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Engineering Management and Modular Design: A Path to Robust Manufacturing Processes

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Abstract: Manufacturing environments, characterized by dynamic changes and uncertainties, demand effective strategies to minimize disruptions. This study introduces an innovative approach that integrates engineering management principles with modular design to prioritize risk mitigation and enhance robustness in manufacturing processes. From a systems engineering perspective, all manufacturing activities are perceived as interconnected components within a unified system. Leveraging the Axiomatic Design (AD) theory and the Design Structure Matrix (DSM) method, the study modularizes manufacturing process architecture to effectively curb risk propagation and manage system complexity. This study identifies the most optimal design as a pivotal architectural configuration, significantly improving the structural robustness and stability of the System of Interest (SOI). Empirical evidence supports this design's capability to reduce complexities, thereby enhancing robustness within the broader system architecture. Notably, the proposed approach results in a substantial reduction in complexity, with the most optimal design exhibiting an approximately 82.79 percent reduction in work volume compared to the original design. Our research underscores the critical relationship between manufacturing and engineering management. Effective collaboration between these domains optimizes resource allocation, decision-making processes, and overall organizational strategy, leading to improved production processes and increased efficiency. Importantly, the study demonstrates a significant enhancement in modularization, resulting in elevated overall robustness in manufacturing processes. This highlights the proactive involvement of engineering management in the design phase to address production challenges, ultimately optimizing system performance. Thus, this research contributes to both practical applications and academic discourse by offering a novel approach to enhancing the robustness in manufacturing processes. By integrating engineering management principles and modular design strategies, organizations can fortify their processes against disruptions and effectively adapt to evolving circumstances.

Keywords: Axiomatic Design (AD) Theory; Design Structure Matrix (DSM); engineering management; manufacturing architecture modularization; manufacturing management; modular system architecture; robustness

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1. Introduction

To manufacture a product, effective and efficient utilization of technical personnel, physical resources, and information is crucial [1,2]. The responsibility for this crucial task is generally assigned to engineering management [3]. Engineering management is a diverse

field that combines the principles of engineering, business administration, and management to plan, design, organize, supervise, and lead technical projects, teams, and organizations. It applies engineering and management principles to ensure that engineering projects are completed on time, within budget, and to the required quality standards. The responsibilities of an engineering manager include coordinating and collaborating with different stakeholders involved in a project, such as engineers, clients, vendors, and regulatory bodies while managing people, resources, and risk. Engineering management encompasses a broad range of topics, including technology management, quality control, project management, cost analysis, design, procurement, construction, commissioning, project control, quality assurance/quality control, project service, and more. Ultimately, engineering management aims to effectively and efficiently utilize technical personnel, physical resources, and information to produce products or services that meet an organization's goals and objectives [3–6].

The resource allocation, decision-making processes, and the overall organizational strategy are handled by manufacturing management to ensure effective operations [1,7–9]. In this regard, manufacturing management can significantly impact engineering management [10].

Based on the provided definition, manufacturing management refers to the planning, coordination, and control of the production process to ensure that goods are produced efficiently, on time, and to the required quality standards. It involves managing the resources and activities involved in the manufacturing process, including people, materials, equipment, and information [11].

Inefficient manufacturing management can lead to the suboptimal use of resources, delays in production schedules, and reduced productivity, negatively impacting engineering management. On the other hand, by implementing effective manufacturing management systems, organizations can optimize resource allocation and streamline the decision-making processes. This can result in improved production processes and increased efficiency in utilizing technical personnel and physical resources [8,12,13].

Often, manufacturing environments may experience various rapid and sudden changes, uncertainty, unforeseen risks, unpredictable events, and/or uncontrollable fluctuations [14]. Considering that manufacturing management assumes the role of overseeing resource allocation, decision-making processes, and the overarching organizational strategy, it is crucial that the manufacturing management is capable of identifying, analyzing, and mitigating potential risks that may arise during the production process. This includes risks related to equipment failure, supply chain disruptions, safety hazards, quality issues, and other factors that may impact the production process or product quality [15].

The poor design of manufacturing processes can significantly contribute to the occurrence and propagation of operational risks [16–18]. A poorly designed manufacturing process architecture lacks an alignment with good design principles, leading to complexity, low modularity, inefficient resource allocation, and limited flexibility. This deficiency increases the risk of errors, defects, and safety hazards while hindering adaptation to evolving requirements and unforeseen challenges. Inefficient processes drive up production costs, waste materials, and introduce more errors. They also impede problem identification and resolution, resulting in delays and complications. Poor process design also limits visibility and hampers process improvement over time [16]. On the other hand, A well-designed manufacturing process architecture offers benefits to manufacturing and engineering management. It facilitates bottleneck detection and improvement identification, supported by comprehensive documentation and efficient communication channels. Real-time monitoring enables prompt issue detection and resolution, enhancing overall

efficiency [19]. Effective design is crucial in minimizing the likelihood of operational risks and their potential impact on manufacturing processes [14].

The design of manufacturing processes has a cascading effect on engineering management in addition to manufacturing management. In fact, the design and management of manufacturing processes have a significant impact on engineering management. Engineering teams bear the responsibility of designing, implementing, and improving these processes, which necessitates specific skills and expertise aligned with the complexity and level of automation employed. Furthermore, the effectiveness of engineering management systems, including quality control and continuous improvement programs, relies on the underlying architecture of manufacturing. Therefore, the design of manufacturing process architecture falls within the scope of engineering management responsibilities, offering an opportunity for them to make a substantial impact.

Achieving a well-designed architecture for manufacturing processes is crucial, and manufacturing management plays a pivotal role in contributing to engineering management. One of the most effective and critical ways in which manufacturing management can make this contribution is by actively participating in the design phase of a product. By involving manufacturing experts from the outset, potential production and assembly challenges can be identified and addressed proactively, resulting in an optimized manufacturing process. This collaborative approach ensures the development of an efficient and streamlined process, ultimately leading to the creation of high-quality products.

2. Design of Robust Architecture for Manufacturing Processes

When it comes to manufacturing processes, particularly in the face of environmental disturbances, the significance of robustness cannot be overstated. A robust design for manufacturing processes is key to ensuring that a manufacturing process can withstand, adapt to, and recover from any unforeseen disruptions that may arise.

Al-Refaie [20] contributed to the understanding and modeling of robustness, highlighting the need for comprehensive methodologies that consider the various factors influencing performance. Koc et al. [21] conducted a study on process parameter variation in worm hydroforming, aiming to optimize quality, robustness, and capability. They employed response surface analysis with a Box–Behnken design to optimize parameters and evaluate process capability using univariate indices, such as Cp and Cpk. However, the study did not consider the interrelationships among response variables and noise variables, indicating the need to account for these factors in robustness assessments. The challenges associated with noise variables in robustness studies were highlighted by Mevik et al. [22] and Robinson et al. [23]. Their work emphasized the limitations of certain designs, such as BBD, in effectively accounting for noise variables, which are crucial for studying robustness.

Scholz-Reiter et al. [24] suggested improving robustness by enhancing production capacities through resource utilization optimization. They explore how optimizing resource utilization can contribute to robustness in production systems. Karimi and Djokoto [25] also discussed the topic of robust stability analysis, further emphasizing the importance of accounting for uncertainties and disturbances in manufacturing processes. Kusumoto et al. [26] also discuss robust management in manufacturing systems, focusing on product and process robustness. They emphasize the importance of state-space analysis and structured analysis tools in achieving robustness. Alem and Morabito [27] implement a robust optimization scheduling approach in furniture manufacturing. Their study surpasses deterministic worst-case methods in most situations, demonstrating the effectiveness of robust optimization techniques in improving robustness in manufacturing processes. Meyer et al. [28] conducted research to analyze the influence of capacity adjustments on the performance robustness of different operational key figures in manufacturing systems.

Their study investigated the trade-off between the robustness of operational performance and cost efficiency, emphasizing the importance of systems being able to withstand fluctuations and disturbances to maintain high performance and profitability. Mondal et al. [29] focused on the measurement and modeling of robustness in serial multi-stage manufacturing processes. They employed sensitivity analysis and sensitivity matrices to evaluate and measure the robustness of these processes. The authors highlighted the complexities and interactions present in multi-stage processes, emphasizing the need for a comprehensive understanding of robustness measurement. However, they acknowledged that their methods were more suitable for large batch production scenarios and may not be effective in situations such as one-kilogram production. Additionally, Mondal et al. [30] introduced a modeling approach that incorporated input-output and in-process parameters to assess and model process robustness in manufacturing systems. They demonstrated the application of their approach through a numerical example involving a two-stage worm gear manufacturing process. Malmström et al. [31] explored the relationship between resource constraints and robustness in smaller companies. Their findings contribute to understanding the challenges faced by these companies in achieving and maintaining high levels of robustness. Montgomery [32] emphasized the importance of interaction effects and noise variables in achieving robustness in design and manufacturing. He highlighted the need to understand their impact and efficiently incorporate them in experiments. Montgomery also discussed the relationship between process capability and robustness, emphasizing the need for further modeling and understanding. These insights contribute to the understanding of robust design and process robustness. Xiong et al. [33] conducted research on evaluating the robustness of production systems. They introduced indicators related to material variances, free capacity, and the overlap between slack periods and machine failure. Their studies explored the system's ability to handle disruptions and maintain smooth operations. Additionally, they focused on evaluating robustness in a flexible job shop problem using the concept of float time. Their research provided valuable insights into the impact of machine and tool breakdowns on the robustness of production systems. Becker et al. [34] defined MS robustness as the ratio of feasible operations with disruptions of a specific machine to the total feasible operations without disruptions. Sharda and Banerjee [35] presented a mathematical optimization model for designing a robust manufacturing system (MS). Their model incorporated factors such as processing times, equipment failure and repairs, and product demand to improve performance in the face of uncertainties. The model aimed to minimize the makespan, the mean work-in-progress (WIP) time, and the number of machines, considering these uncertainties during the design process. Stricker and Lanza (2014) [36] conducted research that supports the importance of robustness in production systems. They utilized the Value-at-Risk (VaR) measure as an indicator of robustness and explored its implications in uncertain environments. Their work contributes to the understanding of robustness and its role in the success of production systems. Beber and Becker (2014) focused on exploring the relationship between topological characteristics and dynamic behavior in manufacturing networks. They highlighted the importance of the network's static structure, represented by its topology, and the material flow within the network in influencing factors such as performance and robustness [37]. Varas et al. (2014) contributed to the field of robust optimization by demonstrating its benefits in reducing variability and uncertainty in production schedules. Their work specifically focused on a sawmill scenario, highlighting the effectiveness of robust optimization strategies [38]. Benderbal et al. [39] emphasized the significance of technical disruptions in production systems. They analyzed the impact of these disruptions on system robustness and focused on optimizing schedules and designs. Benderbal et al. [39] explored robustness in a reconfigurable production system using an average-based measure that quantified

potential delays from machine failure. Their study highlighted various approaches to measuring robustness, including time span, float time, and average-based measures, providing insights into the system's ability to handle variations and disruptions. Tian et al. [40] introduced sensitivity analysis to analyze the effects of machining parameters in the electrical discharge machining process. Their research focused on understanding the sensitivity of these parameters and their impact on the overall process. Putnik et al. [41] studied the impact of system size and network structure on the robustness of production networks under changing demand. They defined robustness as the ratio of production rate with perturbations to production rate without perturbations, exploring the relationship between system characteristics and robustness. Their research assessed robustness in manufacturing systems without specifying the approach or measure used. Stricker et al. [42], their work reinforces the notion that high robustness is associated with costs. They provide insights into the trade-off between robustness and cost considerations in manufacturing systems. Giannetti and Ransing [43] improved output quality in the steel foundry industry using tolerance synthesis to assess process robustness. Their robustness indicator, a likelihood ratio, compared the likelihood of achieving the expected output using modified input parameter regions. Validation of their methodology demonstrated its potential to improve output quality. Zhao et al. [44] investigated the performance evaluation of the axial ventilator in the turbofan engine lubrication system. Their study aimed to assess the sensitivity of the ventilator's performance to different factors. Meyer [45] examined the role of redundancy in achieving robustness in manufacturing system performance. The study derived specific definitions of robustness and redundancy for the manufacturing context and explored indicators such as nestedness and elementary flux modes. Analysis of different manufacturing system configurations revealed a significant correlation between redundancy and robustness. These findings emphasized the potential of incorporating robustness in the design of manufacturing systems. Boorla and Howard [46] contribute to the discussion of robust management in manufacturing systems. They highlight the significance of robustness measures and analysis in ensuring the resilience of products and manufacturing processes. Sakhaii et al. [47] further contribute to the topic of technical disruptions in production systems. Their research explores the optimization of system characteristics and the impact of these disruptions. Moslemi et al. [48] focus on modeling robustness in multistage manufacturing systems, introducing process capability as a surrogate measure of robustness. They utilize response surfaces and a robust coefficient estimation method to analyze quality characteristics. The results demonstrate the superiority of the robust multistage process and highlight the relationship between robustness and capability in multistage manufacturing. This research contributes to understanding robustness in multistage processes and the use of robustness indices as surrogates. Zeng and Yen [49], their work focuses on the impact of global value chains on production systems. They highlight how optimizing costs in these chains can increase vulnerability to factors like geo-political disputes and transportation issues, further emphasizing the need for robustness.

Zhang et al. [50], their research primarily focuses on ensuring robustness in manufacturing systems through technology control. They address the importance of technological advancements and control mechanisms in achieving robustness. Himmiche et al. [51] conducted a study on the impact of disturbances and uncertainties on meeting deadlines in a production system. They evaluated various machine capacity plans and assessed the likelihood of meeting deadlines under these conditions. Additionally, their research focused on addressing technical disruptions, such as machine and tool breakdowns, and optimizing system characteristics to enhance robustness. Efthymiou et al. [52] explore robustness in the aerospace domain, applying their metric in a supplier flow workshop. Their approach quantifies capability and enhances controllability across scenarios using likelihood-based

indicators. The case study showcases the practical application of their approach, providing valuable insights into production system robustness in the aerospace industry. Pagone et al. [53] focused on the association between high robustness and costs. They contribute to the understanding of the economic implications of achieving and maintaining robustness in manufacturing operations.

Frederico et al. [54] addressed the challenges posed by digitization in production systems. They highlight the need for rapid adaptation to new technologies, business models, and competitors, underscoring the importance of robustness in these dynamic environments. Martín et al. [55] illustrated the benefits of a robust optimization approach in achieving high robustness at lower costs in an automotive supplier context. Their study compared the performance of the robust optimization approach with heuristic planning approaches for production schedules, emphasizing the cost-effectiveness of the robust optimization strategy.

Hyder et al. [56] tackled uncertainty and sustainability in cloud manufacturing, exploring tools and proposing a Collaborative Cloud Service Platform (CCSP) to enhance supplier-customer-manufacturer relations while considering robustness and sustainability in service composition. Stockmann et al. [57] emphasized a holistic approach to assess robustness in production systems, considering tradeoffs between performance, resource requirements, and output. Their methodology evaluated robustness from an input-throughput-output perspective, connecting it with adjacent capabilities for a comprehensive understanding of production system robustness. Liang and Li [58] explored cooperation uncertainty's impact on robustness in manufacturing service systems (MSS). They proposed a methodology treating MSS as a network of service subsystems to identify critical paths and standardize cooperation mechanisms for enhanced robustness.

Table 1 presents a comprehensive overview of the significant aspects of the present study in comparison to the relevant studies found in the literature. The table showcases the diverse range of studies in the literature, which primarily concentrate on various aspects such as developing mathematical/statistical methods, presenting informative process capability indices, incorporating robust design principles, introducing useful robustness measures, and considering the complexity of interrelationships among manufacturing processes to tackle the issue of robustness in manufacturing process structure. Additionally, a select few of these studies also approach the problem from systems engineering perspective, specifically addressing the concept of system architecture. To achieve such robustness, a system engineering approach is adopted in the present study. This approach recognizes that all activities involved in forming the manufacturing process should be viewed as an integrated system, working together harmoniously to enhance its robustness. It is worth noting that within this category of studies, only a limited number of works propose modularization as an effective approach for achieving robustness in manufacturing processes. Table 1 provides an overview of studies that utilize the Axiomatic Design (AD) theory to modularize the system architecture and contribute to the design of robust manufacturing processes. However, the literature review reveals that the focus has mainly been on the allocated architecture of the system, neglecting the significance of the process architecture in system robustness. According to the AD theory [59], the physical components of the system, which are part of the physical architecture, are influenced by a set of process variables (such as men, machines, methods, and materials) belonging to the process architecture. Therefore, this study emphasizes the importance of considering modularity in the process architecture, as it indirectly supports modularity in the allocated architecture. In other words, examining the modularity of the process domain architecture is crucial for the effective allocation of components within the physical system. The literature currently lacks a clear understanding of how modularization of manufacturing process architecture can effectively enhance

the robustness of the system architecture while minimizing system complexity. This gap emphasizes the need for a mathematical model that elucidates the relationship between manufacturing process architecture robustness and system architecture modularization. Such a model would provide valuable support to systems engineers in designing robust manufacturing process architecture.

Table 1. Features of the present research compared with the relevant research.

	Features							
	Development of a Statistical/ Mathematical Optimization Model	**Process Capability Indices Consideration**	**Utilization of Robust Design Principle**	**Utilization of Response Surface Methodology**	**Development of Measurement of Robustness**	**Complexity of Interrelationship in Manufacturing Processes**	**Consideration of Manufacturing Process Architecture**	**Modularization of Manufacturing Process Architecture**
This Research	✔	✔	✔	✔	✔	✔	✔	✔
Al-Refaie (2011) [20]	✔		✔	✔	✔	✔		
Koc et al. (2011) [21]	✔		✔	✔	✔	✔		
Mevik et al. (2001) [22]	✔		✔	✔	✔	✔		
Robinson, Borror, and Myers (2004) [23]	✔		✔	✔	✔	✔		
Scholz-Reiter et al. (2011) [24]	✔		✔	✔	✔	✔		
Karimi and Djokoto (2012) [25]	✔		✔	✔	✔	✔		
Kusumoto et al. (2012) [26]	✔		✔	✔	✔	✔		
Alem and Morabito (2012) [27]	✔		✔	✔	✔	✔		
Meyer et al. (2013) [28]	✔		✔	✔	✔	✔		
Mondal et al. (2013) [29]	✔	✔	✔	✔	✔	✔		
Malmström et al. (2013) [31]	✔		✔	✔	✔	✔		
Montgomery (2013) [32]	✔	✔	✔	✔	✔	✔		
Mondal et al. (2013) [30]	✔		✔	✔	✔	✔		
Becker et al. (2013) [34]	✔		✔	✔	✔	✔		
Sharda and Banerjee (2013) [35]	✔		✔	✔	✔	✔		
Xiong et al. (2013) [33]	✔	✔	✔	✔	✔	✔		
Stricker and Lanza (2014) [36]	✔		✔	✔	✔	✔		
Bebera and Becker (2014) [37]	✔		✔	✔	✔	✔		
Varas et al. (2014) [38]	✔	✔	✔	✔	✔	✔		
Benderbal et al. (2015) [39]	✔	✔	✔	✔	✔	✔		
Tian et al. (2015) [40]	✔		✔	✔	✔	✔		
Putnik et al. (2015) [41]	✔		✔	✔	✔	✔		
Stricker et al. (2015) [42]	✔		✔	✔	✔	✔		
Giannetti and Ransing (2016) [43]	✔		✔	✔	✔	✔		
Zhao et al. (2016) [44]	✔		✔	✔	✔	✔		
Meyer (2016) [45]	✔		✔	✔	✔	✔		
Boorla and Howard (2016) [47]	✔		✔	✔	✔	✔		
Sakhaii et al. (2016) [47]	✔		✔	✔	✔	✔		
Moslemi et al. (2017) [48]	✔		✔	✔	✔	✔		
Zeng and Yen (2017) [49]	✔		✔	✔	✔	✔		
Zhang et al. (2017) [50]	✔		✔	✔	✔	✔		
Himmiche et al. (2018) [51]	✔		✔	✔	✔	✔		
Efthymiou et al. (2018) [52]	✔		✔	✔	✔	✔		
Pagone et al. (2019) [53]	✔		✔	✔	✔	✔		
Frederico et al. (2020) [54]	✔		✔	✔	✔	✔		
Martín et al. (2020) [55]	✔		✔	✔	✔	✔		
Hyder et al. (2021) [56]	✔		✔	✔	✔	✔		
Stockmann et al. (2021) [57]	✔		✔	✔	✔	✔		
Liang and Li (2022) [58]	✔		✔	✔	✔	✔		

The purpose of this study is to address this significant gap in the literature and develop a mathematical model that precisely defines the proposed approach. By clarifying the relationship between manufacturing process architecture and system architecture through modularization, the model aims to facilitate the creation of a robust characteristic in the manufacturing process architecture while ensuring controlled system complexity.

To modularize the system architecture and consider the identified modules more effectively, this study employs the DSM methodology.

This paper is organized as follows: the introduction provides an overview of the study; Section 2 discusses the robust architecture for manufacturing processes, including a literature review and identification of research gaps; Section 3 presents the background materials related to the topic; Section 4 describes the research method and mathematical model development, specifically focusing on the relationship between "modularity" and the property of "robustness of manufacturing processes". In this section, we present a case study and

apply the robustness analysis method to the manufacturing processes of Barez Industrial Group, an Iranian company; Section 5 concludes the paper by discussing the conclusions drawn from the robustness analysis method and providing practical recommendations.

3. Background Material

3.1. Robustness

There is a wide variety of definitions of robustness. According to Carlson and Doyle [60], robustness is "the maintenance of some desired system characteristic despite fluctuations in the behavior of its component parts or its environment". Fricke and Schulz [61] define robustness as "a system's ability to be insensitive towards changing environments. Robust systems deliver their intended functionality under varying operating conditions without being changed". We use the definition by Barber and Salido [62]: robustness is the ability of a system to withstand stress, pressure, perturbations, unpredictable changes, or variability in its operating environment without loss of functionality.

3.2. Axiomatic Design (AD) Theory

The Axiomatic Design (AD) Theory is a coherent framework rooted in techniques and logical thought processes aimed at conducting design activities in a systematic and scientific manner [59]. The primary elements employed within AD encompass 'Domains', 'Mapping and Zigzagging', the 'Independence (First) Axiom', and the 'Information (Second) Axiom'.

The Axiomatic Design (AD) method is a well-structured approach established to guide design activities across four distinct design domains: the 'Customer Domain', the 'Functional Requirements (FRs) Domain', the 'Physical or Design Parameters (DPs) Domain', and the 'Process Variables (PVs) Domain' (as depicted in Figure 1). The customer domain encapsulates customer attributes (CAs). These attributes' elements need to be transformed into functional requirements (FRs) and constraints (Cs) within the functional domain. To fulfill these FRs, design parameters (DPs) are established within the physical domain. Ultimately, to bring the system into production, process variables (PVs) are defined within the process domain. The design process operates as a dynamic interplay between two adjacent domains, cascading in a top-to-bottom manner, commencing at the system level and progressively delving into sublevels of finer detail until a comprehensive representation of the system of interest emerges. The linkage between two contiguous domains is aptly named the 'zigzagging' process, achieved by methodically breaking down the system into smaller design components (as illustrated in Figure 1).

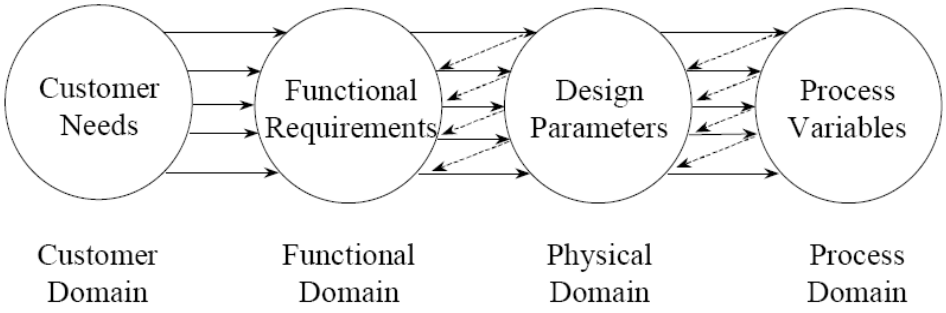


Figure 1. Design domains in the Axiomatic Design (AD) theory.

The AD theory offers two design axioms for gauging the quality of solutions and provides guidance on how to assess and choose from various alternatives [59].

- **Independence Axiom:** Preserve the autonomy of the FRs (DPs). This axiom emphasizes that each FR (DP) should maintain its autonomy. Therefore, system designers face

a pivotal challenge in disassembling intricate systems into subsystems characterized by independent FRs (DPs).

- **Information Axiom:** Minimize the informational complexity of a design. This axiom asserts that among designs adhering to the Independence Axiom, the one with the lowest informational complexity is regarded as the optimal design choice. The informational complexity associated with a particular FR (DP) quantifies the likelihood of achieving a given FR (DP) successfully [59].

In allocation between functional and physical domains, the informational complexity of a design with a single FR and DP can be expressed as the logarithm of the reciprocal of the probability of the system success in fulfilling the FR (P, Equation (1)), as follows:

$$I = log_2 \frac{1}{P} \quad (1)$$

where 'I' denotes the information content, measured in bits (logarithm to base 2), and signifies the extent of effort needed to accomplish the given FR.

