Sustainable Manufacturing Systems for Uncertainty and Shock Scenarios: A Systems Engineering-Based Approach to Robust Design and Resilience Assessment

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***Abstract*—Global manufacturing systems are confronting severe challenges from escalating uncertainties and shock events, such as geopolitical conflicts, pandemics, and climate change. Traditional paradigms for designing sustainable manufacturing systems have demonstrated significant vulnerability in coping with these dynamic disturbances. To address this issue, this paper proposes a systems engineering framework that integrates robust design and resilience assessment. The framework adapts and extends the macro-micro design cycle model, aiming to systematically enhance the adaptive and restorative capacities of manufacturing systems in uncertain environments. The macro-cycle of the framework defines the full lifecycle stages, from cognition and scenario definition, through robust architecture design and domain-specific resilience design, to resilience assessment and validation. While the integration of advanced technologies such as the system dynamics model and digital twin technology offers significant potential, these technologies often require substantial data resources and high-performance computing. In practice, companies may face challenges in fully implementing these technologies. A phased approach, starting with smaller-scale pilot applications, should be considered to allow companies to adapt to these technologies gradually, based on their available resources. While the results of the case study demonstrate the effectiveness of the proposed framework, the system dynamics model used for simulation relies on assumptions based on industry reports and expert interviews. To enhance the reliability of the data, future research should consider calibrating the model with real-world operational data and conducting additional validation through multi-scenario testing. This will ensure that the simulation results reflect real-world conditions and reduce the risks of over-simplification. This research provides a theoretical model and practical guidance for building sustainable and resilient manufacturing systems in complex, dynamic environments. Its primary theoretical contribution lies in the systematic integration of robust design, resilience assessment, and sustainability objectives within a unified systems engineering framework.**

Keywords—Sustainable Manufacturing, System Resilience, Uncertainty, Systems Engineering, Robust Design, Shock Scenarios

I. Introduction

The global manufacturing network is navigating an era of unprecedented turbulence. The reshaping of the geopolitical landscape, sudden public health crises like the COVID-19 pandemic, the increasing frequency of extreme climate events, and the rapid iteration of disruptive technologies collectively constitute a complex environment fraught with uncertainty and shocks [1, 2]. These shock events propagate rapidly through globalized supply chain networks, posing severe challenges to the stability, efficiency, and sustainability of traditional manufacturing systems [3]. Historically, the design of manufacturing systems has predominantly focused on the optimization of efficiency and cost, with sustainability being discussed mainly under stable and predictable boundary conditions. However, when faced with sudden external shocks, these highly optimized "lean" systems often exhibit significant vulnerability due to a lack of redundancy and flexibility, leading to production stoppages, delivery delays, and even supply chain collapse [4]. Consequently, how to build manufacturing systems that can not only withstand and adapt to shocks but also recover quickly from them—that is, to enhance system "resilience"—while simultaneously ensuring economic, social, and environmental sustainability, has become a core issue of concern for both academia and industry [5].

Against this backdrop, this paper aims to answer a central research question: How can uncertainty and shock scenarios be prospectively and systematically integrated into the early design stages of a manufacturing system to create a new generation of systems that are both sustainable and highly resilient? This requires a shift from traditional, static sustainability assessments to a dynamic, lifecycle-oriented resilience design thinking.

Existing research provides a vital theoretical foundation for addressing this question but also reveals clear gaps. In the field of sustainable manufacturing, methods like Life Cycle Assessment (LCA) are well-established but mostly assume a relatively stable external environment [6]. In the area of supply chain resilience, a large body of research concentrates on risk management and disruption recovery strategies at the operational level, such as multi-sourcing and holding safety stock [7, 8], but seldom deeply integrates these tactics with the initial design process of products and manufacturing

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systems. Robust Design methodologies, such as the Taguchi method, aim to reduce the sensitivity of product performance to uncertainties in the manufacturing process [9]. However, their application is often confined to parameter optimization at the product or process level, lacking consideration for macro-level shocks at the system architecture level. Although some scholars have called for the integration of sustainability and resilience [10], existing frameworks often assess them as separate objectives. A comprehensive systems engineering methodology that can intrinsically and synergistically optimize these two dimensions throughout the entire process from conceptual to detailed design is still missing. This research fragmentation makes it difficult for enterprises to find systematic solutions in practice, often leaving them in a dilemma of being "sustainable but not robust" or "robust but not sustainable."

To fill these research gaps, the objective of this paper is to propose and validate a systems engineering-based design framework for sustainable manufacturing systems oriented towards uncertainty and shock scenarios. The core contribution of this framework is its systematic integration of scenario analysis, robust design, resilience assessment, and sustainability principles, providing manufacturing enterprises with a complete methodology from strategy to execution. This study is positioned as an interdisciplinary exploration, merging the holistic thinking of systems engineering, the domain knowledge of manufacturing science, and the cutting-edge theories of sustainable development and resilience engineering. It aims to offer a new design paradigm to meet the challenges of an era rife with "black swans" and "gray rhinos."

The remainder of this paper is organized as follows: Section 2 provides an in-depth literature review of relevant theories, including sustainable manufacturing, system resilience, uncertainty management, and systems engineering. Section 3 elaborates on the proposed integrated systems engineering framework, including its macro design cycle and micro iterative process. Section 4 presents a case study of a New Energy Vehicle power battery manufacturing system to demonstrate the application of the framework for robust design and resilience assessment. Section 5 discusses the results of the case study in depth and compares them with existing research. Finally, Section 6 concludes the paper and outlines future research directions.

