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# Only What's Needed: Frugal Smart Systems for Resilience in Manufacturing

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**Abstract.** Manufacturing systems across industries are increasingly exposed to uncertainties that threaten their resilience and competitiveness. To address these challenges, manufacturers are integrating digital and smart technologies into production processes to enhance system intelligence, predictability and reconfigurability. However, many legacy (brownfield) systems struggle to leverage these technologies effectively. This paper adopts a systems engineering perspective to compare the concepts of frugal, resilient, and smart systems, aiming to identify the requirements for designing resource-efficient and adaptable manufacturing systems. Building on this conceptual foundation, a method for mapping and visualization of essential functions within brownfield systems is introduced. It enables the identification of minimal reconfiguration efforts needed to maintain performance under uncertainty. An illustrative example shows the application of the method to brownfield assembly systems, supporting strategic interventions for resilience enhancement. The work provides both a conceptual framework and a practical tool to support resilient reconfiguration and resource-efficient operation in manufacturing.

**Keywords:** Systems Engineering · Frugal Manufacturing · Resilient Manufacturing · Smart Manufacturing · Minimal Adaptability · Essential Function

## 1 Introduction

In today's volatile geopolitical and economic climate, manufacturers face a growing number of disruptions that demand continuous adaptation of existing (brownfield) systems. These disruptions include sudden shifts in market dynamics, global crises, and mounting pressures from climate change, decarbonization targets, and sustainability regulations.

Manufacturers must economically react to these disruptions. These reactions include: (i) changes in the systems' structure and behavior, supported with (ii) timely reconfiguration decisions taken in often tight timeframes and/or after the occurrence of unexpected events. Changes in the systems' structure involve physical reconfigurations, changes in

the systems' behavior involve varied work instructions and logistics flows. Reconfiguration decision involve strategic, tactical and operational decisions, and need to ensure that systems are able to implement the up next (strategic, tactical, and operational) reconfiguration with a reduced reconfiguration effort (time, cost and ramp-up).

To survive and remain competitive, manufacturers must adopt systems engineering methodologies to guide reconfiguration decisions throughout the system's lifecycle. The majority of existing manufacturing systems are brownfield systems, that is, legacy production environments developed incrementally over time. These systems are typically characterized by a mix of aging equipment, undocumented processes, and low levels of digitalization, which makes reconfiguration particularly challenging. Therefore, implementing systems engineering methodologies to guide reconfiguration decisions remains highly challenging, as shown in [1].

A research question is introduced as follows: "How to support the implementation of systems engineering methodologies in manufacturing for resilience?"

Systems engineering methodologies are structured, interdisciplinary approaches for the design, analysis, and management of complex systems across their life cycle [2, 3]. In the context of manufacturing, they are particularly valuable for supporting systems that must rapidly adapt their structure and behavior in response to disruptions, uncertainty, and evolving demands [4, 5].

To address the research question, this paper adopts the systems engineering lens to outline the essential characteristics of future manufacturing systems that ensure resilience. It shows the impact of frugality, smartness, and resilience on manufacturing systems, considering (i) system's structure, (ii) behavior, and (iii) scope of the reconfiguration decision. Frugality emphasizes minimalism in resource use and is vital for sustainable development [6]. Resilience ensures that systems can absorb shocks and recover from disruptions [7]. Smartness, enabled through digital technologies, enhances adaptability by improving system-level predictability and reconfigurability [8]. Moreover, a method for the identification of essential functions of brownfield systems is proposed. This method allows to map and visualize the essential functions of a system, that is a prerequisite for the development of increasingly frugal, smart, and resilient systems. An illustrative example is provided to demonstrate the method.

## 2 Comparison Between Frugality, Resilience, and Smartness

In recent years, frugal innovation has attracted increasing attention from researchers in the field of manufacturing, as evidenced by a growing number of publications indexed in Scopus. Frugality in manufacturing systems refers to the engineering of essential functionalities at minimal cost and complexity, ensuring that the system delivers its core performance and expected outcomes to the customer. It intentionally avoids over-engineering, thereby reducing the total cost of ownership, including maintenance, repair, and overhaul, while promoting functional adequacy and resource efficiency. In the literature on frugal manufacturing systems, the frugal product has basic features that particularly appeal to consumers who, by necessity or choice, value products with basic functionality and quality [9]. Taking outset in product frugalization, needed for sustainability, the concept of frugality is applied to manufacturing systems [10]. A frugal

manufacturing system targets essential functionality and basic quality, while dramatically reducing material, energy, and process complexity [6, 11]. It is highly relevant for sustainability, as it relies on minimal yet essential transformation processes to produce products that meet basic needs [12].

