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Reconfigurable manufacturing systems and competency islands in modern production

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Abstract: This paper explores the concept and evolution of Reconfigurable Manufacturing Systems (RMS), focusing on their importance in modern manufacturing. RMS allows rapid changes in production capacity and functionality, adapting to market demands. The paper also introduces Competency Islands, a concept reshaping future manufacturing systems by enabling modular, decentralized production environments.

Keywords: Reconfigurable Manufacturing Systems; Competency Islands; Modular Production; Smart Manufacturing; Robotics

Rekonfigurowalne systemy produkcyjne i wyspy kompetencji we współczesnej produkcji

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Streszczenie: Artykuł przedstawia koncepcję i ewolucję Rekonfigurowanych Systemów Produkcyjnych (RMS), koncentrując się na ich znaczeniu we współczesnej produkcji. RMS umożliwiają szybkie zmiany w zdolnościach produkcyjnych i funkcjonalności, dostosowując się do wymagań rynku. Artykuł wprowadza również koncepcję Wysp Kompetencyjnych, które kształtują przyszłe systemy produkcyjne poprzez umożliwienie modułowych, zdecentralizowanych środowisk produkcyjnych.

Słowa kluczowe: Rekonfigurowane Systemy Produkcyjne; Wyspy Kompetencyjne; Produkcja Modułowa; Inteligentna Produkcja; Robotyka

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1. Introduction

Reconfigurable Manufacturing Systems (RMS) represent a significant shift in production flexibility and adaptability, emerging as an essential paradigm in the manufacturing industry since the 1990s. These systems were introduced as a response to the growing need for manufacturing systems capable of rapid adaptation to market fluctuations and diverse product demands. The idea behind RMS is based on the reconfiguration of production machines and systems, allowing for a change in flexibility to accommodate different product types or production volumes. In the early stages, reconfiguration efforts focused primarily on individual machines, which were divided into functional components that could be modified or replaced to achieve the desired level of flexibility. Over time, however, the concept expanded to include the entire production system. This broader concept, often referred to as changeability, represents an advanced level of flexibility, allowing organizations to rapidly adapt both technologies and organizational structures without significant investments. Changeability is a key feature in today's manufacturing systems, as it allows for responsiveness to unexpected demands and resilience against disruptions. As defined by [1], changeability is the combination of resilience and responsiveness. Flexibility is seen as the potential for modification within predefined dimensions and scenarios, while responsiveness represents the ability to react outside these expected parameters [2]. Together, these elements form the backbone of modern RMS, which are designed to accommodate frequent changes in product types and quantities without requiring significant overhauls of the production system. Frequent production changes can disrupt production flow, leading to a loss of production capacity and, consequently, profit [3,4]. Therefore, the speed and efficiency with which a production system can be reconfigured are critical to maintaining competitiveness. RMS, by design, minimizes downtime during such transitions, ensuring that production systems can be quickly adapted to new product requirements [5,6]. These systems are typically modular, integrating reconfigurable machines and equipment that allow for a "plug and produce" approach [7,8]. This enables companies to quickly integrate new technologies and production methods with minimal disruption [9]. In Slovakia, where the industry structure heavily relies on automotive and heavy manufacturing, the implementation of RMS is especially relevant. RMS offer companies the ability to dynamically adjust production capacity and functions, making them particularly useful in industries with high variability in product demand and stringent timelines. The adoption of RMS in Slovakia's manufacturing sector is not just a technological advancement but a necessary step towards maintaining global competitiveness.

2. Materials and Methods

Reconfigurable Manufacturing Systems (RMS) are complex, dynamic production systems designed to adapt rapidly to changes in production demand and product type. The key characteristics of RMS, such as modularity, scalability, and convertibility, form the foundation of these systems, ensuring that both hardware and software can be easily reconfigured to meet new production requirements.

2.1 Modularity

Modularity is a core principle of RMS, where the system is composed of interchangeable units or modules. These modules can be quickly integrated into or removed from the production line, depending on the current manufacturing needs. This modular structure allows production systems to switch between different product families with minimal reconfiguration time. The concept of modularity ensures that the overall system can maintain flexibility without requiring a complete overhaul of the existing infrastructure. In RMS, modularity extends beyond physical components to include software systems as well. Control software is designed to be reconfigurable, enabling seamless integration with new hardware components or changes in production requirements. This flexibility allows the system to handle different types of products or fluctuating production volumes with minimal downtime.