With the assumption of a uniform probability density function (pdf), the information content 'I' can be formulated as depicted in the following Equation (2) (Figure 2):

$$I = log_X \frac{(Area\ of\ the\ system\ Range)}{(Area\ of\ the\ common\ range)} \quad (2)$$

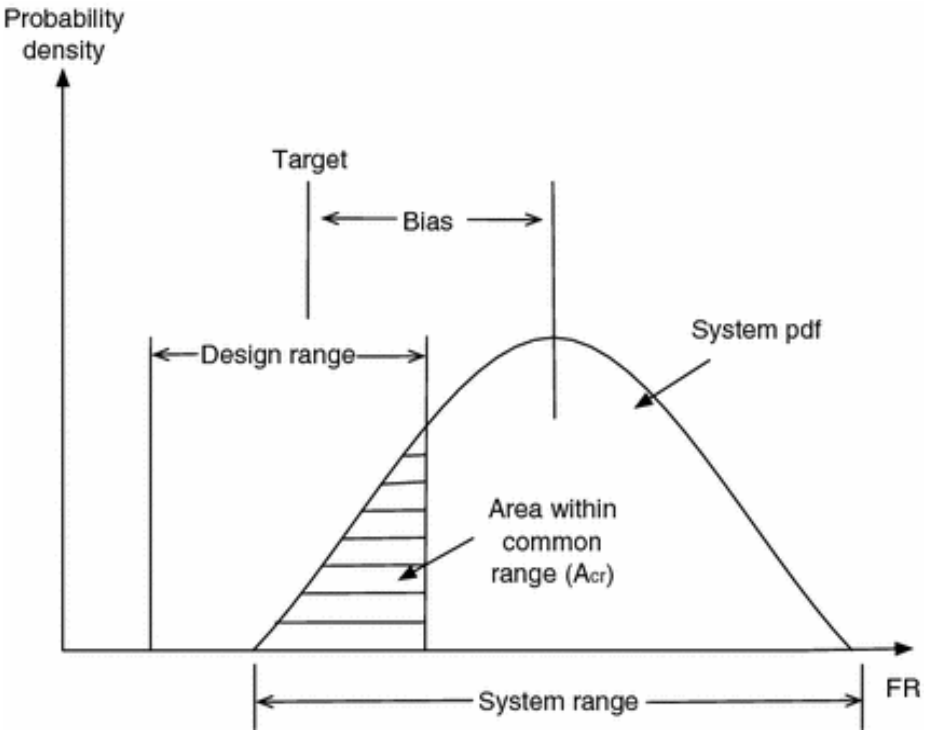


Figure 2. Probability of success in fulfilling a functional requirement (FR).

The system range's extent is represented as SR, calculated from the probability density function of the FR. In essence, the SR of a particular FR signifies the performance range, PR, linked with the FR in question. The shared range's size, CR, constitutes the segment of the earlier mentioned area within the design range, DR, as illustrated in Figure 2. The DR defines the admissible scope linked to the relevant FR.

In the context of an uncoupled design involving n FRs (DPs), the aggregate information is formulated according to the following Equation (3):

$$I = \sum_{i=1}^{n} -log_2 P_i = \sum_{i=1}^{n} I_i \quad (3)$$

where 'P_i' represents the probability of FRi (DP_i) being fulfilled by DPi (PVi).

3.3. Design Structure Matrix (DSM) Methodology

A Design Structure Matrix (DSM) stands as a potent method for illustrating intricate interdependencies among components within a system. Serving as a versatile and straightforward modeling tool, the DSM aids in the design, depiction, and management of systems. The DSM encapsulates a system's architecture by denoting interactions and dependencies among its elements. Forming a binary square matrix with m columns and rows, along with n non-zero elements, where m symbolizes the nodes and n signifies the directed connections linking them, the DSM captures the intrinsic structure. Within a set of m elements within a system, the corresponding DSM takes shape as an m×m matrix, wherein the system elements occupy row and column headings, following the same order. Precedence relationships manifest in the matrix's off-diagonal entries. In a binary DSM, the value of entry ij (column i, row j) is one (or marked by "X" or "•") when element j depends on element i (i.e., i feeds j), while otherwise, it remains zero (or left vacant). Sequentially aligning the elements as they appear in the DSM, marks below the diagonal denote forward information from element i to j, and those above the diagonal embody feedback information from element j to i.

Central to the DSM analysis is the aspiration to minimize feedback loops, achieved by orchestrating the sequencing of processes/elements, thereby facilitating a lower-triangular DSM formation. The marks above the diagonal signify feedback couplings, contrasting with the sub-diagonal marks denoting feed-forward couplings. The above-diagonal markings connote iterative interactions, which should ideally be reduced as much as feasible. However, when feedback marks cannot be eliminated, the implicated elements can be categorized into iterative sub-cycles. In Figure 3, for example, items (1, 2, 3) and items (6, 7, 8, 9, 10) fall into two such iterative sub-cycles.

Typically, the realization of this objective necessitates a two-step approach: partitioning and tearing hold promise for achieving optimal results [14,63,64].

3.4. Modularity in System Architecture

Definition 1. *The literature review underscores the wide array of definitions associated with the term 'Modularity' [65,66]. Generally, the definition of modularity emanates from the characterization of the constituent modules within a system. In essence, these definitions can primarily be categorized into two groups: 'Structural' definitions (These pertain to the relationships and interactions among the system components [67]. 'Architectural' definitions (These address the connections between system components and the functions established at a specific abstraction level within the functional domain [68] or through the relationships between models of physical and/or logical representations of systems [69,70]. Regarding the notion of modularization within each of these classes, a comprehensive elucidation has been provided by Efatmaneshnik et al. [71]. In general, the process of modularization aims to maximize the dependency within modules while minimizing relations or interactions between modules [65,72].*

	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14
Item1	**1**	**1**		**1**										
Item2	**1**	**2**	**1**		**1**									
Item3		**1**	**3**											
Item4				**4**					**1**					
Item5		**1**			**5**							**1**	**1**	**1**
Item6			**1**			**6**				**1**	**1**			
Item7				**1**			**7**	**1**	**1**	**1**				
Item8							**1**	**8**						
Item9							**1**		**9**					
Item10						**1**	**1**			**10**				
Item11										**1**	**11**			
Item12									**1**		**1**	**12**		
Item13													**13**	**1**
Item14													**1**	**14**

Figure 3. Design Structure Matrix (DSM) illustrating the interconnections among elements within the system.

3.5. Measures of Modularity for an Individual Architecture (Functional/Physical/Process Architecture)

Various modularity indices assess system architecture. Jung and Simpson [73], Bonvoisin et al. [74] reviewed many. Tools like modularity matrix [75], heuristics [68], DSM [76], axiomatic design [59], etc., identify modules. This study chooses DSM for module identification, considering its benefits.

To gauge modularity using the Design Structure Matrix (DSM) methodology, the literature offers a range of metrics [77]; Hölttä-Otto and de Weck [78]; Hölttä-Otto et al. [79]. The research emphasizes studying important interactions between element pairs. Among various modularity measures, the focus is on those developed from interactions among the elements. Notably, five key metrics stand out: 'Grouping Capability Index (*GCI*)', 'Grouping Efficacy', 'Grouping Efficiency', 'Utilization Rate (*U*)', and 'Modularization Function' [80,81], which have been frequently utilized [82].

Before proceeding to the measures, establishing the notation is beneficial. Let N_1 be the count of 1 s in diagonal blocks, N_2 be the count of 0 s in diagonal blocks, N_3 be the count of 0 s in off-diagonal blocks, and N4 be the count of 1 s in off-diagonal blocks. Moreover, $N_1 + N_2$ indicates the total number of elements (0 s and 1 s) in diagonal blocks, and $N_3 + N_4$ represents the total number of elements (0 s and 1 s) in off-diagonal blocks. The following section provides a detailed outline of the measures.

1. Grouping capability index

The Grouping Capability Index (*GCI*) signifies the capacity of a collection of interdependent entities to establish a module (Equation (4)).

$$GCI = 1 - \frac{N_4}{N_1 + N_4} \tag{4}$$

2. Grouping efficacy

Grouping efficacy, denoted as τ, quantifies the ability of a module or group to perform a task. It is contingent on the successful clustering of elements within a group. (Equation (5)).

$$\tau = \frac{1 - \frac{N_4}{N_1+N_4}}{1 - \frac{N_2}{N_1+N_4}} \quad (5)$$

3. Grouping efficiency

Grouping efficiency, represented as η, serves as a measure of the fit quality for a modular solution within a module. A higher η value indicates a more suitable modular arrangement. η (Equation (6)) symbolizes the relative capacity of components to form a module or group, as well as the compactness of a module.

$$\eta = q.\eta_1 + (1 - q)\eta_2 \quad (6)$$

η_1 and η_2 are expressed by Equations (7) and (8), respectively.

$$\eta_1 = \frac{N_1}{N_1 + N_2} \quad (7)$$

$$\eta_2 = \frac{N_3}{N_3 + N_4} \quad (8)$$

where, q is a weighting factor ($0 < q < 1$);

4. Utilization rate

Utilization rate, denoted as U, indicates the extent to which components within a given system are dedicated to forming modules and how effectively they contribute to building modular systems (Equation (9)).

$$U = \frac{N_1}{N_1 + N_2} \quad (9)$$

5. Modularization Function

The Modularization Function, denoted as $M(u)$, was initially developed by Mikkola and Gassmann [81], and subsequently refined by Mikkola [80].

$$M(u) = e^{-\frac{u^2}{2Ns\delta}} \quad (10)$$

where 'u' signifies the count of distinctive elements/components encompassed within an architecture; "N" denotes the total number of standard and unique components, calculated as $N = nSTD + u$; δ represents the average intensity of coupling among elements/components and modules; "s" indicates the substitutability factor of unique elements/components within other systems. Additionally, there exists a relationship between δ (coupling intensity) and "k" (number of interfaces in a module), expressed as $\delta \sim (k/n)$, where "n" represents the count of components in a module.

3.6. Measure of Modularity Between Two Adjacent Domains

It is possible to determine a quantitative measure of independence for a given design matrix. Suh [59] proposes two metrics of independence: reangularity, R, and semangularity, S. Reangularity evaluates the orthogonality between DPs and serves as a measure of interdependence.

$$R = sin\ (\theta) = (1 - Cos^2(\theta))^{\frac{1}{2}} \quad (11)$$

The angle between the DP axes is denoted by θ (Equation (11)). To provide additional clarity on the concept of reangularity, let us examine a two-dimensional case.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} = \begin{Bmatrix} A_{11} \\ A_{12} \end{Bmatrix} \cdot DP_1 + \begin{Bmatrix} A_{21} \\ A_{22} \end{Bmatrix} \cdot DP_2 \quad (12)$$

where A_{ij} represents the entry (i, j) of the DM and relates DP_j to FR_i $(i, j = 1, 2)$. Equation (12) can be rewritten as

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} = C_1 \cdot (DP_1) + C_2 \cdot (DP_2) \quad (13)$$

where

$$C_1 = \begin{Bmatrix} A_{11} \\ A_{12} \end{Bmatrix} \quad \text{fl} \quad C_2 = \begin{Bmatrix} A_{21} \\ A_{22} \end{Bmatrix}$$

From linear algebra,

$$cos\ (\theta) = \frac{C_1 \cdot C_2}{|C_1| \cdot |C_2|} \quad (14)$$

For the nth dimensional case, reangularity is

$$R = \prod_{\substack{i=1,\ n-1 \\ j=i+1,\ n}} \left(1 - \frac{\left(\sum_{k=1}^{n} A_{ki} \cdot A_{kj}\right)^2}{\left(\sum_{k=1}^{n} A_{ki}^2\right) \cdot \left(\sum_{k=1}^{n} A_{kj}^2\right)}\right)^{\frac{1}{2}} \quad (15)$$

The metric S quantifies the angular relationship between the axes of DPs and FRs, evaluating the correlation between a given FR and any pair of DPs. In terms of coupling, S represents the magnitude of the diagonal elements in a normalized DM. In the case of an nth-dimensional scenario,

$$S = \prod_{j=1}^{n} \left(\frac{|A_{jj}|}{\left(\sum_{k=1}^{n} A_{kj}^2\right)^{\frac{1}{2}}}\right) \quad (16)$$

Both R and S have a maximum value of 1, corresponding to an uncoupled (ideal) design. As the degree of coupling increases, both reangularity and semangularity decrease. In particular, when R or S is equal to 0, the design is considered fully coupled.

3.7. Metrics for System Robustness

System robustness reflects the degree of system coupling. According to the mathematical equations for R and S, it is clear that, as both R and S belong to the interval [0, 1], the larger R and S are, the greater $R \times S$ is. Concerning the information content of a system, I, the smaller the information content is, the smaller is the variability of the system where $(R \times S)/I$ becomes larger and can be employed to quantify the robustness of a system [83].

3.8. Robustness Analysis Method

The robustness analysis method looks at the relationship among system elements and evaluates alternative sequences. Managers can then choose the best organization of elements to improve modularization and overall system robustness. The steps of the method are described in the following and presented schematically in Figure 4:

Step 1: Consider manufacturing processes as an integrated system;
Steps 2 and 3: Develop functional and physical architecture of the system;
Step 4: Design manufacturing process architecture for robustness;
Steps 5, 6, and 7: Use DSM to modularize the physical architecture of the system;
Step 8: Map the physical to the functional architecture of the system;

Steps 9 and 10: Calculate the system architecture's information content and robustness;

Steps 11, 12, and 13: Use the AD theory to modularize the mapping between the new physical architecture and the functional architecture;

Step 14 and 15: Recompute the system architecture's information content and robustness;

Step 16: Compute the overall robustness of the system.

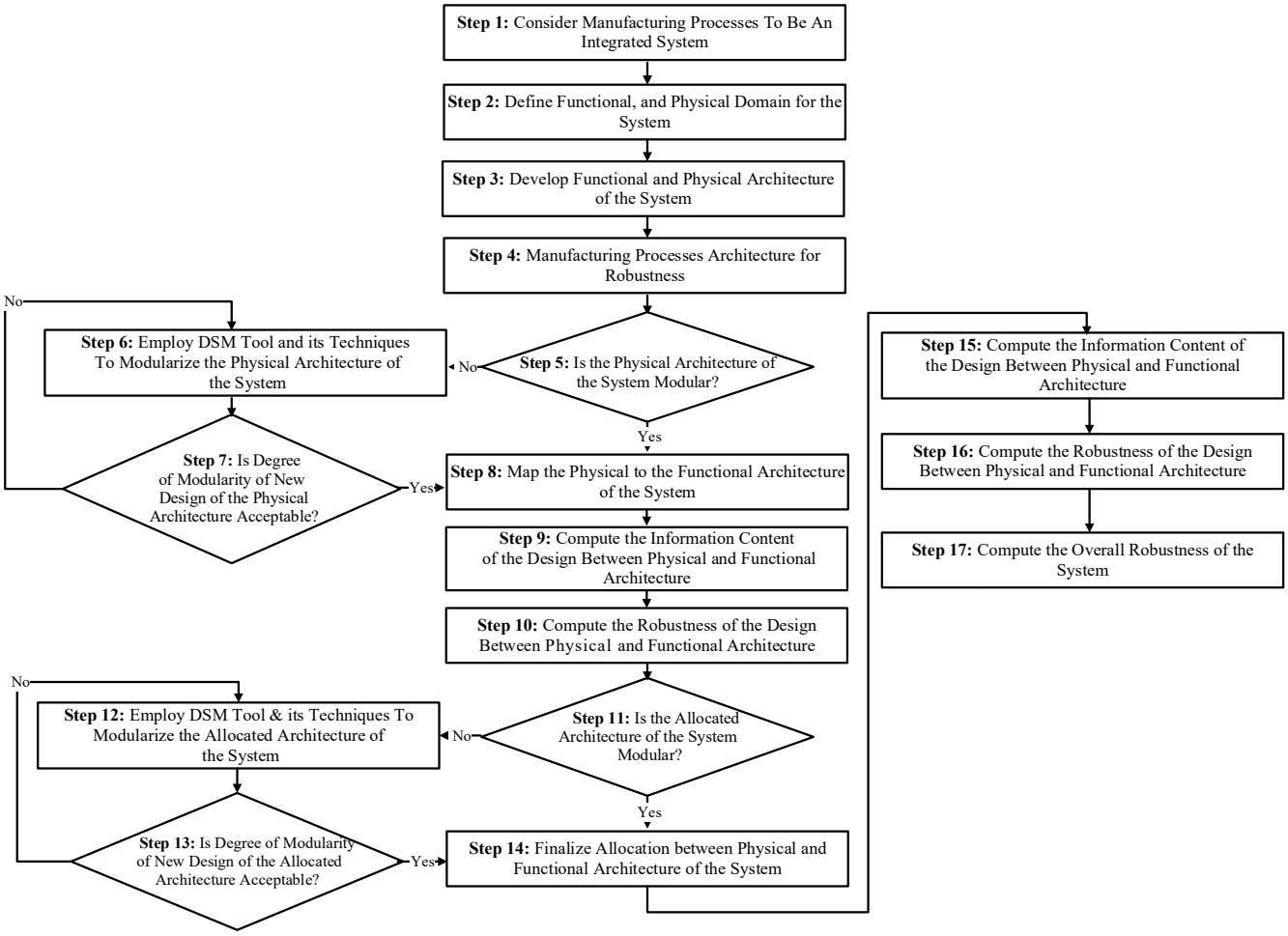


Figure 4. Methodology for the Robust Analysis Method.

3.9. Contribution of the Study: Modularity and Robustness

Once robustness is analyzed, mapping between a system's functional and physical architectures needs to be done, and the determination of how well the physical elements satisfy the functional elements needs to be evaluated. A literature review of design robustness has indicated that both physical component redundancy and limiting the degradation of physical components have been mentioned by several authors [84,85]. In the present study, the focus is on avoiding propagation of failure/disruption/ disturbance, i.e., suppression of disturbances and redundancy in some of physical component in the physical architecture. To avoid propagation failures in a system, the functional and physical components should not be coupled, and the physical components should be independent. Robustness is achieved by having a significant level of modularity that avoids propagation of noise from an affected/impaired module or element to other modules. Following is a mathematical investigation that demonstrates that modularity suppresses disturbances in the physical architecture as shown in Figure 5, where better modularity leads to better contact elements,

and ultimately, greater project success. The mathematical analysis underpins the use of AD Theory and DSM in the robustness analysis method.

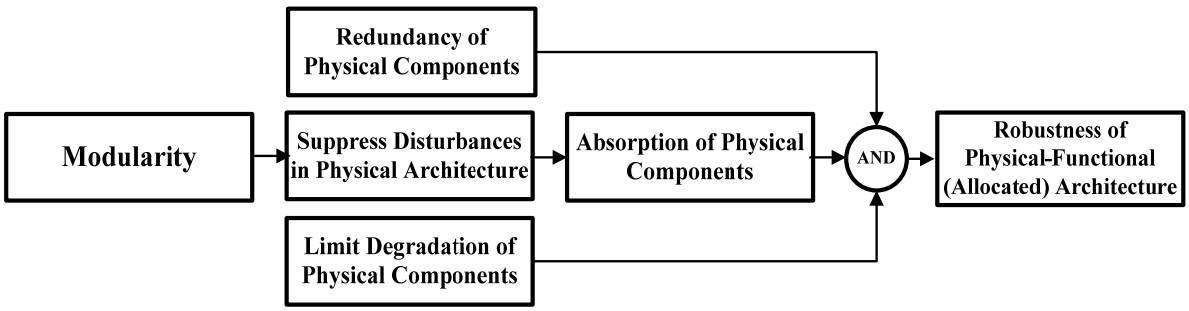


Figure 5. Modularity and Robustness.

3.10. Modularity and System Variance

System robustness can be improved by minimizing variance [86,87]. In a multi-FR design, the prerequisite for minimizing variance is the satisfaction of the independence axiom. To mathematically consider the relationship for coupling, i.e., the absence of modularity and system variance, consider an n dimensional case as in the following:

$$\begin{Bmatrix} M_1^{FR} \\ M_2^{FR} \\ \vdots \\ M_n^{FR} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix} \cdot \begin{Bmatrix} M_1^{DP} \\ M_2^{DP} \\ \vdots \\ M_n^{DP} \end{Bmatrix} \tag{17}$$

where M_i^{FR} (i = 1, 2, . . ., n) represents the i-th module in FRs domain,

M_i^{DP} (i = 1, 2, . . ., n) represents the i-th module in DPs domain,

$[A]$ represents a DM which associates DP-based modules with FR-based modules, and

A_{ij} (i = 1, 2, . . ., n and j = 1, 2, ..., n) are DM submatrices that have one or more dimensions where M_j^{DP} (j = 1, 2, . . ., n) is allocated to the M_i^{FR} (i = 1, 2, . . ., n).

In addition, $\left[A\right]^T$ represents the transposition of the matrix as in the following:

$$[A]^T = \begin{bmatrix} A_{11} & A_{21} & \dots & A_{n1} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{1n} & A_{2n} & \dots & A_{nn} \end{bmatrix} \tag{18}$$

$\boldsymbol{M}^{FR}$ is expressed as

$$\boldsymbol{M}^{FR} = [A] \cdot \boldsymbol{M}^{DP} \tag{19}$$

where M^{FR} represents the domain of FR-based modules (the functional domain), and M^{DP} represents the domain of DP-based modules (the physical domain).

The random variability of M^{FR}, i.e., δM^{FR} can be expressed as

$$\boldsymbol{\delta M}^{FR} = [A] \cdot \boldsymbol{\delta M}^{DP} \tag{20}$$

where $\delta \boldsymbol{M}^{DP}$ represents random variability of $\boldsymbol{M}^{DP}$. It is clear that $\delta \boldsymbol{M}^{FR}$ and $\delta \boldsymbol{M}^{DP}$ are

$$\delta \boldsymbol{M}^{FR} = \begin{bmatrix} \delta M_1^{FR} \\ \delta M_2^{FR} \\ \vdots \\ \delta M_m^{FR} \end{bmatrix} \tag{21}$$

$$\delta \boldsymbol{M}^{DP} = \begin{bmatrix} \delta M_1^{DP} \\ \delta M_2^{DP} \\ \vdots \\ \delta M_m^{DP} \end{bmatrix} \tag{22}$$

where δM_i^{FR} represents the random variability in M_i^{FR} (I = 1, 2, …, m), and δM_j^{DP} represents the random variability in M_j^{DP} (j = 1, 2, …, m).

The transposition of Equation (20) is

$$\left(\delta \boldsymbol{M}^{FR}\right)^{\boldsymbol{T}} = \left(\delta \boldsymbol{M}^{DP}\right)^{T} \cdot [A]^{T} \tag{23}$$

Therefore, the variance of the $\boldsymbol{M}^{FR}$ is

$$E\left\{\left(\delta \boldsymbol{M}^{FR}\right) \cdot \left(\delta \boldsymbol{M}^{FR}\right)^{\boldsymbol{T}}\right\} = E\left\{\left([A] \cdot \delta \boldsymbol{M}^{DP}\right) \cdot \left(\left(\delta \boldsymbol{M}^{DP}\right)^{T} \cdot [A]^{T}\right)\right\} \tag{24}$$

$$= [A] \cdot E\left\{\left(\delta \boldsymbol{M}^{DP}\right) \cdot \left(\delta \left(\boldsymbol{M}^{DP}\right)^{\boldsymbol{T}}\right)\right\} \cdot [A]^{T} \tag{25}$$

where E expresses the mathematical expectation. Hence, the variance of $\boldsymbol{M}^{FR}$, $Var\left(\boldsymbol{M}^{FR}\right)$, is

$$Var\left(\boldsymbol{M}^{FR}\right) = [A] \cdot \sum_{\boldsymbol{M}^{DP}} \cdot [A]^{T} \tag{26}$$

where $\sum_{\boldsymbol{M}^{DP}}$. Represents the variance-covariance matrix for $\boldsymbol{M}^{DP}$.