II. Literature Review

To construct the research framework of this paper, we have systematically reviewed the existing literature in four core areas: sustainable manufacturing systems, manufacturing system resilience, shock scenarios and uncertainty management, and systems engineering and robust design.

A. Sustainable Manufacturing Systems

Sustainable manufacturing aims to achieve sustainability throughout the entire lifecycle of manufacturing activities by integrating economic, environmental, and social considerations [11]. Its core philosophy is to create economic value while minimizing negative environmental impacts and actively fulfilling social responsibilities. Life Cycle Assessment (LCA) is one of the most widely used tools in this field, employed to quantify the environmental footprint of a product or service throughout its entire lifecycle, from raw material acquisition, production, and use to end-of-life disposal [6]. However, the traditional paradigm of sustainable manufacturing research is mostly conducted under a relatively stable macroeconomic environment. Its assessment models and optimization methods often assume stable supply chains, predictable market demand, and an unchanging policy landscape. This static or quasi-static perspective means that when faced with drastic external shocks, the sustainability performance of traditional manufacturing systems can be significantly compromised, and they may even fail to maintain basic operations [10].

B. Manufacturing System Resilience

System resilience is commonly defined as the ability of a system to absorb impacts, adapt to changes, and rapidly recover its core functions after suffering a disturbance or shock [4, 5]. In the manufacturing context, resilience implies that a system can cope with a wide range of disruptive events, from supplier defaults to natural disasters, and maintain production continuity. Research on resilience initially focused heavily on the supply chain level, with scholars proposing various strategies to enhance supply chain resilience, such as building redundant inventory, diversifying suppliers, and increasing information transparency [7, 8]. In recent years, the research perspective has gradually expanded from the supply chain to the entire manufacturing system. Alexopoulos et al. proposed a quantitative assessment method based on a "penalty of change" to measure the resilience of manufacturing systems in the face of disruptions like COVID-19, identifying flexible technologies such as additive manufacturing as key enablers of resilience [1]. De Marchi et al. developed a comprehensive model incorporating both qualitative and quantitative assessments to evaluate the resilience of manufacturing enterprises before, during, and after a crisis [12]. While these studies have laid a foundation for quantifying and assessing resilience, they mostly focus on evaluating existing systems or making improvements at the operational level, with less emphasis on how to build resilience as an inherent attribute from the initial design stage of the system.

C. Shock Scenarios and Uncertainty Management

Manufacturing systems face a wide range of uncertainties, which can be categorized into operational level (e.g., equipment failure, quality fluctuations) and strategic level (e.g., technological shifts, market upheavals, policy risks) [13]. Shock scenario analysis is a critical tool for managing strategic-level uncertainty. It involves constructing a series of plausible future events that could have a significant impact on the system (e.g., trade wars, raw material embargoes) to assess vulnerabilities and formulate contingency plans [2]. In the field of supply chain risk management, scholars have used models such as discrete-event simulation and system dynamics to simulate the ripple effects of pandemics like COVID-19 on supply chains and to analyze post-shock risks like "disruption tails" [3]. Particularly in industries highly dependent on global supply chains, such as NEV batteries, assessing the supply disruption risk of critical minerals (e.g., lithium, cobalt, nickel) has become a research hotspot. Studies have shown that supply disruptions from upstream mineral enterprises can have a massive impact on the resilience of the entire battery supply chain, and the effects of disruptions in different minerals are heterogeneous [14, 15]. Although this research provides profound insights into shock propagation mechanisms, how to effectively feed the results of scenario analysis back into the robust design of the manufacturing system remains a challenge.

D. Systems Engineering and Robust Design

Systems engineering provides a holistic, interdisciplinary approach to designing and managing complex systems. It emphasizes starting from stakeholder needs and using a structured process to define system requirements, perform functional analysis, design the architecture, and conduct integration and verification throughout the entire system lifecycle [16]. Robust design is a vital branch of systems engineering, aiming to make a system's performance output stable in the face of various uncertain "noises" [9]. The Taguchi method and Design for Six Sigma are classic examples of robust design, which reduce a system's sensitivity to manufacturing process variations through parameter and tolerance design. More recently, robust manufacturing system design has been advanced by incorporating methods like multi-objective genetic algorithms, Petri nets, and Bayesian uncertainty representation [17]. However, traditional robust design focuses more on micro-level parameter and process uncertainties. Its applicability is limited when it comes to dealing with macro-level, structural shock scenarios. Elevating the principles of robust design from the product and process level to the system architecture level is an essential requirement for coping with a turbulent external environment.

E. Summary of Research Gaps

Synthesizing the literature review above, we identify several key gaps in current research. First, sustainability and resilience objectives are often studied in isolation. Most studies either focus on optimizing sustainability in a stable environment or on enhancing resilience under shocks, lacking an integrated framework that can simultaneously consider and synergistically optimize both objectives [10]. Second, resilience assessment is disconnected from the system design process. Existing resilience assessments are mostly "post-mortem" analyses, which are ill-suited to provide forward-looking guidance for architectural decisions and parameter choices during the design phase. Third, the application scope of robust design methods is limited. Traditional robust design excels at handling internal parameter variations but falls short in addressing external, structural shocks. Finally, a comprehensive systems engineering methodology that spans the entire lifecycle to guide the design of sustainable manufacturing systems for uncertainty is lacking. These research gaps form the motivation and theoretical entry point for the new framework proposed in this paper, which attempts to build a systems engineering framework that systematically integrates sustainability principles, shock scenario analysis, system-level robust design, and dynamic resilience assessment.

