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Article

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

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Abstract: Manufacturing environments, characterized by rapid, unpredictable changes, uncertainties, risks, and uncontrollable fluctuations, pose significant challenges to minimizing disruptions in processes. This study introduces an innovative approach that prioritizes curbing risk propagation among processes to enhance robustness. It emphasizes the integration of engineering management principles and modular design within manufacturing. Adopting a system engineering perspective, all manufacturing process activities are viewed as interrelated components within a unified system. By employing Axiomatic Design (AD) theory and the Design Structure Matrix (DSM) method, manufacturing process architecture is modularized, yielding heightened robustness. The proposed mathematical model equips engineering and manufacturing managers with a potent tool for designing robust processes while adeptly managing system complexity. The study's outcomes underscore a substantial enhancement in modularization, leading to elevated overall robustness in manufacturing processes. To validate the methodology, the architectural design of manufacturing processes is examined in a real-case scenario, specifically the Barez Industrial Group in Iran. This verification substantiates the 'manufacturing processes' of the case, presenting an optimally modularized architecture. The results affirm the proposed approach's efficacy, demonstrating improved modularization that contributes to bolstered robustness in manufacturing processes.

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

1. Introduction

To manufacture a product, effective and efficient utilization of technical personnel, physical resources, and information is crucial (Chang, 2005; Sharon et al., 2011). The responsibility for this crucial task is generally assigned to engineering management (Savage et al., 2019). 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 (Lannes, 2001; Farr et al., 2001; Daughton, 2017; Savage et al., 2019).

The resource allocation, decision-making processes, and the overall organizational strategy are handled by manufacturing management to ensure effective operations (Womack and Jones, 2003; Chang, 2005; Jacobs et al., 2011). In this regard, manufacturing management can significantly impact engineering management (Ahmad et al., 2017).

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. (Stevenson, 2019).

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, by implementing effective manufacturing management systems, organizations can optimize resource allocation and streamline decision-making processes. This can result in improved production processes and increased efficiency in utilizing technical personnel and physical resources. (Chase et al., 1998; Jacobs et al., 2004; Slack et al., 2010; Egilmez et al., 2018).

Often, manufacturing environments may experience various rapid and sudden changes, a lot of uncertainty, unforeseen risks, unpredictable events, and/or uncontrollable fluctuations (Mollajan et al., 2023). 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 enough 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 (Pallagst et al., 2013; Selviaridis et al., 2014; Egilmez et al., 2018).

The poor design of manufacturing processes can significantly contribute to the occurrence and propagation of operational risks (Rahmani and Thomson, 2011; Mollajan et al., 2021; Mollajan et al., 2022). A poorly designed manufacturing process architecture lacks 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 (Rahmani and Thomson, 2011). 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 (Cheng et al., 2012). Effective design is crucial in minimizing the likelihood of operational risks and their potential impact on manufacturing processes (Mollajan et al., 2023).

The design of manufacturing processes has a cascading effect on engineering management in addition to manufacturing management. In fact, 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 processes 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 (2011) contributed to the understanding and modeling of robustness, highlighting the need for comprehensive methodologies that consider the various factors influencing performance. Koc et al. (2011) 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 C_p and C_{pk} . 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. (2001) and Robinson, Borrer, and Myers (2004). 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. (2011) 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 (2012) also discussed the topic of robust stability analysis, further emphasizing the importance of accounting for uncertainties and disturbances in manufacturing processes. Kusumoto et al. (2012), they 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 (2012) 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. (2013) 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. (2013) 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 (2013) 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. (2013) 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 (2013) 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. (2013) 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. (2013) defined MS robustness as the ratio of feasible operations with disruptions of a specific machine to the total feasible operations without disruptions. The specific details or context of their research are not mentioned in the text. Sharda and Banerjee (2013) 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 makespan, mean work-in-progress (WIP), and the number of machines, considering these uncertainties during the design process. Mondal et al. (2014) critically reviewed robust approaches for measuring and modeling process robustness in product and manufacturing processes. This research contributed to understanding the effectiveness of existing methodologies and techniques in assessing and modeling process robustness. Taguchi's concept of process robustness emphasized designing processes less sensitive to variations and disruptions for consistent performance. Stricker and Lanza (2014) 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. Bebera and Becker (2014) focused on exploring the relationship between the 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. 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. Benderbal et al. (2015) emphasized the significance of technical disruptions in production systems. They analyzed the impact of these disruptions on system robustness and focus on optimizing schedules and designs. Tian et al. (2015) 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. (2015) 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. Benderbal et al. (2015) 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. Stricker et al. (2015), 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 (2016) 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 in improving output quality. Zhao et al. (2016) 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 (2016) 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 (2016) 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. (2016) 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. (2017) 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 (2017), 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. (2017), 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. (2018) 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. (2018) 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. (2019) 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. (2020) 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. (2020) 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. (2021) 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. (2021) 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 (2022) 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.

Exhibit 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

Al-Refaie (2011)	✓		✓	✓	✓	✓
Koc et al. (2011)	✓		✓	✓	✓	✓
Mevik et al. (2001)	✓		✓	✓	✓	✓
Robinson, Borrer, and Myers (2004)	✓		✓	✓	✓	✓
Nourelfat h (2011)	✓		✓	✓	✓	✓
Scholz-Reiter et al. (2011)	✓		✓	✓	✓	✓
Karimi and Djokoto (2012)	✓		✓	✓	✓	✓
Kusumoto et al. (2012)	✓		✓	✓	✓	✓
Alem and Morabito (2012)	✓		✓	✓	✓	✓
Meyer et al. (2013)	✓		✓	✓	✓	✓
Mondal et al. (2013)	✓	✓	✓	✓	✓	✓
Malmström et al. (2013)	✓		✓	✓	✓	✓
Montgomery (2013)	✓	✓	✓	✓	✓	✓
Mondal et al. (2013)	✓		✓	✓	✓	✓
Becker et al. (2013)	✓		✓	✓	✓	✓
Sharda and Banerjee (2013)	✓		✓	✓	✓	✓
Xiong et al. (2013)	✓	✓	✓	✓	✓	✓
Mondal et al. (2014)	✓		✓	✓	✓	✓
Stricker and Lanza (2014)	✓		✓	✓	✓	✓
Bebera and Becker (2014)	✓		✓	✓	✓	✓
Varas et al. (2014)	✓	✓	✓	✓	✓	✓

Benderbal et al. (2015)	✓	✓	✓	✓	✓	✓
Tian et al. (2015)	✓		✓	✓	✓	✓
Putnik et al. (2015)	✓		✓	✓	✓	✓
Benderbal et al. (2015)	✓		✓	✓	✓	✓
Stricker et al. (2015)	✓		✓	✓	✓	✓
Giannetti and Ransing (2016)	✓		✓	✓	✓	✓
Zhao et al. (2016)	✓		✓	✓	✓	✓
Meyer (2016)	✓		✓	✓	✓	✓
Boorla and Howard (2016)	✓		✓	✓	✓	✓
Sakhaii et al. (2016)	✓		✓	✓	✓	✓
Moslemi et al. (2017)	✓		✓	✓	✓	✓
Zeng and Yen (2017)	✓		✓	✓	✓	✓
Zhang et al. (2017)	✓		✓	✓	✓	✓
Himmiche et al. (2018)	✓		✓	✓	✓	✓
Efthymiou et al. (2018)	✓		✓	✓	✓	✓
Pagone et al. (2019)	✓		✓	✓	✓	✓
Frederico et al. (2020)	✓		✓	✓	✓	✓
Martín et al. (2020)	✓		✓	✓	✓	✓
Hyder et al. (2021)	✓		✓	✓	✓	✓
Stockman et al. (2021)	✓		✓	✓	✓	✓
Liang and Li (2022)	✓		✓	✓	✓	✓

3. Background Material

3.1. Robustness

There is a wide variety of definitions for robustness. According to Carlson and Doyle (2002), robustness is “the maintenance of some desired system characteristic despite fluctuations in the behavior of its component parts or its environment”. Fricke and Schulz (2005) 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 (2011): 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 (Suh, 1990). 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 Exhibit 2). 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 fulfil 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 Exhibit 2).