Assume that the DP-based modules, $\boldsymbol{M}^{DP}$, are statistically independent of each other. Hence,

$$\Sigma_{\boldsymbol{DP}} = \begin{bmatrix} \Sigma_{11} & 0 & \dots & 0 \\ 0 & \Sigma_{22} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & \Sigma_{mm} \end{bmatrix} \tag{27}$$

where Σ_{ii} represents the variance or variance-covariance matrix of module M_i^{DP} and ($i = 1, 2, \dots, m$) when the module is one dimensional or multi-dimensional. Then,

$$Var(\mathbf{M^{FR}}) = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix} \cdot \begin{bmatrix} \Sigma_{11} & 0 & \dots & 0 \\ 0 & \Sigma_{22} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & \Sigma_{mm} \end{bmatrix} \cdot \begin{bmatrix} A_{11} & A_{21} & \dots & A_{n1} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{1n} & A_{2n} & \dots & A_{nn} \end{bmatrix}$$

$$= \begin{bmatrix} A_{11}^2.\Sigma_{11} + \dots + A_{1n}^2.\Sigma_{mm} & A_{11}.A_{21}.\Sigma_{11} + \dots + A_{1n}.A_{2n}.\Sigma_{mm} & \dots & A_{11}.A_{n1}.\Sigma_{11} + \dots + A_{1n}.A_{nn}.\Sigma_{mm} \\ A_{21}.A_{11}.\Sigma_{11} + \dots + A_{2n}.A_{1n}.\Sigma_{mm} & A_{21}^2.\Sigma_{11} + \dots + A_{2n}^2.\Sigma_{mm} & \dots & A_{21}.A_{n1}.\Sigma_{11} + \dots + A_{2n}.A_{nn}.\Sigma_{mm} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1}.A_{11}.\Sigma_{11} + \dots + A_{nn}.A_{1n}.\Sigma_{mm} & A_{n1}.A_{21}.\Sigma_{11} + \dots + A_{nn}.A_{2n}.\Sigma_{mm} & \dots & A_{n1}^2.\Sigma_{11} + \dots + A_{nn}^2.\Sigma_{mm} \end{bmatrix} \tag{28}$$

Hence,

$$Var\left(M_1^{FR}\right) = A_{11}^2 \cdot \Sigma_{11} + A_{12}^2 \cdot \Sigma_{22} + \dots + A_{1n}^2 \cdot \Sigma_{mm} \tag{29}$$

$$Var\left(M_2^{FR}\right) = A_{21}^2 \cdot \Sigma_{11} + A_{22}^2 \cdot \Sigma_{22} + \ldots + A_{2n}^2 \cdot \Sigma_{mm} \tag{30}$$

$$\vdots$$

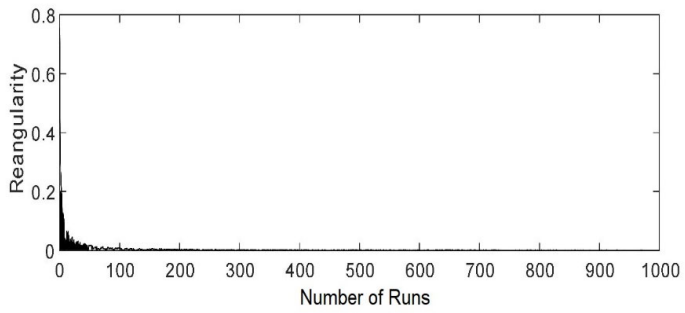
$$Var\left(M_n^{FR}\right) = A_{n1}^2 \cdot \Sigma_{11} + A_{n2}^2 \cdot \Sigma_{22} + \ldots + A_{nn}^2 \cdot \Sigma_{mm} \tag{31}$$

Moreover, the system variance, $Var\ (Sys)$

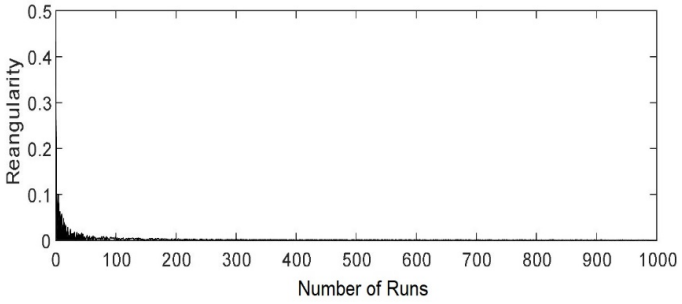
$$= A_{11}^2 \cdot \Sigma_{11} + A_{12}^2 \cdot \Sigma_{22} + \ldots + A_{1n}^2 \cdot \Sigma_{mm} + A_{21}^2 \cdot \Sigma_{11} + A_{22}^2 \cdot \Sigma_{22} + \ldots + A_{2n}^2 \cdot \Sigma_{mm} + A_{n1}^2 \cdot \Sigma_{11} + A_{n2}^2 \cdot \Sigma_{22} + \ldots + A_{nn}^2 \cdot \Sigma_{mm} \tag{32}$$

$$= (A_{11}^2 + A_{21}^2 + \ldots + A_{n1}^2) \cdot \Sigma_{11} + \left(A_{12}^2 + A_{22}^2 + \ldots + A_{n2}^2\right) \cdot \Sigma_{22} + \ldots + (A_{1n}^2 + A_{2n}^2 + \ldots + A_{nn}^2) \cdot \Sigma_{mm} \tag{33}$$

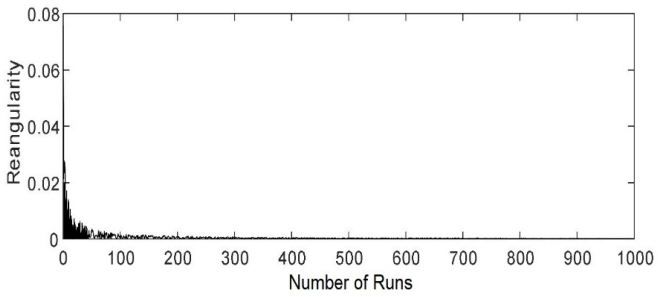
The larger the off-diagonal entries become, the higher is the system variance, i.e., a higher system variance indicates a more coupled system design. The development of a simple, well-defined equation to clarify the relationship between reangularity/semangularity and the lack of modularity may not be easy. However, the behavior of semangularity and reangularity with respect to the magnitude of off-diagonal entries of the *DM* are relatively similar. To demonstrate the degree of coupling, i.e., the lack of system modularity, for *DMs* with higher dimensions, computer simulation was used for four square *DMs* with sizes of 2 × 2, 3 × 3, 5 × 5, and 10 × 10 that were randomly generated 1000 times. The magnitude of the off-diagonal elements gradually increased as the number of runs increased, which showed the effect of coupling on semangularity/reangularity and system variance. Figure 6a–d show reangularity versus lack of modularity where reangularity becomes smaller as the size of off-diagonal elements increases. Figure 6e–h shows the system variance versus lack of modularity, where system variance becomes larger as the size of off-diagonal elements increases. This underlines the need to reduce the coupling among system elements, as done in the robustness analysis method.



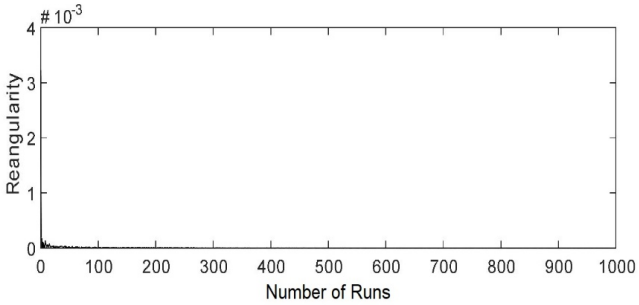
(**a**)



(**b**)



(**c**)



(**d**)

Figure 6. *Cont.*

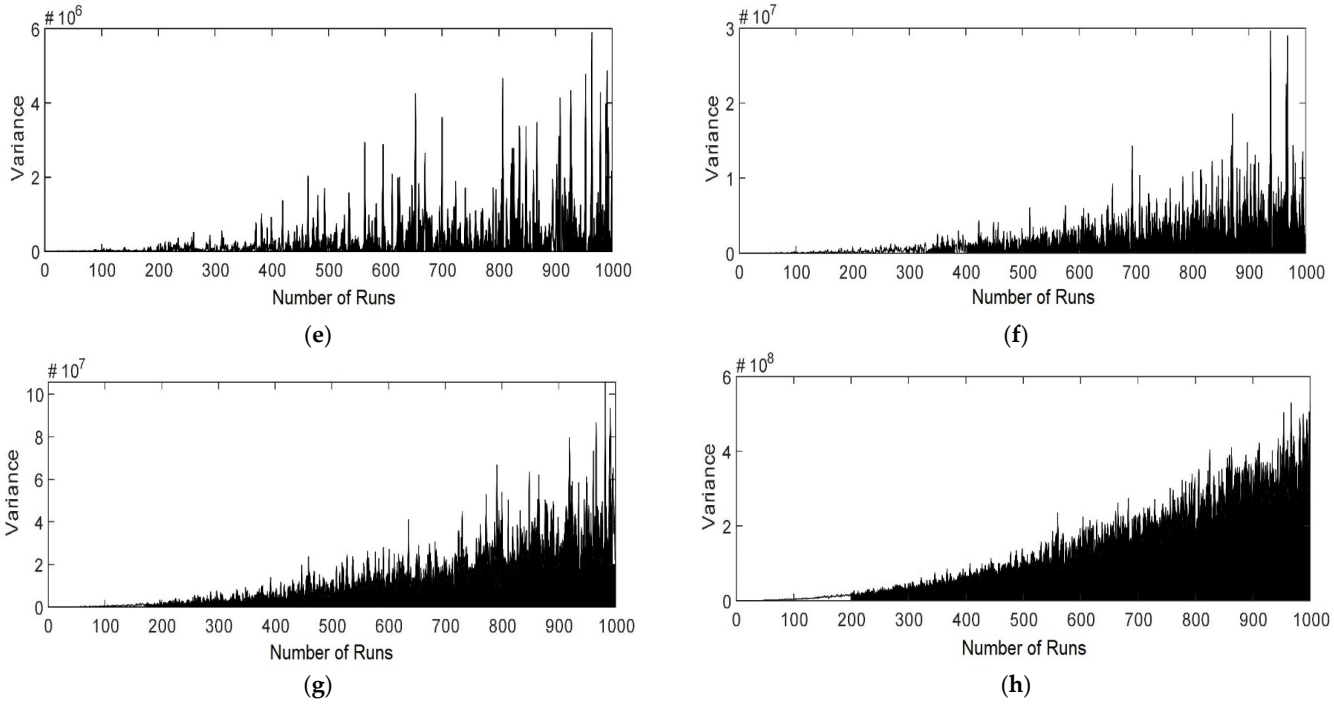


Figure 6. (**a**) System reangularity due to the lack of modularity for a 2 × 2 DM. (**b**) System reangularity due to the lack of modularity for a 3 × 3 DM. (**c**) System reangularity due to the lack of modularity for a 5 × 5 DM. (**d**) System reangularity due to the lack of modularity for a 10 × 10 DM. (**e**) System variance due to the lack of modularity for a 2 × 2 DM. (**f**) System variance due to the lack of modularity for a 3 × 3 DM. (**g**) System variance due to the lack of modularity for a 5 × 5 DM. (**h**) System variance due to the lack of modularity for a 10 × 10 DM.

3.11. Modularization of the Allocated Architecture (Mapping Between Two Adjacent Domains)

The allocated architecture of a system refers to the organization of physical elements that yields a design solution which satisfies the functional requirements of a system [88]. Therefore, modularity of the allocated architecture is essential to achieving a robust system. Sometimes, due to possible disruptions in an operational environment, redundant elements are used to increase a system's reliability to have a better chance of system success. When creating modules, it is important to determine whether there is any element or module that is redundant since the use of redundant elements may result in a loss of system modularity.

Concerning the improvement of system reliability, the present study adopts the notion of redundancy from AD theory, where in redundant designs, there are more *DPs* than FRs to satisfy the *FRs* (Suh, 2001 [59]). For instance, a system objective may be described by a few components in such a way that if the most appropriate component is not able to satisfy the objective, other associated component, as redundant elements, can be used to meet the objective. Nevertheless, system modularity must be ensured. The following two subsections provide more detail about the modularization of the allocated architecture in the absence and presence of redundant physical modules.

3.12. Modularization of the Allocated Architecture in the Absence of Redundant Physical Modules

To map between DP-based and FR-based domains, consider a multi-*FR* design

$$M_i^{FR} = f(M_1^{DP} \text{ fl } M_2^{DP} \text{ fl } \ldots \text{ fl } M_n^{DP}) \quad (34)$$

where M_i^{FR} represents the ith module in the functional domain ($i = 1, 2, ..., n$), and M_i^{DP} represents the ith module in the physical domain ($i = 1, 2, ..., n$).

Note that M_i^{FR} or M_i^{DP} can be a module which can encompass only one element or several fully/partially coupled elements. Using Equation (34), the derivative of M_i^{FR}, i.e.,

$$d(M_i^{DP}) = \frac{\partial f(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP})}{\partial M_1^{DP}} \cdot d(M_1^{DP}) + \ldots + \frac{\partial f(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP})}{\partial M_n^{DP}} \cdot d(M_n^{DP}) \quad (35)$$

Or

$$d(M_i^{FR}) = \sum_{j=1}^{n} \frac{\partial f(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP})}{\partial M_j^{DP}} \cdot d(M_j^{DP}) = \sum_{j=1}^{n} \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot d(M_j^{DP}) \quad (36)$$

where, $d(M_i^{DP})$ represents the derivation of M_i^{DP}. If M_i^{FR} or M_i^{DP} is a module of only one element, Equation (36) can be utilized straightforwardly. However, when M_i^{FR} or M_i^{DP} is a vector which includes several fully/partially coupled elements, Equation (36) needs to be expressed as the following. Let M_i^{FR} and M_i^{DP} (i = 1, 2, …, n) be a vector that includes a specific subset of *FRs* and *DPs*, respectively. Then,

$$M_i^{FR} = \begin{bmatrix} FR_1^i \\ FR_2^i \\ \vdots \\ FR_{l_1}^i \end{bmatrix} \quad (37)$$

and

$$M_j^{DP} = \begin{bmatrix} DP_1^j \\ DP_2^j \\ \vdots \\ DP_{k_1}^j \end{bmatrix} \quad (38)$$

It is assumed that *FRs* are independent of each other whereas the associated *DPs* are partially/fully coupled to each other. Therefore, M_j^{DP} can be expressed as

$$M_j^{DP} = \begin{bmatrix} DP_1^j \\ DP_2^j \\ \vdots \\ DP_{k_1}^j \end{bmatrix} = \begin{bmatrix} 0 & x_{1\text{fl}2} & \ldots & x_{1\text{fl}k_1} \\ x_{2\text{fl}1} & 0 & \ldots & x_{2\text{fl}k_1} \\ \vdots & \vdots & \ldots & \vdots \\ x_{k_1\text{fl}1} & x_{k_1\text{fl}2} & \ldots & 0 \end{bmatrix} \cdot \begin{bmatrix} DP_1^{M_j} \\ DP_2^{M_j} \\ \vdots \\ DP_{k_1}^{M_j} \end{bmatrix} \quad (39)$$

where M_j^{DP} represents the jth module in the physical domain with k_1 *DP* elements,

DP_p^j represents the pth member of jth module ($p = 1, 2, \ldots, k_1$),

$DP_q^{M_j}$ represents the qth member of the jth module ($q = 1, 2, \ldots, k_1$), and

$x_{p,q}$ represents the entry (p,q) in matrix *X* and signifies the degree of dependency between DP_p^j and $DP_q^{M_j}$ ($p = 1, 2, \ldots, k_1$; $q = 1, 2, \ldots, k_1$).

Matrix X in which all diagonal elements are zero is employed to express that every element of M_j^{DP} is coupled with the remaining elements. Then,

$$M_j^{DP} = \boldsymbol{X} \cdot \boldsymbol{DP}^{M_j}; j = 1, 2, \ldots, n \quad (40)$$

In addition, assume that $\boldsymbol{A}$ is the design matrix $(l_1 \times k_1)$ which allocates *DPs* into *FRs* that belong to the module M_i^{FR}. Therefore,

$$M_i^{FR} = \boldsymbol{A} \cdot M_j^{DP}; i = 1, 2, \ldots, n \text{ and } j = 1, 2, \ldots, n \tag{41}$$

Incorporating Equation (40) into Equation (41)

$$M_i^{FR} = \boldsymbol{A} \cdot \boldsymbol{X} \cdot \boldsymbol{DP}^{M_j}; i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{42}$$

Let

$$\boldsymbol{B}_{l_1 \times k_1} = \boldsymbol{A}_{l_1 \times k_1} \times \boldsymbol{X}_{k_1 \times k_1} \tag{43}$$

Then, Equation (43) is

$$M_i^{FR} = \boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}; i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{44}$$

Using Equation (44), the derivative of M_i^{FR}, i.e., $d(M_i^{FR})$ (i = 1, 2, . . ., n), is

$$d(M_i^{FR}) = d(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}); i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{45}$$

where

$$d\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right) = \frac{\partial\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right)}{\partial\left(\boldsymbol{DP}^{M_j}\right)} \cdot d(\boldsymbol{DP}^{M_j}); i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{46}$$

In order to compute $\frac{\partial\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right)}{\partial\left(\boldsymbol{DP}^{M_j}\right)}$, consider $\frac{\partial\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right)_s}{\partial\left(\boldsymbol{DP}^{M_j}\right)_t}$. Now, $\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right)_{\mathbf{s}}$ is

$$\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right)_s = \sum_{z=1}^{k_1} \boldsymbol{B}_{\text{sflz}} \cdot \boldsymbol{DP}^{M_j}{}_z; i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{47}$$

Therefore,

$$\frac{\partial\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right)_s}{\partial\left(\boldsymbol{DP}^{M_j}\right)_t} = \frac{\partial}{\partial\left(\boldsymbol{DP}^{M_j}\right)_t} \sum_{z=1}^{k_1} \boldsymbol{B}_{\text{sflz}} \cdot \boldsymbol{DP}^{M_j}{}_z = \boldsymbol{B}_{\text{sflt}}; i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{48}$$

and,

$$\left(\frac{\partial \boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}}{\partial\left(\boldsymbol{DP}^{M_j}\right)_t}\right)_s = \frac{\partial\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right)_s}{\partial\left(\boldsymbol{DP}^{M_j}\right)_t} = \left(\frac{\partial \boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}}{\partial \boldsymbol{DP}^{M_j}}\right)_{\text{sflt}} = \boldsymbol{B}_{\text{sflt}}; i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{49}$$

Hence,

$$\frac{\partial(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j})}{\partial(\boldsymbol{DP}^{M_j})} = \boldsymbol{B}; i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{50}$$

and

$$d\left(\boldsymbol{B} \cdot \boldsymbol{DP}^{M_j}\right) = \boldsymbol{B} \cdot d(\boldsymbol{DP}^{M_j}); i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{51}$$

or

$$d(M_i^{FR}) = \boldsymbol{B} \cdot d(\boldsymbol{DP}^{M_j}); i = 1, 2, \ldots, \text{and } j = 1, 2, \ldots, n \tag{52}$$

where $(\boldsymbol{B})_{l_1 \times k_1} = (\boldsymbol{A})_{l_1 \times k_1} \times (\boldsymbol{X})_{k_1 \times k_1}$.

$d(M_i^{FR})$ must be within the required tolerance; thus,

$$d(M_i^{FR}) = (d(M_i^{FR}))_0 + \delta(M_i^{FR}) \tag{53}$$

where $d((M_i^{FR}))_0$ is the desired change in M_i^{FR} due to a change in $M^{DP}s$, and $\delta((M_i^{FR}))$ is the required tolerance.

In an uncoupled design, $d(M_i^{FR})$ must be equal to $d((M_i^{FR}))_0$. The deviation from this ideal condition, $d(M_i^{FR}) - d((M_i^{FR}))_0$, is given by $\sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot dM_j^{DP}$ or $B.d(DP^{M_j})$ where M_i^{FR} or M_i^{DP} is a module of only one element (case I) or a vector (case II) that includes several fully/partially coupled elements. For an uncoupled system, the required tolerance, $\delta\left(M_i^{FR}\right)$ must be $\geq \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot dM_j^{DP}$ or $\geq B.d\left(DP^{M_j}\right)$ in case I or II.

For case I,

$$\delta((M_i^{FR})) > \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot dM_j^{DP} \tag{54}$$

and for case II,

$$\delta((M_i^{FR})) > \boldsymbol{B} \cdot d(\boldsymbol{DP}^{M_j}) \tag{55}$$

Specifically, for case I, consider $M_i^{FR} = \sum_{j=1}^{n} A_{ij} \cdot M_j^{DP}$, then,

$$d(M_i^{FR}) = \sum_{j=1}^{n} \left(\frac{\partial}{\partial M_j^{DP}} \left(\sum_{k=1}^{n} A_{ik} \cdot M_k^{DP} \right)\right) \cdot dM_j^{DP} \tag{56}$$

or,

$$d(M_i^{FR}) = \sum_{j=1}^{n} \left(\sum_{k=1}^{n} \frac{\partial}{\partial M_j^{DP}} (A_{ik} \cdot M_k^{DP})\right) \cdot dM_j^{DP} \tag{57}$$

Using Equation (54)

$$d(M_i^{FR}) = \sum_{j=1}^{n} \left(\sum_{k=1}^{n} \left(A_{ik} \cdot \frac{\partial M_k^{DP}}{M_j^{DP}} + \frac{\partial A_{ik}}{M_j^{DP}} \cdot M_k^{DP}\right)\right) dM_j^{DP} \tag{58}$$

Specifically, for case II, consider $M_i^{FR} = \sum_{j=1}^{l_1} B_{ij} \cdot DP_j^{M_j}$, then,

$$d(M_i^{FR}) = \sum_{j=1}^{l_1} B_{ij} \cdot d(DP_j^{M_j}) \tag{59}$$

or,

$$d(M_i^{FR}) = \sum_{j=1}^{n} \left(\sum_{k=1}^{n} \frac{\partial}{\partial M_j^{DP}} (A_{ik} \cdot M_k^{DP})\right) \cdot dM_j^{DP} \tag{60}$$

Therefore,

$$d(M_i^{FR}) = \sum_{j=1}^{n} \left(\sum_{k=1}^{n} \left(A_{ik} \cdot \frac{\partial M_k^{DP}}{M_j^{DP}} + \frac{\partial A_{ik}}{M_j^{DP}} \cdot M_k^{DP}\right)\right) dM_j^{DP} \tag{61}$$

Equation (61) provides a criterion for determining when the off-diagonal elements of a basic matrix can be disregarded.

3.13. Independence and Tolerance Theorem

An independence and tolerance theorem can be formulated as follows: In case I, a design is considered uncoupled when the specified tolerance, $\delta(M_i^{FR})$, exceeds...

$$d(M_i^{FR}) = \sum_{j=1}^{n} (\sum_{k=1}^{n} (A_{ik} \cdot \frac{\partial M_k^{DP}}{M_j^{DP}} + \frac{\partial A_{ik}}{M_j^{DP}} \cdot M_k^{DP})) dM_j^{DP} \quad (62)$$

Therefore, the non-diagonal elements of the design matrix can be disregarded. If the A_{ik} ($k = 1, 2, ..., n$), which represents the stiffnesses relating changes of M_i^{FR} to the changes of M_k^{DP}, are constant, then...

$$d(M_i^{FR}) = \sum_{j=1}^{n} (\sum_{k=1}^{n} (A_{ik} \cdot \frac{\partial (M_k^{DP})}{M_j^{DP}})) d(M_j^{DP}) \quad (63)$$

If $\sum_{j=1}^{n} (\sum_{k=1}^{n} (A_{ik} \cdot \frac{\partial (M_k^{DP})}{M_j^{DP}})) d(M_j^{DP}) < \delta((M_i^{FR})$, then, the design is uncoupled.

3.14. Modularization of the Allocated Architecture in Presence of Redundant Physical Modules

$$M^{FR} = f\left(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP}\right) \quad (64)$$

In this case, there are more $M^{DP}s$ than $M^{FR}s$, resulting in random variability (or noise) introduced by the excess $M^{DP}s$ that can affect the variability of M^{FR}. It is crucial for the variability to remain within the design range to ensure proper functionality. Therefore,

$$\delta M^{FR} = \frac{\partial f(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP})}{\partial M_i^{DP}} \Delta M_i^{DP} + \sum_{\substack{j=1 \\ i \neq j}}^{n} \frac{\partial f(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP})}{\partial M_i^{DP}} \cdot \delta M_j^{DP} \quad (65)$$

The random variability in M^{FR} is denoted as δM^{FR}, and the variability of M_i^{DP} is represented by ΔM_i^{DP}.

In an ideal one-M^{FR} design, only a single M^{DP} is necessary, as any additional $M^{DP}s$ introduce the possibility of random variability. The first term on the right-hand side (RHS) of Equation (65) accounts for the compensation effect of the primary M^{DP}, which is selected to vary M^{FR}, while the second term represents the cumulative random variability or noise introduced by any extra $M^{DP}s$. To ensure proper functionality, it is crucial to adjust the error term ΔM_i^{DP} in two possible ways to achieve ΔM_i^{DP}.

1. Setting the coefficient ($\frac{\partial f}{\partial M^{DP}}$) that corresponds to any additional $M^{DP}s$ to zero involves eliminating all random variability from every M^{DP}, which is not practical given the variability that arises during manufacturing and assembly.
2. To address the issue of random variability in $M^{DP}s$, it is necessary to set all values of $M^{DP}s$ except for the chosen M_i^{DP} to be fixed during operations, allowing that specific M^{DP} to vary M^{FR}. This step is equivalent to setting the second term on the RHS of Equation (65) as a constant. Once this adjustment is made, the next step involves adjusting ΔM_i^{DP} to compensate for any accumulated errors by setting the first and second terms on the RHS equal to one another. Then,

$$\frac{\partial f(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP})}{\partial M_i^{DP}} \Delta M_i^{DP} = -\sum_{\substack{j=1 \\ i \neq j}}^{n} \frac{\partial f(M_1^{DP} \text{fl } M_2^{DP} \text{fl } \ldots \text{fl } M_n^{DP})}{\partial M_i^{DP}} \cdot \delta M_j^{DP} \quad (66)$$

This approach eliminates the random fluctuations that may arise from additional M^{DP} units used during operations, while ensuring that the tolerance range specified in the

design is met for M^{DP}. The primary M_i^{DP} unit must be capable of compensating for any random variations resulting from the use of extra M^{DP} units.

