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AI-enabled Design for Resilience and Adaptability in Concurrent Engineering Education

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Abstract: The many interdependencies of product, process, manufacturing, supply and life cycle decisions in a concurrent engineering product development process can also increase the risk of operational disruptions due to the speed of development and the high degree of interdependency. Requirements change; supplier volatility, component obsolescence, cyber-physical defects, regulatory changes, and environmental risks can cascade quickly through interacting design decisions. This paper proposes a more inclusive conceptual model for the introduction of the integration of AI for design of resilience and adaptability within the context of concurrent engineering education. It maintains five core principles, which are linked directly and closely to fundamental capacities for resilience: Modularity, Redundancy, Flexibility, Feedback and Learning, and Collaborative Networks; and links these to five core capacities: Anticipation, Absorption, Recovery, Adaptation, and Learning. Additionally, the paper differentiates between resilience and reliability, robustness, flexibility and adaptability; introduces a life cycle risk-to-design workflow; and clarifies the role of digital twins, configuration management, change-impact analysis and cross-functional governance in providing evidence-based educational and industrial responses. The analysis does not consider resilience as a product attribute, but rather as a property of a system – one that is created by the interplay of technical architecture, organizational coordination, the relationships with suppliers, information quality and recovery procedures. The manuscript draws from a comprehensive review of the latest published literature and contains conceptual integration and an executable validation plan to inform future research and engineering education at different points in the life cycle and in complex industries.

Keywords: Concurrent engineering; Resilience engineering; Adaptable design; Modularity; Redundancy; Flexibility; Change propagation; Digital twins; Lifecycle engineering; Supply-chain risk.

Introduction

The engineering industry today faces a context of changing customer demands, fast technological progress, fluctuating supplies, climate-related risks and challenges, cyber threats, and highly globalized value chains. In this complex environment, product architectures need to be both structurally sound during normal operation and resilient to stand up to, adapt to, and recover from unforeseen operational challenges. In concurrent engineering, the product design, manufacturing planning, procurement, verification and service life cycle activities are carried out concurrently, which is where this balance is very important. Concurrent engineering reduces the delays that are typical in the development process by having downstream functions in the engineering process with the design. But with parallel workflows, the coordination complexity is great: changes to a design in one technical area can lead to changes in other subsystems, affect thermal performance, impact supply chains and affect regulatory compliance. These are two basic properties of a system that must be carefully distinguished for achieving systemic stability: resilience, that is, the ability of the system to withstand, absorb, and reorganize after the disturbances without loss of important functions, and adaptability, that is the ability to change the system configuration, behavior, or structure when it is required to do so by external demands. Modern engineering education must incorporate the use of AI directly into the concurrent

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engineering pedagogy to prepare future professionals for these very complex trade-offs.

The integration of AI in concurrent engineering shifts the focus from a linear approach to problem-solving to an interactive, data-driven collaborative learning process. Pedagogical constructs such as modularity, redundancy, flexibility, feedback and learning, and collaborative networks are the foundational principles of system resilience and adaptability when supported by the application of computational intelligence. Modularity helps to isolate failures in subsystems and allows for quick replacement of components. Machine learning algorithms, in educational environments, can identify and model complex interface dependencies that then automatically suggest the most optimal architectural boundaries, which are the balance between functional independence and efficiency of manufacturing. The inclusion of predictive machine learning models enables engineering students to assess how different modular design options affect the toolpaths, material distribution, and performance of additive manufacturing processes (Alli et al., 2024; Ekengwu et al., 2026). Moreover, although redundancy is critical to deal with failure, if redundancy is not optimized, it imposes significant penalties on system mass, power consumption, and life cycle cost. The use of AI-driven generative design tools enables students to perform extensive trade-off analyses, thereby optimizing the system reliability along with real-time failure prognosis (Wang et al. 2013). Students assess the level of hardware and software redundancy in AI-powered digital twin environments and design proportionate levels of resilience based on quantitative risk profiles (Lin et al., 2026).

Systemic Flexibility: The ability of a product or system to change modes of operation when functional requirements or environmental conditions change. The students study high-level computing concepts like the neuromorphic computing and adaptive control systems which enable dynamic reconfiguration of processing paths in smart infrastructure and embedded systems, when faced with physical or cyber disturbances (Firoozi et al., 2024; Sharbaf, 2026). The application of these concepts in the concurrent engineering coursework shows how adaptability can be directly integrated in physical and cyber-physical architectures. Moreover, resilient design requires closed loop, feedback mechanisms which converts sensor telemetry into actionable design improvements. Students in a lab environment, apply machine learning algorithms to analyze real-time machinery vibration signals and operational sensor streams (Onwurah et al., 2026). In this practical approach, students learn to apply in-service failure data back to the upstream design processes to continuously cycle the design and continuously assure the life cycle quality (Ekengwu et al., 2026).

Concurrent engineering, at the organizational level, depends on the ability to coordinate multi-disciplinary teams, which span technical disciplines. By embedding agentic AI platforms within a student project setting, an agentic network appears that enables the student teams to collaborate with AI agents to guide and manage the changes in requirements, track parameters across domains, and take care of life cycle trade-offs (Maldonado-Romo et al., 2026). The convergence of physical engineering and computational intelligence becomes more evident in hardware-software co-optimization concepts, which emphasize the design of physical systems to best optimize for AI hardware integration (Devgan, 2026). The implementation of these computational approaches in educational contexts enables a human-centric learning environment, where students' skillsets meet the needs of the industry (Ciano et al., 2025; Holzinger et al., 2026).