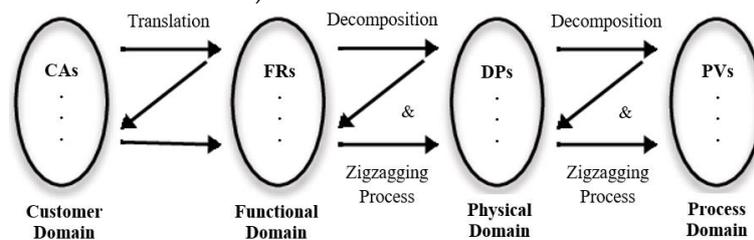


Exhibit 2. Design domains in Axiomatic Design (AD) theory.

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 (Suh, 2001).

- **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 (Suh, 2001).

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 system success in fulfilling the FR (P, Equation 1);

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

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 Equation (2);

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

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 Exhibit 3. 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 Equation (3);

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

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

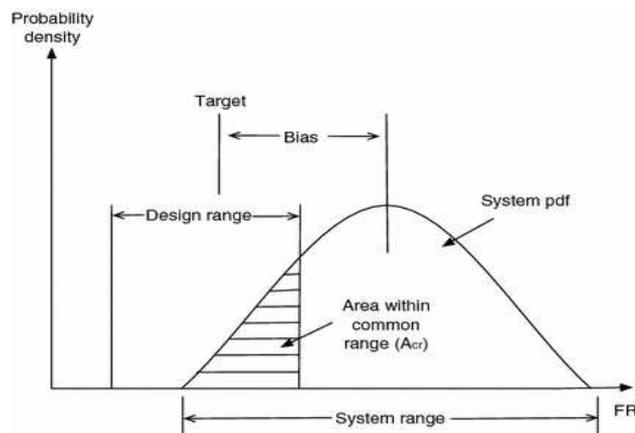


Exhibit 3. Probability of success in fulfilling a functional requirement (FR).

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 modelling 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 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 Exhibit 4, 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 (Eppinger and Browning, 2012; Huang et al., 2015), holds promise for achieving optimal results.

Exhibit 4. Design Structure Matrix (DSM) illustrating the interconnections among elements within the system.

	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
Item ₁		1		1										
Item ₂	1		1		1									
Item ₃		1												
Item ₄								1						
Item ₅		1									1	1	1	
Item ₆			1						1	1				
Item ₇				1				1	1	1				
Item ₈							1							
Item ₉							1							
Item ₁₀						1	1							
Item ₁₁									1					
Item ₁₂								1		1				
Item ₁₃													1	
Item ₁₄												1		

3.4. Modularity in System Architecture

Definition

The literature review underscores the wide array of definitions associated with the term 'Modularity' (Gershenson et al., 2003; Lameche et al., 2017). 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 (Browning, 2001)). 'Architectural' definitions (These address the connections between system components and the functions established at a specific abstraction level within the functional domain (Stone et al., 2000), or through the relationships between models of physical and/or logical representations of systems (Faulconbridge and Ryan, 2014; Kruchten, 1995)). Regarding the notion of modularization within each of these classes, a comprehensive elucidation has been provided by Efatmaneshnik et al. (2018). In general, the process of modularization aims to maximize the dependency within modules while minimizing relations or interactions between modules (Baldwin and Clark, 2003; Gershenson et al., 2003).

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

Various modularity indices assess system architecture. Jung and Simpson (2017), Bonvoisin et al. (2016) reviewed many. Tools like modularity matrix (Dahmus et al., 2001), heuristics (Stone et al., 2000), DSM (Steward, 1981), axiomatic design (Suh, 2001), 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 (Yu, Yassine, and Goldberg, 2007; Hölttä-Otto and de Weck, 2007; Hölttä-Otto et al., 2012). The research emphasizes studying important interactions between element pairs. Among various modularity measures, 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' (Mikkola, 2006; Mikkola and Gassmann, 2003), which have been frequently utilized (Gupta, 2019; Al-Bashir et al., 2016).

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

$$GCI = 1 - \frac{N_4}{N_1 + N_4} \quad (4)$$

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.

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

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 (2003), and subsequently refined by Mikkola (2006).

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

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 (2001) proposes two metrics of independence: reangularity, R, and semangularity, S. Reangularity evaluates the orthogonality between DPs and serves as a measure of interdependence.

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

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

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

From linear algebra,

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

For the nth dimensional case, reangularity is

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

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,

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

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*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*S)/I becomes larger and can be employed to quantify the robustness of a system (Gao and He, 2015).

3.8. Robustness Analysis Method

The robustness analysis method looks at the relationship among contract clauses and evaluates alternative sequences. Managers can then choose the best organization of clauses to improve modularization and overall contract robustness. The steps of the method are described below and presented schematically in Exhibit 5:

- Steps 1 Consider manufacturing processes as an integrated system
- Step 2, 3 Develop functional and physical architecture of the system
- Step 4 Design manufacturing processes architecture for robustness
- Steps 5, 6, 7 use DSM to modularize the physical architecture of the system
- Step 8 Map the physical to the functional architecture of the system
- Step 9, 10 Calculate system architecture's information content and robustness
- Steps 11, 12, 13 use AD theory to modularize the mapping between the new physical architecture and the functional architecture
- Step 14, 15 Recompute system architecture's information content and robustness
- Step 16 compute the overall robustness of the system.

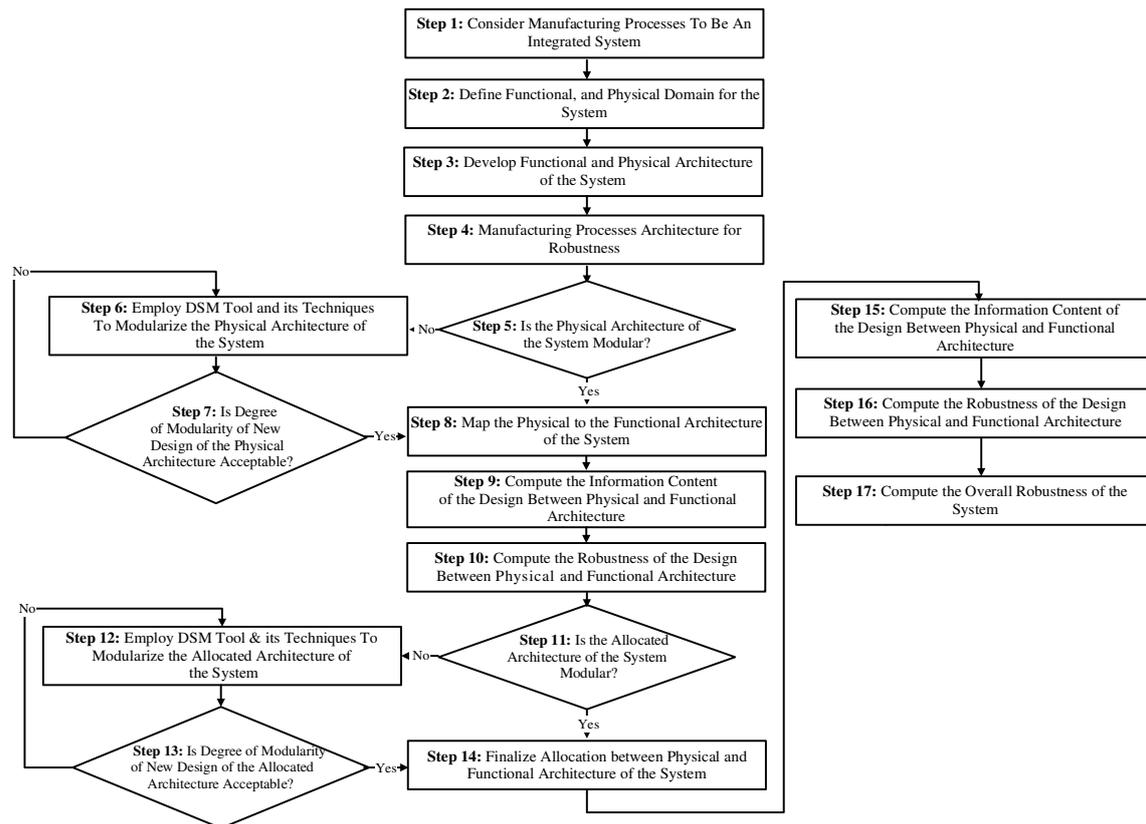


Exhibit 5. Methodology for the Robust Analysis Method.