3.15. Multi-M^{FR} Design

In a multi-M^{FR} design where the number of M^{DP} units exceeds that of M^{FR} units, the design becomes redundant and each M^{FR} unit may be affected by multiple M^{DP} units. Consequently,

$$\left\{M^{FR}\right\} = [Square\ DM]\left\{M^{DP}\right\} + [Extra\ Matrix]\left\{M^{DP}\right\}^{Extra} \tag{67}$$

Let us consider the following scenario: $\{M^{DP}\}$ represents the M^{DP}s selected to fulfill the vector $\{M^{FR}\}$, with the number of $M^{DP}s$ in $\{M^{DP}\}$ being equal to the number of $M^{FR}s$ in $\{M^{FR}\}$. The vector $\{M^{DP}\}^{Extra}$, which appears as the second term on the right-hand side of Equation (67), contains redundant $M^{DP}s$ that remain after $\{M^{DP}\}$ satisfies $\{M^{FR}\}$, but these extra $M^{DP}s$ may not be explicitly known. The square matrix [Square DM] represents the relationship between $\{M^{FR}\}$ and $\{M^{DP}\}$, while [Extra Matrix] describes how the extra M^{DP}s affect the $M^{FR}s$. To ensure compliance with the independence axiom, [Square DM] should be either diagonal or triangular. On the other hand, [Extra Matrix] can take any form, including a full matrix, and still satisfy the independence axiom as long as [Square DM] is diagonal or triangular. Specifically, let's look at a special case of Equation (67) where we are dealing with a multi-M^{FR} design consisting of k $M^{FR}s$ and numerous $M^{DP}s$.

$$\begin{Bmatrix} M_1^{FR} \\ M_2^{FR} \\ \vdots \\ M_k^{FR} \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 & 0 \\ 0 & A_{22} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & A_{kk} \end{bmatrix} \cdot \begin{Bmatrix} M_1^{DP} \\ M_2^{DP} \\ \vdots \\ M_k^{DP} \end{Bmatrix} + \begin{bmatrix} X & X & X & X & \dots & X \\ X & X & X & X & \dots & X \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ X & X & X & X & \dots & X \end{bmatrix} \cdot \begin{Bmatrix} M_{k+1}^{DP} \\ M_{k+2}^{DP} \\ \vdots \\ M_n^{DP} \end{Bmatrix} \tag{68}$$

where M_i^{FR} represents the ith ($i = 1, 2, \dots, k$) module in the functional domain,

M_j^{DP} represents the jth ($j = 1, 2, \dots, n$) module in the physical domain,

DP_p^j represents the pth member of jth module in the physical domain for ($p = 1, 2, \dots, k_1$), and A_{ii} represents the sub-design matrix within DM and relates DPs of M_i^{DP} to the associated FRs of M_i^{FR} to satisfy them.

The first term on the right-hand side (RHS) of Equation (68) represents an uncoupled design, while the second term depicts a fully coupled design. However, even with the presence of the second term, this design can still be treated as an uncoupled design if we establish a fixed value for M_{k+1}^{DP} through M_n^{DP}. We can then use M_1^{DP}, M_2^{DP}, ... and M_n^{DP} to ensure the independence of M_1^{FR}, M_2^{FR}, ... and M_k^{FR}. In such cases, the design range of M^{FR} would be:

$$\Delta M_i^{FR} = \frac{\partial M_i^{FR}}{\partial M_i^{DP}} \cdot \Delta M_i^{DP} + \sum_{j=k+1}^{j=n} \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot \delta M_j^{DP} \text{fl and} \tag{69}$$

$$\Delta M_i^{FR} = \frac{\partial M_i^{FR}}{\partial M_i^{DP}} \cdot \Delta M_i^{DP} + \sum_{j=k+1}^{j=n} [Extra\ Terms] \tag{70}$$

When the diagonal design matrix of the first term on the right-hand side (RHS) of Equation (68) is substituted with a triangular matrix in Equation (71), the resultant design can be treated as a decoupled design

$$\begin{Bmatrix} M_1^{FR} \\ M_2^{FR} \\ \vdots \\ M_k^{FR} \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & \dots & 0 \\ A_{21} & A_{22} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ A_{k1} & A_{k2} & A_{k3} & A_{kk} \end{bmatrix} \cdot \begin{Bmatrix} M_1^{DP} \\ M_2^{DP} \\ \vdots \\ M_k^{DP} \end{Bmatrix} + \begin{bmatrix} X & X & X & X & \dots & X \\ X & X & X & X & \dots & X \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ X & X & X & X & X & X \end{bmatrix} \cdot \begin{Bmatrix} M_{k+1}^{DP} \\ M_{k+2}^{DP} \\ \vdots \\ M_n^{DP} \end{Bmatrix} \quad (71)$$

Random variability in M_{k+1}^{DP} through M_n^{DP} can be counteracted by using fixed values for M_1^{DP}, M_2^{DP}, …, and M_k^{DP}, provided that any extra terms are fixed first and remain the same across all locations where they are used. In this manner, the design range ΔM^{FR} may be achieved using M_j^{DP} ($j = 1, 2, \dots, k$), which is:

$$\Delta M_i^{FR} = \frac{\partial M_i^{FR}}{\partial M_i^{DP}} \cdot \Delta M_i^{DP} + \sum_{\substack{j=1 \\ j \neq i}}^{k} \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot \Delta M_j^{DP} + \sum_{j=k+1}^{n} \frac{\partial M_i^{FR}}{\partial M_k^{DP}} \cdot \delta M_k^{DP} \quad (72)$$

$$= \frac{\partial M_i^{FR}}{\partial M_i^{DP}} \cdot \Delta M_i^{DP} + \sum_{\substack{j=1 \\ j \neq i}}^{k} \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot \Delta M_j^{DP} + (Extra\ Terms) \quad (73)$$

M_i^{DP} is the primary controller for M_i^{FR}. M_j^{DP} are secondary controllers chosen to satisfy $\mathrm{M_j^{FR}}$, with a secondary effect on M_i^{FR} due to off-diagonal elements. M_k^{DP} is not a primary controller and is the source of random variability. ΔM_j^{DP} ($j = 1, 2, \dots, k$) should be set first according to the sequence defined by the triangular matrix to control the corresponding M_j^{FR} ($j = 1, 2, \dots, k$). The variability caused by the extra terms can be fixed by eliminating δM_j^{DP} ($j = k, k + 1, \dots, n$) through fixing $\mathrm{M_k^{DP}}$. Finally, ΔM_i^{FR} can be controlled using ΔM_i^{DP}. If Square *DM*, the first term on the right-hand side of Equation (73), is a full matrix, the design is coupled, which violates the independence axiom. In this case, it is not possible to satisfy the independence of each M^{FR} when unknown $M^{DP}s$ introduce random variability.

The previous discussion holds significant implications for designing a robust system that satisfies multiple $M^{FR}s$ simultaneously. In a multi-M^{FR} design, the selection of M_1^{DP}, M_2^{DP}, and M_3^{DP} must meet the same set of conditions. However, in a decoupled multi-M^{FR} design, we must also satisfy an additional condition for the elements of a triangular design matrix.

$$\left(\frac{\partial f}{\partial M^{DP}}\right)_{diagonal} \gg \left(\frac{\partial f}{\partial M^{DP}}\right)_{off-diagonal} \quad (74)$$

If Equation (74) is not satisfied, it indicates an unacceptable design resulting from choosing the wrong $M^{DP}s$. For instance, consider a scenario where diagonal elements have a smaller magnitude than off-diagonal elements. This implies that M_2^{DP} and M_3^{DP}, selected to control M_2^{FR} and M_3^{FR}, respectively, have a greater impact on M_1^{FR} than M_1^{DP} has on M_1^{FR}. In extreme cases, when one of the diagonal elements is significantly smaller than the off-diagonal elements, the design becomes coupled because one M^{DP} can influence more than *two* $M^{FR}s$. Additionally, if the number of $M^{DP}s$ is less than the number of $M^{FR}s$ due to one or more diagonal elements being zero, the design becomes coupled due to an insufficient number of $M^{DP}s$.

4. Application

This study focuses on verifying the proposed methodology for analyzing the robustness of manufacturing processes in the Iranian tire industry, specifically within 'Barez Industrial Group', an enterprise based in Tehran, Iran, specializing in Tire Manufacturing since its establishment in 1984.

The manufacturing processes under investigation are the 'system of interest' (SOI), and their architecture is analyzed in this study. Considering the dynamic nature of manufacturing environments, the study emphasizes the system's ability to cope with rapid changes. The existing architecture is examined from the perspective of robustness, aiming to identify any shortcomings or limitations. If significant weaknesses are detected, the study proposes a new architecture design based on the engineering design methodology presented in this research, ensuring the system's capability for robustness. By addressing the critical point of verifying the proposed methodology and emphasizing the importance of robustness in tmanufacturing processes, this study contributes valuable insights to the field of tire manufacturing and engineering design practices within 'Barez Industrial Group'.

4.1. Functional Architecture of the SOI

In step 2 of the research method, the functional architecture of the system of interest (SOI) is addressed and its constituent elements are studied. Applying the Axiomatic Design (AD) theory, the elements of the SOI within the functional domain of the system are identified, considering the elements as 'Functional Requirements' and tagging them with FRs. Table 2 presents and describes these FRs of the SOI.

Table 2. Description of the leaf functional requirements (FRs) of the SOI.

Code	Description	Code	Description
FR_{1111}	Organize meetings for the research committee.	FR_{1139}	Request the required tests and follow up on the test.
FR_{1112}	Make a decision about the annual budget.	$FR_{113,10}$	Prepare and archive APQP file documents.
FR_{1113}	Define new projects for the offices.	$FR_{113,11}$	Prepare documents and archive SQA documents.
FR_{1114}	Decide on the duration of projects.	$FR_{113,12}$	Check and prepare a product requirements chart, and turn it into a technical specification.
FR_{1115}	Complete the project charter.	$FR_{113,13}$	Perform the process of improvement and change.
FR_{1121}	Conduct phenomenological studies of the project.	FR_{1141}	Check test requests.
FR_{1122}	Select the initial formulation.	FR_{1142}	Coordinate to receive tires from the production line.
FR_{1123}	Produce the experimental mixture.	FR_{1143}	Plan to take the test.
FR_{1124}	Evaluate the results.	FR_{1144}	Run the test.
FR_{1125}	Optimize the formulation.	FR_{1145}	Review and analyze results.
FR_{1126}	Produce a prototype.	FR_{1146}	Generate test reports.
FR_{1127}	Acknowledge the research objectives.	FR_{1151}	Manage knowledge of the combined design process and the final product in all design aspects.
FR_{1128}	Design the production process for in-line mixing.	FR_{1152}	Support the knowledge management process to fix product line defects.
FR_{1129}	Prepare mixed pre-production samples.	FR_{1153}	Manage previous knowledge within the organization.
$FR_{112,10}$	Prepare pre-production stage tires.	FR_{1154}	Coordinate the holding of internal seminars.
$FR_{112,11}$	Validate to achieve project goals.	FR_{1155}	Coordinate and disseminate new sciences in the field of tire production.
$FR_{112,12}$	Perform daily line production.	FR_{1156}	Receive and archive lessons learned related to research and development projects.
$FR_{112,13}$	Prepare the mixture reference recipe and deliver it to the Research and Development Documentation Center.	FR_{1157}	Publish lessons learned at the organization level.
$FR_{112,14}$	Prepare project documentation and store a copy in the archive of the mixture design office and deliver another copy to the documentation center.	FR_{1221}	Select the size and brand of comparable tires.
FR_{1131}	Design the template profile and pattern.	FR_{1222}	Request to buy.
FR_{1132}	Simulate and certify the design.	FR_{1223}	Determine the test and its standard.
FR_{1133}	Prepare template drawings.	FR_{1231}	Issue processes based on design department ORDERS.
FR_{1134}	Prepare the Common Technical Document (CTD).	FR_{1232}	Check the production notifications sent by the process department to decide on issuing or not issuing the process.

Table 2. *Cont.*

Code	Description	Code	Description
FR_{1135}	Build the ORDER design.	FR_{1233}	Prepare PFMEA for all radial tire production processes.
FR_{1136}	Issue the manufacturing process.	FR_{1234}	Investigate and eliminate the reasons for the non-functioning of the radial tire in the test center tests.
FR_{1137}	Issue the baking process.	FR_{1235}	Carry out projects defined in meetings.
FR_{1138}	Experimentally construct and cook, then examine defects and uniformity.	FR_{1236}	Prepare and update work standards for different parts of radial riding.

4.2. Originate the Functional Architecture of the SOI in DSM Representation

Following steps 3–6 of the method, the DSM tool portrays the functional architecture of the system of interest (SOI). Figure 7 shows the original architecture design. Positive values above the diagonal in the original DSM signify substantial coupling, suggesting changes in one element affect others. To curtail change propagation, a beneficial solution called 'modularization' is suggested.

4.3. Significance of Each System Element Within the Functional Architecture of the SOI

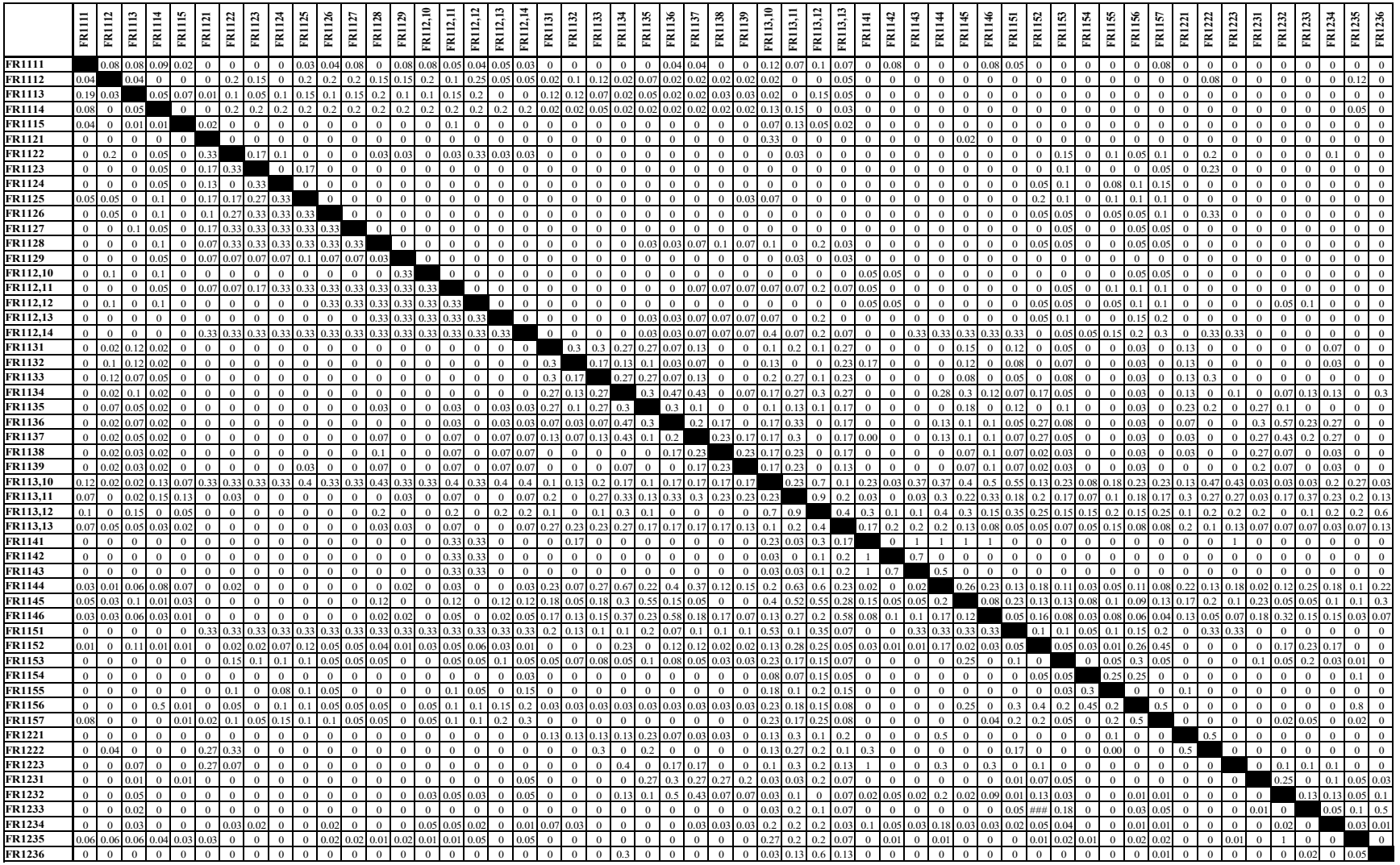
4.3.1. Initial Significance of Each System Element

Each SOI element's significance is assessed by 'C_1' (system architecture dependency) and 'C_2' (element's info dependency on architecture). 'C_1' gauges system's reliance on an element, while 'C_2' measures element's info contribution and input from the system.

For insights into element significance, percentage average dependencies are calculated from the original Numerical Design Structure Matrix (NDSM) of the architecture. Tables 3 and 4 display this, providing a comprehensive view of individual element importance and role in the SOI.

Table 3. Percentage of information provided by each system element for the entire system (NDSM rows).

Code	Percentage (%)	Code	Percentage (%)	Code	Percentage (%)
FR_{1121}	0.57	FR_{1231}	1.36	FR_{1157}	1.87
FR_{1115}	0.6	FR_{1138}	1.38	FR_{1152}	1.9
FR_{1129}	0.69	FR_{1235}	1.38	$FR_{112,11}$	1.96
$FR_{112,10}$	0.73	FR_{1113}	1.44	FR_{1223}	2.04
FR_{1124}	0.83	FR_{1112}	1.52	FR_{1136}	2.25
FR_{1154}	0.87	FR_{1142}	1.55	FR_{1137}	2.26
FR_{1123}	0.88	FR_{1131}	1.55	FR_{1146}	2.44
FR_{1236}	0.96	$FR_{112,13}$	1.55	FR_{1134}	2.49
FR_{1233}	0.99	FR_{1232}	1.56	$FR_{113,13}$	2.64
FR_{1111}	1.04	FR_{1221}	1.56	FR_{1156}	2.75
FR_{1234}	1.11	$FR_{112,12}$	1.59	FR_{1145}	2.87
FR_{1155}	1.12	FR_{1222}	1.6	FR_{1144}	3.11
FR_{1125}	1.19	FR_{1133}	1.64	FR_{1141}	3.17
FR_{1139}	1.25	FR_{1128}	1.68	$FR_{113,11}$	3.72
FR_{1132}	1.27	FR_{1153}	1.74	$FR_{113,12}$	3.92
FR_{1122}	1.29	FR_{1143}	1.77	$FR_{112,14}$	3.94
FR_{1127}	1.31	FR_{1114}	1.79	FR_{1151}	4.34
FR_{1126}	1.32	FR_{1135}	1.82	$FR_{113,10}$	5.85