In the literature on resilient manufacturing systems, resilience is usually defined as the ability of system to recover from an undesired state and to a desired state [13]. The following requirements for manufacturing resilience are emphasized [14]: agility, robustness, and survivability. Agility is the ability of a system to quickly and flexibly adapt to changes, emphasizing reconfigurability and responsiveness to disruptions, and focusing on speed and efficiency in adjusting to unexpected conditions. Robustness is the ability of a system to resist disturbances and continue operating as intended, it relies on stability, predictability, and preventative measures (e.g. redundancies). Survivability is the ability of a system to endure extreme disruptions and recover from them, it requires both agility (to adapt) and robustness (to resist failures). Moreover, resilience encompasses the capacity to adapt and transform into a more robust configuration that can better prevent, absorb, or withstand future disruptions [15].

In the literature on smart manufacturing systems, smartness is commonly associated with the system's capability to adapt and respond to the environment through learning and informed decision-making. Smart manufacturing systems are often understood as cyber-physical systems, in which physical operations are integrated with digital technologies that enable monitoring, analysis, and actuation [16, 17]. These systems support predictability, through the monitoring of key variables and trends, and reconfigurability, through the system's ability to adjust operations with reduced effort [8].

Literature on frugal and resilient manufacturing systems often draws comparisons with smart manufacturing systems. Building on [6], the concept of smart frugal manufacturing system (SFMS) is introduced. An SFMS is a frugal system that fulfills two essential cyber-requirements: (i) it controls operations based on the physical principles governing its processes, and (ii) it enables effective interaction between the manufacturing system and decision-making functions.

Lee et al. [14] highlights a pressing need to improve manufacturing resilience by embracing automation, digitization, and artificial intelligence, arguing that smart and digital technologies should be leveraged to develop proactive strategies to mitigate the risks of disruptions.

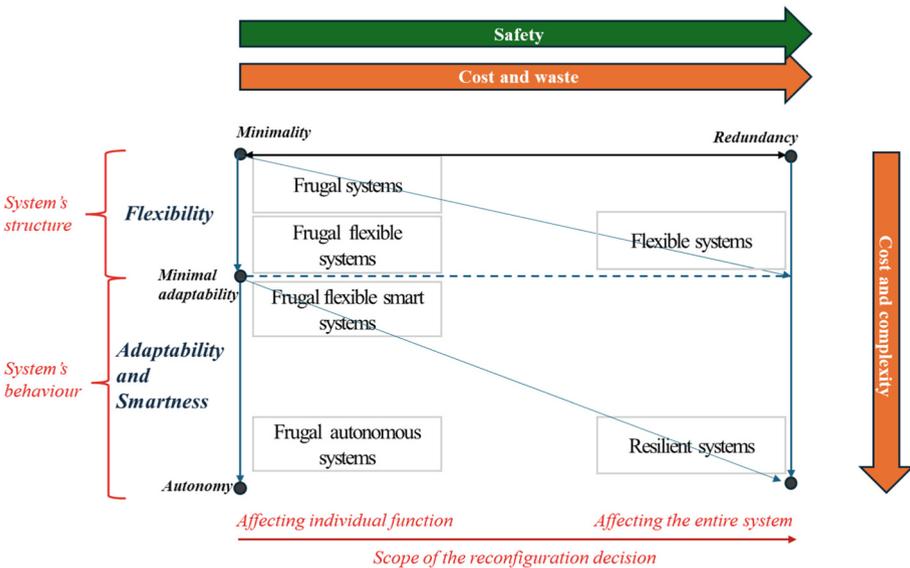
To finalize the comparison between frugality, resilience, and smartness, the systems engineering lens is adopted in Table 1. Table 1 considers the manufacturing system's structure, its behavior, and the (generic) reconfiguration decision that is required during a system's lifecycle. In Table 1, flexibility is a property of both the resilient system's structure and behavior. Structurally, it involves adjustable hardware to support variation in operations. Behaviorally, it represents the ability of the system to respond to changes within a predefined range with reasonable effort [18]. In Table 1, adaptability is used to characterize a smart system's behavior. Unlike flexibility, adaptability refers to the system's ability to respond to environmental and external changes. Generally, adaptability requires certain degrees of flexibility in both the structure and behavior of the system.