3.9. Contribution of the Study: Modularity and Robustness

Once robustness is analysed, mapping between a contract's functional and physical architectures needs to be done, and 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 (Jackson and Ferris, 2013; Jackson et al., 2015). 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 contract, 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 clause to other modules. Following is a mathematical investigation that demonstrates that modularity suppresses disturbances in the physical architecture as shown in Exhibit 6, where better modularity leads to better contact clauses, and ultimately, greater project success. The mathematical analysis underpins the use of AD Theory and DSM in the robustness analysis method.

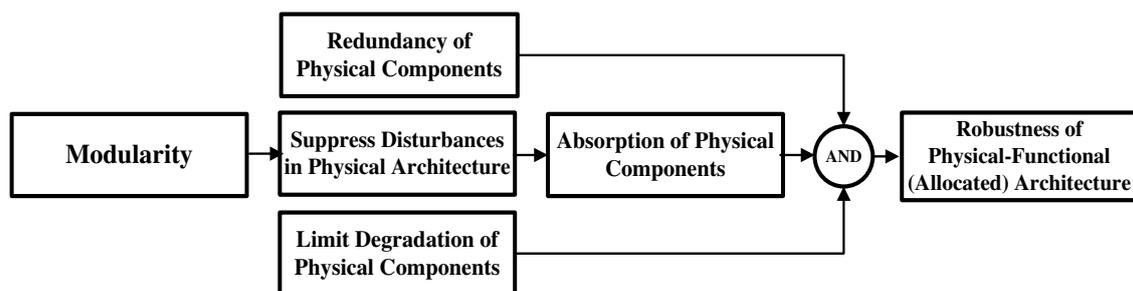


Exhibit 6. Modularity and Robustness.

3.10. Modularity and System Variance

System robustness can be improved by minimizing variance. 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

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

where M_i^{FR} ($i=1, 2, \dots, n$) represents the i^{th} module in FRs domain, M_i^{DP} ($i=1, 2, \dots, n$) represents the i^{th} module in DPs domain, $[A]$ represents a DM which associates DP-based modules with FR-based modules, and A_{ij} ($i=1, 2, \dots, n$ and $j=1, 2, \dots, n$) are DM submatrices that have one or more dimensions where M_j^{DP} ($j=1, 2, \dots, n$) is allocated to the M_i^{FR} ($i=1, 2, \dots, n$).

In addition, $[A]^T$ represents the transposition of the matrix.

$$[A]^T = \begin{bmatrix} A_{11} & A_{21} & \dots & A_{n1} \\ A_{12} & A_{22} & \dots & A_{n2} \\ \vdots & \vdots & \vdots & \vdots \\ A_{1n} & A_{2n} & \dots & A_{nn} \end{bmatrix} \quad (18)$$

\mathbf{M}^{FR} is expressed as

$$\mathbf{M}^{FR} = [A] \cdot \mathbf{M}^{DP} \quad (19)$$

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

The random variability of \mathbf{M}^{FR} , i.e., $\delta\mathbf{M}^{FR}$ can be expressed as

$$\delta\mathbf{M}^{FR} = [A] \cdot \delta\mathbf{M}^{DP} \quad (20)$$

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

$$\delta\mathbf{M}^{FR} = \begin{bmatrix} \delta M_1^{FR} \\ \delta M_2^{FR} \\ \vdots \\ \delta M_m^{FR} \end{bmatrix} \quad (21)$$

$$\delta\mathbf{M}^{DP} = \begin{bmatrix} \delta M_1^{DP} \\ \delta M_2^{DP} \\ \vdots \\ \delta M_m^{DP} \end{bmatrix} \quad (22)$$

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

The transposition of equation (20) is

$$(\delta\mathbf{M}^{FR})^T = (\delta\mathbf{M}^{DP})^T \cdot [A]^T \quad (23)$$

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

$$E\{(\delta\mathbf{M}^{FR}) \cdot (\delta\mathbf{M}^{FR})^T\} = E\{([A] \cdot \delta\mathbf{M}^{DP}) \cdot ((\delta\mathbf{M}^{DP})^T \cdot [A]^T)\} \quad (24)$$

$$= [A] \cdot E\{(\delta\mathbf{M}^{DP}) \cdot (\delta\mathbf{M}^{DP})^T\} \cdot [A]^T \quad (25)$$

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

$$\text{Var}(\mathbf{M}^{FR}) = [\mathbf{A}] \cdot \sum_{\mathbf{M}^{DP}} \cdot [\mathbf{A}]^T \quad (26)$$

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

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

Hence,

$$\Sigma_{DP} = \begin{bmatrix} \Sigma_{11} & 0 & \dots & 0 \\ 0 & \Sigma_{22} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & \Sigma_{mm} \end{bmatrix} \quad (27)$$

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,

$$\begin{aligned} \text{Var}(\mathbf{M}^{FR}) &= \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix} \cdot \begin{bmatrix} \Sigma_{11} & 0 & \dots & 0 \\ 0 & \Sigma_{22} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & \Sigma_{mm} \end{bmatrix} \cdot \begin{bmatrix} A_{11} & A_{21} & \dots & A_{n1} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{1n} & A_{2n} & \dots & A_{nn} \end{bmatrix} \\ &= \begin{pmatrix} A_{11}^2 \cdot \Sigma_{11} + \dots + A_{1n}^2 \cdot \Sigma_{mm} & A_{11} \cdot A_{21} \cdot \Sigma_{11} + \dots + A_{1n} \cdot A_{2n} \cdot \Sigma_{mm} & \dots & A_{11} \cdot A_{n1} \cdot \Sigma_{11} + \dots + A_{1n} \\ A_{21} \cdot A_{11} \cdot \Sigma_{11} + \dots + A_{2n} \cdot A_{1n} \cdot \Sigma_{mm} & A_{21}^2 \cdot \Sigma_{11} + \dots + A_{2n}^2 \cdot \Sigma_{mm} & \dots & A_{21} \cdot A_{n1} \cdot \Sigma_{11} + \dots + A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} \cdot A_{11} \cdot \Sigma_{11} + \dots + A_{nn} \cdot A_{1n} \cdot \Sigma_{mm} & A_{n1} \cdot A_{21} \cdot \Sigma_{11} + \dots + A_{nn} \cdot A_{2n} \cdot \Sigma_{mm} & \dots & A_{n1}^2 \cdot \Sigma_{11} + \dots + A_{nn}^2 \end{pmatrix} \quad (28) \end{aligned}$$

Hence,

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

$$\text{Var}(M_2^{FR}) = A_{21}^2 \cdot \Sigma_{11} + A_{22}^2 \cdot \Sigma_{22} + \dots + A_{2n}^2 \cdot \Sigma_{mm} \quad (30)$$

$$\vdots \quad \vdots$$

$$\text{Var}(M_n^{FR}) = A_{n1}^2 \cdot \Sigma_{11} + A_{n2}^2 \cdot \Sigma_{22} + \dots + A_{nn}^2 \cdot \Sigma_{mm} \quad (31)$$

Moreover, the system variance, $\text{Var}(\text{Sys})$

$$\begin{aligned} &= A_{11}^2 \cdot \Sigma_{11} + A_{12}^2 \cdot \Sigma_{22} + \dots + A_{1n}^2 \cdot \Sigma_{mm} + A_{21}^2 \cdot \Sigma_{11} + A_{22}^2 \cdot \Sigma_{22} + \dots + A_{2n}^2 \\ &\quad \cdot \Sigma_{mm} + A_{n1}^2 \cdot \Sigma_{11} + A_{n2}^2 \cdot \Sigma_{22} + \dots + A_{nn}^2 \cdot \Sigma_{mm} \quad (32) \end{aligned}$$

$$\begin{aligned} &= (A_{11}^2 + A_{21}^2 + \dots + A_{n1}^2) \cdot \Sigma_{11} + (A_{12}^2 + A_{22}^2 + \dots + A_{n2}^2) \cdot \Sigma_{22} + \dots + (A_{1n}^2 \\ &\quad + A_{2n}^2 + \dots + A_{nn}^2) \cdot \Sigma_{mm} \quad (33) \end{aligned}$$

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 was gradually increased as the number of runs increased, which showed the effect of coupling on semangularity/reangularity and system variance. Exhibits 7a-d show reangularity versus lack of modularity where reangularity becomes smaller as the size of off-diagonal elements increases. Exhibits 7e-h show 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 contract clauses as done in the robustness analysis method.