	FR1111	FR1112	FR1113	FR1114	FR1115	FR1121	FR1122	FR1123	FR1124	FR1125	FR1126	FR1127	FR1128	FR1129	FR112,10	FR112,11	FR112,12	FR112,13	FR112,14	FR1131	FR1132	FR1133	FR1134	FR1135	FR1136	FR1137	FR1138	FR1139	FR113,10	FR113,11	FR113,12	FR113,13	FR1141	FR1142	FR1143	FR1144	FR1145	FR1146	FR1151	FR1152	FR1153	FR1154	FR1155	FR1156	FR1157	FR1221	FR1222	FR1223	FR1231	FR1232	FR1233	FR1234	FR1235	FR1236
FR1111		0.08	0.08	0.09	0.02	0	0	0	0	0.03	0.04	0.08	0	0.08	0.08	0.05	0.04	0.05	0.03	0	0	0	0	0	0.04	0.04	0	0	0.12	0.07	0.1	0.07	0	0.08	0	0	0	0.08	0.05	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0
FR1112	0.04		0.04	0	0	0	0.2	0.15	0	0.2	0.2	0.2	0.15	0.15	0.2	0.1	0.25	0.05	0.05	0.02	0.1	0.12	0.02	0.07	0.02	0.02	0.02	0.02	0.02	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0	0	0	0	0	0.12	0
FR1113	0.19	0.03		0.05	0.07	0.01	0.1	0.05	0.1	0.15	0.1	0.15	0.2	0.1	0.1	0.15	0.2	0	0	0.12	0.12	0.07	0.02	0.05	0.02	0.02	0.03	0.03	0.02	0	0.15	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1114	0.08	0	0.05		0	0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.02	0.02	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.13	0.15	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0
FR1115	0.04	0	0.01	0.01		0.02	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0.13	0.05	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1121	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1122	0	0.2	0	0.05	0	0.33		0.17	0.1	0	0	0	0.03	0.03	0	0.03	0.33	0.03	0.03	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0.15	0	0.1	0.05	0.1	0	0.2	0	0	0	0	0.1	0	0
FR1123	0	0	0	0.05	0	0.17	0.33		0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.05	0	0.23	0	0	0	0	0	0	0
FR1124	0	0	0	0.05	0	0.13	0	0.33		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.1	0	0.08	0.1	0.15	0	0	0	0	0	0	0	0	0	0
FR1125	0.05	0.05	0	0.1	0	0.17	0.17	0.27	0.33		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.07	0	0	0	0	0	0	0	0	0	0	0.2	0.1	0	0.1	0.1	0.1	0	0	0	0	0	0	0	0	0	0
FR1126	0	0.05	0	0.1	0	0.1	0.27	0.33	0.33	0.33		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.05	0	0.05	0.05	0.1	0	0.33	0	0	0	0	0	0	0	0
FR1127	0	0	0.1	0.05	0	0.17	0.33	0.33	0.33	0.33		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0.05	0.05	0	0	0	0	0	0	0	0	0	0
FR1128	0	0	0	0.1	0	0.07	0.33	0.33	0.33	0.33	0.33	0.33		0	0	0	0	0	0	0	0	0	0	0.03	0.03	0.07	0.1	0.07	0.1	0	0.2	0.03	0	0	0	0	0	0	0	0	0.05	0.05	0	0	0.05	0.05	0	0	0	0	0	0	0	0	0
FR1129	0	0	0	0.05	0	0.07	0.07	0.07	0.07	0.1	0.07	0.07	0.03		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,10	0	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0.33		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.05	0	0	0	0	0	0	0	0	0	0.05	0.05	0	0	0	0	0	0	0	0	0
FR112,11	0	0	0	0.05	0	0.07	0.07	0.17	0.33	0.33	0.33	0.33	0.33	0.33	0.33		0	0	0	0	0	0	0	0	0	0	0.07	0.07	0.07	0.07	0.07	0.2	0.07	0.05	0	0	0	0	0	0	0	0.05	0	0.1	0.1	0.1	0	0	0	0	0	0	0	0	0	0
FR112,12	0	0.1	0	0.1	0	0	0	0	0	0	0.33	0.33	0.33	0.33	0.33	0.33		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.05	0	0.05	0.1	0.1	0	0	0	0	0.05	0.1	0	0	0	0	0	0	0	0	0	0	0
FR112,13	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0.33	0.33	0.33		0	0	0	0	0	0.03	0.03	0.07	0.07	0.07	0	0.2	0	0	0	0	0	0	0	0	0	0	0.05	0.1	0	0	0.15	0.2	0	0	0	0	0	0	0	0	0
FR112,14	0	0	0	0	0	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33		0	0	0	0	0.03	0.03	0.07	0.07	0.07	0.4	0.07	0.2	0.07	0	0	0.33	0.33	0.33	0.33	0.33	0	0.05	0.05	0.15	0.2	0.3	0	0.33	0.33	0	0	0	0	0	0	0	0
FR1131	0	0.02	0.12	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.3	0.3	0.27	0.27	0.07	0.13	0	0	0.1	0.2	0.1	0.27	0	0	0	0	0.15	0	0.12	0	0.05	0	0	0.03	0	0.13	0	0	0	0	0	0.07	0	0
FR1132	0	0.1	0.12	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3		0.17	0.13	0.1	0.03	0.07	0	0	0.13	0	0	0.23	0.17	0	0	0	0	0.12	0	0.08	0	0.07	0	0	0.03	0	0.13	0	0	0	0	0.03	0	0
FR1133	0	0.12	0.07	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.17		0.27	0.27	0.07	0.13	0	0	0.2	0.27	0.1	0.23	0	0	0	0	0.08	0	0.05	0	0.08	0	0	0.03	0	0.13	0.3	0	0	0	0	0	0	0
FR1134	0	0.02	0.1	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.27	0.13	0.27		0.3	0.47	0.43	0	0.07	0.17	0.27	0.3	0.27	0	0	0	0.28	0.3	0.12	0.07	0.17	0.05	0	0	0.03	0	0.13	0	0.1	0	0.07	0.13	0.13	0	0.3
FR1135	0	0.07	0.05	0.02	0	0	0	0	0	0	0	0	0.03	0	0	0.03	0	0.03	0.03	0.27	0.1	0.27	0.3		0.3	0.1	0	0	0.1	0.13	0.1	0.17	0	0	0	0	0.18	0	0.12	0	0.1	0	0	0.03	0	0.23	0.2	0	0.27	0.1	0	0	0	0
FR1136	0	0.02	0.07	0.02	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0.03	0.03	0.07	0.03	0.07	0.47	0.3		0.2	0.17	0	0.17	0.33	0	0.17	0	0	0	0.13	0.1	0.1	0.05	0.27	0.08	0	0	0.03	0	0.07	0	0	0.3	0.57	0.23	0.27	0	0
FR1137	0	0.02	0.05	0.02	0	0	0	0	0	0	0	0	0.07	0	0	0.07	0	0.07	0.07	0.13	0.07	0.13	0.43	0.1	0.2		0.23	0.17	0.17	0.3	0	0.17	0.00	0	0	0.13	0.1	0.1	0.07	0.27	0.05	0	0	0.03	0	0.03	0	0	0.27	0.43	0.2	0.27	0	0
FR1138	0	0.02	0.03	0.02	0	0	0	0	0	0	0	0	0.1	0	0	0.07	0	0.07	0.07	0	0	0	0	0	0.17	0.23		0.23	0.17	0.23	0	0.17	0	0	0	0	0.07	0.1	0.07	0.02	0.03	0	0	0.03	0	0.03	0	0	0.27	0.07	0	0.03	0	0
FR1139	0	0.02	0.03	0.02	0	0	0	0	0	0.03	0	0	0.07	0	0	0.07	0	0.07	0.07	0	0	0	0.07	0	0	0.17	0.23		0.17	0.23	0	0.13	0	0	0	0	0	0.07	0.1	0.07	0.02	0.03	0	0	0.03	0	0	0	0.2	0.07	0	0.03	0	0
FR113,10	0.12	0.02	0.02	0.13	0.07	0.33	0.33	0.33	0.33	0.4	0.33	0.33	0.43	0.33	0.33	0.4	0.33	0.4	0.4	0.1	0.13	0.2	0.17	0.1	0.17	0.17	0.17	0.17		0.23	0.7	0.1	0.23	0.03	0.37	0.37	0.4	0.5	0.55	0.13	0.23	0.08	0.18	0.23	0.23	0.13	0.47	0.43	0.03	0.03	0.03	0.2	0.27	0.03
FR113,11	0.07	0	0.02	0.15	0.13	0	0.03	0	0	0	0	0	0	0.03	0	0.07	0	0	0.07	0.2	0	0.27	0.33	0.13	0.33	0.3	0.23	0.23	0.23		0.9	0.2	0.03	0	0.03	0.3	0.22	0.33	0.18	0.2	0.17	0.07	0.1	0.18	0.17	0.3	0.27	0.27	0.03	0.17	0.37	0.23	0.2	0.13
FR113,12	0.1	0	0.15	0	0.05	0	0	0	0	0	0	0	0.2	0	0	0.2	0	0.2	0.2	0.1	0	0.1	0.3	0.1	0	0	0	0	0.7	0.9		0.4	0.3	0.1	0.1	0.4	0.3	0.15	0.35	0.25	0.15	0.15	0.2	0.15	0.25	0.1	0.2	0.2	0.2	0	0.1	0.2	0.2	0.6
FR113,13	0.07	0.05	0.05	0.03	0.02	0	0	0	0	0	0	0	0.03	0.03	0	0.07	0	0	0.07	0.27	0.23	0.23	0.27	0.17	0.17	0.17	0.13	0.1	0.2	0.4		0.17	0.2	0.2	0.2	0.13	0.08	0.05	0.05	0.07	0.05	0.15	0.08	0.08	0.2	0.1	0.13	0.07	0.07	0.03	0.07	0.13		
FR1141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0	0	0	0.17	0	0	0	0	0	0	0	0.23	0.03	0.3	0.17		0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
FR1142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0.1	0.2	1		0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1143	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0	0	0	0	0	0	0	0	0	0	0	0.03	0.03	0.1	0.2	1	0.7		0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1144	0.03	0.01	0.06	0.08	0.07	0	0.02	0	0	0	0	0	0.02	0	0.03	0	0	0.03	0.23	0.07	0.27	0.67	0.22	0.4	0.37	0.12	0.15	0.2	0.63	0.6	0.23	0.02	0	0.02		0.26	0.23	0.13	0.18	0.11	0.03	0.05	0.11	0.08	0.22	0.13	0.18	0.02	0.12	0.25	0.18	0.1	0.22	0	0
FR1145	0.05	0.03	0.1	0.01	0.03	0	0	0	0	0	0	0.12	0	0	0.12	0	0.12	0.12	0.18	0.05	0.18	0.3	0.55	0.15	0.05	0	0	0.4	0.52	0.55	0.28	0.15	0.05	0.05	0.2		0.08	0.23	0.13	0.13	0.08	0.1	0.09	0.13	0.17	0.2	0.1	0.23	0.05	0.05	0.1	0.1	0.3	0	0
FR1146	0.03	0.03	0.06	0.03	0.01	0	0	0	0	0	0	0	0.02	0.02	0	0.05	0	0.02	0.05	0.17	0.13	0.15	0.37	0.23	0.58	0.18	0.17	0.07	0.13	0.27	0.2	0.58	0.08	0.1	0.1	0.17	0.12		0.05	0.16	0.08	0.03	0.08	0.06	0.04	0.13	0.05	0.07	0.18	0.32	0.15	0.15	0.03	0.07	0
FR1151	0	0	0	0	0	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.2	0.13	0.1	0.1	0.2	0.07	0.1	0.1	0.1	0.53	0.1	0.35	0.07	0	0	0.33	0.33	0.33	0.33		0.1	0.1	0.05	0.1	0.15	0.2	0	0.33	0.33	0	0	0	0	0	0
FR1152	0.01	0	0.11	0.01	0.01	0	0.02	0.02	0.07	0.12	0.05	0.05	0.04	0.01	0.03	0.05	0.06	0.03	0.01	0	0	0	0.23	0	0.12	0.12	0.02	0.02	0.13	0.28	0.25	0.05	0.03	0.01	0.01	0.17	0.02	0.03	0.05		0.05	0.03	0.01	0.26	0.45	0	0	0	0	0.17	0.23	0.17	0	0
FR1153	0	0	0	0	0	0.15	0.1	0.1	0.1	0.05	0.05	0.05	0	0	0.05	0.05	0.1	0.05	0.05	0.07	0.08	0.05	0.1	0.08	0.05	0.03	0.03	0.23	0.17	0.15	0.07	0	0	0	0	0	0.25	0	0.1	0		0	0.05	0.3	0.05	0	0	0	0.1	0.05	0.2	0.03	0.01	0
FR1154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0.08	0.07	0.15	0.05	0	0	0	0	0	0	0	0.05	0.05		0.25	0.25	0	0	0	0	0	0	0	0.1	0	0
FR1155	0	0	0	0	0	0	0.1	0	0.08	0.1	0.05	0	0	0	0	0.1	0.05	0	0.15	0	0	0	0	0	0	0	0	0	0.18	0.1	0.2	0.15	0	0	0	0	0	0	0	0	0.03	0.3		0	0	0.1	0	0	0	0	0	0	0	0
FR1156	0	0	0	0.5	0.01	0	0.05	0	0.1	0.1	0.05	0.05	0.05	0	0.05	0.1	0.1	0.15	0.2	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.23	0.18	0.15	0.08	0	0	0	0	0	0.25	0	0.3	0.4	0.2	0.45	0.2		0.5	0	0	0	0	0	0	0.8	0
FR1157	0.08	0	0	0	0.01	0.02	0.1	0.05	0.15	0.1	0.1	0.05	0.05	0	0.05	0.1	0.1	0.2	0.3	0	0	0	0	0	0	0	0	0	0.23	0.17	0.25	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0.02	0.05	0	0.02	0
FR1221	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0.13	0.13	0.13	0.23	0.07	0.03	0.03	0	0.13	0.3	0.1	0.2	0	0	0	0.5	0	0	0	0	0.1	0	0	0	0	0		0.5	0	0	0	0	0	0	0
FR1222	0	0.04	0	0	0.27	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.2	0	0	0	0	0	0.13	0.27	0.2	0.1	0.3	0	0	0	0	0	0	0.17	0	0	0	0.00	0	0	0.5		0	0	0	0	0	0
FR1223	0	0	0.07	0	0	0.27	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0.17	0.17	0	0	0	0.1	0.3	0.2	0.13	1	0	0	0.3	0	0.3	0	0.1	0	0	0	0	0	0	0		0	0.1	0.1	0.1	0	0
FR1231	0	0	0.01	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0	0	0.27	0.3	0.27	0.27	0.2	0.03	0.03	0.2	0.07	0	0	0	0	0	0	0	0.01	0.07	0.05	0	0	0	0	0	0	0	0		0.25	0	0.1	0.05	0.03
FR1232	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0.03	0.05	0.03	0	0.05	0	0	0	0.13	0.1	0.5	0.43	0.07	0.07	0.03	0.1	0	0.07	0.02	0.05	0.02	0.2	0.02	0.09	0.01	0.13	0.03	0	0	0.01	0.01	0	0	0	0	0	0		0.13	0.13	0.05	0.1
FR1233	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.2	0.1	0.07	0	0	0	0	0	0	0	0.05	###	0.18	0	0	0.03	0.05	0	0	0	0.01	0		0.05	0.1	0.5
FR1234	0	0	0.03	0	0	0	0.03	0.02	0	0	0.02	0	0	0	0.05	0.05	0.02	0	0.01	0.07	0.03	0	0	0	0	0.03	0.03	0.03	0.2	0.2	0.2	0.03	0.1	0.05	0.03	0.18	0.03	0.03	0.02	0.05	0.04	0	0	0.01	0.01	0	0	0	0	0.02	0		0.03	0.01
FR1235	0.06	0.06	0.06	0.04	0.03	0.03	0	0	0	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.05	0	0.05	0	0	0	0	0	0	0	0	0	0.27	0.2	0.2	0.07	0	0.01	0	0.01	0	0	0	0.01	0.02	0.02	0	0.01	0	0.02	0.02	0	0	0.01	0	1	0	0	
FR1236	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0.03	0.13	0.6	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0.02	0	0.05	

Figure 7. Displaying the initial SOI design using a Numerical Design Structure Matrix (NDSM).

Table 4. Percentage of information input received by each system element from the entire system (NDSM columns).

Code	Percentage (%)	Code	Percentage (%)	Code	Percentage (%)
FR_{1111}	0.85	$FR_{112,14}$	1.56	FR_{1145}	2.13
FR_{1112}	0.94	FR_{1131}	1.77	FR_{1146}	1.76
FR_{1113}	1.13	FR_{1132}	1.35	FR_{1151}	1.82
FR_{1114}	1.3	FR_{1133}	1.88	FR_{1152}	1.84
FR_{1115}	0.63	FR_{1134}	2.83	FR_{1153}	1.72
FR_{1121}	1.62	FR_{1135}	2.18	FR_{1154}	0.99
FR_{1122}	2.08	FR_{1136}	2.36	FR_{1155}	1.42
FR_{1123}	1.92	FR_{1137}	2.22	FR_{1156}	1.98
FR_{1124}	1.94	FR_{1138}	1.44	FR_{1157}	1.97
FR_{1125}	2.01	FR_{1139}	1.28	FR_{1221}	1.57
FR_{1126}	1.79	$FR_{113,10}$	3.53	FR_{1222}	2.07
FR_{1127}	1.64	$FR_{113,11}$	3.83	FR_{1223}	1.74
FR_{1128}	1.9	$FR_{113,12}$	4.13	FR_{1231}	1.33
FR_{1129}	1.68	$FR_{113,13}$	2.93	FR_{1232}	1.97
$FR_{112,10}$	1.59	FR_{1141}	2.41	FR_{1233}	1.43
$FR_{112,11}$	2.38	FR_{1142}	1.04	FR_{1234}	1.51
$FR_{112,12}$	2.01	FR_{1143}	1.8	FR_{1235}	1.4
$FR_{112,13}$	1.46	FR_{1144}	2.51	FR_{1236}	1.43

Figures 8 and 9 are included to provide a clearer visual representation of the information presented in Tables 3 and 4, respectively.

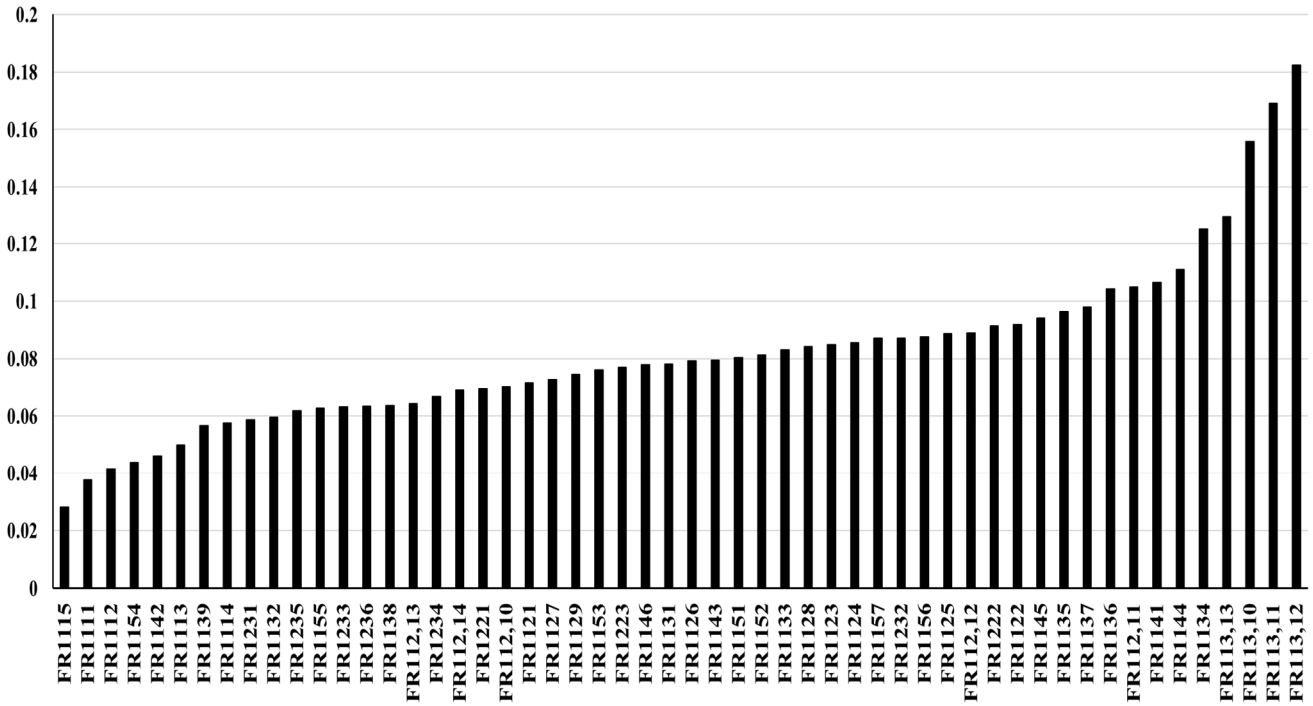


Figure 8. Prioritization of the proportion of information contribution from each system element to the entire SOI (NDSM rows).

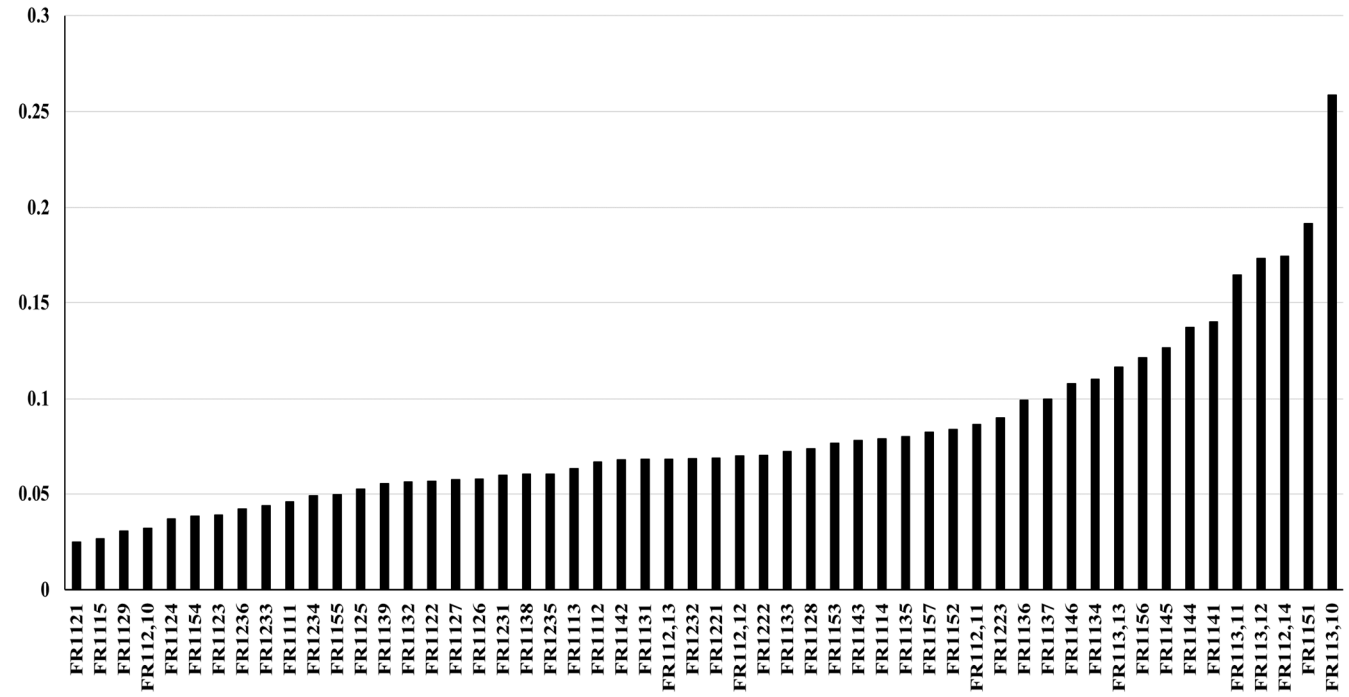


Figure 9. Prioritization of the percentage of information input received by each system element from the entire SOI (NDSM columns).

Furthermore, Figure 10 offers a comparison between the 'percentage of information feed that each system element can provide' and the 'percentage of information inputs that each system element receives' for/from the entire SOI.

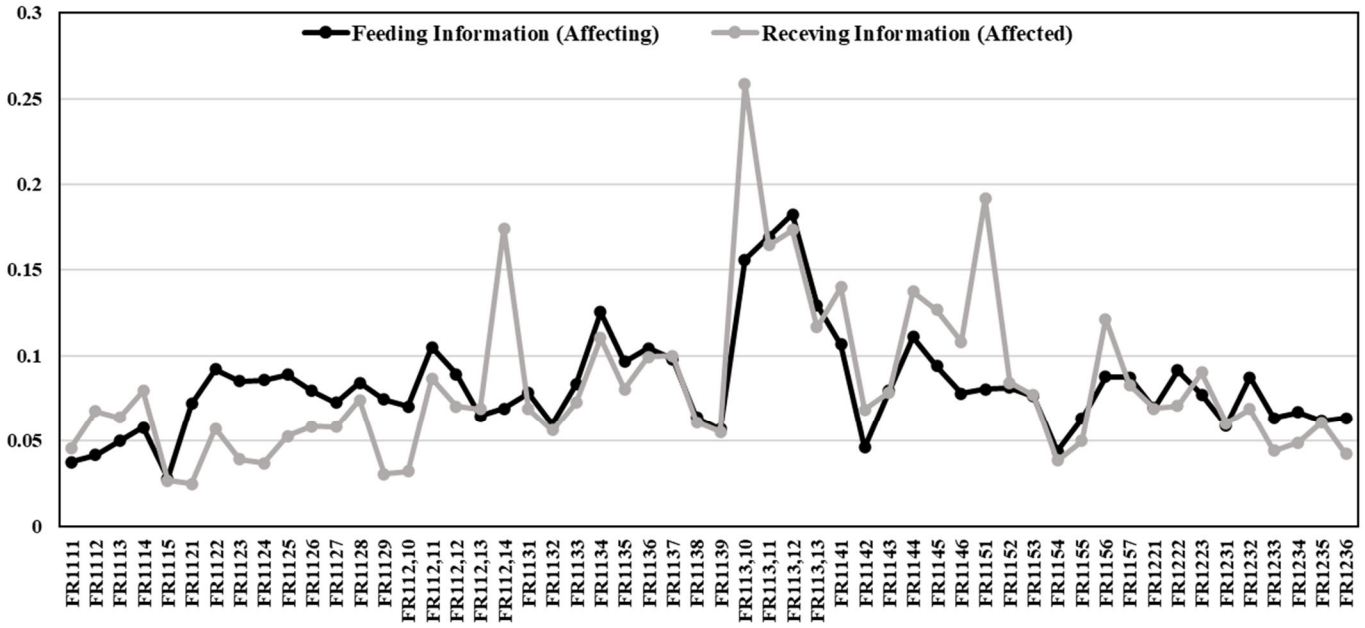


Figure 10. Comparing info contributions and input percentages for each system element overall.

In the figures provided, criteria C_1 and C_2 vary for each system element. For example, '$FR_{113,10}$', '$FR_{113,11}$', and '$FR_{113,12}$' show maximal information feed (C_1) and receive the highest information inputs (C_2) from the entire system. However, it is crucial to evaluate each process based on both criteria simultaneously to avoid misinterpretation. To address

this, the study introduces the 'compound measure' weighting method, explained further in the following section.

4.3.2. Compound Weights of Each System Element

To assign weights to each element, two criteria, 'C_1' and 'C_2', are introduced with equal values ($WC_1 = 0.5$, $WC_2 = 0.5$). Subsequently, two Multi-Criteria Decision Making (MCDM) methods, 'SAW' and 'TOPSIS,' are employed. The resulting weights obtained from these methods are collectively referred to as 'Compound Weights' in this study. Table 5 displays the final compound weights of each element within the SOI, based on the outcomes from the SAW and TOPSIS methods.

Table 5. Compound weight of each element of the SOI.

FRs	SAW	TOPSIS	FRs	SAW	TOPSIS
FR_{1111}	0.009	0.005	FR_{1139}	0.013	0.010
FR_{1112}	0.012	0.010	$FR_{113,10}$	0.045	0.059
FR_{1113}	0.013	0.010	$FR_{113,11}$	0.038	0.044
FR_{1114}	0.015	0.014	$FR_{113,12}$	0.040	0.047
FR_{1115}	0.006	0.000	$FR_{113,13}$	0.028	0.031
FR_{1121}	0.012	0.010	FR_{1141}	0.027	0.032
FR_{1122}	0.018	0.016	FR_{1142}	0.013	0.011
FR_{1123}	0.015	0.013	FR_{1143}	0.018	0.017
FR_{1124}	0.015	0.013	FR_{1144}	0.028	0.032
FR_{1125}	0.017	0.015	FR_{1145}	0.024	0.028
FR_{1126}	0.016	0.014	FR_{1146}	0.020	0.022
FR_{1127}	0.015	0.013	FR_{1151}	0.029	0.037
FR_{1128}	0.018	0.017	FR_{1152}	0.019	0.019
FR_{1129}	0.013	0.011	FR_{1153}	0.017	0.017
$FR_{112,10}$	0.012	0.010	FR_{1154}	0.009	0.005
$FR_{112,11}$	0.022	0.023	FR_{1155}	0.013	0.010
$FR_{112,12}$	0.018	0.018	FR_{1156}	0.023	0.026
$FR_{112,13}$	0.015	0.013	FR_{1157}	0.019	0.019
$FR_{112,14}$	0.025	0.033	FR_{1221}	0.016	0.014
FR_{1131}	0.017	0.015	FR_{1222}	0.019	0.018
FR_{1132}	0.013	0.010	FR_{1223}	0.019	0.019
FR_{1133}	0.018	0.017	FR_{1231}	0.013	0.011
FR_{1134}	0.027	0.030	FR_{1232}	0.018	0.017
FR_{1135}	0.020	0.020	FR_{1233}	0.013	0.009
FR_{1136}	0.023	0.025	FR_{1234}	0.013	0.011
FR_{1137}	0.022	0.024	FR_{1235}	0.014	0.012
FR_{1138}	0.014	0.012	FR_{1236}	0.012	0.009

Figure 11 compares compound weights of each element from the TOPSIS and SAW methods with the originally computed weights (from C_1 and C_2 only).