III. A Systems Engineering Framework for Resilient and Sustainable Manufacturing

To systematically address the aforementioned challenges, this paper constructs a systems engineering framework for sustainable manufacturing systems oriented towards uncertainty and shock scenarios. The core idea of this framework is to treat resilience as an intrinsic attribute that permeates the entire system design lifecycle, rather than as an add-on feature for post-hoc remediation. It adapts and extends the systems engineering approach for sustainable innovation proposed by van Erp et al. [5] and deeply integrates theories of robust design, resilience assessment, and uncertainty management. The framework adopts a dual-cycle structure, comprising a "Macro Cycle" that defines the main design process and a "Micro Cycle" for iterative optimization at each stage.

A. Framework Overview

The framework (Figure 1) is intended to provide a structured thinking and operational path for design teams. The Macro Cycle divides the entire resilient system design process into four logically progressive stages, ensuring that all activities, from strategic scenario definition to implementation-level assessment and validation, are coherently linked. The Micro Cycle, inspired by the SPADE model proposed by Haskins [16], is adapted into an iterative process for resilience enhancement. It ensures that at each stage of the macro-cycle, specific solutions are generated and optimized through a rigorous, stakeholder-centric, and problem-oriented loop.

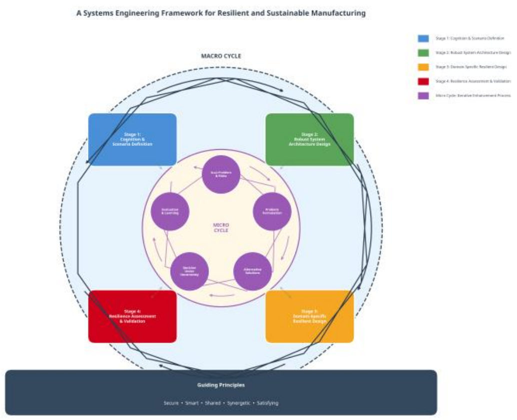

Fig. 1. A Systems Engineering Framework for Resilient and Sustainable Manufacturing

B. The Macro Cycle: The Resilient System Design Lifecycle

The macro cycle defines four main stages from concept to validation, ensuring that resilience design is integrated throughout.

Stage 1: Cognition & Scenario Definition

This stage is the starting point of the entire framework. Its goal is to gain a deep understanding of the system's macro-environment and to identify uncertainties and shocks that could have a significant impact. Key activities include:

1) System Boundary and Stakeholder Analysis: Define the boundaries of the manufacturing system, identify all key internal and external stakeholders (e.g., suppliers, customers, employees, government regulators), and analyze their expectations and risk concerns.

2) Uncertainty Source Identification: Use analytical tools like PESTLE (Political, Economic, Social, Technological, Legal, Environmental) to systematically scan and identify various sources of uncertainty that could affect the system.

3) Shock Scenario Construction: Based on the identified key uncertainties, construct a series of specific and plausible shock scenarios. Each scenario should detail its trigger factors, scope of impact, intensity, duration, and probability of occurrence. For example, in the NEV battery manufacturing case, scenarios could include "the price of a critical raw material (e.g., lithium) increases by 300% within three months" or "a major export market imposes new trade barriers."

Stage 2: Robust System Architecture Design

With a full understanding of potential shocks, the goal of this stage is to design a top-level system architecture with inherent robustness to minimize its sensitivity to external disturbances. This is not about seeking a single optimum but rather a design that performs "good enough" across multiple future scenarios. Key strategies include:

4) Modular Design: Decompose the complex manufacturing system into relatively independent modules connected by standard interfaces. This helps to isolate failures and allows for the rapid replacement or upgrade of affected parts.

5) Redundancy and Diversification: Introduce redundancy or diversification at critical nodes (e.g., suppliers, production lines, logistics routes). For example, establishing a "primary-backup" supplier system or designing flexible production units capable of manufacturing multiple products.

6) Decoupling and Buffering: Set up buffers (e.g., strategic inventory) between different parts of the system to decouple interdependencies and absorb upstream fluctuations, preventing the rapid propagation of disruptions.

Stage 3: Domain-Specific Resilient Design & Integration

This stage refines the macro architectural principles into specific manufacturing domains. It involves designing and integrating specific resilience-enhancing measures for different segments of the value chain.

7) Supply Chain Resilience: Design the supply chain network topology, develop a supplier collaboration and risk monitoring platform, and use digital twin technology for real-time visualization and stress testing of the supply chain.

8) Production Operations Resilience: Adopt technologies like flexible automation and Reconfigurable Manufacturing Systems (RMS) to improve the responsiveness of production lines to product changeovers and capacity adjustments. Concurrently, enhance the resilience of human resources through cross-training and knowledge management.