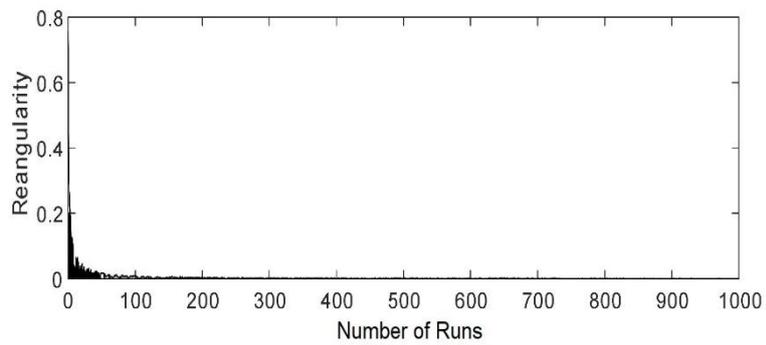


Exhibit 7a. System reangularity due to lack of modularity for a 2x2 DM

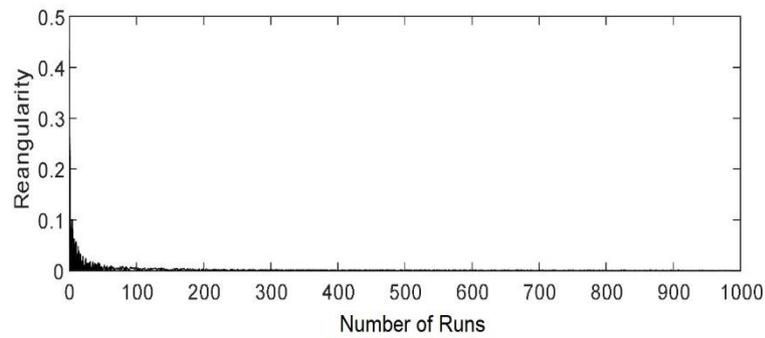


Exhibit 7b. System reangularity due to lack of modularity for a 3x3 DM

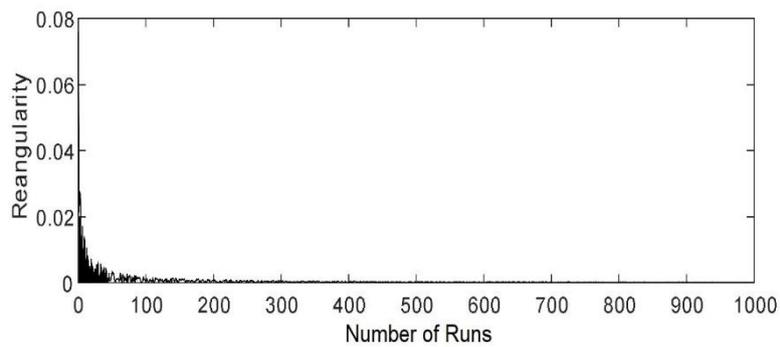


Exhibit 7c. System reangularity due to lack of modularity for a 5x5 DM

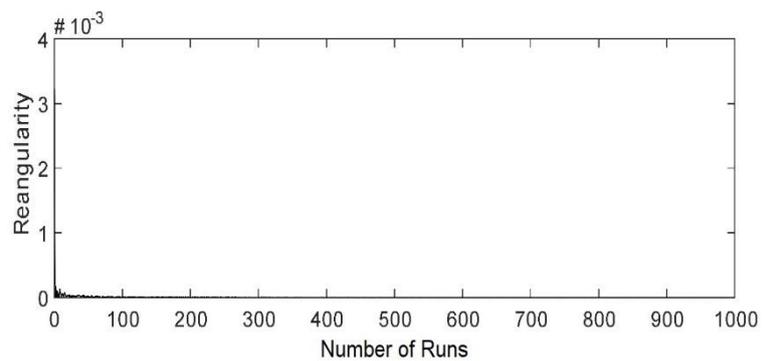


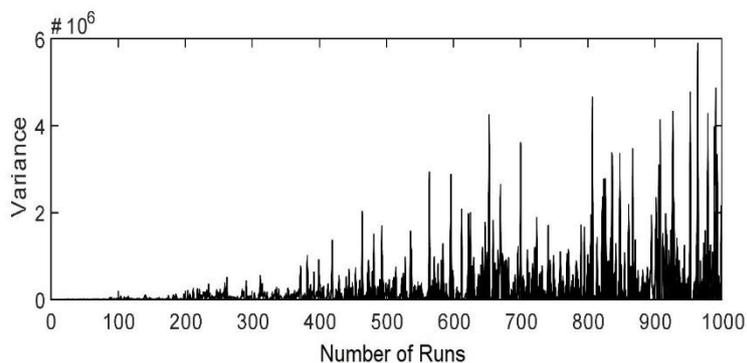
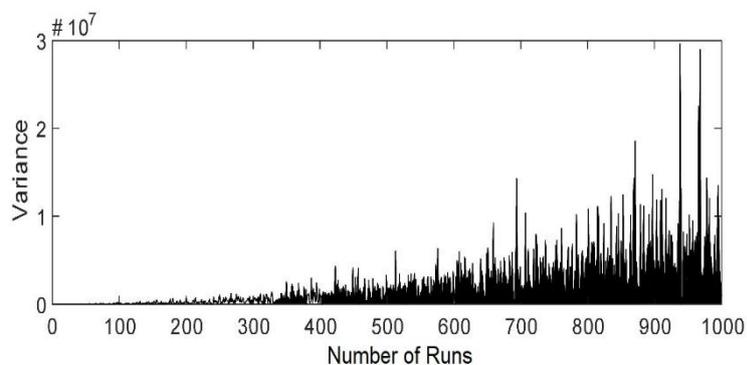
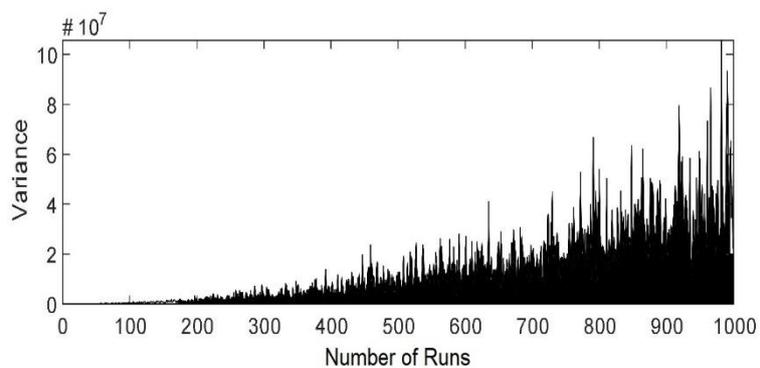
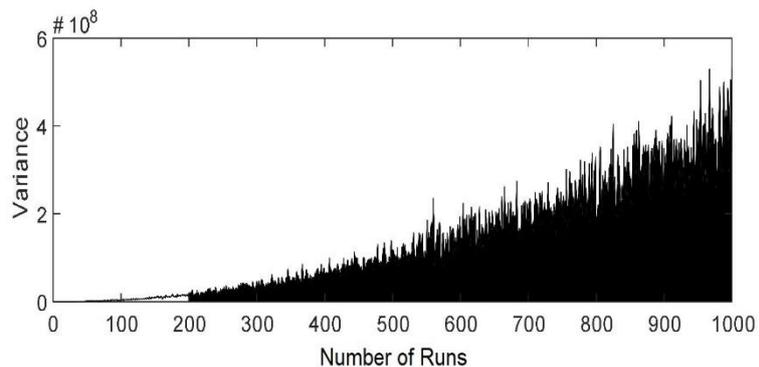
Exhibit 7d. System reangularity due to lack of modularity for a 10x10 DM**Exhibit 7e.** System variance due to lack of modularity for a 2x2 DM**Exhibit 7f.** System variance due to lack of modularity for a 3x3 DM**Exhibit 7g.** System variance due to lack of modularity for a 5x5 DM

