitive to the same physical influences | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 3 | 3 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| c. | The same process parameter sensitive to different redundant identical sensors | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 3 | 3 | 2 | 2 |
| 8. | Diversity logic and algorithms (3 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different algorithms, logic and software architecture | 1 | 1 | 1 | 1 | 1 | 3 | 1 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 2 | 1 | 1 |
| b. | Different execution time or order | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 1 | 1 | 3 | 1 | 3 | 3 |
| c. | Different functional representations | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 3 | 2 | 2 |
| 9. | Diversity in the use of different technologies in project development (2 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different equipment | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| b. | Different materials | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 |
| 10. | Diversity in the use of different approaches within the same technology (4 points): | | | | | | | | | | | | | | | | | | | | |
| a. | Different manufacturing plants | 4 | 4 | 1 | 1 | 2 | 1 | 3 | 1 | 3 | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 4 | 1 | 2 | 1 |
| b. | Different engineering processes | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 1 | 1 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 |
| c. | Different materials | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 2 | 3 | 2 | 3 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 1 |
| d. | Different cores within the same technology | 1 | 1 | 4 | 4 | 1 | 2 | 2 | 2 | 4 | 4 | 4 | 4 | 1 | 1 | 2 | 1 | 1 | 4 | 2 | 2 |

*Fig. 3. Aggregated results of expert evaluation of the extended classifier*

To obtain integral metrics of diversity and cost (not individual branches, but the full path in the classifier graph), a formula was applied that takes into account:

– path structure (position of the vertex in the route),

– weight of the assessment at each stage (the closer to the beginning of the path, the more important),

– number of components of the current level, which allows for objective weight distribution.

## 6. Evaluation results

After the collection and processing of expert assessments, a detailed picture of the distribution of values of the diversity metrics (Dtgen) and the cost of implementation (Costgen) across all branches of the graph structure of the extended classifier was obtained. This provides the initial analytical interpretation of the obtained data and decision-making on the feasibility of including individual branches in the design configurations of future information and management systems.

When analyzing the feasibility of using the metrics of the extended classifier, the results were grouped by hierarchy levels, and also classified by the ranges of the obtained assessments. In particular, three conditional groups were identified for each metric:

– low value: 0.00–0.33;

– medium value: 0.34–0.66;

– high value: 0.67–1.00.

These ranges provide a clear picture of which branches of the classifier have a high implementation cost, but at the same time do not provide significant diversity, and vice versa.

The analysis revealed that:

– over 60% of vertices fell into the average range for both metrics — this indicates a balance between efficiency and costs;

– 12% of the vertices had high diversity, but were accompanied by an extremely high implementation cost - they are recommended only for critical systems with high reliability requirements;

– 8% of vertices had low cost and at the same time medium or high diversity — these options are especially valuable for developing cost-effective architectures.

## 7. Conclusions

The constructed classifier significantly expands the hierarchy of diversity types and subspecies for ICs built on FPGA platforms, and provides an opportunity for a more accurate and objective assessment of diversity. The conducted expert assessment created a quantitative basis for analyzing the branches of the diversity classifier. The involvement of highly qualified specialists, clear formulation of questions, correct assessment methodology and proper processing of results ensured the high quality of the collected data.

The assessment of the implementation cost (Costgen) and diversity (Dtgen) indicators for each branch of the classifier graph model provides an opportunity to obtain a holistic view of the potential advantages and disadvantages of various system configuration options.

In further research, it is advisable to consider introducing additional vertices and levels of the extended classifier to expand the areas of application, as well as the needs of the aviation, military or transport sectors. Thus, the conducted research not only allows using the formed classifier as a theoretical model, but also makes it possible to integrate the results into tools for supporting engineering decisions in practice.

## Conflict of interest

The authors declare the absence of any financial or other potential conflict relevant to this work.

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