Figure 1 integrates Table 1 and compares the concepts of frugality, smartness, and resilience considering (i) structure, (ii) behavior, and (ii) scope of the reconfiguration

**Table 1.** Systems engineering lens to characterize frugality, resilience, and smartness in manufacturing systems

Aspects	Frugality	Resilience	Smartness
System’s structure	Essential functions Minimal complexity	Redundant functions, Flexibility	Cyber-physical functions
System’s behavior	Minimal use of resources	Flexibility, robustness, survivability	Adaptability, context-awareness
Reconfiguration decision	Not emphasized	Identify more robust configurations	Anticipate future requirements

decision. The scope of the reconfiguration decisions can vary: it is minimal when it concerns individual functions of the system, and maximal, when it involves the entire system, including consideration of the external context and environment.



**Fig. 1.** Impact of frugality, smartness, and resilience on manufacturing systems, considering (i) system’s structure, (ii) behavior, and (ii) scope of the reconfiguration decision.

In this paper, essential functions are defined as those functions whose implementation is required to fulfill current product demand. Their identification is foundational to improving resilience in brownfield systems.

In terms of system's structure, minimality is opposed to redundancy. Increasing redundancy in a system's physical structure may enhance resilience, safety, and reliability, but also leads to higher costs, and equipment waste. Thus, designers must strike an appropriate balance between frugality and redundancy when configuring the structure of a manufacturing systems to ensure functionality, sustainability, and economic performance. The system's structure can implement flexibility, resulting in greater cost and complexity, while providing the foundation for adaptability.

In terms of system's behavior, increasing levels of adaptability and smartness enable reconfigurations throughout the system's life cycle, but they also introduce additional cost and complexity. As shown in Fig. 1, greater adaptability and smartness enhance the ability of individual system functions to rapidly, or even autonomously, implement reconfigurations within tight timeframes or in response to unexpected events. Minimal adaptability refers to the capability of an individual function to react efficiently and promptly to anticipated changes. In addition, smartness allows predictability, through trend monitoring and risk identification, and reconfigurability, through planned adjustments with minimal effort [8]. As shown in Fig. 1, adaptability and smartness range from providing minimal adaptability to upcoming changes, to enabling real-time adaptability and autonomy. However, real-time adaptation is rarely feasible in practice due to its complexity and cost, making minimal adaptability a more pragmatic and achievable target.

Another key dimension of both system's structure and behavior is the scope of the reconfiguration decision. A reconfiguration might concern only one individual function, or an entire system.

All the dimensions introduced in Fig. 1 can be used to support the implementation of systems engineering methodologies for resilient manufacturing. System-level resilience emerges from the interplay between: (i) adaptability and smartness, (ii) flexibility, and (iii) redundancy, which together secure the continuity of essential functions.

In this paper, essential functions are defined as those functions whose implementation is required to fulfill current product demand. Their identification is foundational to improving resilience in brownfield systems.