Exhibit 7h. System variance due to lack of modularity for a 10x10 DM

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

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

Concerning the improvement of contract 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; Park, 2007; Heo and Lee, 2007; Gonçalves-Coelho et al., 2012). For instance, a contract objective may be described by a few clauses in such a way that if the most appropriate clause is not able to satisfy the objective, other associated clauses, as redundant elements, can be used to meet the objective. Nevertheless, contract 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

$$M_i^{FR} = f(M_1^{DP}, M_2^{DP}, \dots, M_n^{DP}) \quad (34)$$

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

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., $d(M_i^{FR})$

$$= \frac{\partial f(M_1^{DP}, M_2^{DP}, \dots, M_n^{DP})}{\partial M_1^{DP}} \cdot d(M_1^{DP}) + \dots + \frac{\partial f(M_1^{DP}, M_2^{DP}, \dots, M_n^{DP})}{\partial M_n^{DP}} \cdot d(M_n^{DP}) \quad (35)$$

Or

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

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} ($i=1, 2, \dots, n$) 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

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

where M_j^{DP} represents the j^{th} module in the physical domain with k_1 DP elements, DP_p^j represents the p^{th} member of j^{th} module ($p=1, 2, \dots, k_1$), $DP_q^{M_j}$ represents the q^{th} member of the j^{th} module ($q=1, 2, \dots, k_1$), and $x_{p,q}$ represents the entry (p,q) in matrix X and signifies the degree of dependency between DP_p^j and $DP_q^{M_j}$ ($p=1, 2, \dots, k_1$; $q=1, 2, \dots, k_1$).

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,

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

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

$$M_i^{FR} = A \cdot M_j^{DP}; i=1, 2, \dots, n \text{ and } j=1, 2, \dots, n \quad (41)$$

Incorporating equation (40) into equation (41)

$$M_i^{FR} = A \cdot X \cdot DP^{M_j}; i=1, 2, \dots, \text{ and } j=1, 2, \dots, n \quad (42)$$

Let

$$B_{l_1 \times k_1} = A_{l_1 \times k_1} \times X_{k_1 \times k_1} \quad (43)$$

Then, equation (43) is

$$M_i^{FR} = B \cdot DP^{M_j}; i=1, 2, \dots, \text{ and } j=1, 2, \dots, n \quad (44)$$

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

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

Where

$$d(B \cdot DP^{M_j}) = \frac{\partial(B \cdot DP^{M_j})}{\partial(DP^{M_j})} \cdot d(DP^{M_j}) \quad i=1, 2, \dots, \text{ and } j=1, 2, \dots, n \quad (46)$$

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

$$(B \cdot DP^{M_j})_s = \sum_{z=1}^{k_1} B_{s,z} \cdot DP^{M_j}_z; i=1, 2, \dots, \text{ and } j=1, 2, \dots, n \quad (47)$$

Therefore,

$$\frac{\partial(\mathbf{B} \cdot \mathbf{DP}^{M_j})_s}{\partial(\mathbf{DP}^{M_j})_t} = \frac{\partial}{\partial(\mathbf{DP}^{M_j})_t} \sum_{z=1}^{k_1} \mathbf{B}_{s,z} \cdot \mathbf{DP}^{M_j}_z = \mathbf{B}_{s,t} ; i=1, 2, \dots, \text{ and } j=1, 2, \dots, n \quad (48)$$

And,

$$\left(\frac{\partial \mathbf{B} \cdot \mathbf{DP}^{M_j}}{\partial(\mathbf{DP}^{M_j})_t}\right)_s = \frac{\partial(\mathbf{B} \cdot \mathbf{DP}^{M_j})_s}{\partial(\mathbf{DP}^{M_j})_t} = \left(\frac{\partial \mathbf{B} \cdot \mathbf{DP}^{M_j}}{\partial \mathbf{DP}^{M_j}}\right)_{s,t} = \mathbf{B}_{s,t}; i=1, 2, \dots, \text{ and } j=1, 2, \dots, n \quad (49)$$

Hence,

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

And

$$d(\mathbf{B} \cdot \mathbf{DP}^{M_j}) = \mathbf{B} \cdot d(\mathbf{DP}^{M_j}) ; i=1, 2, \dots, \text{ and } j=1, 2, \dots, n \quad (51)$$

Or

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

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

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

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

where $d((M_i^{FR}))_0$ is the desired change in M_i^{FR} due to a change in M_j^{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 $\sum_{j=1}^n \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot dM_j^{DP}$ or $\mathbf{B} \cdot d(\mathbf{DP}^{M_j})$ 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, $\delta(M_i^{FR})$ must be $\geq \sum_{j=1}^n \frac{\partial M_i^{FR}}{\partial M_j^{DP}} \cdot dM_j^{DP}$ or $\geq \mathbf{B} \cdot d(\mathbf{DP}^{M_j})$ in case I or II.

For case I,

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

and for case II,

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

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

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

Or,

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

Using equation (54)

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

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

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

Or,

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

Therefore,

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

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...

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

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

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

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

$$M^{FR} = f(M_1^{DP}, M_2^{DP}, \dots, M_n^{DP}) \quad (64)$$

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's crucial for the variability to remain within the design range to ensure proper functionality. Therefore,

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

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's 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's 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,

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

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. B. 2. 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,

$$\{M^{FR}\} = [\text{Square DM}] \{M^{DP}\} + [\text{Extra Matrix}] \{M^{DP}\}^{Extra} \quad (67)$$

Let's 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.

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

where M_i^{FR} represents the i^{th} ($i=1, 2, \dots, k$) module in the functional domain, M_j^{DP} represents the j^{th} ($j=1, 2, \dots, n$) module in the physical domain,

DP_p^j represents the p^{th} member of j^{th} module in the physical domain for ($p=1, 2, \dots, k_1$), and A_{ii} represents the sub-design matrix within DM and relates DP's 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 $M_1^{DP}, M_2^{DP}, \dots$ and M_n^{DP} to ensure the independence of $M_1^{FR}, M_2^{FR}, \dots$ and M_k^{FR} . In such cases, the design range of M^{FR} would be:

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

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

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 $M_1^{DP}, M_2^{DP}, \dots$, 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:

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

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

M_i^{DP} is the primary controller for M_i^{FR} . M_j^{DP} are secondary controllers chosen to satisfy 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 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 analysing 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 analysed 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 manufacturing 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. Exhibit 8 presents and describes these FRs of the SOI.

Exhibit 8. Description of the leaf functional requirements (FRs) of the SOI.

Code	Description	Code	Description
FR1111	Organize meetings for the research committee.	FR1139	Request the required tests and follow up on the test.
FR1112	Make a decision about the annual budget.	FR113,10	Prepare and archive APQP file documents.
FR1113	Define new projects for the offices.	FR113,11	Prepare documents and archive SQA documents.
FR1114	Decide on the duration of projects.	FR113,12	Check and prepare a product requirements chart, and turn it into a technical specification.
FR1115	Complete the project charter.	FR113,13	Perform the process of improvement and change.
FR1121	Conduct phenomenological studies of the project.	FR1141	Check test requests.
FR1122	Select the initial formulation.	FR1142	Coordinate to receive tires from the production line.