The use of AI in concurrent engineering education is not just about optimizing the learning process; it's about incorporating responsible engineering principles and ethical governance into the curriculum (Shinde et al., 2026). In the product life cycle, students need to assess the transparency of algorithms, data privacy, ecological sustainability, and liability in the safety domain (Shinde et al., 2026). Altering engineering curricula to these technologies also helps to address the impacts of cross-cultural and organizational aspects, which involves changing the way future engineers learn and collaborate in a digital environment (Ekaterina & Alina, 2026; Mohamad et al., 2026). Developing the capabilities of human-in-the-loop control in an automated world demands workforce resilience, which allows the workforce to keep up with the development of AI capabilities (Fatima et al., 2026).

Finally, a full life cycle view acknowledges that engineering resilience is not limited to the properties of the product; concurrent engineering organizations must have the operational capability to sense the disruptions that are emerging, to take cross-functional decisions, and to make controlled modifications (Donelli & Nagel, 2025; Hosseinzadeh & Taghipour, 2025). This all-encompassing approach connects socio-technical work systems, operational resilience, and lean production paradigms in complex industrial fields (Rosso & Saurin, 2018; Rubio-Romero et al., 2018; Wang et al., 2026). In extreme conditions and situations like critical transport infrastructure, or operation load changes like energy systems, adaptability is one of the key points for maintaining system performances (Senapati et al., 2025; Abdelmoumen et al., 2026). Modern engineering curricula combine AI-driven design methods with fundamental concurrent engineering concepts, giving

students a holistic, risk-informed framework that equips them with the tools needed to design, produce, and operate flexible and resilient systems that can withstand the challenges of complex environments in a global market.

Method

Review design and scope

A scoping review is suitable as a first step since resilience-oriented design is a concern of engineering design, reliability, systems engineering, supply-chain management, organizational resilience and sustainability. The review needs to outline definitions, principles, methods, measures and sectors prior to trying to pool effects. A systematic review with a more stringent comparability criteria may be appropriate if the authors subsequently restrict the question to a specific intervention, e.g. modular architecture, change recovery time.

Identify search sources and search terms.

Search Scopus and Web of Science (when available), Engineering Village/Compendex, IEEE Xplore, ScienceDirect and reference chaining. Mix words for Resilience with words for CE and design. A sample query is: TITLE-ABS-KEY((resilient OR adaptable OR robust OR flexibile OR recover) AND (concurrent engineering OR product development OR engineering design OR design for resilience OR design for recovery OR design for changes OR design for change propagation OR design for supply chain)). Use correct syntax for the specific database and maintain an exact history and dates of searches.

Inclusion and exclusion criteria

Add engineering and management peer-reviewed studies specifically focused on product/system resilience, adaptability, design change, or recovery or resilience-enabling architecture. Present conceptual frameworks, case studies, experiments, simulation studies and validated methods but keep them in a different category. Do not include general commentaries without a well-founded basis, only social or ecological studies that are not relevant to the subject, or duplicate documents. Industry reports may be used as grey literature, if allowed by the review protocol, but should not be used without a warning: these reports should not be combined without any warning with peer-reviewed evidence.

Screening and data extraction

Where possible, records should be reviewed independently by two reviewers. Document the reasons for full-text exclusion and the actual counts using a flow diagram. Derive definitions, system boundary, lifecycle stage, disturbance type, design principle, method, metrics, evidence type, trade-offs, limitations and context. Consider that resilience is not measurable as a competence, a quality, a process or a result of a disaster.

Quality appraisal and synthesis

Critically evaluate evidence based on study design. All papers should be evaluated for model assumptions, verification and validation; case studies, transparency and triangulation; experiments, design and controls and measurement; and conceptual papers, construct clarity and logical coherence. Synthesis should highlight the patterns and conflicting results. A quantitative meta-analysis should be attempted only when measures, scenarios and study designs are reasonably similar.

Transparency

Archive search strings, screening rules, extraction fields and coding decisions. Only declare protocol registration if it has been registered. Identify peer reviewed results, industry reports, conceptual suggestions and the author's own interpretations. The distinction is important because the term resilience is used and understood in a variety of ways without an operational measure in place.

Result and Discussion

Resilience and Adaptability

1. *Resilience as a Lifecycle Capability*

The literature review highlights the need for a synthesis of essential lifecycle capabilities to serve as the basic fundamentals for designing for resilience and adaptability in the concurrent engineering process using AI (Ciano et al., 2025). In the evaluated corpus, resilience is always described not just as the ability to endure single stress tests, but as a holistic architectural capacity that involves specific essential functions, anticipating disturbance scenarios, tolerating disturbance and developing organizational learning cycles (Holzinger et al., 2026). Sociotechnical integration of human operators and intelligent systems, in order to control complex disruptions, is stressed across industrial sectors (Rosso & Saurin, 2018; Rubio-Romero et al., 2018). The literature, however, emphasizes that resilience needs to be strictly limited as infinite resilience is economically and technically prohibitive in today's manufacturing ecosystems (Donelli & Nagel, 2025). To this end, future engineers need to be trained in specifying necessary functional baselines for targeted operational scenarios, thus setting clear recovery goals for safety-critical systems and commercial consumer products (Hosseinzadeh & Taghipour, 2025).