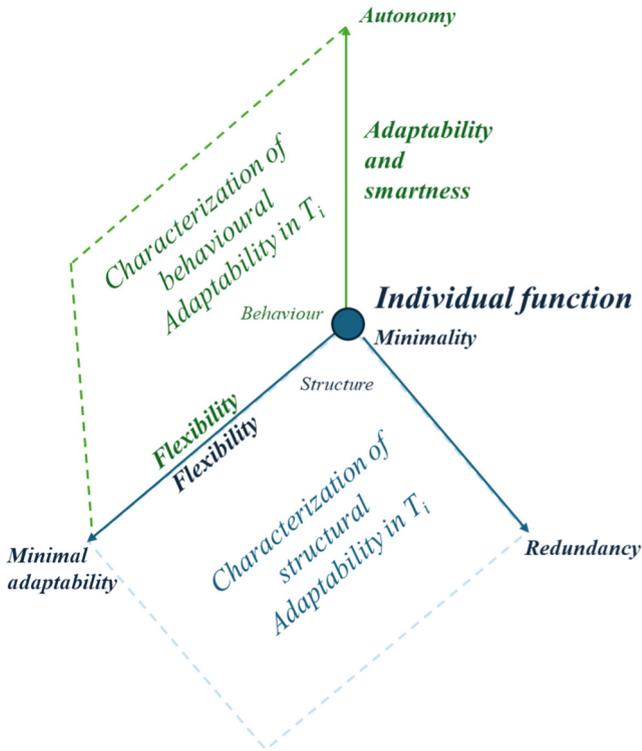
The system's ability to maintain performance under uncertainty depends on how these characteristics are implemented in individual functions, and how they change over time.

### **3 Characterization of the Essential Functions of a Brownfield Manufacturing System**

To survive and remain competitive, manufacturers must adopt systems engineering methodologies to guide reconfiguration decisions throughout the lifecycle of brownfield systems. The first step in applying a systems engineering approach to improve resilience in such systems is the identification and characterization of the system's essential functions.

Figure 2 provides a framework for characterizing the individual functions of manufacturing systems with respect to resilience. It considers minimality, redundancy, flexibility, adaptability and smartness. This framework can be used to assess the essential

functions of a brownfield manufacturing system at a given time horizon ( $T_0$ ), as well as to anticipate required functions in an upcoming time horizon ( $T_1$ ).



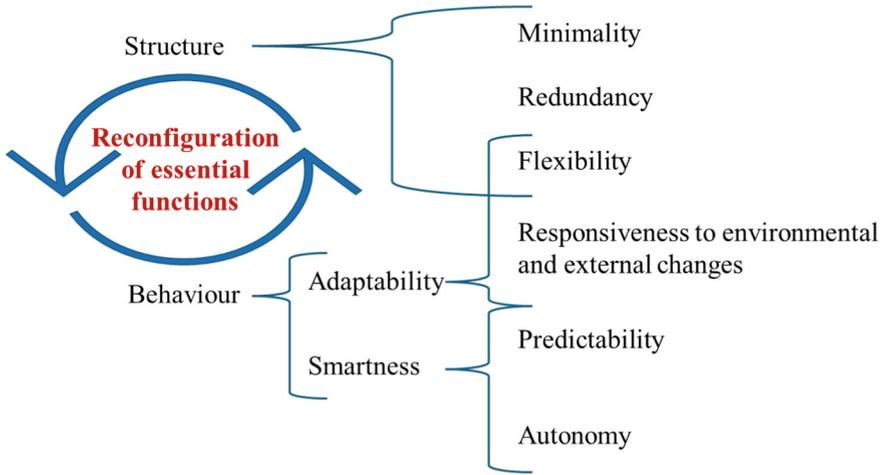
**Fig. 2.** A characterization of individual functions of manufacturing systems for resilience

In dynamic brownfield systems, essential functions must be continuously monitored to ensure they maintain adequate levels of adaptability and smartness over time. As shown in Fig. 3, the reconfiguration effort of individual functions – or of the system as a whole – depends on the structure and behavior of those functions.

The resilient structure of a brownfield system is determined by the degree of minimality, redundancy, and flexibility present in its essential functions at the current time ( $T_0$ ). The resilient behavior of the system, in turn, is constrained by this structure, and must support at least a minimal level of adaptability. Adaptability refers to the system’s ability to apply flexibility in practice, as well as to respond to environmental and external changes.

Finally, there are positive cause-effect relations between the structural and behavioral characteristics of the system and its essential functions. Learning from these relationships enables the continuous improvement of system resilience.

System-level resilience can be improved in a brownfield system once its essential functions have been identified.



**Fig. 3.** Resilient structure and behavior of essential functions influencing the reconfiguration effort of the manufacturing system (adapted from [8])

In a frugal and smart manufacturing system that guarantees minimal adaptability for resilience, the essential functions are provided with minimal levels of flexibility and smartness.