FR1123	Produce the experimental mixture.	FR1143	Plan to take the test.
FR1124	Evaluate the results.	FR1144	Run the test.
FR1125	Optimize the formulation.	FR1145	Review and analyze results.
FR1126	Produce a prototype.	FR1146	Generate test reports.
FR1127	Acknowledge the research objectives.	FR1151	Manage knowledge of the combined design process and the final product in all design aspects.
FR1128	Design the production process for in-line mixing.	FR1152	Support the knowledge management process to fix product line defects.
FR1129	Prepare mixed pre-production samples.	FR1153	Manage previous knowledge within the organization.
FR112,10	Prepare pre-production stage tires.	FR1154	Coordinate the holding of internal seminars.
FR112,11	Validate to achieve project goals.	FR1155	Coordinate and disseminate new sciences in the field of tire production. Receive and archive lessons learned related to research and development projects.
FR112,12	Perform daily line production.	FR1156	Publish lessons learned at the organization level.
FR112,13	Prepare the mixture reference recipe and deliver it to the Research and Development Documentation Center.	FR1157	Select the size and brand of comparable tires.
FR112,14	Prepare project documentation and store a copy in the archive of the mixture design office and deliver another copy to the documentation center.	FR1221	Request to buy.
FR1131	Design the template profile and pattern.	FR1222	Determine the test and its standard.
FR1132	Simulate and certify the design.	FR1223	Issue processes based on design department ORDERS.
FR1133	Prepare template drawings.	FR1231	Check the production notifications sent by the process department to decide on issuing or not issuing the process.
FR1134	Prepare the Common Technical Document (CTD).	FR1232	Prepare PFMEA for all radial tire production processes.
FR1135	Build the ORDER design.	FR1233	Investigate and eliminate the reasons for the non-functioning of the radial tire in the test center tests.
FR1136	Issue the manufacturing process.	FR1234	Carry out projects defined in meetings.
FR1137	Issue the baking process.	FR1235	Prepare and update work standards for different parts of radial riding.
FR1138	Experimentally construct and cook, then examine defects and uniformity.	FR1236	

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). Exhibit 9 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 'C₁' (system architecture dependency) and 'C₂' (element's info dependency on architecture). 'C₁' gauges system's reliance on an element, while 'C₂' 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. Exhibits 10 and 11 display this, providing a comprehensive view of individual element importance and role in the SOI;

Exhibit 10. Percentage of information provided by each system element for the entire system (NDSM rows).

Code	Percentage (%)	Code	Percentage (%)	Code	Percentage (%)
FR1121	0.57	FR1231	1.36	FR1157	1.87
FR1115	0.6	FR1138	1.38	FR1152	1.9
FR1129	0.69	FR1235	1.38	FR112,11	1.96
FR112, 10	0.73	FR1113	1.44	FR1223	2.04
FR1124	0.83	FR1112	1.52	FR1136	2.25
FR1154	0.87	FR1142	1.55	FR1137	2.26
FR1123	0.88	FR1131	1.55	FR1146	2.44
FR1236	0.96	FR112,13	1.55	FR1134	2.49
FR1233	0.99	FR1232	1.56	FR113,13	2.64
FR1111	1.04	FR1221	1.56	FR1156	2.75
FR1234	1.11	FR112,12	1.59	FR1145	2.87
FR1155	1.12	FR1222	1.6	FR1144	3.11
FR1125	1.19	FR1133	1.64	FR1141	3.17
FR1139	1.25	FR1128	1.68	FR113,11	3.72
FR1132	1.27	FR1153	1.74	FR113,12	3.92
FR1122	1.29	FR1143	1.77	FR112,14	3.94
FR1127	1.31	FR1114	1.79	FR1151	4.34
FR1126	1.32	FR1135	1.82	FR113,10	5.85

Exhibit 11. Percentage of information input received by each system element from the entire system (NDSM columns).

Code	Percentage (%)	Code	Percentage (%)	Code	Percentage (%)
FR1111	0.85	FR112,14	1.56	FR1145	2.13
FR1112	0.94	FR1131	1.77	FR1146	1.76
FR1113	1.13	FR1132	1.35	FR1151	1.82
FR1114	1.3	FR1133	1.88	FR1152	1.84
FR1115	0.63	FR1134	2.83	FR1153	1.72
FR1121	1.62	FR1135	2.18	FR1154	0.99
FR1122	2.08	FR1136	2.36	FR1155	1.42
FR1123	1.92	FR1137	2.22	FR1156	1.98
FR1124	1.94	FR1138	1.44	FR1157	1.97
FR1125	2.01	FR1139	1.28	FR1221	1.57
FR1126	1.79	FR113,10	3.53	FR1222	2.07
FR1127	1.64	FR113,11	3.83	FR1223	1.74
FR1128	1.9	FR113,12	4.13	FR1231	1.33
FR1129	1.68	FR113,13	2.93	FR1232	1.97
FR112,10	1.59	FR1141	2.41	FR1233	1.43
FR112,11	2.38	FR1142	1.04	FR1234	1.51
FR112,12	2.01	FR1143	1.8	FR1235	1.4
FR112,13	1.46	FR1144	2.51	FR1236	1.43

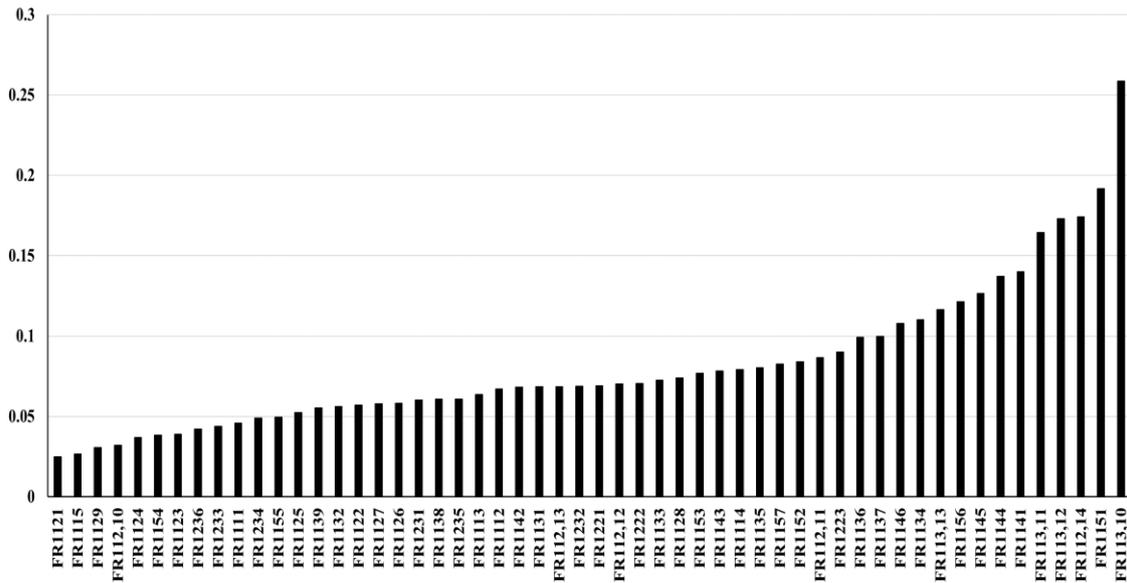


Exhibit 13. Prioritization of the percentage of information input received by each system element from the entire SOI (NDSM columns).

Furthermore, Exhibit 14 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;

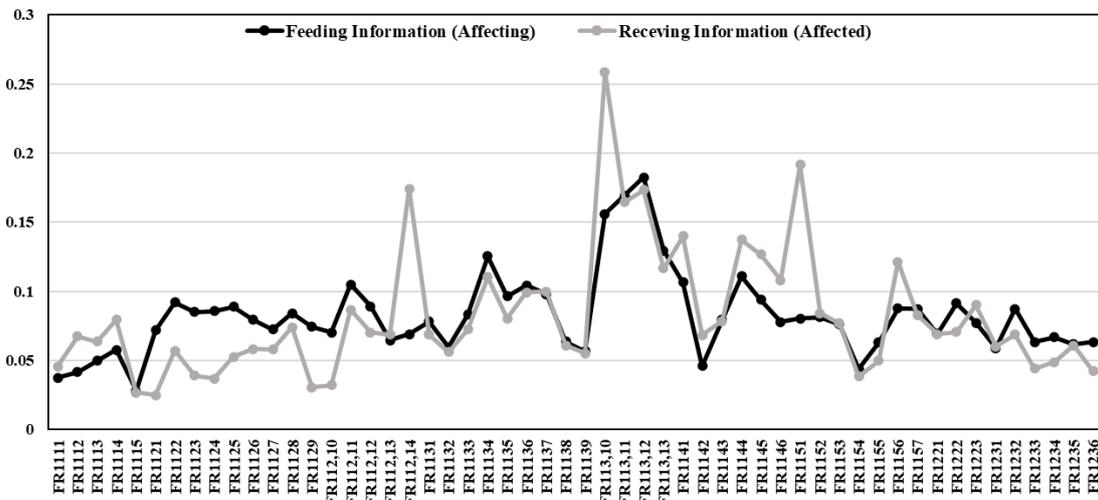


Exhibit 14. Comparing the information contribution and input percentages for each system element within the entire system.