2.2 Scalability

Another important aspect of RMS is scalability, which refers to the system's ability to modify production capacity by adding or removing resources. This can be achieved through the addition or removal of machines, tools, or other production equipment. Scalability ensures that the system can adapt to increases or decreases in product demand without significant disruptions to the production process. For example, in a scenario where demand for a specific product family increases, additional machines can be introduced to the system to accommodate the higher production volume. Similarly, if demand decreases, machines can be removed or repurposed for other tasks, optimizing the use of available resources and minimizing operational costs.

2.3 Convertibility

Convertibility refers to the system's ability to change its functionality to meet new production requirements. In RMS, convertibility is achieved through the reconfiguration of existing machines, control systems, and production processes. This ability to transform the functionality of a production system is crucial for handling product diversification, especially in industries where new models or product variants are frequently introduced. Convertibility also plays a critical role in reducing the time required to transition between different product types. By leveraging reconfigurable hardware and software, companies can swiftly adapt their production systems to new products without the need for extensive retooling or investment in new equipment.

2.4 System Configuration

The success of any RMS depends heavily on its configuration. System configuration defines how machines, tools, transport systems, and control software are arranged to maximize efficiency. The choice of configuration has a direct impact on the overall performance of the RMS, influencing production throughput, lead times, and flexibility. The configuration of RMS is often guided by mathematical models that calculate the optimal arrangement of machines based on the planned production volume, time, and reliability. According to [3], the number of possible configurations for a system of N machines with m ways of arrangement can be calculated using the following formulas:

1. The total number of configurations:

$$K = \sum_{m-1}^{N} \binom{N-1}{m-1} = 2^{N-1} \tag{1}$$

2. The number of different configurations of the production system for a specific number of machines N and arrangement ways m:

$$K = \left(\frac{(N-1)!}{(N-m)!\,(m-1)!} \right) \tag{2}$$

These equations provide a framework for determining the number of possible system configurations, helping manufacturers select the most efficient arrangement based on their specific production needs. The mathematical models also help in optimizing the utilization of equipment, ensuring that capacity is maximized while downtime is minimized.

2.5 Diagnosability

Diagnosability is another crucial feature of RMS, ensuring that the system can automatically detect and diagnose issues related to equipment malfunctions or product defects. This is achieved through integrated sensors and control systems that monitor the performance of machines in real-time. Diagnosability helps reduce downtime by quickly identifying the root causes of problems and implementing corrective actions. This capability is particularly important in maintaining the high levels of efficiency and productivity required in modern manufacturing environments.

2.6 Simulation Models

To optimize the configuration of RMS, simulation models are often used. These models allow manufacturers to test various configurations in a virtual environment before implementing them in real production systems. For example, publication [5] developed a methodology for designing reconfigurable manufacturing lines using simulation software such as Simio. Figure 1 illustrates the results of a simulation model for a reconfigurable line, showing how machine utilization can be maximized based on specific production scenarios.