2. *Reliability, Robustness, Flexibility and Adaptability*

Literature findings also differentiate between critical structural characteristics such as reliability, robustness, flexibility and adaptability. Reliability deals with failure-free operation in time while robustness considers parameter variations in pre-defined parameter envelopes; flexibility or adaptability are concerned with multi-configuration operation and dynamic response to environmental degradation (Wang et al., 2013; Senapati et al., 2025). Bibliometric and full-text investigations into IOT-based systems have shed light on the operational dynamics of distributed architectures and how they cope with interconnected system failures and shifts (Abdelmoumen et al., 2026). Review results show that AI-based design platforms support the engineering student to deal with the trade-offs between different design alternatives, including the identification of design alternatives that produce strong designs that are difficult to change but are easy to vary, and the identification of which design alternatives are difficult to change and easy to vary, such as modular or redundant architectures that may have vulnerabilities in the interfaces (Lin et al., 2026). Students use AI-powered design platforms to simulate these interactions, making it possible to physically design a structure while optimizing for advanced computational flexibility and neuromorphic execution pathways (Devgan, 2026; Firoozi et al., 2024).

3. *Resilience of products, processes and organizations*

Multi-tiered evidence synthesis shows comprehensive resilience is product, process and organizational. Product resilience maintains engineered artifacts, whereas process and organizational resilience determines the ability of a development team to coordinate resources, communicate in a coordinated manner, and progress safely on their development projects when encountering disruption or changes in their supply chain or tools (Maldonado-Romo et al., 2026). Based on educational literature, the multi-level couplings are well reflected by the artificial intelligence platforms, which shows that a modular product becomes a failure when there are no fast qualification processes, technical documentation, or skilled employees in the organizations (Ekaterina & Alina, 2026; Mohamad et al., 2026).

4. *Concurrent Engineering and Change Propagation*

Concurrent engineering literature suggests that a key research area is the propagation of change, especially when there are concurrent engagements and integration at the early stages (Wang et al., 2026). Advanced data-driven dependency models empower student teams to pinpoint crucial interfaces and single failure points before modifications start to propagate uncontrollably through the interdependent subsystems (Alli et al., 2024; Ekengwu et al., 2026).

Uncertainty and Risk

The literature reviewed highlights the need to differentiate between known hazards, ambiguous requirements, vulnerabilities in the supply chain, model uncertainty, and interactions between unknown components in order to deal with uncertainty. The research indicates that students use machine learning frameworks to analyse real-time machinery vibration signals and operational sensor telemetry to convert the data into predictions that inform risk prioritisation (Onwurah et al., 2026). Furthermore, recent scholarly research places emphasis on the importance of engineers considering security engineering designs and ethical responsibilities in the development process, while preserving the transparency of algorithms, privacy of data and liability in safety-critical applications (Scharbaf, 2026; Shinde et al., 2026).

Lifecycle Perspective

A comprehensive lifecycle approach, which covers the conceptual phase, advanced manufacturing monitoring, and end-of-life management and material recycling, can help build resilient workforces to ensure that they can adapt to the evolution of technology while keeping human oversight and sustainable practices at the centre of their work (Fatima et al., 2026).

The Five Design Principles

1. Modularity

Modularity is a way of dividing an extensive system into smaller, more manageable components or subsystems that communicate with each other over clear, well-defined interfaces, allowing for the independent development, replacement, upgrading, and reconfiguration of the subsystems. AI concurrent engineering education can be made modular, where the boundary between modules can be easily matched to functional and organizational module boundaries (Ciano et al., 2025), to reduce the downstream design change caused by local changes. Machine learning algorithms analyze the dependencies of the interfaces and assist the learners in developing a stable definition of the interfaces that enables multi-team, parallel work flows (Holzinger et al., 2026). Modularity, however, relies heavily on the quality of the interfaces; interfaces that are not clearly defined result in adding up of tolerances and hidden dependencies that affect the overall performance of the system (Lin et: al., 2026). Students are taught how to weigh costs associated with interface, physical mass and volume, and software integration with the expected value of change isolation.

2. *Redundancy*

Redundancy means having more than one component, capacity, supply route or information source to keep things running if one fails. In the intelligent concurrent engineering design system, redundancy is measured in conjunction with the failure prognosis and real-time reliability parameters (Wang et al., 2013). Learners learn that redundancy is not only about duplication, but if both the primary and the backup components have the same software defect, power source, or supplier, then the redundancy is ineffective (Hosseinzadeh & Taghipour, 2025). Elements that are redundant must be separately validated and have clear activation protocols. Design decisions must consider the likely losses that will be avoided and the recovery benefits, but also consider the acquisition, maintenance and integration costs (Donelli & Nagel, 2025).

3. *Flexibility*

Flexibility allows products, processes and organisations to adapt to operational changes without having to be completely redesigned. This is due to the use of adjustable parameters, reconfigurable manufacturing, software-defined functionality and interchangeable parts (Senapati et al., 2025). Students in educational contexts learn about advanced computing paradigms, like neuromorphic computing and adaptive control systems, that facilitate smart infrastructure to dynamically reconfigure processing pathways during disturbances (Firoozi et al., 2024; Sharbaf, 2026). Excessive flexibility puts greater validation demands and manufacturing costs on the product, so students learn to tie flexibility to realistic operational conditions, with definite changeover times and performance envelopes.