#### 4 Method for Mapping and Visualization of Essential Functions and Minimal Adaptability Requirements of Brownfield Systems

As introduced in Sect. 2, essential functions are those functions whose implementation is required to fulfill current product demand. Their identification is foundational to improving the resilience in brownfield systems. This section presents a method to map and visualize essential functions, based on the product mix manufactured in the current time horizon. The method also uses these essential functions to define the system’s minimal adaptability requirements. It is a variation of the method proposed in [19].

The method is built on a few key assumptions. It considers brownfield manufacturing systems composed of workstations, each executing specific processes or functions necessary for current production. The identification of essential functions of this brownfield system depends directly on the products being manufactured. The method is tailored for discrete products, which are composed of multiple components assembled through structured manufacturing processes, making it particularly suited to assembly systems. It also accounts for systems that manufacture multiple product families, defined as groups of related products sharing common components, and, by extension, similar manufacturing functions.

The method consists of four steps, which are explained in this section. Steps 1 and 2 are in the product domain, while steps 3 and 4 are in the manufacturing system domain. Figure 4 illustrates the method and the network-based approach used to identify essential functions and define a frugal smart system with minimal adaptability. In Fig. 4, green

boxes represent elements in the product domain, and blue boxes represent elements in the manufacturing domain. This color coding is consistently used in subsequent figures to help distinguish these domains.

Step 1 involves collecting product-related data, primarily Bills of Materials (BOMs) and product family groupings. These may be determined directly or derived using clustering methods [19, 20].

Step 2 derives the minimal set of common components across each product family that defines a frugalized product, one that meets essential functional requirements under frugal demand.

Step 3 maps these essential components to their corresponding essential manufacturing processes using workstation layout data. Under the assumption that each workstation performs one process per component set, layout data serves as a proxy for the Bill of Processes (BOP). A network mapping between components and workstations, either via a mapping function or a dual network model, reveals the essential workstations, and thereby the essential functions. The mapping of product components to manufacturing workstations can be represented as a bipartite network, where nodes on one side represent components and nodes on the other represent workstations. This network model provides a structured view of the relationships between what is produced and how it is produced, and supports both visualization and identification of essential functions.

Step 4 uses the identified essential workstations to define minimal adaptability requirements. This involves selecting relevant Key Performance Indicators (KPIs), such as mean time between failures, to determine the data that must be collected to monitor and enhance resilience. This step supports defining a frugal smart system with minimal adaptability.

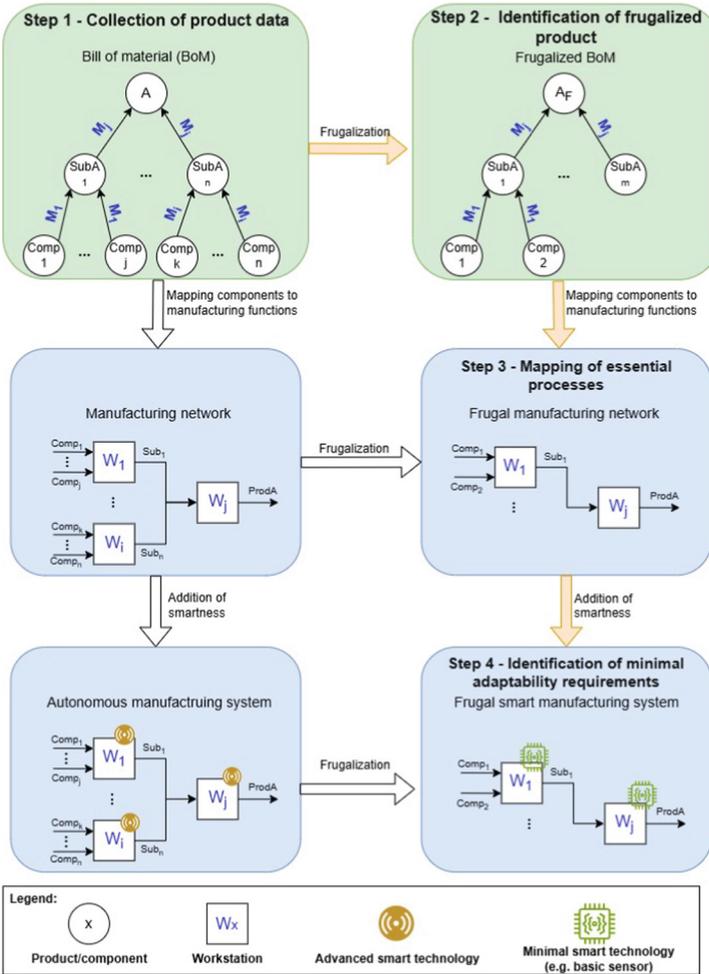
## 5 Application of the Method in an Illustrative Example