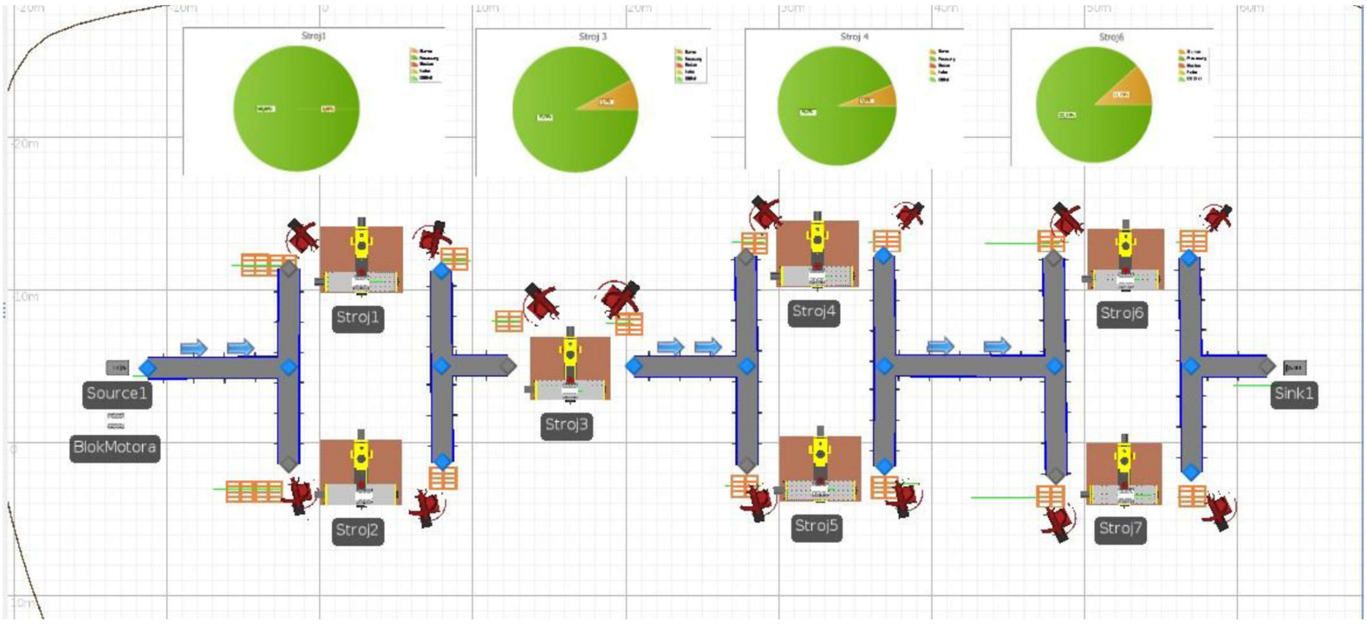

Figure 1. Results of a simulation model for a reconfigurable line [5]

Simulation models provide a valuable tool for analyzing different configurations and their impact on system performance. They also allow manufacturers to anticipate potential issues and adjust their system designs accordingly, leading to more efficient and adaptable production systems

3. Results

The implementation of Reconfigurable Manufacturing Systems (RMS) has demonstrated significant improvements in manufacturing efficiency, flexibility, and scalability. These systems, when properly configured, allow companies to respond to market changes with minimal disruption to their production processes. The results presented in this section focus on the key benefits of RMS and the effectiveness of different system configurations.

3.1. Benefits of Reconfigurable Manufacturing Systems

One of the primary advantages of RMS is the reduction in ramp-up time—the period required for a reconfigured production system to achieve stable, planned production parameters, such as production volume, lead time, and quality. As shown in Figure 2, companies utilizing RMS experience faster transitions between production cycles, significantly reducing downtime and increasing overall production efficiency.

RMS enables the rapid adaptation of production capacity and functionality, particularly in industries with frequent product changes. For example, automotive manufacturers often need to retool their production lines to accommodate new vehicle models. RMS allows for these transitions to occur seamlessly, without the need for extensive downtime or the complete replacement of existing equipment. This flexibility is a key factor in maintaining competitiveness in industries where product life cycles are becoming increasingly shorter. Additionally, RMS facilitates the modular integration of new technologies, such as automated robotics and artificial intelligence, into existing production lines. The "plug and produce" approach allows manufacturers to quickly integrate advanced technologies, leading to faster production cycles, improved product quality, and lower operating costs. This capability also enables companies to remain agile in a rapidly evolving technological landscape, where innovations in manufacturing processes and equipment are continually emerging.