4. *Feedback and Learning*

Observed behaviour data is fed back, and learning mechanisms link this to updated system models, maintenance schedules, and future iterations of the system design. In the advanced lab, students implement machine learning models based on live machinery vibration data and operational sensor telemetry data (Onwurah et al., 2026). This telemetry system is integrated with digital twin applications, converting the raw data into predictive insights for quality control and process optimization (Ekengwu et al., 2026). Feedback will enhance resilience only in the context of trustworthy data pipelines, clear quality control, and a set of rules for escalation, where student teams are able to translate empirical evidence into controlled actionable design changes.

5. *Collaborative Networks*

In case of disruption, collaborative networks are established where multidisciplinary designers, manufacturers, suppliers, logistics providers and customers share their capacities and know-how in alternative ways (Maldonado-Romo et al., 2026). By embedding agentic AI platforms into student project contexts, collaborative design networks can be formed where autonomous AI agents help manage tracked parameters across domains and trade-offs in the supply chain. Students learn the value of creating explicit boundaries, escalation contacts and collaborative protocols, with clear understanding of who needs to be involved to ensure safe and secure flow of critical information when needed and to deal with any governance risks, conflicting incentives and intellectual property issues that networks may present (Shinde et al., 2026; Fatima et al., 2026).

Table 1. Summary of Core Design Principles, Mechanisms, Trade-offs, and Evaluative Questions for Resilience-Oriented Concurrent Engineeri

Principle	Primary mechanism	Potential benefits	Costs / failure modes	Design questions
Modularity	Localise change through explicit interfaces	Replacement, upgrade, parallel development	Interface failures, added connectors, integration burden	Which changes should be isolated, and are interfaces stable and testable?
Redundancy	Provide alternate capacity or paths	Continuity, graceful degradation, recovery options	Cost, mass, maintenance, common-cause failure	Is the backup independent, available and periodically tested?
Flexibility	Enable controlled reconfiguration	Response to requirement or supply variation	Validation burden, specialist skills, extra modes	Which variations are plausible and what changeover time is acceptable?
Feedback and learning	Detect, interpret and incorporate evidence	Earlier warning, improved future decisions	Bad data, alert fatigue, slow governance	Who validates signals and converts them into authorized action?
Collaborative networks	Access distributed resources and knowledge	Alternative suppliers, expertise and response capacity	Conflicting incentives, IP exposure, coordination delays	What information and decisions must be shared during disruption?

Table 1 associates the 5 founding principles of design (modularity, redundancy, flexibility, feedback and learning, and collaborative networks) with their key mechanisms, benefits, likely failures, and design evaluative questions. This matrix will be a crucial decision making instrument for student teams and for practitioners in the context of AI-supported concurrent engineering education. It shows that all forms of resilience have a structural and economic cost associated with them, for example, between modular isolation and the complexity of integration, or between redundancy and common-cause failures. Finally, the framework helps students choose appropriate, capability-driven capabilities instead of attempting to design an inefficient, over-engineered solution for complete product lifecycles.

The resilience lifecycle loop is shown in figure 1 as a continuous process to improve the reliability and adaptability of the system in the context of AI-based concurrent engineering education. It starts with the definition of basic functions and basic conditions, moves to disruption scenarios and finally to the selection of the suitable architectural and process options. The system is first verified in both normal and disturbed conditions before monitoring, detection, absorption, safe degradation, recovery and reconfiguration can take place. Rewiew and learning inform updated requirements and design, as illustrated in Figure 1, for continuous improvement. Feedback loops tie all stages together and configuration control tracks evidence, approved modifications and deployed versions, which allows for systematic learning and sustained operational Resilience over complex manufacturing networks (Donelli & Nagel, 2025; Hosseinzadeh & Taghipour, 2025).

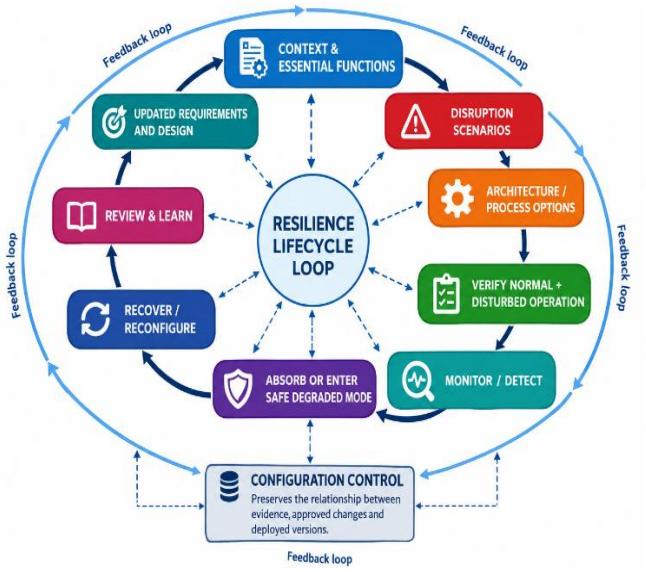

Figure 1. Resilience lifecycle loop

Integrated Framework for Resilience-Oriented Concurrent Engineering

The proposed pedagogical and technical framework integrates the five fundamental resilience principles with five distinct operational capability stages: anticipation, absorption, recovery, adaptation, and learning (Ciano et al., 2025; Holzinger et al., 2026). Anticipation identifies plausible disruptions and vulnerable system dependencies before operational deployment. Absorption maintains essential functions or limits the severity of performance degradation during shocks. Recovery restores acceptable performance within a defined time frame, while adaptation alters the system or its operational strategy when original design assumptions no longer hold true. Finally, learning leverages empirical evidence from tests and disturbances to improve future design governance and system architecture (Rosso & Saurin, 2018; Rubio-Romero et al., 2018).