As observed in the aforementioned figures, it is evident that the criteria C_1 and C_2 for each system element are not identical. For instance, while elements 'FR_{113,10}', 'FR_{113,11}', and 'FR_{113,12}' demonstrate maximal percentage of information feed they can provide for the entire system (i.e., C_1), they also receive the highest percentage of information inputs from the entire system (i.e., C_2). However, it is essential to avoid potential misinterpretation, as the significance of each process (i.e., each node of the network representing the system architecture of the SOI) should be evaluated based on both criteria concurrently.

To achieve this, the present study utilizes a weighting method known as the 'compound measure,' proposed within this research. The subsequent section will delve into further details about this approach.

4.3.2. Compound Weights of each system element

To establish a singular weight for each element, two criteria, namely 'C₁' and 'C₂' are introduced with equal values (i.e., $WC_1 = 0.5$, $WC_2 = 0.5$). Subsequently, two Multi-Criteria Decision Making (MCDM) weighting methods, 'SAW' and 'TOPSIS,' are utilized. The resulting weights obtained through these methods are collectively referred to as 'Compound Weights' in this study.

Exhibit 15 displays the final compound weights of each element within the SOI, based on the outcomes derived from the SAW and TOPSIS methods.

Exhibit 15. Compound weight of each element of the SOI.

	SAW	TOPSIS	FRs	SAW	TOPSIS
FR1111	0.009	0.005	FR1139	0.013	0.010
FR1112	0.012	0.010	FR113,10	0.045	0.059
FR1113	0.013	0.010	FR113,11	0.038	0.044
FR1114	0.015	0.014	FR113,12	0.040	0.047
FR1115	0.006	0.000	FR113,13	0.028	0.031
FR1121	0.012	0.010	FR1141	0.027	0.032
FR1122	0.018	0.016	FR1142	0.013	0.011
FR1123	0.015	0.013	FR1143	0.018	0.017
FR1124	0.015	0.013	FR1144	0.028	0.032
FR1125	0.017	0.015	FR1145	0.024	0.028
FR1126	0.016	0.014	FR1146	0.020	0.022
FR1127	0.015	0.013	FR1151	0.029	0.037
FR1128	0.018	0.017	FR1152	0.019	0.019
FR1129	0.013	0.011	FR1153	0.017	0.017
FR112,10	0.012	0.010	FR1154	0.009	0.005
FR112,11	0.022	0.023	FR1155	0.013	0.010
FR112,12	0.018	0.018	FR1156	0.023	0.026
FR112,13	0.015	0.013	FR1157	0.019	0.019
FR112,14	0.025	0.033	FR1221	0.016	0.014
FR1131	0.017	0.015	FR1222	0.019	0.018
FR1132	0.013	0.010	FR1223	0.019	0.019
FR1133	0.018	0.017	FR1231	0.013	0.011
FR1134	0.027	0.030	FR1232	0.018	0.017
FR1135	0.020	0.020	FR1233	0.013	0.009
FR1136	0.023	0.025	FR1234	0.013	0.011
FR1137	0.022	0.024	FR1235	0.014	0.012
FR1138	0.014	0.012	FR1236	0.012	0.009

Exhibit 16 presents a comparison of the compound weight of each element obtained from both the TOPSIS method and the SAW method, alongside the weights originally computed (i.e., weights obtained from C₁ and C₂ only).

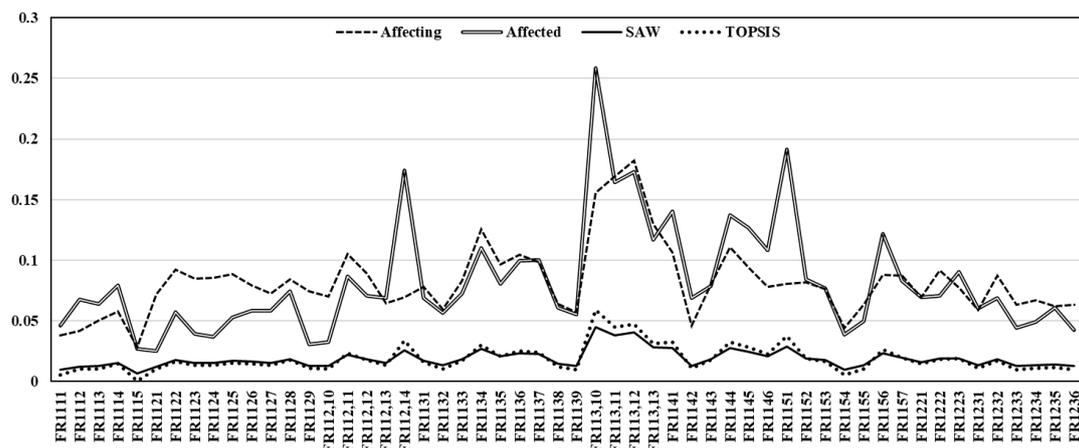


Exhibit 16. Comparing the compound weights of each element with their original individual weights.

As the figure illustrates, there are considerable differences between the original weights and the weights obtained from applying the MCDM methods. However, the latter weights (i.e., weights given by the SAW and TOPSIS methods) are nearly similar, while also being more reasonable and acceptable.

Given the considerable similarity between the results obtained from the SAW and TOPSIS methods, for the sake of simplicity and without losing generality, the weights given by the TOPSIS method are used to continue the analyses. Exhibit 17 presents the updated prioritization of the elements based on the compound weights derived from the TOPSIS method;

Exhibit 17. 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. 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 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 (Exhibits A₁-A₆). To diminish the coupling, the partitioning technique is applied for each of the resulted architecture. Exhibits 19–24 display the outcomes.

Exhibit 25 presents all the fundamental information (i.e., N_1 - N_4) necessary for computing the criteria, introduced in section 2.3.2, used to measure the architecture modularity;

Exhibit 25: Fundamental details regarding the introduced measures of modularity.

Designs \ N_s	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

Using the information provided in Exhibit 25, Exhibit 26 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;

Exhibit 26. Assessing the degree of modularity for Designs I through 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

Exhibits 27a-27d display the scores of each design concerning the modularity measures utilized in Exhibit 26.