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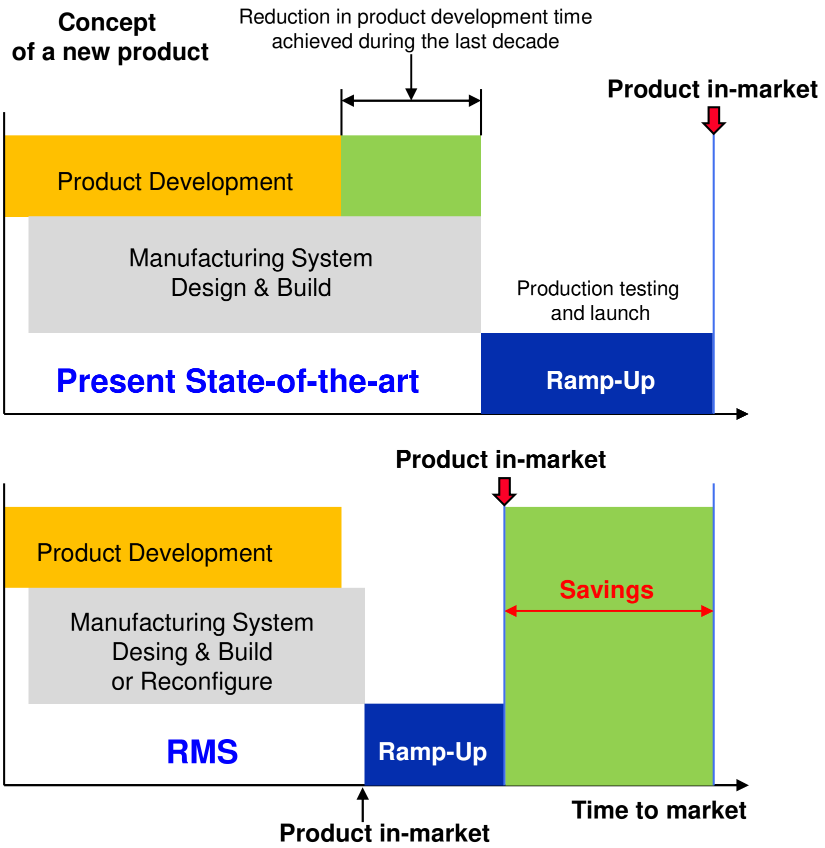

Figure 2. Benefits of RMS [3]

3.2. Configuration of Production Systems

The configuration of a production system directly influences its ability to achieve maximum efficiency. Each configuration offers different levels of flexibility, scalability, and production capacity. In RMS, the number of possible configurations increases exponentially with the number of machines and ways of arranging them. For example, as calculated using the formula provided in the Materials and Methods section, a system with seven machines and seven arrangement methods yields 64 possible configurations. If the system is arranged in exactly three levels, there are 15 possible configurations [3]. This vast number of configurations allows manufacturers to choose the most efficient setup based on their production requirements. The flexibility provided by RMS configurations is essential for industries that need to adjust their production lines frequently. For example, when the demand for a specific product increases, manufacturers can rearrange the configuration to increase production capacity. Conversely, when demand decreases, machines can be reallocated to other tasks, optimizing resource use and minimizing idle time.

3.3. Impact on Slovak Industry

The introduction of RMS into Slovak industry, particularly in the automotive and heavy manufacturing sectors, has the potential to revolutionize production processes. These industries are characterized by high product variability and demand for customized production solutions. The ability of RMS to adapt quickly to changing product requirements makes it an ideal solution for these sectors. In Slovakia, RMS could play a crucial role in improving the efficiency of production systems, particularly in reducing the time and cost associated with reconfiguring production lines for new products. Figure 3 presents a simulation model of an RMS designed for a specific manufacturing program. The model demonstrates how RMS can optimize production capacity, reduce downtime, and improve overall system performance, particularly in industries where production needs vary frequently.