1. *Step 1: Define Essential Functions and Acceptable Degradation*

Resilience design in modern engineering education begins with core functional requirements rather than an arbitrary list of preferred technologies. Students learn to identify the specific services that must remain available, the minimum acceptable performance level during a disruption, the maximum tolerable interruption duration, and the precise conditions under which a safe shutdown is preferable (Wang et al., 2013). Different functions carry varying levels of criticality; for example, a cyber-physical system may tolerate the loss of convenience features while strictly preserving core safety monitoring and essential communication channels (Sharbaf, 2026). Requirements must be quantifiable and measurable. Asserting that a product should be resilient is too vague to verify; instead, robust specifications identify the disturbance vector, operating conditions, minimum retained function, recovery target, and testable boundaries (Senapati et al., 2025).

2. *Step 2: Build a Disruption and Dependency Model*

Students and engineering teams must map hazards, disturbances, and dependencies across hardware components, software modules, supply chains, manufacturing processes, human operators, and physical infrastructure. Standard component-level failure lists often overlook common-cause events such as regional power outages, cloud service interruptions, transport bottlenecks, or compromised cybersecurity credentials (Sharbaf, 2026). Comprehensive dependency mapping integrates design structure matrices, data flow diagrams, supplier networks, and regulatory compliance paths (Abdelmoumen et al., 2026). By utilizing machine learning algorithms and advanced

data analytics, learners identify single points of failure, long-lead procurement items, opaque software dependencies, and interfaces whose alterations trigger extensive cross-domain verification (Alli et al., 2024; Ekengwu et al., 2026).

3. Step 3: Select Proportionate Resilience Strategies

Resilience strategies must be matched directly to failure consequences and operational recovery needs. Modularity is prioritized where change frequencies are high and stable interface standards are achievable (Lin et al., 2026). Redundancy is warranted for safety-critical functions where operational interruption is unacceptable, while flexibility handles environments where requirements shift within known operational bounds. Furthermore, feedback mechanisms detect early warning signals before catastrophic failure occurs, and collaborative networks supply external resources during major disruptions (Maldonado-Romo et al., 2026). These strategies operate best as cohesive portfolios rather than isolated fixes. Redundancy complements modularity, and collaborative networks supply alternative components, though portfolios must be tested against credible operational scenarios rather than theoretical checklists (Wang et al., 2026).

4. Step 4: Integrate Decisions into Concurrent Engineering Governance

Resilience requirements must remain visible across all functional domains within concurrent engineering organizations. Stakeholders spanning design, manufacturing, procurement, quality assurance, field service, cybersecurity, and sustainability must agree on risk ownership, open assumptions, and change approval workflows (Shinde et al., 2026). Early design reviews incorporate supply continuity, repairability, substitution rules, software updateability, and end-of-life disposal constraints. Formal decision records connect specific requirements to selected architectures, supporting evidence, accepted risks, and validation activities, allowing rapid response without bypassing safety or quality obligations (Fatima et al., 2026).

5. Step 5: Verify Under Normal and Disrupted Conditions

Verification protocols must encompass both ordinary performance and credible disturbance scenarios. In educational and industrial settings, this involves fault injection, accelerated environmental testing, supplier substitution trials, degraded-mode evaluations, and cyber-physical scenario simulations (Devgan, 2026; Firoozi, 2024). Tests verify that backup systems activate correctly, system safety is preserved, and recovery procedures remain feasible with available personnel and tools. While digital twins and AI-driven simulations help explore costly or hazardous scenarios, students must account for model fidelity, data quality, and underlying assumptions, recognizing that simulated environments represent approximations rather than absolute truths (Lin et al., 2026).

6. Step 6: Monitor, Respond, and Learn

During operational execution, engineers must define clear anomaly signals, action thresholds, responsible agents, and escalation pathways. Response playbooks identify safe degraded modes, alternative component suppliers, rollback procedures, and decision authorities. Following an event, systematic post-incident reviews compare expected outcomes against actual performance, analyzing detection speed, preserved functions, recovery duration, and secondary consequences. Insights update system requirements, module architectures, supplier qualifications, and training curricula under strict configuration control to prevent untracked variation (Ekaterina & Alina, 2026; Mohamad et al., 2026; Onwurah et al., 2026).

Table 2. Summary of Resilience Capability Stages, Core Evaluative Questions, Example Evidence, and Decision Outputs in Concurrent Engineering

Stage	Core question	Example evidence	Decision output
Anticipation	What could disrupt essential functions?	Hazard analysis, dependency map, scenarios, supplier exposure	Prioritized scenarios and risk assumptions
Absorption	What function can be preserved during disturbance?	Degraded-mode test, reserve capacity analysis	Minimum service and safe-state requirements
Recovery	How quickly can acceptable performance return?	Recovery drill, repair trial, replacement lead time	Recovery-time objective and playbook
Adaptation	Can the system change when conditions change?	Substitution test, configuration study, change-impact model	Approved reconfiguration paths
Learning	How will evidence change future design?	Incident review, field data, corrective action closure	Updated design rules, requirements and controls

.