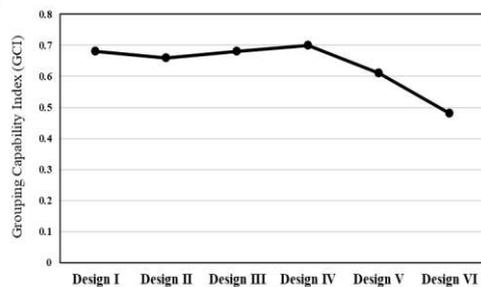


Exhibit 27a. Magnitude of Modularity in Design I-Design VI Based on Grouping Capacity Criterion (GCI) Criterion

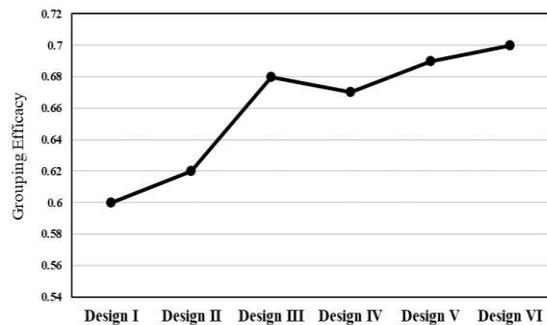


Exhibit 27b. Magnitude of Modularity in Design I-Design VI Based on Grouping Efficacy Criterion

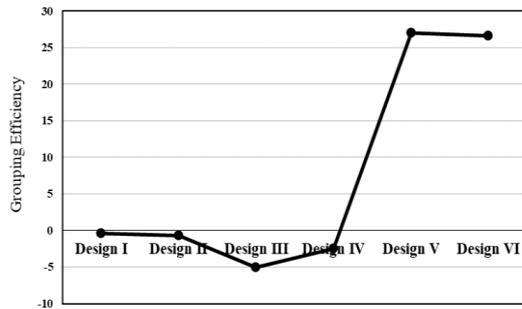


Exhibit 27c. Magnitude of Modularity in Design I-Design VI Based on Grouping Efficiency Criterion

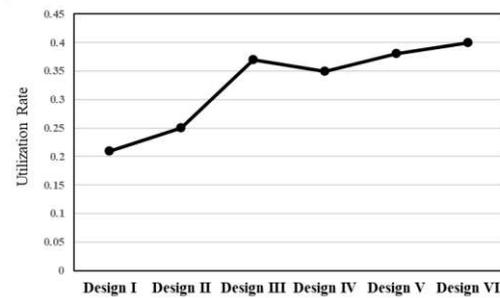


Exhibit 27d. Magnitude of Modularity in Design I-Design VI Based on Utilization Rate Criterion

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 (Exhibit 28). The modules included in this analysis are referred to as the unique components of the modularization function.;

Based on Exhibit 28, 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.

Exhibit 28. 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_i})
Sub-System ₁	M ₁	FR1111	0	0	0
		FR1112			
		FR1122			
		FR1121			
		FR112,12			
		FR1126			
Sub-System ₂	M ₂	FR1124	13	13	0
		FR1125			
		FR113,10			
		FR1128			
		FR1127			
		FR113,12			
Sub-System ₃	M ₃	FR1113	0	0	0
Sub-System ₄	M ₄	FR1114	0	0	0
Sub-System ₅	M ₅	FR1115	0	0	0
Sub-System ₆	M ₆	FR1129	0	0	0
Sub-System ₇	M ₇	FR112,10	0	0	0
Sub-System ₈	M ₈	FR112,11	0	0	0
Sub-System ₉	M ₉	FR112,13	0	0	0
Sub-System ₁₀	M ₁₀	FR112,14	0	0	0
Sub-System ₁₁	M ₁₁	FR1131	0	0	0
Sub-System ₁₂	M ₁₂	FR1132	0	0	0
Sub-System ₁₃	M ₁₃	FR1133	0	0	0
Sub-System ₁₄	M ₁₄	FR1134	1	1	0

		FR1136				
Sub-System ₁₅	M15	FR1135	0	0	0	0
Sub-System ₁₆	M16	FR1137	0	0	0	0
Sub-System ₁₇	M17	FR1138	0	0	0	0
Sub-System ₁₈	M18	FR1139	0	0	0	0
Sub-System ₁₉	M19	FR113,13	0	0	0	0
Sub-System ₂₀	M20	FR1144	0	0	0	0
Sub-System ₂₁	M21	FR1145	0	0	0	0
Sub-System ₂₂	M22	FR1146	0	0	0	0
Sub-System ₂₃	M23	FR1151	0	0	0	0
Sub-System ₂₄	M24	FR1152	0	0	0	0
Sub-System ₂₅	M25	FR1153	0	0	0	0
Sub-System ₂₆	M26	FR1154	0	0	0	0
Sub-System ₂₇	M27	FR1155	0	0	0	0
Sub-System ₂₈	M28	FR1156	0	0	0	0
Sub-System ₂₉	M29	FR1157	0	0	0	0
Sub-System ₃₀	M30	FR1221	0	0	0	0
Sub-System ₃₁	M31	FR1222	0	0	0	0
		FR1223				
Sub-System ₃₂	M32	FR1141	3	3	0	0
		FR1143				
		FR1142				
Sub-System ₃₃	M33	FR1231	0	0	0	0
Sub-System ₃₄	M34	FR1232	0	0	0	0
Sub-System ₃₅	M35	FR1233	0	0	0	0
Sub-System ₃₆	M36	FR1234	0	0	0	0
Sub-System ₃₇	M37	FR1235	0	0	0	0
Sub-System ₃₈	M38	FR1236	0	0	0	0

Regarding the optimal design VI, it is crucial to mention that among all developed subsystems (i.e., subsystems 1-38), subsystem₂, subsystem₃₂, and subsystem₁₄ 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 subsystems, 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., subsystems 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 Exhibit 29 and Exhibit 30.

Exhibit 29 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 Exhibit 30. 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 Exhibit 30, 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. Exhibit 30 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.

Exhibit 29. 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
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

Upon close examination of Exhibit 30, 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.

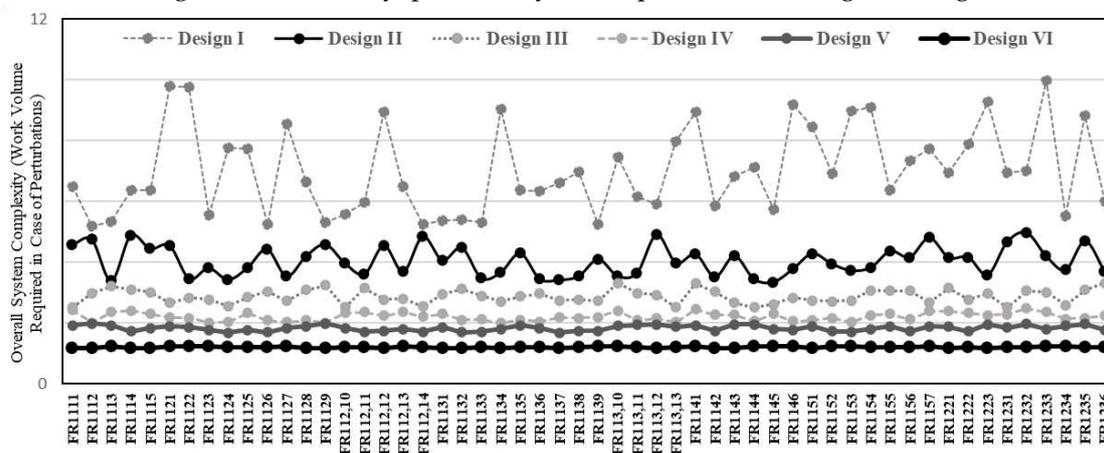


Exhibit 30. Comparison of robustness factor of each system element among the Designs I –VI.

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.

Exhibit 30 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. Discussion and Conclusion

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 emphasizes the importance of modularity within the manufacturing process architecture. Considering modularity in the process domain architecture indirectly supports modularity in the allocated architecture, fostering a comprehensive approach that optimizes component allocation within the physical system.

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.

The successful integration of engineering management principles with modular design strategies introduces new avenues for enhancing robustness and efficiency in manufacturing processes. By proactively engaging engineering management in the design phase and applying our modularization approach, manufacturing organizations can enhance their overall system robustness and improve their capacity to respond to changing circumstances effectively.

Looking ahead, our research calls for further investigations into the interplay between manufacturing management and engineering management. Understanding the dynamics of this relationship will allow organizations to optimize resource allocation and streamline decision-making processes while fostering a culture of collaboration and knowledge exchange between engineering and manufacturing teams.

Moreover, our study opens avenues for future research in the development of comprehensive strategies that address other essential dimensions of manufacturing processes. Studies focused on process legality, reliability, adaptability, and recoverability will contribute to a more comprehensive understanding of resilient manufacturing processes.

Develop a resilience framework for manufacturing processes that encompasses not only robustness but also other dimensions such as flexibility, adaptability, and recoverability. This framework would provide a holistic view of manufacturing process resilience and guide decision-makers in making informed choices to enhance overall system resilience.

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

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