9) Cyber-Physical System (CPS) Resilience: Ensure the cybersecurity and data reliability of the Manufacturing Execution System (MES) and Industrial Internet of Things (IIoT) platforms, and establish data backup and disaster recovery mechanisms.

Stage 4: Resilience Assessment & Validation

While the resilience assessment and validation stage provides valuable quantitative analysis, implementing advanced technologies like system dynamics models and digital twins requires substantial computing power and data integration capabilities. For industries with fewer resources, a more scalable solution could be developed, beginning with simpler models and expanding to more complex simulations as technological capabilities and data availability improve.

10) Modeling and Simulation: Build a dynamic simulation model of the manufacturing system. Common methods include System Dynamics, Agent-Based Modeling, or Discrete-Event Simulation. The model must be able to reflect the dynamic behavior of the system under shock.

11) Resilience Metrics Quantification: Define a clear set of resilience assessment metrics. Typical metrics include: degree of performance loss (e.g., maximum production capacity drop), recovery time, recovery cost, and absorptive capacity (the maximum shock intensity the system can withstand without functional degradation).

12) Alternative Comparison and Selection: Run the simulation model under the constructed shock scenarios to obtain resilience metric data for each design alternative. Combine these results with economic cost and sustainability assessments (e.g., LCA) to perform a multi-criteria decision analysis and select the overall optimal system design.

C. The Micro Cycle: The Iterative Resilience Enhancement Process

The micro cycle is a continuous, iterative problem-solving loop that operates within each stage of the macro cycle, ensuring that every design decision is well-considered.

1) Stakeholders & Risks: For the specific problem at the current stage, re-examine the relevant stakeholders and the specific risks they face.

2) Problem Formulation: Translate a vague challenge (e.g., "improve supply chain resilience") into one or more clear, quantifiable engineering problems (e.g., "How to reduce the disruption risk of critical component A's supplier by 50% with a procurement cost increase of no more than 10%?").

3) Alternative Robust Solutions: Use creative methods like brainstorming or TRIZ (Theory of Inventive Problem Solving) to generate multiple possible solutions for the defined problem.

4) Decision-making under Uncertainty: Evaluate the performance, cost, and risk of each alternative solution under different scenarios. Methods like decision matrices or Pareto analysis can be used to trade-off between multiple (often conflicting) objectives and select the most robust solution.

5) Evaluation & Learning: Conduct small-scale tests or detailed simulations of the selected solution to evaluate its effectiveness. Document the evaluation results and the knowledge gained during the process as input for the next iteration or the next macro-cycle stage.

D. Principles for Resilience and Sustainability

To guide the application of the entire framework, we adapt the Integrated Value model proposed by Visser [5] and combine it with the core ideas of resilience engineering to distill five guiding principles:

- Secure: Emphasizes the reliability, safety, and anti-fragility of the system. The design should be able to predict and withstand potential threats and shocks, ensuring the continuity of core functions, which is the cornerstone of resilience.

- Smart: Emphasizes the use of information technology and data-driven methods. Through technologies like digital twins and AI-based prediction, it enables real-time situational awareness, early risk warning, and intelligent decision-making, thereby enhancing the system's adaptive capacity.
- Shared: Emphasizes openness and collaboration. By sharing information, resources, and risks with supply chain partners and even cross-industry players, it builds a more resilient ecosystem rather than an isolated "corporate fortress."
- Synergetic: Emphasizes resource efficiency and the circular economy. By designing closed-loop supply chains and promoting industrial symbiosis, it not only reduces the environmental footprint (sustainability) but also reduces dependence on external inputs through diversified resource sources and internal circulation (resilience).
- Satisfying: Emphasizes a human-centric approach. A truly resilient system must consider not only hardware and processes but also the well-being, skills, and satisfaction of its employees. A positive and healthy organizational culture is the strongest soft power for coping with crises.

These five principles collectively form the value foundation of this framework, ensuring that in the pursuit of resilience, the economic, environmental, and social objectives of sustainable development are comprehensively and synergistically achieved.

IV. Case Study: New Energy Vehicle Power Battery Manufacturing System

Although the case study provides a relevant and insightful application of the framework, it is based on assumptions regarding the data from the NEV battery manufacturing system. To improve the robustness of the findings, future studies should collect real-time data from actual NEV manufacturers and use these data to refine the system dynamics model. Additionally, further testing should be done in other industries to ensure that the framework performs reliably in different contexts and real-world conditions. Second, the industry is highly globalized, with long and complex supply chains that are extremely sensitive to uncertainties such as geopolitical shifts, raw material price volatility, and technological disruptions [14]. Finally, the production and recycling of power batteries involve significant environmental and social issues, making it an ideal "testbed" for an integrated sustainability and resilience framework.

A. *Case Background Description*

The manufacturing system for NEV power batteries is a classic complex system. Its value chain spans from upstream mineral resource extraction (e.g., lithium, cobalt, nickel), to midstream manufacturing of key materials like cathodes, anodes, electrolytes, and separators, and finally to downstream cell assembly, battery pack integration, and delivery to automotive OEMs. The system's vulnerabilities are mainly manifested in the following aspects:

- Highly Concentrated Raw Material Supply: The geographical distribution of key raw materials like lithium and cobalt is extremely uneven, with mining and refining capacities highly concentrated in a few countries and regions. This makes the supply chain highly susceptible to geopolitical conflicts, policy changes in resource-rich nations, or production disruptions at a single major mine [15].
- Technological Route Uncertainty: Battery technology is still in a state of rapid iteration. The shift from Lithium Iron Phosphate (LFP) to high-nickel ternary (NCM/NCA) and towards future solid-state batteries could lead to the rapid obsolescence of existing production equipment and supply chain investments.
- Dynamic and Variable Policy Environment: Government subsidy policies for NEVs, environmental regulations, tariff policies, and battery recycling requirements are constantly changing, creating huge uncertainty for long-term corporate strategic planning.
- Complex Production Processes: Battery production involves dozens of precision processes with extremely high requirements for environmental cleanliness and process parameter control. Minor fluctuations in any single step can affect the performance and safety of the final product.