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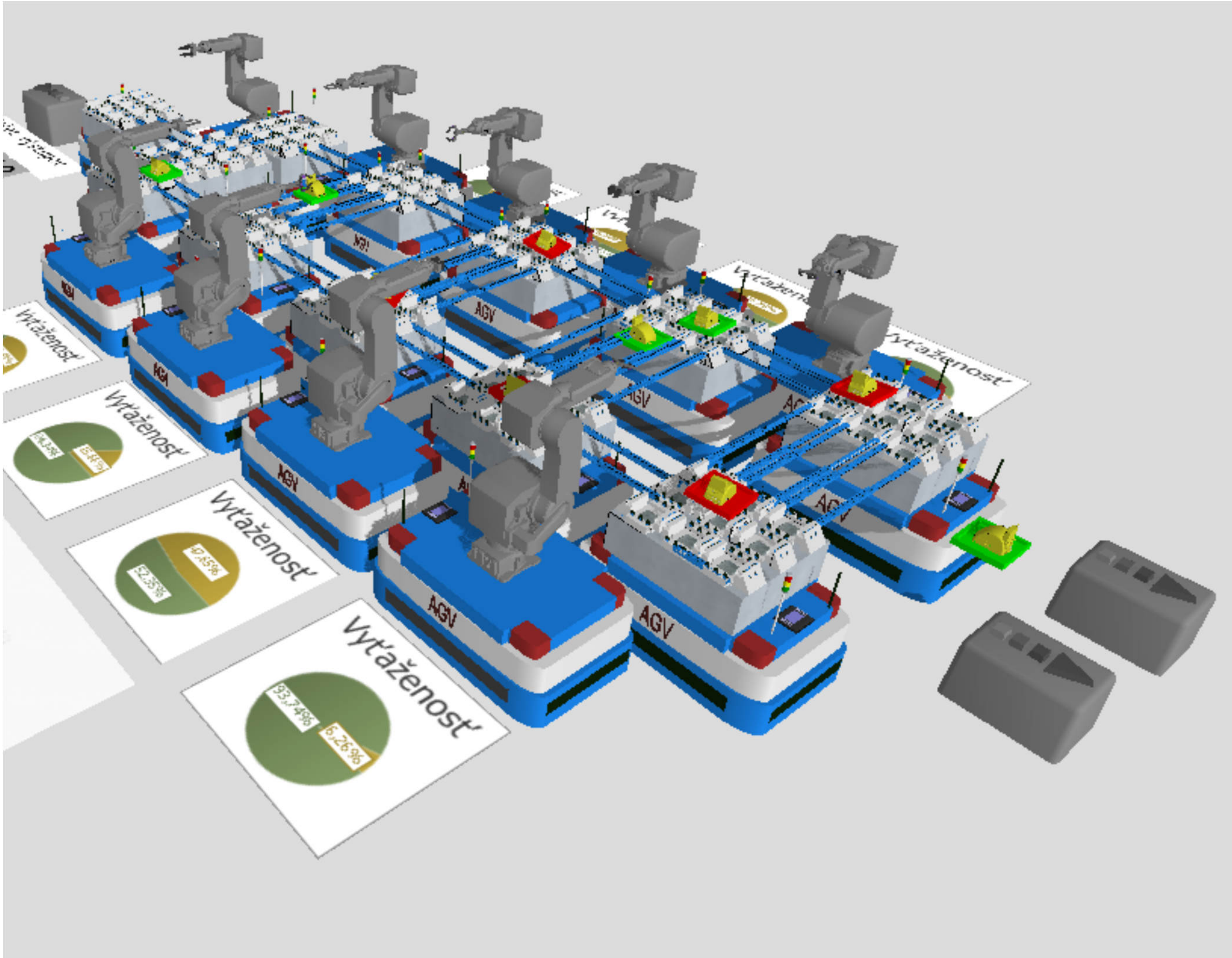

Figure 3. RMS for a specified manufacturing program [4]

Moreover, RMS can support the growing trend toward mass customization in manufacturing. Slovak industries that rely on high-volume production, such as automotive manufacturing, can benefit from the modularity and scalability of RMS. These systems allow manufacturers to produce small batches of highly customized products while maintaining high levels of efficiency and cost-effectiveness.

3.4. Simulation Results

The use of simulation models in designing RMS has provided valuable insights into system performance under different configurations. Author [5] developed a methodology for configuring manufacturing lines using reconfigurability elements and applied simulation tools such as Simio to test the effectiveness of these configurations. The simulation model highlights the advantages of dynamic reconfigurability over static systems, as shown in Figure 4. Dynamic RMS can continuously adjust to production requirements, improving machine utilization and reducing idle time, while static systems are less adaptable to changes in product demand or production volume.