Table 2 outlines the five sequential resilience capability stages—anticipation, absorption, recovery, adaptation, and learning—detailing their core guiding questions, example evidence, and actionable decision outputs. In concurrent engineering education, this table provides a structured, multi-tier methodology for student teams to move beyond static design. By connecting empirical evidence (such as dependency maps and recovery drills) to concrete outputs (such as risk assumptions and playbooks), learners systematically govern how systems withstand, recover from, and evolve through unexpected operational disturbances.

Digital Twins, Digital Threads and AI-powered Resilience.

Digital twins and connected models provide a powerful asset that supports system resilience in concurrent engineering education by tying together design intent, physical configuration, test evidence and operational behavior (Lin et al., 2026). An extensive digital thread provides absolute traceability from initial requirements to component specifications, manufacturing instructions and field telemetry, giving engineering teams the ability to know at a moment's notice which deployed systems are affected by new risks or material changes (Donelli & Nagel, 2025).

The usefulness of any digital twin is completely dependent on the analytical purpose it serves. In practice, models can be used for a variety of purposes—including to analyze different components, to simulate manufacturing processes and identify potential bottlenecks, and to forecast equipment failures for maintenance—with each application having clear definitions of the inputs, frequency of updates, evidence of validation, and scope of the model's operation (Ekengwu et al., 2026). AI also plays a crucial role in this landscape by powering automated anomaly detection, real-time maintenance prioritization, and change-impact analysis (Onwurah et al., 2026). But, automated systems have the potential to produce false alarms or non-causal outputs, and high consequence engineering decisions require certain human-in-the-loop review, transparency and traceable evidence (Scharbaf, 2026; Shinde et al., 2026).

Moreover, using AI in design helps speed up alternative generation by producing a range of architectural designs in a generative design platform, offering alternatives based on mass, cost, and performance (Maldonado-Romo et al., 2026). In contemporary education, students are trained to directly include resilience conditions in generative processes – conditions like modular replaceability, loss of components, or single-supplier dependence. In the end, these computational tools are not substitutes for engineering judgment, but they make complex life cycle trade-offs transparent to accountable decision makers that will yield robust system adaptability (Holzinger et al., 2026; Fatima et al., 2026).

Economics of trade-offs and decision economics.

Resilience investments have an initial investment cost with potential benefits with future operational disturbances. In concurrent engineering education, student groups need to determine the probability and impact of disruptions, downtime costs, recovery times, and reversibility of the architecture (Holzinger et al., 2026). Due to the lack of empirical information, the ranges of scenarios and sensitivity analysis provide a more honest assessment than individual expected-value numbers (Wang et al., 2013).

There are specific economic implications of each resilience strategy. Around the same time modularity lowers the cost of change propagation, it can increase initial cost of components and interfaces. Redundancy means no downtime if there's a failure, but also adds to the physical mass, energy and maintenance costs. Moreover, the validation area is amplified with flexibility, real-time monitoring necessitates sensor network and cybersecurity protection, and coordination complexities are added with the collaborative networks (Hosseinzadeh & Taghipour, 2025; Sharbaf, 2026).

The compromises must be assessed at the system level, not in separate subsystems. For instance, choosing a low cost component could increase supplier concentration risk, and an over-optimised manufacturing process would reduce spare capacity. Multi-criteria decision analysis provides for structured discussions, as long as the weightings are made clear and do not result in compromising safety objectives that cannot be negotiated (Shinde et al., 2026).

Most importantly, resilience is not the same as over-engineering or unlimited spending on resources. Proper education goal: Proportional Capability: "Reserve capacity, modularity and flexibility must be adequate to satisfy the defined service and recovery requirements without wasting precious resources" (Donelli & Nagel, 2025). Future engineers can learn to set defensible design envelopes, assess economic robustness for credible design scenarios, and balance decision making in complex concurrent workflows through the use of artificial intelligence-enabled design platforms (Maldonado-Romo et al., 2026; Fatima et al., 2026).

Table 3. Summary of Decision Dimensions, Evaluative Questions, and Potential Indicators for Resilience-Oriented Concurrent Engineering

Decision dimension	Questions to ask	Potential indicator
Disruption exposure	Which scenarios are plausible, and how uncertain are estimates?	Scenario coverage; supplier concentration; hazard exposure
Consequence	What essential function is lost and who is affected?	Severity class; safety or service criticality
Recovery	How long until minimum and full performance return?	Time to safe state; time to restore service
Architecture	Can a failure or change be isolated?	Dependency centrality; interface stability; substitution complexity
Lifecycle cost	What is the cost of prevention, reserve, response and downtime?	Total lifecycle cost under multiple scenarios
Sustainability	What are the material, energy and end-of-life implications?	Repairability, resource use, reuse and recovery options
Governance	Can the organization approve and deploy a change safely?	Change approval time; evidence traceability; training readiness

Table 3 establishes seven critical decision dimensions—ranging from disruption exposure and recovery timelines to architecture, lifecycle economics, sustainability, and governance—alongside their key evaluative questions and potential quantitative indicators. Within AI-enabled concurrent engineering education, this matrix equips learners with a comprehensive framework for multi-criteria trade-off analysis. By translating qualitative resilience goals into measurable indicators, student teams can rigorously balance technical performance, cost efficiency, and environmental sustainability across complex product lifecycles.