B. *Application of the Macro Cycle*

We follow the four stages of the macro cycle proposed in Section 3 to analyze the system design process of a virtual power battery manufacturing company (hereinafter referred to as "BattCo").

1) *Stage 1: Cognition & Scenario Definition*

In the cognition stage, BattCo's design team first identified the key uncertainties affecting its manufacturing system and constructed two representative shock scenarios for subsequent stress testing:

- Scenario A: Critical Raw Material Supply Disruption. It is assumed that the country where BattCo's main cobalt supplier is located announces a six-month export ban on cobalt ore and related products due to domestic political turmoil. This scenario would directly impact BattCo's raw material procurement, leading to soaring costs and production interruptions.
- Scenario B: Major Market Trade Barrier. It is assumed that the main export market for BattCo's products (accounting for 40% of its sales) suddenly imposes a 50% punitive tariff on imported power batteries to protect its domestic industry, rendering BattCo's products uncompetitive in that market.

2) *Stage 2: Robust System Architecture Design*

In response to the above scenarios, the design team proposed two distinct system architecture alternatives for comparison:

- Alternative 1 (Traditional Cost-Optimal Architecture): This alternative follows the traditional principle of cost minimization. In terms of the supply chain, it involves signing long-term, large-volume contracts with a few suppliers located in low-cost regions to gain price advantages. For production, it establishes a large-scale, centralized "gigafactory" in China to achieve economies of scale. In product design, it focuses on the high-nickel ternary battery technology that was mainstream at the time.

- Alternative 2 (Robust and Resilient Architecture): This alternative is designed with resilience and sustainability as core principles. For the supply chain, it adopts a "core + diversification" strategy, i.e., deep collaboration with 1-2 core suppliers while cultivating 2-3 backup suppliers in different regions (near-shoring). It also invests in cobalt recycling technology to establish an "urban mine" as a supplementary source. For production, it employs a "global footprint + flexible manufacturing" model. In addition to the core factory in China, it establishes two smaller but highly flexible regional factories in Europe and North America. These factories can switch between different technology routes (e.g., NCM and LFP) based on market demand and supply chain conditions. For product design, it uses a modular battery pack design to facilitate repair, second-life use, and disassembly for recycling.

3) Stage 3: Domain-Specific Resilient Design & Integration

Within the framework of Alternative 2, the design team further designed specific resilience-enhancing measures:

- Supply Chain Domain: A supply chain digital twin platform based on blockchain is established to achieve real-time tracking and visualization of material flow, information flow, and capital flow from mine to factory. The platform has a built-in risk warning model that can predict potential supply disruption risks in advance based on unstructured data such as geopolitical news and satellite imagery.

- Production Operations Domain: The production lines of the regional factories are designed based on the Reconfigurable Manufacturing System (RMS) concept. Key equipment (e.g., coating machines, stacking machines) uses standardized modules, allowing for line reconfiguration within 48 hours to adapt to the production of cells with different sizes and chemical systems. A training and certification system for multi-skilled workers is also established.

4) Stage 4: Resilience Assessment & Validation

To quantitatively compare the resilience of the two alternatives, we built a System Dynamics model. The model includes several subsystems such as supply chain, production, inventory, and finance, and can simulate the changes in the company's Key Performance Indicators (KPIs) over time under the two shock scenarios.

- Model Construction: The core causal loops of the model include the "demand-production-inventory" loop and the "supply disruption-capacity decline-revenue loss" loop. Key parameters are set based on industry reports and expert interviews, such as supplier switching time, line reconfiguration cost, and tariff impact.

- Resilience Metrics: We use a "performance loss curve" (Figure 2) to visually represent and quantify resilience. Based on this curve, the following core metrics can be calculated:

a) Absorptive Capacity: The magnitude of performance decline after the shock occurs.

b) Recovery Speed: The time required for the system's performance to recover from its lowest point to a normal level.

c) Total Performance Loss: The area enclosed between the performance loss curve and the normal performance level line, representing the total loss caused by the shock.

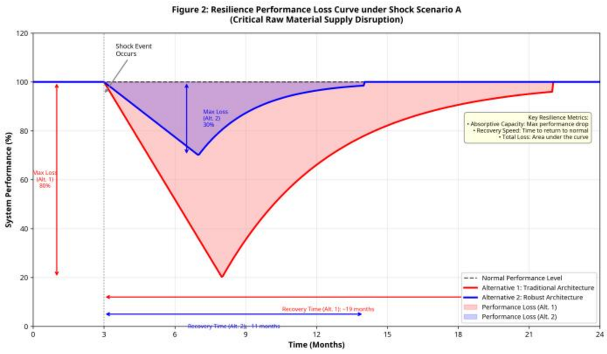

Fig. 2. Schematic of the Resilience Performance Loss Curve

C. Application of the Micro Cycle

During the third stage of the macro cycle, when the design team was devising specific supply chain strategies for Alternative 2, they applied the micro cycle to solve a specific problem: "How to cope with a 200% increase in the price of cobalt metal in the short term (e.g., one month)?"