The method is applied to an illustrative example involving a manufacturing system that assembles three product types: city bikes, mountain bikes, and e-bikes. Each product type is offered in three sizes: small, medium and large. Additionally, city bikes and e-bikes are available in low-bar and high-bar frame configurations. This results in 15 variants.

In this example, essential functions are those performed by the workstations involved in producing the frugalized product, although they are not explicitly mentioned.

In step 1, BOMs of the existing products and their corresponding family groupings are collected. Figure 5 shows aggregated BOMs for the three types. Components shared across all types form the core, while mountain bike and e-bike specific components are highlighted in red and orange, respectively. Subassemblies and final products are indicated by blue and dark-blue circles. A similarity analysis of the aggregate BOMs, shows that the city and e-bike variants belong to the same product family, while mountain bikes form a separate family. For simplicity, the focus is on the larger family of 12 city and e-bike variants.

In step 2, the frugalized product is derived by simplifying the product family. City bikes are the simplest variant, sharing most components with others, this is also noticeable in Fig. 5. Based on this comparison, the frugalized product is the city bike. Additional

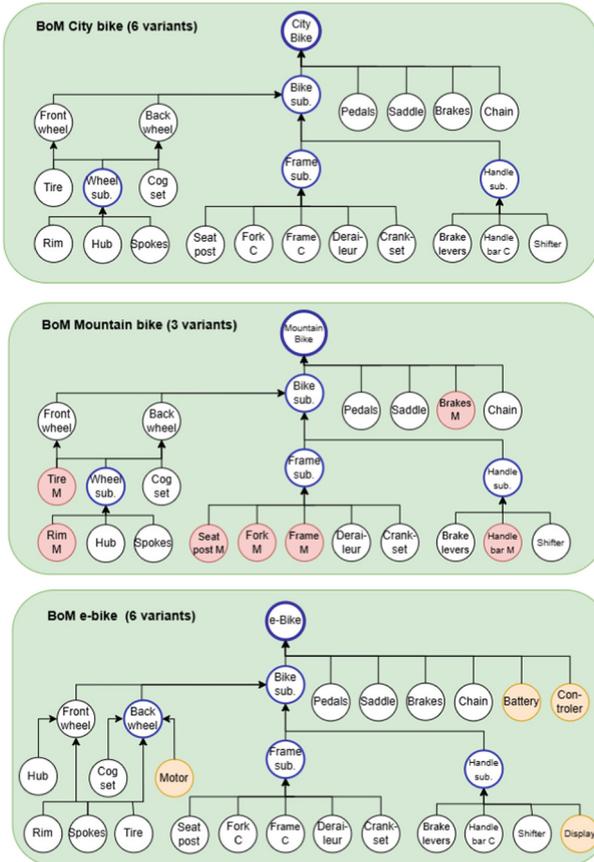


**Fig. 4.** Proposed method and network-based approach to identify essential functions and define a frugal smart system with minimal adaptability

frugalization removes the cog set, derailleur, and shifter, replacing them with a single back gear. This results in a single-speed city bike. Since sizes involve scaled parts and frame type complexity is comparable, the chosen reference is a single-speed, low-bar city bike.

Step 3 maps the frugal BOM onto the workstation network. Since the frugalized product is a strict subset of the full product mix, its workstations are also a subset of the brownfield system. These essential workstation are identified by tracing which ones assemble components of the frugalized bike. Figure 6 shows the resulting network, where nodes represent workstations and edges represent process flows. These workstations deliver the core manufacturing functions and are thus essential.