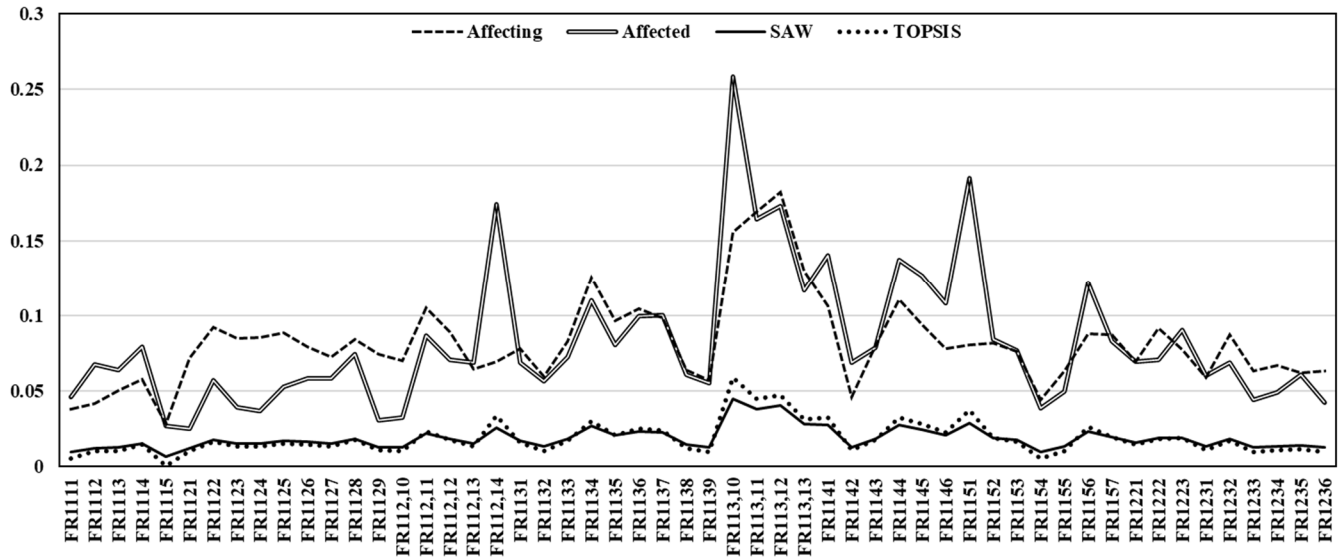


Figure 11. Comparing the compound weights of each element with their original individual weights.

The figure shows significant disparities between original weights and those from MCDM methods. However, the weights from SAW and TOPSIS are similar and more reasonable.

Due to the substantial similarity between SAW and TOPSIS results, and to maintain simplicity and generality, weights from the TOPSIS method are used for further analysis. Table 6 displays the updated prioritization of elements based on these compound weights.

Table 6. Prioritization of elements according to their compound weights determined by the TOPSIS method.

System Element	Priority	Compound Weight	System Element	Priority	Compound Weight
$FR_{113,10}$	29	0.0449	FR_{1131}	20	0.0168
$FR_{113,12}$	31	0.0404	FR_{1125}	10	0.0167
$FR_{113,11}$	30	0.0378	FR_{1126}	11	0.0160
FR_{1151}	39	0.0286	FR_{1221}	46	0.0157
$FR_{113,13}$	32	0.0281	FR_{1127}	12	0.0151
FR_{1144}	36	0.0276	FR_{1114}	4	0.0151
FR_{1141}	33	0.0272	$FR_{112,13}$	18	0.0150
FR_{1134}	23	0.0269	FR_{1123}	8	0.0149
$FR_{112,14}$	19	0.0255	FR_{1124}	9	0.0148
FR_{1145}	37	0.0243	FR_{1138}	27	0.0141
FR_{1136}	25	0.0231	FR_{1235}	53	0.0139
FR_{1156}	44	0.0230	FR_{1234}	52	0.0135
FR_{1137}	26	0.0224	FR_{1231}	49	0.0134
$FR_{112,11}$	16	0.0220	FR_{1132}	21	0.0132
FR_{1146}	38	0.0204	FR_{1155}	43	0.0130
FR_{1135}	24	0.0203	FR_{1129}	14	0.0127
FR_{1157}	45	0.0193	FR_{1139}	28	0.0127
FR_{1222}	47	0.0187	FR_{1113}	3	0.0126
FR_{1152}	40	0.0187	FR_{1233}	51	0.0125
FR_{1223}	48	0.0187	FR_{1142}	34	0.0125
$FR_{112,12}$	17	0.0184	FR_{1236}	54	0.0124
FR_{1128}	13	0.0181	$FR_{112,10}$	15	0.0123
FR_{1232}	50	0.0180	FR_{1121}	6	0.0118
FR_{1143}	35	0.0179	FR_{1112}	2	0.0118
FR_{1133}	22	0.0178	FR_{1154}	42	0.0094
FR_{1122}	7	0.0175	FR_{1111}	1	0.0093
FR_{1153}	41	0.0173	FR_{1115}	5	0.0062

Consequently, the updated prioritization of the elements can be of significant assistance to managers, enabling them to identify the most and least crucial elements with greater reliability (Figure 12). This, in turn, offers valuable practical insights for making decisions that prioritize robustness.

4.4. Modularization of the Functional Architecture of the SOI

As highlighted in the preceding section, reducing the coupling identified within the functional architecture of the SOI is crucial. According to the principles of DSM methodology, the existence of coupling is inferred from positive values of upper-diagonal entries in the original DSM. However, it is important to note that not all positive values necessarily indicate a significant strength between the involved elements. In certain cases, some interactions between two elements may be negligible, and as a result, the associated values for those entries can be replaced by zero instead. This approach allows us to focus on the more substantial interactions while mitigating the impact of the insignificant ones.

Based on the aforementioned logic, elite members of the SOI were interviewed to determine a set of candidate cut-off points for ignoring the strength of interaction between a given pair of elements. The cut-off point refers to a specific value below which the interactions can be disregarded. As a result, the values '0.10', '0.11', '0.11', '0.12', '0.13', '0.14', and '0.15'—each reflecting the strength of interaction between system elements—are introduced as acceptable candidates for identifying an appropriate cut-off point.

For each candidate, the associated NDSM representation of the functional architecture of interest is presented in Appendix A (Figures A1–A6). To diminish the coupling, the partitioning technique is applied for each of the resulted architecture. Figures 13–18 display the outcomes.

Table 7 presents all the fundamental information (i.e., N_1–N_4) necessary for computing the criteria, introduced in Section 3.5, used to measure the architecture modularity.

Table 7. Fundamental details regarding the introduced measures of modularity.

Designs \ Ns	N_1	N_2	N_3	N_4
Design I	131	499	2226	60
Design II	101	295	2469	51
Design III	86	144	2645	41
Design IV	80	146	2656	34
Design V	54	86	2742	34
Design VI	30	44	2810	32

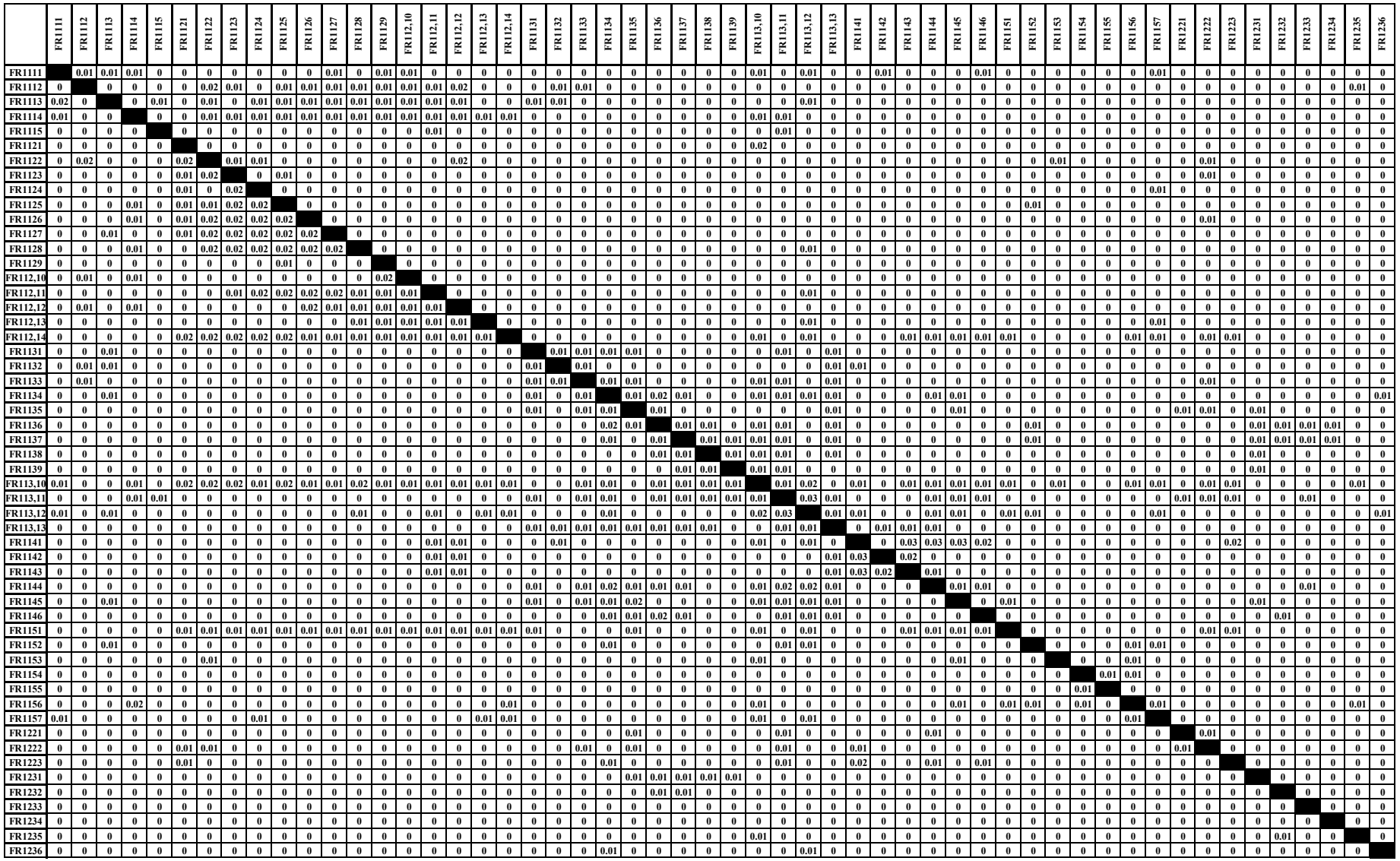


Figure 12. Displaying the initial SOI design in the NDSM with updated weights.

Partitioned DSM [Keep More Than **0.1**]		FR1111	FR1115	FR1129	FR112,10	FR112,11	FR1124	FR1123	FR1121	FR1122	FR1112	FR1125	FR1126	FR1127	FR1128	FR112,12	FR113,10	FR112,13	FR112,14	FR113,12	FR113,11	FR1134	FR1135	FR1136	FR1137	FR113,13	FR1143	FR1141	FR1142	FR1144	FR1145	FR1146	FR1151	FR1222	FR1223	FR1232	FR1131	FR1132	FR1133	FR1138	FR1139	FR1152	FR1153	FR1154	FR1155	FR1221	FR1231	FR1233	FR1234	FR1235	FR1236	FR1113	FR1114	FR1156	FR1157
		1	5	14	15	16	9	8	6	7	2	10	11	12	13	17	29	18	19	31	30	23	24	25	26	32	35	33	34	36	37	38	39	47	48	50	20	21	22	27	28	40	41	42	43	46	49	51	52	53	54	3	4	44	45
FR1111	1	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1115	5	0	**5**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1129	14	0	0	**14**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,10	15	0	0	1	**15**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,11	16	0	0	1	1	**16**	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1124	9	0	0	0	0	0	**9**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1123	8	0	0	0	0	0	0	**8**	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1121	6	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1122	7	0	0	0	0	0	0	0	0	**7**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1112	2	0	0	0	0	0	0	0	0	0	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1125	10	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1126	11	0	0	0	0	0	0	0	0	0	0	0	**11**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1127	12	0	0	0	0	0	0	0	0	0	0	0	0	**12**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1128	13	0	0	0	0	0	0	0	0	0	0	0	0	0	**13**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,12	17	0	0	1	1	1	0	0	0	0	0	0	1	1	1	**17**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,10	29	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	**29**	1	1	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,13	18	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0	**18**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,14	19	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	**19**	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,12	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	**31**	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,11	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	30	**1**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1134	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	**1**	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1135	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**24**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1136	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	**25**	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1137	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**26**	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,13	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**32**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1143	35	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**35**	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1141	33	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	**33**	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1142	34	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	**34**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1144	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	0	**36**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1145	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	0	0	0	0	0	0	**37**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1146	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	**38**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1151	39	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**39**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1222	47	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**47**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1223	48	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1232	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	**50**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1131	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**20**	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1132	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**21**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1133	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**22**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1138	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**27**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1139	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**28**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1152	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**40**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1153	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**41**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1154	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**42**	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1155	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**43**	0	0	0	0	0	0	0	0	0	0	0	0
FR1221	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**46**	0	0	0	0	0	0	0	0	0	0	0
FR1231	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**49**	0	0	0	0	0	0	0	0	0	0	0	0
FR1233	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**51**	0	0	0	0	0	0	0	0	0	0	0
FR1234	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**52**	0	0	0	0	0	0	0	0	0	0	0
FR1235	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**53**	0	0	0	0	0	0	0	0	0	0	0
FR1236	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**54**	0	0	0	0	0	0	0	0	0	0	0
FR1113	3	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	0	0	0
FR1114	4	0	0	1	1	1	1	1	0	1	0	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**4**	0	0
FR1156	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	**44**	1
FR1157	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**45**

Figure 13. Developing a modular design for the SOI architecture with a cutting-point set at 0.10 (Design I).

Partitioned DSM [Keep More Than 0.11]		FR1111	FR1115	FR1129	FR112,10	FR1131	FR1132	FR1133	FR1134	FR1136	FR1137	FR1232	FR1135	FR1138	FR1139	FR113,10	FR1121	FR1122	FR1112	FR1123	FR1125	FR1124	FR1126	FR1127	FR112,12	FR1128	FR112,11	FR112,13	FR112,14	FR113,12	FR113,11	FR113,13	FR1146	FR1151	FR1222	FR1144	FR1145	FR1152	FR1153	FR1154	FR1155	FR1157	FR1221	FR1223	FR1141	FR1143	FR1142	FR1231	FR1233	FR1234	FR1235	FR1236	FR1113	FR1114	FR1156
		1	5	14	15	20	21	22	23	25	26	50	24	27	28	29	6	7	2	8	10	9	11	12	17	13	16	18	19	31	30	32	38	39	47	36	37	40	41	42	43	45	46	48	33	35	34	49	51	52	53	54	3	4	44
FR1111	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1115	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1129	14	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,10	15	0	0	1	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1131	20	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1132	21	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1133	22	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1134	23	0	0	0	0	0	0	0	23	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1136	25	0	0	0	0	0	0	0	1	25	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1137	26	0	0	0	0	0	0	0	1	0	26	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1232	50	0	0	0	0	0	0	0	0	1	1	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1135	24	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1138	27	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1139	28	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,10	29	0	0	1	1	0	0	0	0	0	0	0	0	0	0	29	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1121	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1122	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1112	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1123	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1125	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1124	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1126	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	11	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1127	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,12	17	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	17	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1128	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,11	16	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,13	18	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,14	19	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,12	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	31	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,11	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,13	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1146	38	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1151	39	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1222	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1144	36	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1145	37	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1152	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1153	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1154	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1155	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1157	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	0	0	0	0	0	0	0	0	0	0	0	0
FR1221	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	46	0	0	0	0	0	0	0	0	0	0	0
FR1223	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	1	0	0	0	0	0	0	0	0	0
FR1141	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	1	33	1	0	0	0	0	0	0	0	0
FR1143	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	35	1	0	0	0	0	0	0	0
FR1142	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	34	0	0	0	0	0	0	0	0
FR1231	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49	0	0	0	0	0	0	0
FR1233	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	0	0	0	0	0	0
FR1234	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0	0	0	0
FR1235	53	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	0	0	0	0
FR1236	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54	0	0	0
FR1113	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
FR1114	4	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
FR1156	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	44

Figure 14. Developing a modular design for the SOI architecture with a cutting-point set at 0.11 (Design II).

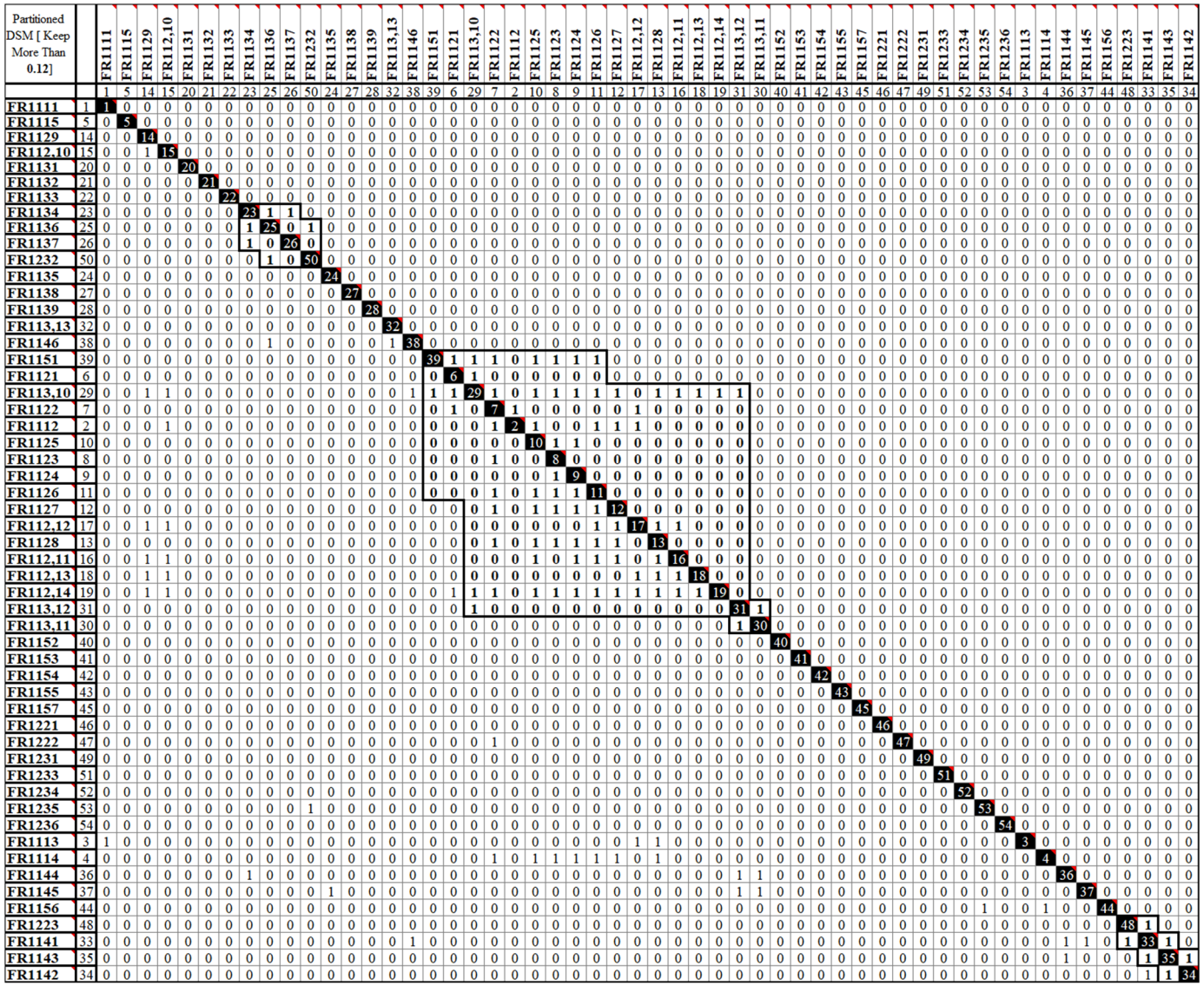


Figure 15. Developing a modular design for the SOI architecture with a cutting-point set at 0.12 (Design III).

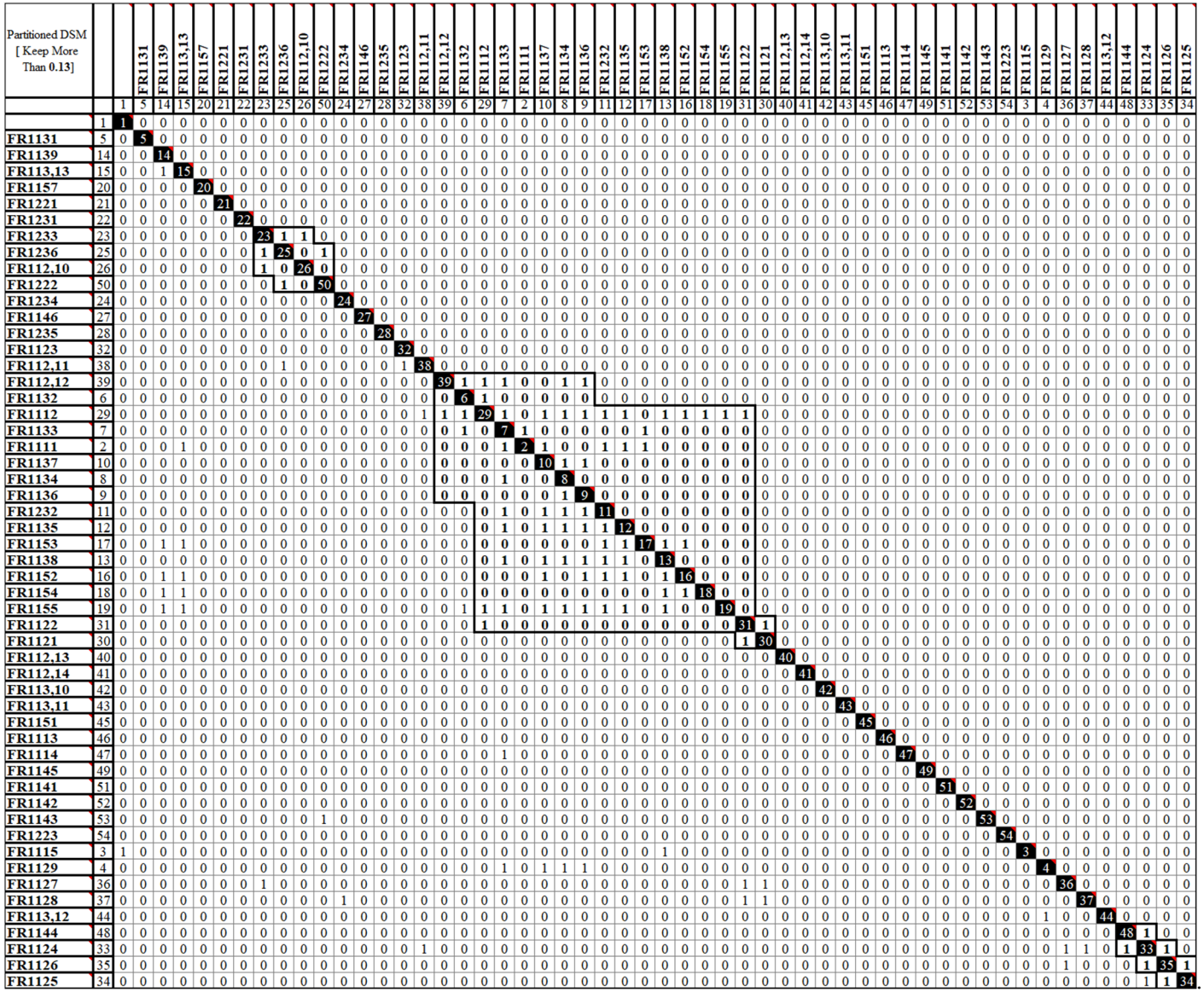


Figure 16. Developing a modular design for the SOI architecture with a cutting-point set at 0.13 (Design IV).

Partitioned DSM [Keep More Than 0.14]		FR1111	FR1112	FR1113	FR1127	FR1128	FR1129	FR1122	FR1121	FR1115	FR1112	FR1114	FR1123	FR1124	FR1125	FR1126	FR112,10	FR1138	FR113,10	FR1139	FR1145	FR112,11	FR112,12	FR112,13	FR112,14	FR1131	FR1133	FR1136	FR1137	FR113,11	FR1143	FR1146	FR1151	FR1152	FR1153	FR1154	FR1155	FR1156	FR1157	FR1222	FR1223	FR1231	FR1232	FR1233	FR1234	FR1132	FR1134	FR1135	FR1142	FR1144	FR1221	FR113,12	FR1141	FR113,13
	1	3	4	5	14	15	16	9	8	7	2	6	10	11	12	13	17	29	31	30	39	18	19	20	21	22	24	27	28	32	37	40	41	42	43	44	45	46	47	49	50	51	52	53	54	23	25	26	36	38	48	33	35	34
	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1111	3	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1112	4	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1113	5	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1127	14	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1128	15	0	0	0	0	1	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1129	16	0	0	0	1	1	16	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1122	9	0	0	0	0	0	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1121	8	0	0	0	0	0	0	0	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1115	7	0	0	0	0	0	0	0	0	7	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1112	2	0	0	0	0	0	0	0	0	1	2	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1114	6	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1123	10	0	0	0	0	0	0	1	1	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1124	11	0	0	0	0	0	0	1	1	1	0	0	1	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1125	12	0	0	0	0	0	0	1	1	1	0	0	1	1	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1126	13	0	0	0	0	0	0	1	1	1	0	0	1	1	1	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,10	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1138	29	0	0	0	0	0	1	1	1	1	0	1	1	0	0	1	0	29	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,10	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	31	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1139	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1145	39	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,11	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,12	19	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,13	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,14	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1131	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1133	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1136	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1137	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,11	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1143	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1146	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1151	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1152	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1153	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1154	44	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1155	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1156	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1157	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1222	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1223	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1231	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	0	0	0	0	0	0	0	0	0	0	0	0
FR1232	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0	0	0	0	0	0	0	0	0	0
FR1233	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	53	0	0	0	0	0	0	0	0	0	0
FR1234	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54	0	0	0	0	0	0	0	0	0
FR1132	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	1	1	0	0	0	0	0	0
FR1134	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	25	0	0	0	0	0	0	0
FR1135	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	26	0	0	0	0	0	0
FR1142	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	36	0	0	0	0	0
FR1144	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	38	0	0	0	0
FR1221	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	1	0	0
FR113,12	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	33	1	0
FR1141	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	35	1
FR113,13	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	34

Figure 17. Developing a modular design for the SOI architecture with a cutting-point set at 0.14 (Design V).