1) Problem Formulation: The problem was defined as "How to control the cost increase of cathode materials to within 30% when the price of cobalt skyrockets, while keeping the basic performance of the cells unchanged?"

2) Alternative Solutions Generation: The team generated three alternative solutions: (a) Immediately activate the procurement contracts signed with backup suppliers, which have relatively fixed prices; (b) Urgently adjust the cathode material formula of some production lines, temporarily switching to a mid-nickel, high-voltage NCM material with lower cobalt content; (c) Use the strategic reserve of cobalt metal while seeking short-term hedging financial instruments in the market.

3) Decision-making under Uncertainty: The team evaluated the pros and cons of each solution. Solution (a) had a fast response but limited backup volume; solution (b) could fundamentally reduce costs but required time for line debugging and product validation; solution (c) could immediately stabilize costs but would consume a valuable strategic reserve. Ultimately, the decision was to adopt a combination of (a) and (b): immediately activate the backup contracts to meet short-term demand while initiating the line conversion procedure as a medium-term solution.

4) Evaluation & Learning: This decision-making process was documented and prompted the team to further optimize the contract terms of backup suppliers and the efficiency of flexible line switching in subsequent designs.

D. Results and Analysis

By running the system dynamics simulation, we obtained a comparison of the resilience performance of the two architectural alternatives under the two shock scenarios (Table I).

TABLE I. COMPARISON OF RESILIENCE METRICS FOR THE TWO ARCHITECTURAL ALTERNATIVES UNDER SHOCK SCENARIOS

Metric	Scenario	Alternative 1 (Traditional)	Alternative 2 (Robust)	Resilience Improvement
Max. Production Capacity Loss	Scenario A (Supply Disruption)	80%	30%	62.5%
	Scenario B (Trade Barrier)	40%	15%	62.5%
Recovery Time (Months)	Scenario A (Supply Disruption)	12	4	66.7%
	Scenario B (Trade Barrier)	9	3	66.7%
Total Profit Loss (M USD)	Scenario A (Supply Disruption)	1200	350	70.8%
	Scenario B (Trade Barrier)	650	150	76.9%
Total Lifecycle Cost (M USD)	-	5000	5500	-10%
Lifecycle Carbon Emissions (kT CO2e)	-	250	270	-8%

While the simulation results clearly demonstrate the potential advantages of Alternative 2 (Robust Architecture), its implementation relies on complex systems such as supply chain diversification, flexible manufacturing, and digital twin platforms. These high-complexity systems need further validation across different industries to ensure that the results are replicable in diverse real-world settings. To mitigate the risk of non-reproducibility, further case studies should be conducted to test the framework's applicability across various industrial environments. In the trade barrier scenario, its global production footprint and flexible manufacturing capabilities enabled it to quickly shift production capacity to unaffected markets, again demonstrating strong shock resistance.

Further analysis reveals that the investment in the robust architecture is not purely a cost. For example, while diversified procurement may not secure the lowest price in the short term, it avoids the huge risk of paying an "exorbitant" price to find alternatives during a supply disruption. Similarly, while the investment in flexible production lines is expensive, it endows the company with the ability to respond quickly to market and technological changes, which is itself a long-term competitive advantage. A comprehensive assessment of cost, sustainability (carbon emissions), and resilience (total profit loss) shows that Alternative 2 has an overwhelming strategic advantage, proving the immense value of making forward-looking resilience investments at the design stage.

V. DISCUSSION

The core of this research lies in constructing and validating a design framework that can systematically integrate sustainability, robustness, and resilience for manufacturing systems. The results of the case study not only demonstrate the framework's operability but also provide profound insights into the complex relationships between these core concepts.

A. *Interpretation of Results and Implications*

The most direct finding from the case study is that resilience is a strategic capability that requires proactive investment, not a passive cost burden. The high efficiency of the traditional cost-optimal architecture (Alternative 1) in a stable environment quickly transformed into immense vulnerability in the face of shocks. The resulting profit loss far exceeded the increased lifecycle cost of the robust and resilient architecture (Alternative 2). This quantitatively proves that viewing resilience investment as a form of "insurance" or a strategic moat is valid. By front-loading resilience assessment into the design stage, our framework enables such investment decisions to be based on data and a rational analysis of future uncertainties, rather than relying solely on intuition.

Second, the study reveals that the effectiveness of resilience strategies is context-dependent. In Scenario A (raw material supply disruption), supply chain diversification and investment in "urban mining" played a decisive role. In contrast, in Scenario B (trade barriers), a global production footprint and production line flexibility became key. This indicates that there is no single "one-size-fits-all" resilience solution. A truly resilient system is the result of an organic combination of multiple strategies. The value of the macro cycle proposed in this framework, particularly the "Cognition & Scenario Definition" stage, lies precisely here—it compels the design team to think about the multiple threats the system may face from the outset, thereby building a defense-in-depth system capable of handling different types of shocks.