Proposed validation

1. *Comparative case studies*

Products or projects with varying architectures, disruption exposure and CE maturity could be explored in a multiple case study. Cases should be chosen to demonstrate variation, not to fit the framework. Requirements, design change records, supplier qualification logs, incident reports, recovery procedures, interview accounts and test results are all useful types of evidence. The unit of analysis might be a product platform, a major change event or a disruption-response process.

2. *Scenario-based design experiment*

A controlled experiment might then give the engineering teams the same design challenge and a phased disruption such as a part from a supplier becoming unavailable or a requirement changing during initial design. The conditions themselves may have different degrees of expertise in providing guidance on the modularity and support in visibility and change-governance of dependency. Outcomes could include time to a valid alternative, requirement coverage, number of unanticipated downstream impacts, safety-critical errors and quality of the rationale. Care must be taken in piloting the scenarios for realism and the difficulty of the tasks.

3. *Operational performance indicators*

These can be: time taken to identify a disruption, time to safe state, time to restore minimum function, time to full recovery, percentage of essential functions retained, number of dependent components that require redesign, time to qualification of substitutions, recurrence time of similar failures, cost of recovery and reoccurrence of similar failures. These indicators need to be established prior to data collection. Recovering speed is not enough unless it has no impact on safety or long term reliability.

4. *Interviews and expert validation*

Interviews can be used to gauge the extent to which the framework represents actual resilience decision making. Participants might include design engineers, reliability engineers, supply-chain managers, service technicians, manufacturing engineers and risk owners. The principle to capability mapping can be reviewed by an expert workshop which can detect missing interactions. The model should not just be validated by experts; it should be challenged.

5. *Analysis plan*

Identify mechanisms and boundary conditions using cross case comparison. Where the sample size and the assignment allow, quantitative scenario studies can be conducted using regression or factorial analysis. If censoring occurs, consider using survival or time-to-event procedures for time-to-recovery results. Report distributions and uncertainty, rather than averages. Conclusions should be subjected to sensitivity analysis to determine whether the results change if different

assumptions are made with regard to the disruptions and if different life cycle cost estimates are used.

6. *Ethics and data governance*

Commercial sensitive or safety critical information can be present in industrial disruption records. Seek organization consent and anonymize companies and people as necessary, secure evidence and don't publish details about vulnerabilities that could be exploited. Describe how confidential information will be dealt with and if AI tools are used to transcribe, classify or analyse.

Table 4. Summary of Validation Questions, Candidate Designs, Quantitative Measures, and Required Evidence for Resilience-Oriented Concurrent Engineering

Validation question	Candidate design	Measures	Evidence needed
Does modularity reduce change propagation?	Matched cases or scenario experiment	Affected components; redesign effort; integration defects	Architecture/interface records and change logs
Does redundancy improve continuity?	Fault-injection or reliability analysis	Essential function retained; recovery time; common-cause risk	Test results, failure-mode model, maintenance evidence
Does feedback improve adaptation?	Longitudinal case or before/after design	Detection lead time; corrective-action closure; recurrence	Sensor/field data and documented response decisions
Do networks improve recovery?	Comparative disruption case study	Time to alternative supply; response coordination; quality impact	Supplier records, contracts, interview and qualification data
Are resilience investments economically proportionate?	Scenario-based life cycle analysis	Total cost under scenarios; downtime avoided; sensitivity ranges	Cost model, scenario assumptions and uncertainty analysis

Table 4 outlines a structured empirical validation protocol designed to test the core hypotheses of the resilience framework. It connects specific validation questions—such as whether modularity reduces change propagation or if redundancy improves operational continuity—with candidate research designs, measurable indicators, and required forms of evidence. Within AI-enabled concurrent engineering education, this protocol provides student researchers and practitioners with a rigorous methodology to move beyond theoretical models. By aligning experimental designs, quantitative metrics (like redesign effort and detection lead time), and verifiable documentation, the table ensures systematic, evidence-based evaluation of resilience strategies across complex product lifecycles.

Governance, standards and organizational implementation

Reaching for resilience cannot be left to a handful of specialists, or tackled just at the end during the verification process. Effective governance has clear ownership for every essential function, risk factor, and recovery objective and integrates cross-functional reviews directly into the concurrent engineering gates, not parallel bureaucracies (Holzinger et al., 2026). Student teams and engineering practitioners will test out the disturbance models and examine high-risk assumptions at each gate and assess the implications of unsettled questions.

The ability to maintain operational resilience can be crucial and is heavily dependent on configuration management. A resilience feature is only effective if the deployed system is exactly like the system used in the validation. The assumptions about redundancy, thermal margins, cybersecurity, and recovery protocols are valid only if underlying components are not substituted without control, if the component is modified for any reason, or if the process of the component's supplier is altered. The assumptions made about redundancy, thermal margins, cybersecurity, and recovery protocols are only valid if the underlying components are not substituted without control, if the component is modified for any reason, or if the process of the component's supplier is altered. Therefore, any workflows with changes need to track the flow of changes through requirements, test procedures, documentation and service instructions.