Partitioned DSM [Keep More Than 0.15]		FR1111	FR1112	FR1122	FR1121	FR112,12	FR1126	FR1123	FR1124	FR1125	FR113,10	FR1128	FR1127	FR113,12	FR113,11	FR1113	FR1114	FR1115	FR1129	FR112,10	FR112,11	FR112,13	FR112,14	FR1131	FR1132	FR1133	FR1134	FR1136	FR1135	FR1137	FR1138	FR1139	FR113,13	FR1144	FR1145	FR1146	FR1151	FR1152	FR1153	FR1154	FR1155	FR1156	FR1157	FR1221	FR1222	FR1223	FR1141	FR1143	FR1142	FR1231	FR1232	FR1233	FR1234	FR1235	FR1236
		1	2	7	6	17	11	8	9	10	29	13	12	31	30	3	4	5	14	15	16	18	19	20	21	22	23	25	24	26	27	28	32	36	37	38	39	40	41	42	43	44	45	46	47	48	33	35	34	49	50	51	52	53	54
FR1111	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1112	2	0	2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1122	7	0	1	7	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1121	6	0	0	0	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,12	17	0	0	0	0	17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1126	11	0	0	1	0	0	11	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1123	8	0	0	1	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1124	9	0	0	0	0	0	0	0	1	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1125	10	0	0	0	0	0	0	0	1	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,10	29	0	0	1	1	0	0	1	0	1	29	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1128	13	0	0	1	0	0	1	1	1	1	0	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1127	12	0	0	1	0	0	1	1	1	1	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,12	31	0	0	0	0	0	0	0	0	0	1	0	0	31	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,11	30	0	0	0	0	0	0	0	0	0	0	0	0	1	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1113	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1114	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1115	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1129	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,10	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,11	16	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,13	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,14	19	0	0	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1131	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1132	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1133	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1134	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1136	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1135	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1137	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1138	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1139	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,13	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1144	36	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1145	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1146	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1151	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1152	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1153	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1154	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1155	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1156	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1157	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	0	0	0	0	0	0	0	0	0	0	0	0
FR1221	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0	0	0	0	0	0	0	0	0	0
FR1222	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	0
FR1223	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	1	0	0	0	0	0	0	0	0
FR1141	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	33	1	0	0	0	0	0	0	0
FR1143	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	35	1	0	0	0	0	0	0
FR1142	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	34	0	0	0	0	0	0
FR1231	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49	0	0	0	0	0
FR1232	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0
FR1233	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	0	0	0
FR1234	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0
FR1235	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	0
FR1236	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54

Figure 18. Developing a modular design for the SOI architecture with a cutting-point set at 0.15 (Design VI).

Using the information provided in Table 8, Figure 19a–d compares the modularity of all six presented designs (i.e., Designs I–VI). Based on the applied criteria, it is concluded that 'Design VI', for the functional architecture of the SOI, exhibits the highest modularity. Therefore, in terms of modularity, this specific design is considered the most optimal for the architecture. Notably, 'Design VI' introduces a new sequence to enhance the architecture while effectively removing significant coupling.

Table 8. Assessing the degree of modularity for Designs I–VI.

		Modularity Measures			
		Grouping Capability Index (GCI)	Grouping Efficacy	Grouping Efficiency	Utilization Rate (U)
Presented Designs	Design I	0.68	−0.42	0.60	0.21
	Design II	0.66	−0.71	0.62	0.25
	Design III	0.68	−5.05	0.68	0.37
	Design IV	0.70	−2.50	0.67	0.35
	Design V	0.61	27.00	0.69	0.38
	Design VI	0.48	26.67	0.70	0.40

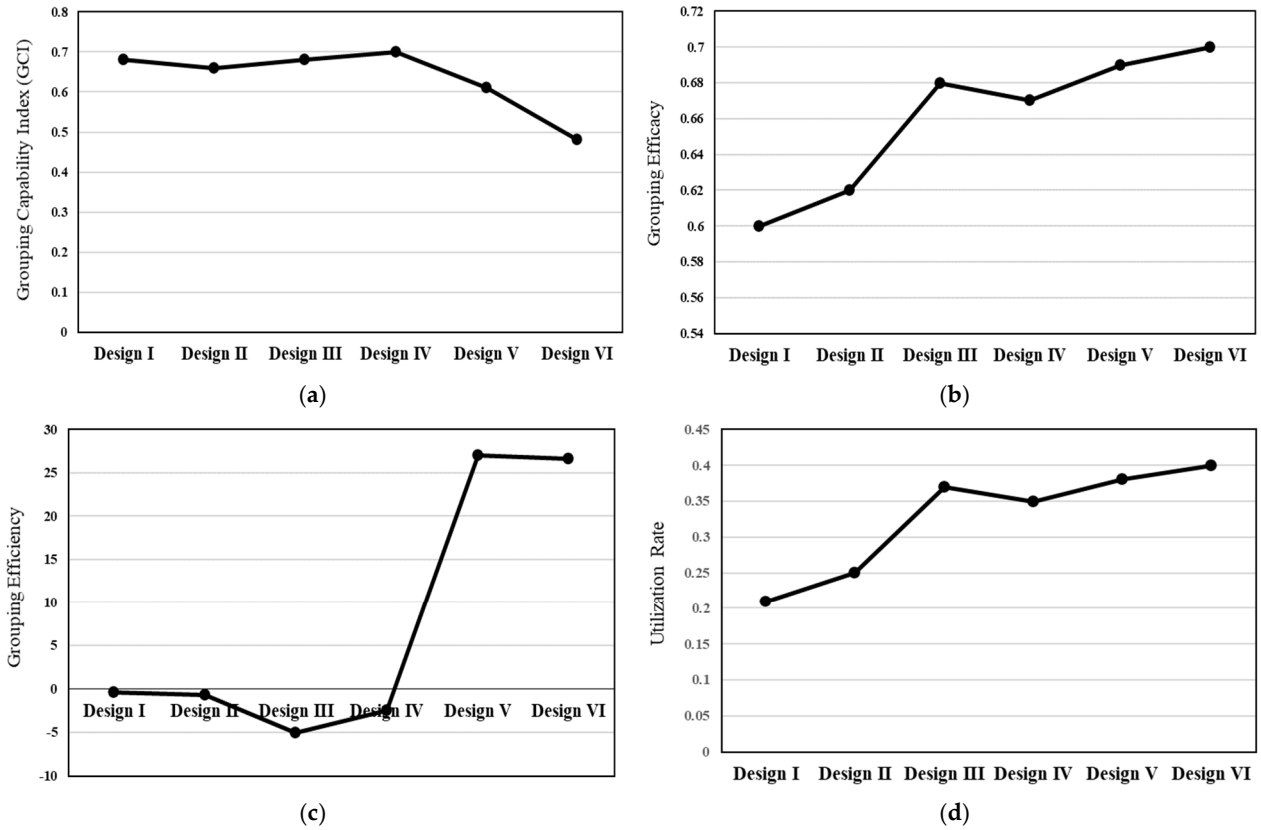


Figure 19. (**a**) Magnitude of Modularity in Design I-Design VI Based on Grouping Capacity Criterion (GCI) Criterion. (**b**) Magnitude of Modularity in Design I-Design VI Based on Grouping Efficacy Criterion. (**c**) Magnitude of Modularity in Design I-Design VI Based on Grouping Efficiency Criterion. (**d**) Magnitude of Modularity in Design I-Design VI Based on Utilization Rate Criterion.

Figure 19a–d displays the scores of each design concerning the modularity measures utilized in Table 8.

Using the modularity measure of the 'modularization function', the thirty-eight hierarchical sub-systems are compared based on the strength of coupling within the involved

modules (Table 9). The modules included in this analysis are referred to as the unique components of the modularization function.

Table 9. Reorganizing the functional architecture into 38 hierarchical sub-systems, inspired by 'Design VI'.

	Modules	Components	Number of Interfaces Within Module	Coupling Within Module(δ_{M_i})	Number of Interfaces Within Sub-System	Coupling Within Sub-System (δ_{MSS_1})
Sub-System1	M1	FR1111	0	0	0	0
Sub-System2	M2	FR1112	13	13	0	0
		FR1122				
		FR1121				
		FR112,12				
		FR1126				
		FR1123				
		FR1124				
		FR1125				
		FR113,10				
		FR1128				
		FR1127				
		FR113,12				
		FR113,11				
Sub-System3	M3	FR1113	0	0	0	0
Sub-System4	M4	FR1114	0	0	0	0
Sub-System5	M5	FR1115	0	0	0	0
Sub-System6	M6	FR1129	0	0	0	0
Sub-System7	M7	FR112,10	0	0	0	0
Sub-System8	M8	FR112,11	0	0	0	0
Sub-System9	M9	FR112,13	0	0	0	0
Sub-System10	M10	FR112,14	0	0	0	0
Sub-System11	M11	FR1131	0	0	0	0
Sub-System12	M12	FR1132	0	0	0	0
Sub-System13	M13	FR1133	0	0	0	0
Sub-System14	M14	FR1134	1	1	0	0
		FR1136				
Sub-System15	M15	FR1135	0	0	0	0
Sub-System16	M16	FR1137	0	0	0	0
Sub-System17	M17	FR1138	0	0	0	0
Sub-System18	M18	FR1139	0	0	0	0
Sub-System19	M19	FR113,13	0	0	0	0
Sub-System20	M20	FR1144	0	0	0	0
Sub-System21	M21	FR1145	0	0	0	0
Sub-System22	M22	FR1146	0	0	0	0
Sub-System23	M23	FR1151	0	0	0	0
Sub-System24	M24	FR1152	0	0	0	0
Sub-System25	M25	FR1153	0	0	0	0
Sub-System26	M26	FR1154	0	0	0	0
Sub-System27	M27	FR1155	0	0	0	0

Table 9. *Cont.*

	Modules	Components	Number of Interfaces Within Module	Coupling Within Module(δ_{M_i})	Number of Interfaces Within Sub-System	Coupling Within Sub-System (δ_{MSS_1})
Sub-System28	M28	FR1156	0	0	0	0
Sub-System29	M29	FR1157	0	0	0	0
Sub-System30	M30	FR1221	0	0	0	0
Sub-System31	M31	FR1222	0	0	0	0
Sub-System32	M32	FR1223	3	3	0	0
		FR1141				
		FR1143				
		FR1142				
Sub-System33	M33	FR1231	0	0	0	0
Sub-System34	M34	FR1232	0	0	0	0
Sub-System35	M35	FR1233	0	0	0	0
Sub-System36	M36	FR1234	0	0	0	0
Sub-System37	M37	FR1235	0	0	0	0
Sub-System38	M38	FR1236	0	0	0	0

Based on Table 9, the SOI in the best design for the physical architecture is optimally organized into thirty-eight hierarchical subsystems. The achieved modularity for the functional architecture of the SOI is considered acceptable.

Regarding the optimal design VI, it is crucial to mention that among all developed subsystems (i.e., sub-systems$_{1–38}$), sub-system$_2$, sub-system$_{32}$, and sub-system$_{14}$ are particularly susceptible to any adjustments due to the presence of coupled elements. For these subsystems, additional techniques like the 'tearing technique' may prove more helpful if all the necessary information for making required assumptions is available.

4.5. Optimal Modularized Design Properties for SOI Functional Architecture and Its Robust Contribution

Through the development of the optimal modular design for the functional architecture of the SOI, the following properties have been achieved:

1. The information flow in the optimal design for the functional architecture follows a top-down approach, where elements placed at a higher priority require little to no information from other elements, while elements at a lower priority may require more information.
2. The information flow in the optimal design is optimally organized into thirty-eight hierarchical sub-systems, ensuring that all necessary information to fulfill the architecture and adapt to new situations is readily available.
3. The information flow in the optimal design is now clearer, simpler, more agile, and more traceable.
4. The achieved modularity in the architecture provides numerous possibilities for robustness. Among the presented subsystems (i.e., sub-systems$_{1–38}$), many places can be easily identified and adjusted to enhance the architecture's robustness in response to new situations.
5. The optimal design highlights places in the architecture where modifications are challenging due to the presence of coupled elements. These places are susceptible to any change or modification, and as a result, they remain unchanged in all possible architectures achieved through adaptation operations. These places are referred to as common platforms.

4.6. Investigating Functional Architecture Robustness and Optimal Design Selection

According to steps 7–10 of the proposed methodology, a simulation study aimed at assessing the robustness of the modularized architecture is conducted, encompassing Designs I to VI. This analysis entails evaluating the capacity of each design to withstand varying levels of complexity, which is indicative of the information content that can be accommodated by each architectural element. The outcomes of this evaluation are outlined in Table 10 and Figure 20.

Table 10. Complexity (work volume) of each SOI element under perturbation (Designs I–VI).

Elements of System Architecture	Design I	Design II	Design III	Design IV	Design V	Design VI
FR_{1111}	6.49	4.57	2.52	2.43	1.92	1.19
FR_{1112}	5.18	4.74	2.99	2.01	1.98	1.19
FR_{1113}	5.33	3.38	3.21	2.36	1.93	1.24
FR_{1114}	6.38	4.87	3.11	2.41	1.73	1.19
FR_{1115}	6.38	4.44	3.02	2.31	1.83	1.18
FR_{1121}	9.79	4.54	2.67	2.18	1.89	1.24
FR_{1122}	9.77	3.45	2.83	2.17	1.87	1.24
FR_{1123}	5.54	3.8	2.77	2.01	1.77	1.24
FR_{1124}	7.78	3.42	2.57	2.03	1.68	1.2
FR_{1125}	7.74	3.81	2.85	2.33	1.78	1.2
FR_{1126}	5.25	4.42	3.04	2.09	1.7	1.22
FR_{1127}	8.56	3.53	2.73	2.03	1.83	1.23
FR_{1128}	6.65	4.19	3.1	2.09	1.9	1.18
FR_{1129}	5.3	4.58	3.25	2.01	1.98	1.18
$FR_{112,10}$	5.59	3.96	2.52	2.33	1.84	1.2
$FR_{112,11}$	5.99	3.6	3.15	2.37	1.72	1.21
$FR_{112,12}$	8.94	4.54	2.77	2.24	1.74	1.19
$FR_{112,13}$	6.48	3.68	2.8	2.36	1.81	1.24
$FR_{112,14}$	5.26	4.84	2.55	2.21	1.71	1.22
FR_{1131}	5.36	4.06	2.95	2.3	1.87	1.19
FR_{1132}	5.41	4.47	3.13	2.11	1.7	1.18
FR_{1133}	5.31	3.47	2.9	2.13	1.71	1.2
FR_{1134}	9.04	3.66	2.71	2	1.81	1.19
FR_{1135}	6.38	4.29	2.88	2.11	1.93	1.22
FR_{1136}	6.35	3.44	2.97	2.04	1.83	1.21
FR_{1137}	6.61	3.41	2.75	2.19	1.68	1.19
FR_{1138}	6.99	3.53	2.77	2.17	1.75	1.2
FR_{1139}	5.25	4.09	2.73	2.2	1.75	1.24
$FR_{113,10}$	7.47	3.54	3.32	2.41	1.91	1.23
$FR_{113,11}$	6.17	3.64	2.98	2.09	1.94	1.2
$FR_{113,12}$	5.93	4.9	2.92	2.15	1.95	1.19
$FR_{113,13}$	7.98	3.97	2.52	2.03	1.88	1.22
FR_{1141}	8.94	4.26	3.3	2.46	1.92	1.24
FR_{1142}	5.85	3.51	3.03	2.27	1.75	1.18
FR_{1143}	6.84	4.2	2.67	2.28	1.95	1.19
FR_{1144}	7.13	3.44	2.51	2.06	1.95	1.24
FR_{1145}	5.73	3.34	2.62	2.31	1.81	1.23
FR_{1146}	9.2	3.77	2.83	2.06	1.77	1.23
FR_{1151}	8.47	4.28	2.75	2.1	1.89	1.18
FR_{1152}	6.91	3.94	2.72	2.17	1.73	1.23
FR_{1153}	8.97	3.72	2.75	2.03	1.71	1.23
FR_{1154}	9.1	3.82	3.08	2.26	1.81	1.22
FR_{1155}	6.38	4.36	3.06	2.31	1.89	1.21
FR_{1156}	7.33	4.16	3.07	2.12	1.73	1.22
FR_{1157}	7.75	4.8	2.69	2.39	1.89	1.23
FR_{1221}	6.94	4.15	3.16	2.4	1.88	1.18
FR_{1222}	7.89	4.16	2.77	2.34	1.73	1.2

Table 10. *Cont.*

Elements of System Architecture	Design I	Design II	Design III	Design IV	Design V	Design VI
FR_{1223}	9.29	3.58	2.97	2.26	1.96	1.18
FR_{1231}	6.94	4.66	2.51	2.29	1.85	1.2
FR_{1232}	7.02	4.97	3.06	2.48	1.97	1.21
FR_{1233}	9.98	4.2	3.02	2.36	1.8	1.25
FR_{1234}	5.53	3.74	2.6	2.14	1.91	1.23
FR_{1235}	8.84	4.69	3.09	2.17	1.97	1.22
FR_{1236}	6	3.7	3.32	2.24	1.77	1.2

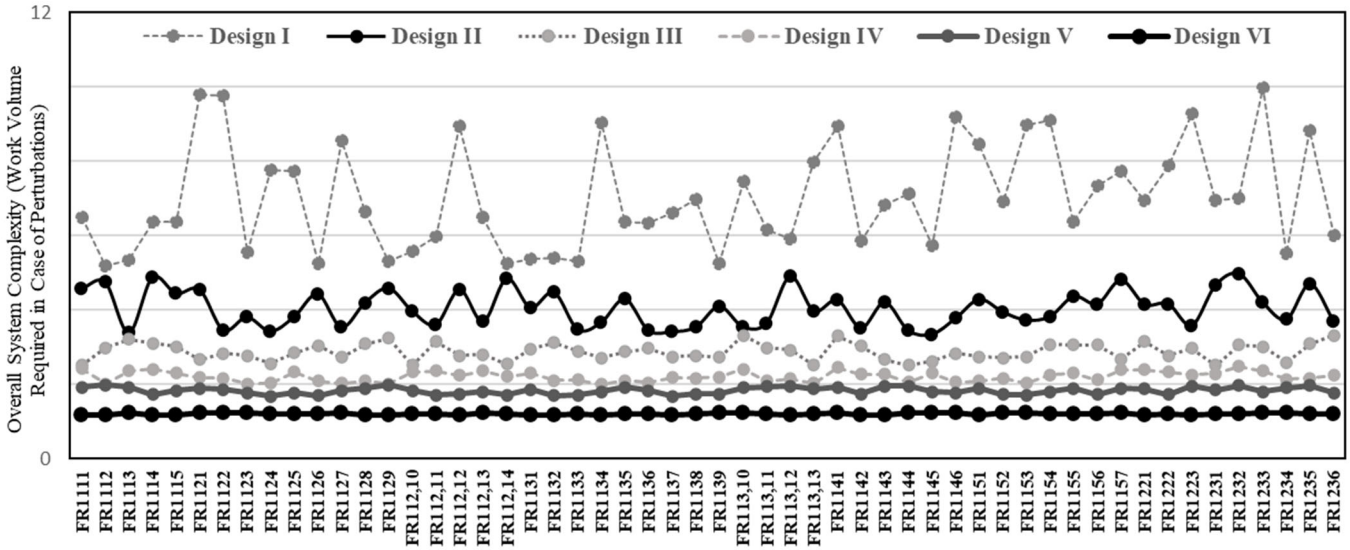


Figure 20. Comparison of robustness factor of each system element among the Designs I–VI.

Table 10 provides an in-depth examination of the functional integration within the System of Interest (SOI), yielding insights into the cohesive functioning of its constituent components. This analysis facilitates the comprehension of the restorative or adaptive effort necessitated in response to damage or modifications. This observation holds true for both the inherent design and the novel modular configurations embraced by the SOI. Of particular interest is the comparative evaluation illuminated by Figure 20. This comparison underscores a discernible dissimilarity between the exigencies of the original design and the alternative modular constructs. A quantitative assessment, quantified in temporal and resource-intensive terms (Bits), reveals a pronounced differential in the demands imposed by the original versus modular design paradigms. This divergence is further elucidated in Figure 20, a visual representation that vividly accentuates these variances. Notably, Design VI emerges as a salient exemplar within this analysis, distinctly showcasing its heightened robustness relative to the original design. Figure 20 supplements this discernment by delineating the correlation between system resilience and complexity. The graph emphasizes a positive link between simple design and effective problem-solving and robustness. In short, avoiding excessive complexity boosts the system's ability to adeptly handle challenges.

Upon close examination of Figure 20, Design VI emerges as the optimal candidate among the array of six distinct modular designs. Notably, Design VI exhibits a pronounced proclivity for effectively navigating challenging scenarios. This proclivity underscores its pre-eminence within the spectrum of designs under scrutiny, particularly in comparison to the original design.

Analogous to a formidable sentinel within the realm of design configurations, Design VI assumes the role of an architectural vanguard. Its singular aptitude lies in the augmentation of the System of Interest's (SOI) structural robustness and stability. Evidently, this revelation signifies Design VI's unique potential to substantially elevate the quality of the SOI's system architecture, thereby endowing it with a heightened capacity to navigate exigent circumstances.

Figure 20 provides empirical support for this observation, wherein the comparative assessment of robustness operations across all six modular designs showcases Design VI as being intrinsically associated with the most modest complexities. This distinct trait bestows upon modularized Design VI a superior capability in effectuating robustness operations within the broader system architecture of the SOI. This assertion holds particularly true when juxtaposed against the original SOI design, further validating Design VI's exceptional competence in orchestrating structural fortitude amidst deviations from anticipated circumstances.

5. Conclusions and Discussion

In this study, we addressed the challenges faced by manufacturing processes in dynamic environments characterized by rapid changes, uncertainties, risks, and uncontrollable fluctuations. Our objective was to enhance the overall robustness of manufacturing processes through an innovative approach that integrates engineering management principles and modular design. By adopting a systems engineering perspective, we treated all manufacturing process activities as interrelated elements of an integrated system, aiming to prevent the spread of risks and disruptions among various processes.

Our research revealed a profound relationship between manufacturing management and engineering management. Manufacturing management plays a pivotal role in overseeing resource allocation, decision-making processes, and the overall organizational strategy for effective operations. Inefficient manufacturing management can lead to suboptimal use of resources, delays in production schedules, and reduced productivity, negatively impacting engineering management. On the other hand, effective manufacturing management systems can optimize resource allocation, streamline decision-making processes, and result in improved production processes and increased efficiency in utilizing technical personnel and physical resources.

Engineering management, in turn, is responsible for overseeing the design, development, and improvement of manufacturing processes. The effectiveness of engineering management systems, including quality control and continuous improvement programs, relies on the underlying architecture of manufacturing. A well-designed manufacturing process architecture is crucial in minimizing the likelihood of operational risks and their potential impact on manufacturing processes.

Our findings showcased a significant improvement in modularization, leading to enhanced overall robustness in manufacturing processes. This highlights the importance of engineering management's proactive involvement in the design phase of manufacturing processes. By engaging manufacturing experts from the outset, potential production and assembly challenges can be addressed proactively, resulting in an optimized and robust manufacturing process.

Furthermore, our research underscores the significance of modularity within manufacturing process architecture. Taking modularity into account in the process domain architecture indirectly supports modularity in the allocated architecture, fostering a comprehensive approach that optimizes component allocation within the physical system. It is crucial to note that, from a system engineering perspective, certain environmental changes, such as market dynamics, geopolitical shifts, or technological advancements, are perceived

as dynamic requirements that must be considered during system redesign. Modular architecture plays a pivotal role in enabling the adaptation of manufacturing processes to these changes. Specifically, the intentional integration of modularity into manufacturing process architecture enhances the feasibility and effectiveness of implementing modifications within specific modules while minimizing the overall impact on manufacturing processes. Additionally, the inherent flexibility of modular architecture enables the seamless integration or removal of modules, thereby facilitating responses to emerging changes within the environment or external influences.