Finally, this study delves into the synergistic and trade-off relationships between sustainability and resilience. In some respects, the two exhibit significant synergy. For example, in the case study, investing in battery recycling technology not only enhanced resilience against raw material supply disruptions by building an "urban mine" but also aligned with the sustainable development principle of a circular economy. However, there are also clear trade-offs. While the global footprint of Alternative 2 enhanced market resilience, its dispersed logistics network also led to higher lifecycle carbon emissions. This trade-off relationship is objective, and avoiding it does not help in making scientific decisions. The contribution of our framework is that it provides a platform to quantitatively assess both dimensions (along with the cost dimension) simultaneously. This allows decision-makers to clearly see the position of different design choices in the three-dimensional space of "sustainability-resilience-cost" and to make informed, data-supported trade-offs based on the company's strategic preferences.

B. *Comparison with Existing Research*

Compared to the existing literature, the contribution of this study is mainly reflected in two aspects: "integration" and "front-loading." First, our work significantly extends the systems engineering approach proposed by van Erp et al. [5].

While they laid the foundation for applying systems engineering to sustainable innovation, our framework operationalizes it by explicitly introducing uncertainty analysis, shock scenarios, and robust design principles to address a specific challenge of today's turbulent environment—resilience. Second, in contrast to the mainstream supply chain resilience literature [7, 8], which mostly focuses on operational-level tactics (e.g., increasing inventory), our framework elevates resilience to the strategic level of system architecture design, achieving a fundamental shift from "passive response" to "proactive design." Third, we have adopted and advanced the resilience quantification assessment method proposed by Alexopoulos et al. [1]. We not only assess the resilience of an existing system but, more importantly, we feed the assessment results back into the design loop to compare and select different design alternatives, thus forming a closed loop of "design-assess-optimize." Finally, this framework provides a concrete and actionable answer to the call for integrating sustainability and resilience made by Roostaie et al. [10]. Through the case study, we not only theoretically explored the possibility of combining the two but also quantitatively measured the synergy and trade-offs between them at a practical level, providing more detailed and in-depth insights than previous studies.

C. Theoretical and Practical Implications

At the theoretical level, the main contribution of this research is the construction of a unified, dual-cycle systems engineering framework that systematically integrates the four previously relatively independent theoretical fields of sustainable manufacturing, system resilience, robust design, and systems engineering. It provides a new theoretical paradigm for designing the next generation of manufacturing systems in an increasingly complex and uncertain world, emphasizing a shift in thinking from static optimization to dynamic adaptation.

At the practical level, the framework provides managers and engineering leaders with a concrete methodology from strategy to execution. It helps companies translate the vague strategic intent of "enhancing resilience" into a series of structured, actionable steps. Specifically, it provides a set of tools for: (1) identifying and structuring complex internal and external uncertainties; (2) designing robust system architectures that can withstand unknown risks; (3) justifying resilience investments with a business case through quantitative analysis, clearly demonstrating their long-term value to management; and (4) making strategic trade-offs between short-term cost efficiency and long-term survivability and sustainable development. In short, it is a powerful strategic decision-support tool.

D. Limitations and Future Research

Despite the progress made in this study, some limitations still exist. First, the case study is based on a system dynamics simulation model. Although its parameters and assumptions are based on industry data and expert knowledge, it is still a simplification of the real world. The "messiness" of organizational decision-making and the unavailability of data in the real world would pose more challenges. Second, the quantitative assessment of some resilience principles, especially the "Satisfying" principle involving people, remains a challenge and was not fully reflected in the quantitative model of this study. Finally, the successful implementation of the framework requires a high level of cross-departmental collaboration and data analysis capabilities within a company, which may pose an application barrier for some organizations.

Based on these limitations, future research can be expanded in the following directions. First, apply the framework to real industrial cases. Through longitudinal case studies in collaboration with companies, the effectiveness of the framework in practical applications can be tested and refined. Second, deepen the resilience assessment model, especially by exploring how to integrate machine learning and artificial intelligence technologies into the framework to achieve real-time risk prediction and dynamic assessment of system resilience. For example, natural language processing could be used to analyze global news to provide early warnings of geopolitical risks. Third, expand the application domain of the framework. The framework could be applied to other complex system design problems that also face high uncertainty, such as energy networks, urban transportation systems, or public health emergency systems, to test its universality.

VI. Conclusion

In an era where the global manufacturing environment is increasingly defined by uncertainty and sudden shocks, traditional design paradigms are no longer adequate to meet the dual demands of long-term survival and sustainable development. To address this core challenge, this paper has proposed and validated a systems engineering-based design framework for sustainable manufacturing systems oriented towards uncertainty and shock scenarios. The core contribution of this framework is that it does not simply juxtapose sustainability and resilience objectives. Instead, through a dual-cycle, structured process, it deeply integrates robust design principles, dynamic resilience assessment, and sustainable development concepts. It provides a clear theoretical model and a practical path for prospectively building a manufacturing system that is economically viable, environmentally friendly, and highly adaptive, right from the initial design stages.

Through a case study of the New Energy Vehicle power battery manufacturing system, we have demonstrated the practical value of the framework. The results quantitatively show that strategic investment in resilience during the design phase, although it may lead to a short-term increase in costs, yields significant long-term returns by avoiding massive losses when faced with external shocks. More importantly, this research reveals the complex synergistic and trade-off relationships between sustainability and resilience. It proves that our framework can provide decision-makers with a quantitative and transparent platform to make wise, data-supported strategic choices in such multi-dimensional, complex decisions.