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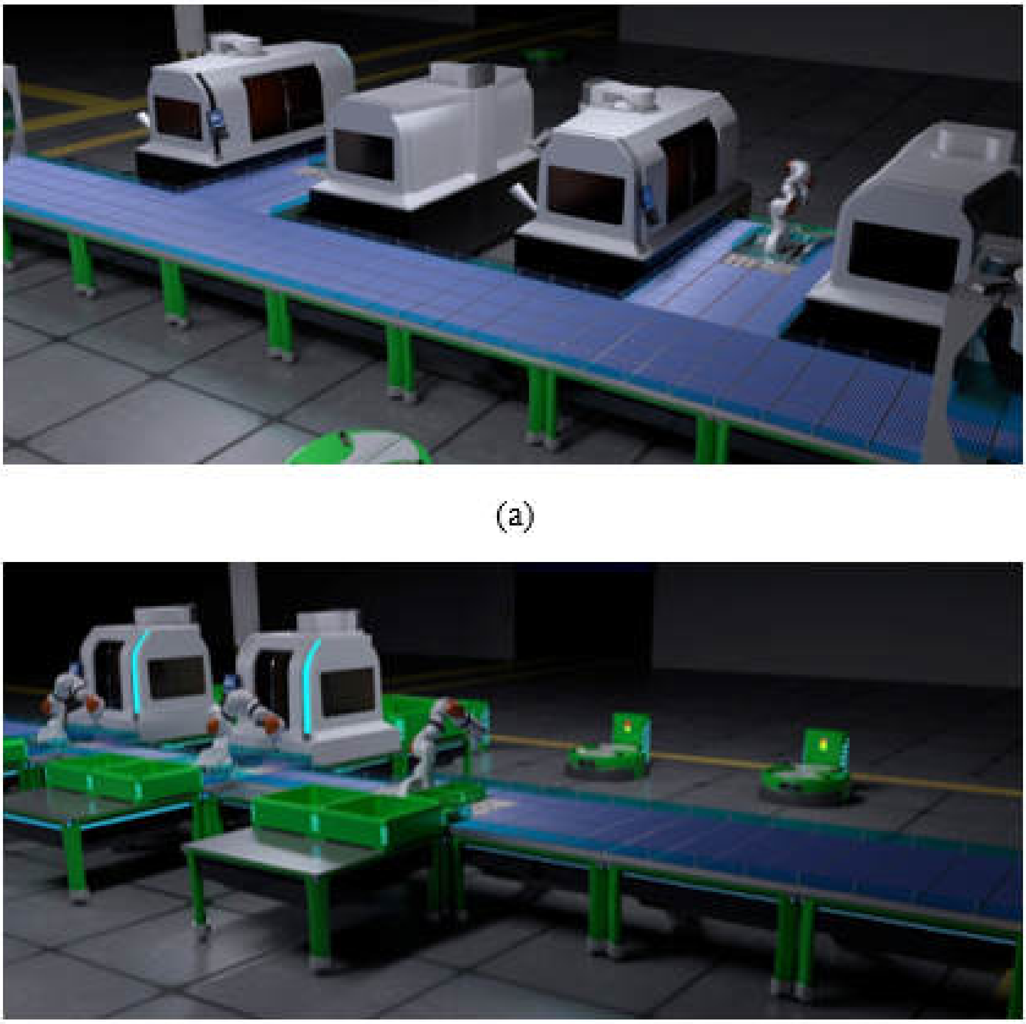

(a)

(b)

Figure 4. Comparison - static RMS (a); dynamic RMS (b) [5]

The simulation results also show that reconfigurable systems reduce the impact of equipment failure on overall production. By enabling quick reconfiguration, RMS can redirect production tasks to other machines within the system, minimizing downtime and maintaining high levels of efficiency even when unexpected equipment failures occur.

Conclusion

Reconfigurable Manufacturing Systems (RMS) represent a significant advancement in the manufacturing industry, offering unparalleled flexibility and scalability in response to rapidly changing market demands. As businesses increasingly seek to produce customized products while maintaining high levels of efficiency, the adoption of RMS has become essential for staying competitive. RMS allows manufacturers to reconfigure their production systems quickly, reducing downtime and maximizing equipment utilization, which leads to improved operational efficiency and profitability. The introduction of RMS into industries such as automotive and heavy manufacturing, particularly in Slovakia, holds immense potential. By leveraging the modular, scalable, and convertible nature of RMS, manufacturers can optimize their production lines to accommodate product variability and fluctuating demand. This capability is especially important in an environment where product life cycles are shortening, and customers demand more customization options. However, the successful implementation of RMS requires overcoming certain challenges, including the complexity of system configuration and the need for significant upfront investment in modular equipment and workforce training. Simulation tools, like those developed by [5], provide a valuable resource for manufacturers to test and optimize their configurations before implementation, ensuring that production systems are capable of meeting the desired performance metrics. Looking forward, the integration of advanced technologies such as artificial

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intelligence, machine learning, and smart robotics into RMS will further enhance the adaptability of these systems. The future of manufacturing is one of organized chaos, where intelligent systems, competency islands, and mobile robots work in harmony to produce goods in a highly flexible and efficient manner. In conclusion, RMS offers a comprehensive solution for modern manufacturing, enabling businesses to adapt to market changes swiftly and cost-effectively. As industries continue to evolve, RMS will play an increasingly critical role in ensuring that manufacturers can meet the demands of a dynamic global market.

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