Additionally, we highlighted the significance of redundancy in certain system elements, as it enhances system reliability while preserving modularity. Engineering management's consideration of redundancy offers another avenue to enhance the overall robustness of manufacturing processes.

Therefore, in summary, in the present study, we have meticulously compared our proposed approach with relevant studies in the literature, as illustrated in Table 1, showcasing the diverse methodologies and strategies utilized in prior research, including mathematical/statistical methods, process capability indices, and robust design principles. However, what distinguishes our study is our adoption of a system engineering perspective, which underscores the importance of considering manufacturing processes as integrated systems to enhance robustness. While some studies have touched upon this perspective, our emphasis on modularization within manufacturing process architecture is unique. We identified a gap in the literature that predominantly focuses on the allocated architecture of the system, overlooking the pivotal role of process architecture in system robustness. By emphasizing the significance of modularity in the process architecture and employing the Axiomatic Design (AD) theory and Design Structure Matrix (DSM) methodology, our study aims to develop a precise mathematical model that elucidates the relationship between manufacturing process architecture robustness and system architecture modularization. We focus on avoiding the propagation of failure/disruption/disturbance by ensuring modularity and independence among physical components in the physical architecture. Our approach seeks to provide invaluable support to systems engineers in designing robust manufacturing process architecture while managing system complexity, thus facilitating the creation of a resilient characteristic in manufacturing process architecture, a distinction from previous research efforts. Through mathematical investigation and analysis, we demonstrate how modularity suppresses disturbances in the physical architecture, underpinning the effectiveness of our approach in enhancing robustness.

The successful integration of engineering management principles with modular design strategies heralds new opportunities for bolstering the robustness and efficiency of manufacturing processes. Through proactive engagement of engineering management during the design phase and the application of our modularization approach, manufacturing organizations stand poised to fortify their overall system robustness and enhance their responsiveness to dynamic circumstances effectively.

Looking ahead, our research beckons further exploration into the intricate interplay between manufacturing management and engineering management. A nuanced understanding of this relationship promises to empower organizations in optimizing resource allocation, refining decision-making processes, and nurturing a culture of collaboration and knowledge exchange between engineering and manufacturing teams.

Moreover, our study illuminates avenues for future research aimed at developing comprehensive strategies that encompass various dimensions of manufacturing processes. Delving into areas such as process legality, reliability, adaptability, and recoverability will contribute to a more holistic comprehension of resilient manufacturing processes. Proposing the development of a resilience framework for manufacturing processes, our research

advocates for a paradigm shift that not only prioritizes robustness but also encompasses flexibility, adaptability, and recoverability. Such a framework holds promise in providing decision-makers with a comprehensive tool to enhance overall system resilience effectively.

Despite these promising prospects, it is essential to acknowledge certain limitations inherent in our study. While we underscore the significance of modular design and engineering management principles in bolstering manufacturing process robustness, the real-world implementation challenges and adoption barriers merit further investigation. Additionally, our focus on the relationship between manufacturing and engineering management may inadvertently overlook other organizational factors influencing process robustness. Moreover, while our research underscores the importance of redundancy in system elements, determining the optimal level of redundancy and its cost-effectiveness across diverse manufacturing contexts warrants empirical validation and refinement.

On a managerial front, our study furnishes several key insights aimed at enhancing the robustness and efficiency of manufacturing processes amidst dynamic environments. Prioritizing effective resource allocation and decision-making processes emerges as a cornerstone for manufacturing management, offering a pathway to mitigate risks and uncertainties while improving production schedules and resource utilization. Equally crucial is the focus on engineering management's role in designing and developing manufacturing processes, ensuring a well-structured architecture that minimizes operational risks. By emphasizing the importance of modularity within the manufacturing process architecture and considering redundancy in system elements, engineering management can further bolster system reliability without compromising modularity. Looking ahead, future research endeavors should delve deeper into exploring the symbiotic relationship between manufacturing and engineering management to optimize resource allocation and decision-making processes. Moreover, the development of a resilience framework encompassing robustness, flexibility, adaptability, and recoverability holds immense potential in guiding decision-makers towards enhancing overall system resilience in manufacturing processes.

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Conflicts of Interest: The authors have no conflicts of interest.

Appendix A

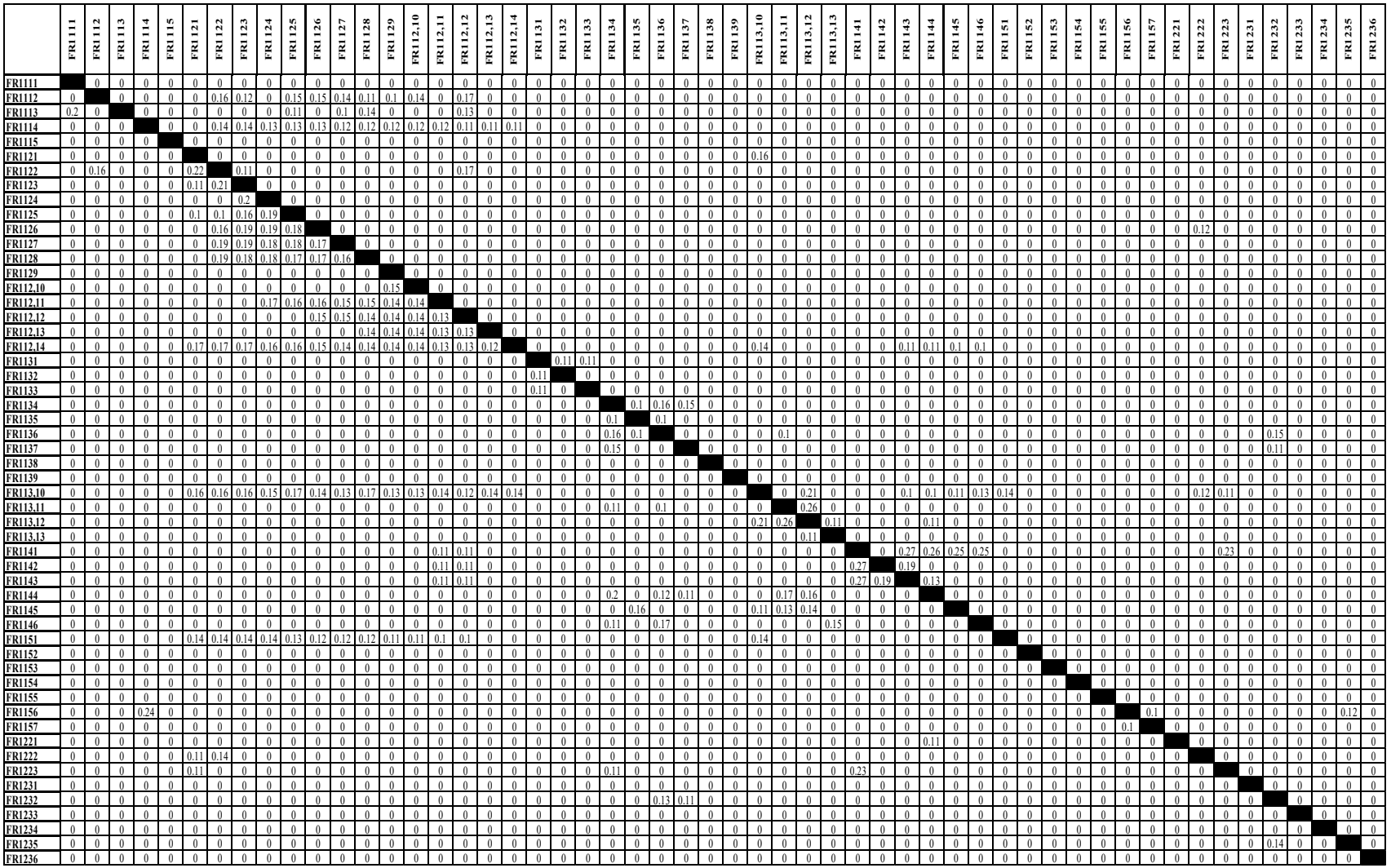


Figure A1. DSM representation of the SOI architecture for cutting point 0.10.

	FR1111	FR1112	FR1113	FR1114	FR1115	FR1121	FR1122	FR1123	FR1124	FR1125	FR1126	FR1127	FR1128	FR1129	FR112,10	FR112,11	FR112,12	FR112,13	FR112,14	FR1131	FR1132	FR1133	FR1134	FR1135	FR1136	FR1137	FR1138	FR1139	FR113,10	FR113,11	FR113,12	FR113,13	FR1141	FR1142	FR1143	FR1144	FR1145	FR1146	FR1151	FR1152	FR1153	FR1154	FR1155	FR1156	FR1157	FR1221	FR1222	FR1223	FR1231	FR1232	FR1233	FR1234	FR1235	FR1236
FR1111		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1112	0		0	0	0	0	0.16	0.12	0	0.15	0.15	0.14	0	0	0.14	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1113	0.2	0		0	0	0	0	0	0	0	0	0	0.14	0	0	0	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1114	0	0	0		0	0	0.14	0.14	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1115	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1121	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1122	0	0.16	0	0	0	0.22		0	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1123	0	0	0	0	0	0	0.21		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1124	0	0	0	0	0	0	0	0.2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1125	0	0	0	0	0	0	0	0.16	0.19		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1126	0	0	0	0	0	0	0.16	0.19	0.19	0.18		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.12	0	0	0	0	0	0
FR1127	0	0	0	0	0	0	0.19	0.19	0.18	0.18	0.17		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1128	0	0	0	0	0	0	0.19	0.18	0.18	0.17	0.17	0.16		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1129	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,10	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,11	0	0	0	0	0	0	0	0	0.17	0.16	0.16	0.15	0.15	0.14	0.14		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,12	0	0	0	0	0	0	0	0	0	0	0.15	0.15	0.14	0.14	0.14	0.13		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,13	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0.14	0.14	0.13	0.13		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,14	0	0	0	0	0	0.17	0.17	0.17	0.16	0.16	0.15	0.14	0.14	0.14	0.14	0.13	0.13	0.12		0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1132	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0.16	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0	0	0	0	0
FR1137	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0
FR1138	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1139	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,10	0	0	0	0	0	0.16	0.16	0.16	0.15	0.17	0.14	0.13	0.17	0.13	0.13	0.14	0.12	0.14	0.14	0	0	0	0	0	0	0	0	0		0	0.21	0	0	0	0	0	0	0	0	0.13	0.14	0	0	0	0	0	0	0.12	0	0	0	0	0
FR113,11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21	0.26		0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0.27	0.26	0.25	0.25	0	0	0	0	0	0	0	0	0	0.23	0	0	0	0	0	0
FR1142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.27	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1143	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.27	0.19		0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.12	0	0	0	0	0.17	0.16	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0	0	0	0	0	0.13	0.14	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1146	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0.15	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1151	0	0	0	0	0	0.14	0.14	0.14	0.14	0.13	0.12	0.12	0.12	0.11	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1152	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1153	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0
FR1154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0
FR1155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
FR1156	0	0	0	0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0.12	0
FR1157	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
FR1221	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.11	0	0	0	0	0	0	0
FR1222	0	0	0	0	0	0.11	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
FR1223	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.23	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
FR1231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
FR1232	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
FR1233	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
FR1234	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
FR1235	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
FR1236	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure A2. DSM representation of the SOI architecture for cutting point 0.11.

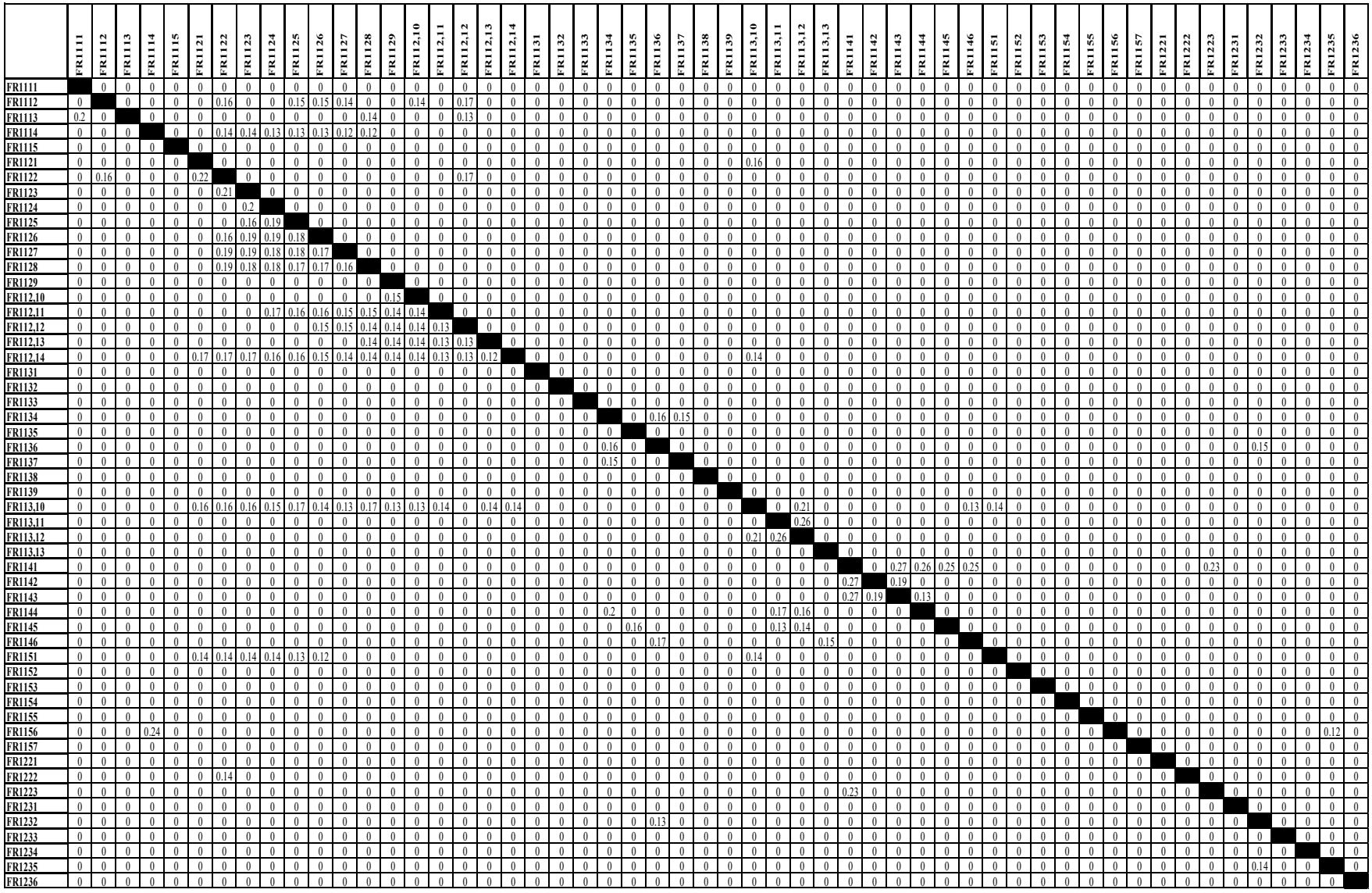


Figure A3. DSM representation of the SOI architecture for cutting point 0.12.

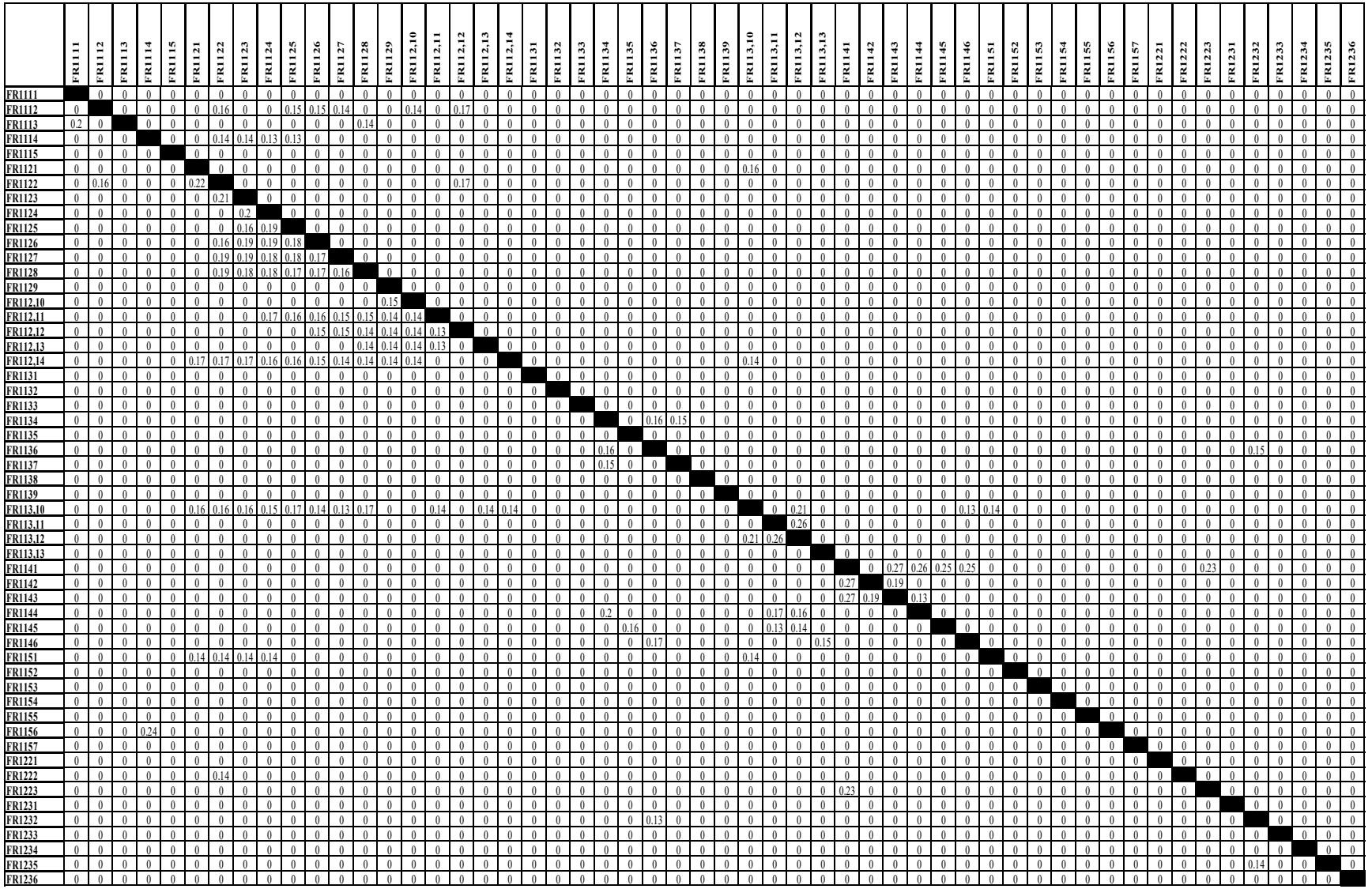


Figure A4. DSM representation of the SOI architecture for cutting point 0.13.

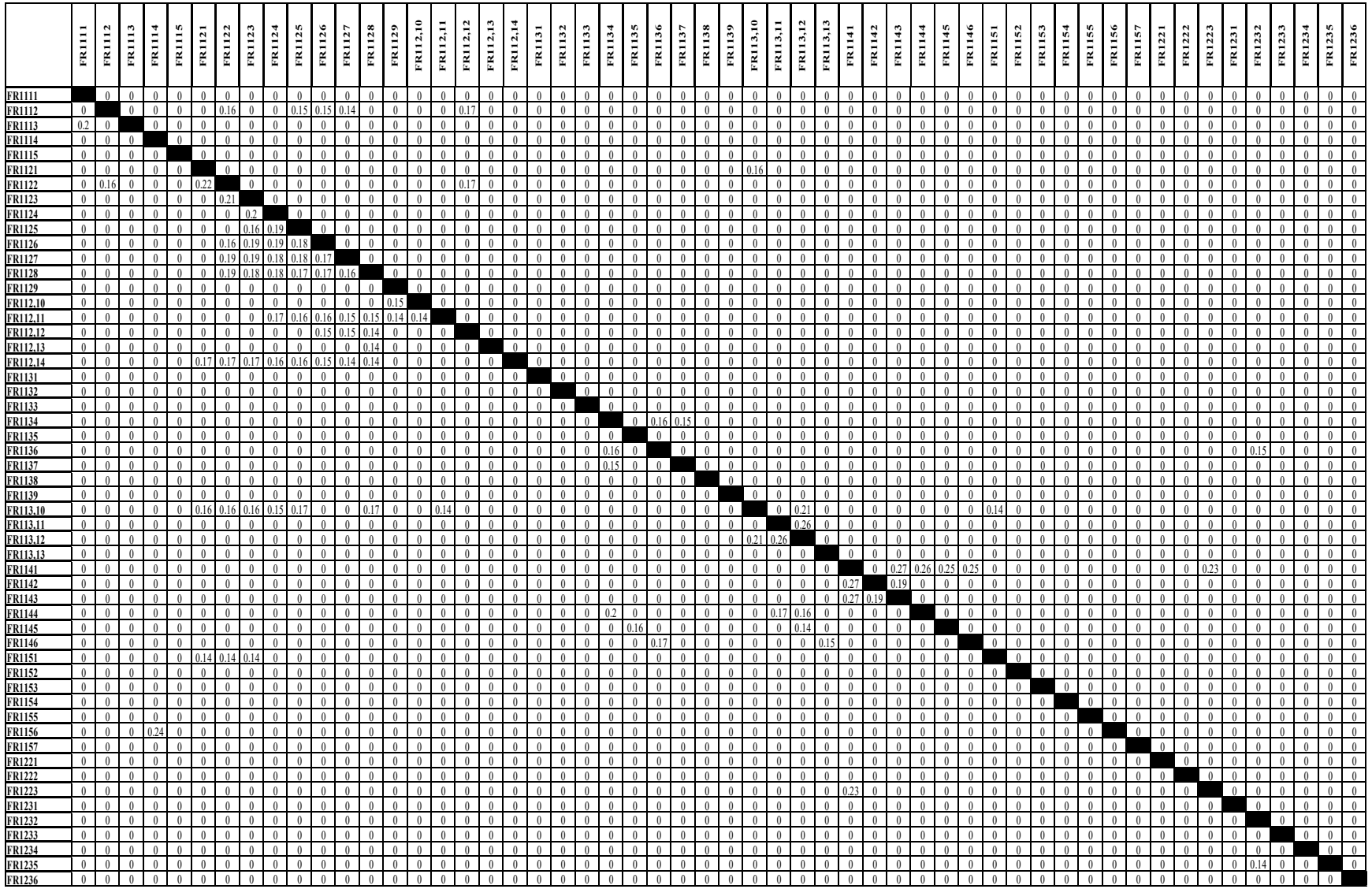


Figure A5. DSM representation of the SOI architecture for cutting point 0.14.

	FR1111	FR1112	FR1113	FR1114	FR1115	FR1121	FR1122	FR1123	FR1124	FR1125	FR1126	FR1127	FR1128	FR1129	FR112,10	FR112,11	FR112,12	FR112,13	FR112,14	FR1131	FR1132	FR1133	FR1134	FR1135	FR1136	FR1137	FR1138	FR1139	FR113,10	FR113,11	FR113,12	FR113,13	FR1141	FR1142	FR1143	FR1144	FR1145	FR1146	FR1151	FR1152	FR1153	FR1154	FR1155	FR1156	FR1157	FR1221	FR1222	FR1223	FR1231	FR1232	FR1233	FR1234	FR1235	FR1236
FR1111		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1112	0		0	0	0	0	0.16	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1113	0.2	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1114	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1115	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1121	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1122	0	0.16	0	0	0	0.22		0	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1123	0	0	0	0	0	0	0.21		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1124	0	0	0	0	0	0	0	0.2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1125	0	0	0	0	0	0	0	0.16	0.19		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1126	0	0	0	0	0	0	0.16	0.19	0.19	0.18		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1127	0	0	0	0	0	0	0.19	0.19	0.18	0.18	0.17		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1128	0	0	0	0	0	0	0.19	0.18	0.18	0.17	0.17	0.16		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1129	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,10	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,11	0	0	0	0	0	0	0	0	0.17	0.16	0.16	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,12	0	0	0	0	0	0	0	0	0	0	0.15	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR112,14	0	0	0	0	0	0.17	0.17	0.17	0.16	0.16	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1132	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1137	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1138	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1139	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,10	0	0	0	0	0	0.16	0.16	0.16	0	0.17	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0.21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21	0.26		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR113,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0.27	0.26	0.25	0.25	0	0	0	0	0	0	0	0	0.23	0	0	0	0	0	0	0	0	0	0	0
FR1142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.27	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1143	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.27	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1146	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1152	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1153	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR1154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0
FR1155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
FR1156	0	0	0	0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0
FR1157	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0
FR1221	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
FR1222	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
FR1223	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
FR1231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
FR1232	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
FR1233	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
FR1234	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
FR1235	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
FR1236	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure A6. DSM representation of the SOI architecture for cutting point 0.15.

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