In summary, this research advocates for and puts into practice a paradigm shift from "static efficiency optimization" to "dynamic adaptive design." We believe that as the global environment continues to be turbulent, embedding resilience as a core capability into the DNA of manufacturing systems will be key for leading enterprises to build their core competitiveness in the future. The framework proposed in this paper provides a feasible intellectual framework and a set of operational tools for this purpose

References

[1] Alexopoulos, K., Anagiannis, I., Nikolakis, N., & Chryssolouris, G. (2022). A quantitative approach to resilience in manufacturing systems. International Journal of Production Research, 60(24), 7178-7193.DOI:10.1080/00207543.2021.2018519

[2] Ivanov, D. (2024). Exiting the COVID-19 pandemic: After-shock risks and avoidance of disruption tails in supply chains. Annals of Operations Research, 335(3), 1627-1644.DOI:10.1007/s10479-021-04047-7

[3] Hohenstein, N. O. (2022). Supply chain risk management in the COVID-19 pandemic: strategies and empirical lessons for improving global logistics service providers' performance. The International Journal of Logistics Management, 33(4), 1336-1365.DOI:10.1108/IJLM-02-2021-0109

[4] Bhamra, R., Dani, S., & Burnard, K. (2011). Resilience: the concept, a literature review and future directions. International journal of production research, 49(18), 5375-5393.DOI:10.1080/00207543.2011.563826

[5] Van Erp, T., Haskins, C., Visser, W., Kohl, H., & Rytter, N. G. M. (2023). Designing sustainable innovations in manufacturing: A systems engineering approach. Sustainable Production and Consumption, 37, 96-111.DOI:10.1016/j.spc.2023.02.007

[6] Cosme, N., Hauschild, M. Z., Molin, C., Rosenbaum, R. K., & Laurent, A. (2019). Learning-by-doing: experience from 20 years of teaching LCA to future engineers. The International Journal of Life Cycle Assessment, 24(3), 553-565.DOI:10.1007/s11367-018-1457-5

[7] Christopher, M., & Peck, H. (2004). Building the resilient supply chain.DOI:10.1108/09574090410700275

[8] Sheffi, Y., & Rice Jr, J. B. (2005). A supply chain view of the resilient enterprise. MIT Sloan management review.

[9] Bergman, B., De Maré, J., Svensson, T., & Loren, S. (Eds.). (2009). Robust design methodology for reliability: exploring the effects of variation and uncertainty. John Wiley & Sons.

[10] Roostaie, S., Nawari, N., & Kibert, C. J. (2019). Integrated sustainability and resilience assessment framework: From theory to practice. Journal of Cleaner Production, 232, 1158-1166.DOI:10.1016/j.jclepro.2019.05.382

[11] Jovane, F., Koren, Y., & Boer, C. R. (2003). Present and future of flexible automation: towards new paradigms. CIRP Annals, 52(2), 543-560.DOI:10.1016/S0007-8506(07)60203-0

[12] De Marchi, M., Friedrich, F., Riedl, M., Zadek, H., & Rauch, E. (2023). Development of a resilience assessment model for manufacturing enterprises. Sustainability, 15(24), 16947.DOI:10.3390/su152416947

[13] Koh, S. L., & Gunasekaran, A. (2006). A knowledge management approach for managing uncertainty in manufacturing. Industrial Management & Data Systems, 106(4), 439-459.DOI:10.1108/02635570610661561

[14] Lou, G., Wang, H., Tu, X., Lai, Z., Ma, H., & Ying, S. (2025). Resilience assessment of the electric vehicle lithium-ion battery supply chain under supply shortages of upstream mineral enterprises. Resources, Conservation and Recycling, 215, 108161.DOI:10.1016/j.resconrec.2025.108161

[15] Shao, L., & Jin, S. (2020). Resilience assessment of the lithium supply chain in China under impact of new energy vehicles and supply interruption. Journal of cleaner production, 252, 119624.DOI:10.1016/j.jclepro.2019.119624

[16] INCOSE (Ed.). (2023). INCOSE systems engineering handbook. John Wiley & Sons.

[17] Sharda, B., & Banerjee, A. (2013). Robust manufacturing system desi gn using multi objective genetic algorithms, Petri nets and Bayesian u ncertainty representation. Journal of Manufacturing Systems, 32(2), 3 15-324.DOI:10.1016/j.jmsy.2013.01.001DOI:10.1016/j.jmsy.2013.01.001

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AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Yiming Liu: Conceptualization, Methodology, Writing - Original Draft, Supervision, Project Administration. Yiming Liu was responsible for the overall research design, framework development, and drafting of the manuscript. He also supervised the research process and managed the project.

Gongyuan Li: Data Curation, Formal Analysis, Investigation, Writing - Review & Editing. Gongyuan Li contributed to data collection, conducted the data analysis, and played a significant role in reviewing and editing the manuscript to improve its clarity and quality.

Dongmao Ye: Software, Visualization, Writing - Review & Editing. Dongmao Ye contributed to the development of simulation models and provided technical expertise for data visualization. Additionally, he contributed to reviewing and editing the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.