Step 4 focuses on defining the requirements for minimal adaptability. It defines what data is needed to improve system resilience. Two aspects are considered: (i) machine operation and (ii) inventory management. Sensors (e.g., vibration, temperature, power) enable early detection of issues like poor lubrication. In workstation W2, for example, vibration sensors support critical wheel balancing operations. Real-time inventory monitoring addresses supply delays or demand shifts. Technologies like machine vision and WMS track frame counts in inventory areas (e.g., for W1) and buffers (e.g., at W4). Low stock can trigger adjustments upstream to maintain flow.



**Fig. 5.** BOMs of the three bicycle types. Unique components for mountain bike and e-bike are shown in red and orange. Subassemblies and final products are indicated by blue and dark-blue circles.

The application of the proposed method to the illustrative example showcases: (i) the identification of a frugalized product (essential components), (ii) the delineation of a frugalized manufacturing system (essential functions), and (iii) the creation of its digital representation for minimal adaptability.

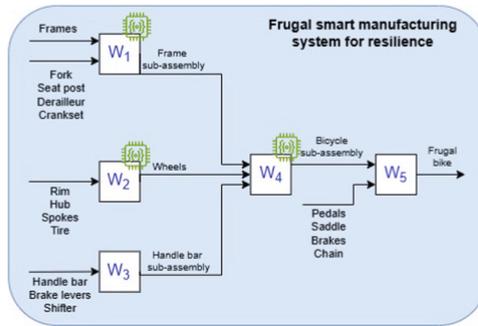


Fig. 6. Network representation of the frugal smart system for bike assembly.

## 6 Conclusion

To address the research question: “how to support the implementation of systems engineering methodologies in manufacturing for resilience” this paper adopts a systems engineering perspective to delineate the essential characteristics of future manufacturing systems that ensure resilience. It explores how the pursuit of frugality, smartness, and resilience of manufacturing systems influences the structure, behavior, and reconfiguration scope of manufacturing systems. These concepts reveal critical tradeoffs and cause-effect relationships that decision-makers must consider when designing and operating resilient manufacturing systems. This work provides both a conceptual framework and a practical method to support the incremental and strategic transformation of legacy (brownfield) manufacturing systems toward greater resilience.

The provided conceptual framework and characterization of the individual functions within manufacturing systems (summarized in Fig. 2) supports the academic understanding of resilient manufacturing. While prior research has explored the intersections of frugality and smartness or smartness and resilience, this paper integrates all three concepts. Compared to existing studies that often focus on individual aspects, such as digitalization or resource efficiency, this work emphasizes their interconnectedness within a holistic systems engineering perspective.

On the practical side, the paper introduces a structured method for mapping and visualizing essential functions in brownfield manufacturing systems. The method enables the identification of frugal smart configurations that offer minimal adaptability, a basic but sufficient alternative to costly and more complex solutions. It also allows practitioners to define stakeholder-driven minimal adaptability requirements. The illustrative example of an assembly system demonstrates how manufacturers can use this method to identify essential functions, and assess adaptability requirements based on product mix and performance goals.

The proposed method has limitations that suggest avenues for future research. It assumes that current product demand defines essential functions, potentially overlooking future adaptability needs driven by changing external conditions. The method simplifies the derivation of functional behavior from system data (e.g., BOMs, BOPs), which may not capture the system’s essential functions. The interpretation of “frugality”

also varies significantly across industries and geographies, necessitating context-specific adaptations. Future work should focus on: (i) developing metrics and methods to evaluate current system characteristics and guide improvements, (ii) build frameworks that incorporate lifecycle, environmental, and external factors to support continuous reconfiguration, and (iii) extend the method with industry-specific data and stakeholder input to enhance its applicability and precision in real-world settings.

This work concretely bridges the gap between systems engineering principles and the operational realities of legacy manufacturing systems. It provides a conceptual framework and a practical method to identify essential functions, enabling both researchers and practitioners to design and implement frugal smart configurations that support resilience under constraints.

**Disclosure of Interests.** The authors have no competing interests to declare that are relevant to the content of this article.

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