Moreover, supplier collaboration needs to be built up in a proactive way before the disruptions happen. True independence between backup suppliers and no shared vulnerabilities should be achieved by defining the boundaries for data sharing, the definition of a data source from an alternative source, and notification obligations through technical contracts (Hosseinzadeh & Taghipour, 2025). Human capability is also essential; procedures need to be practicable under realistic operational stressors; cross training, documentation and regular exercises to prevent single points of failure based on specialised expertise (Fatima et al., 2026).

Last, but not least, resilience governance needs to be in line with sustainability principles. Waste and environmental costs are created by storing unnecessary goods for a short time. When carefully considered and

not taken for granted, integrating modular repair, remanufacturing and circular material flows can contribute to ecological sustainability and systemic resilience (Maldonado-Romo et al., 2026).

The restrictions and specifications.

Resilience is an umbrella concept that is adopted in various fields. It can be defined in different ways in studies, including resistance, recovery, adaptability, survival, continuity or learning. Findings can be misleading if they are not clearly defined or have no operational measures. The suggested framework is used to structure the ideas, but needs to be tested in practice. *Secondly*, disruption scenarios are subjective and likely to be picked by analysts. A successful design for one set of conditions could not be effective for other sets of conditions. Therefore, the selection of scenarios needs to be clearly defined and contain sensitivity analysis, expert challenge and periodic revision.

Thirdly, there's some cost associated with resilience and it can create new failure modes. Adding components, interfaces, sensors, software, suppliers, adds to complexity. The universal level of modularity, redundancy and flexibility cannot be prescriptive for the framework; this is a function of the product's essential functions and risk exposure. *Fourth*, the proposed empirical programme might have access restrictions. Companies might be hesitant to disclose failure data, supplier interdependencies or remediation expenses. Organizational reputation and hindsight may lead to bias when assessing resilience in self-reports. These problems can be overcome, but not eliminated, by triangulation of records, tests and interviews. *Fifth*, Digital twins and AI are not necessarily accurate. The model might be overly confident due to model fidelity, data drift, cyber vulnerabilities and opaque recommendations. The digital layer should be considered a system that has dependencies, recovery needs, and verification needs. *Lastly*, this manuscript is not a completed empirical study or completed systematic review. There are no findings for recovery time, cost savings, sample size, or effect size. There should be a process of testing of the proposed methods and propositions before claims of effectiveness are made.

Future research directions

Comparable metrics of resilience that disaggregate the four components of prevention, absorption, recovery and adaptation and learning should be developed for future research. Products could be compared using a common metric framework and essential functions retained at the sector level. Additionally, investigation of the effects of uncertainty in disturbance probabilities on architecture choices and when scenario performance is more robust than optimization based on expected value.

Further research is required on the relationship between modularity and redundancy and flexibility. These principles can support each other, but can also add up on interface count and verification complexities. Experimental design tasks and digital engineering models could be compared, with scenarios as a commonality.

Resilience is another priority enabled by AI. Studies could look at the effect on change-impact analysis or anomaly detection of using AI, as well as whether human teams are overly reliant on model-generated explanations and the impact of model updates on assurance. Studies should look at both the technical aspects and organizational response, whether it is a prompt response or not.

Research on supply-chain resilience needs to go beyond the number of suppliers. It should represent: upstream concentration, shared infrastructure, substitution qualification, geographic exposure, and time to restore supply. Product architecture and sourcing strategy should be taken together as modularity might not be useful if other modules are not available or have not been tested.

Last but not least, life cycle and circularity research should investigate if products that are repairable, upgradeable and remanufacturable are more resilient in case of material scarcity and changes in technology. This is where lifecycle evidence is needed, and not just a sustainability label. The compromises in terms of durability, upgradability, material use and end-of-life recovery should be considered and analysed explicitly.

Conclusion

Being able to adapt to change and to be resilient are becoming more critical for products that are developed at the same time they are being engineered; the interdependence and shortened timelines that make things more efficient can also cause disruption. A realistic approach starts with the critical functions, plausible disturbance scenarios, and then chooses appropriate architecture and process strategies and checks them against the recovery goals. The five principles that were carried over from the original manuscript – modularity, redundancy, flexibility, feedback and learning, and collaborative networks – provide a practical organisation structure. Their utility relies on how well they're implemented and their context. Stable interfaces are required for modularity; independence and maintainability are required for redundancy; bounded configuration and validation are required for flexibility; trustworthy data and decision

authority are required for feedback; and agreed roles and information sharing rules are needed for networks. These principles are woven into the proposed framework throughout the stages of anticipation, absorption, recovery, adaptation and learning. It integrates resilience into concurrent engineering process, making requirements, architecture, supplier choices, verification and change management all interdependent. The key recommendation was to take resilience as a specific, measurable life cycle need, not a vague goal or set of distinct attributes, and to evaluate the value of resilience as part of a full cost/benefit, complexity, sustain and verification analysis.

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Author Contributions

Sunday Chimezie Anyaora: Conceptualization, methodology, theoretical framework development, literature analysis, supervision, and writing – review and editing. Chidera Sandra Obi: Literature investigation, data curation, conceptual synthesis, framework visualization, writing – original draft, and manuscript revision. Both authors contributed to the intellectual development of the study, critically reviewed the manuscript, and approved the final version for publication.

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Conflicts of Interest

The authors declare that they have no known financial or non-financial conflicts of interest that could have influenced the conceptual development, literature analysis, interpretation, or reporting of this research.

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