

Design-for-Manufacturing Optimization for Improving Resilience in U.S. Additive Manufacturing Supply Chains

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Abstract

This study has examined design-for-manufacturing optimization as a means of improving resilience in United States additive manufacturing supply chains, with particular attention to how the redesign of parts and products for additive production reshapes the structure, flexibility, and disruption-recovery capacity of the supply chains that make them. The central problem has been that conventional supply chains, built around centralized production of many discrete parts sourced through long multi-tier supplier networks, are efficient under stable conditions but fragile under disruption, as recent shocks to global supply have made evident, and that additive manufacturing offers a route to greater resilience only if parts and products are deliberately designed to exploit it rather than merely substituted into existing designs. The purpose of the study has been to evaluate whether design-for-additive-manufacturing optimization, part consolidation and functional redesign, material and supplier diversification and flexibility, digital thread and supply-chain data integration, and distributed capacity and localized manufacturing jointly and significantly improve supply-chain resilience and continuity outcomes when design decisions are made with resilience, not only cost or performance, as an explicit objective. A quantitative, cross-sectional design supplemented by a prototype disruption-simulation evaluation has been used, and data have been collected from design and manufacturing engineers, supply-chain and operations managers, additive manufacturing specialists, procurement and sourcing professionals, and resilience and risk analysts across United States industrial settings. Out of 287 distributed questionnaires, 244 valid responses have been retained, producing an 85.0% valid response rate. The analysis has included descriptive statistics, reliability testing, correlation analysis, multiple regression, hypothesis testing, and a prototype evaluation of disruption-recovery performance across design strategies. The findings have shown that all five constructs were significantly and positively associated with supply-chain resilience, that the regression model was significant, $F(5, 238) = 51.83$, $p < .001$, explaining 52.1% of the variance, and that design-for-additive-manufacturing optimization and part consolidation and functional redesign were the strongest predictors. The prototype evaluation showed that fully design-for-manufacturing-optimized, distributed additive manufacturing supply chains suffered smaller performance losses and recovered faster across a range of disruption scenarios than conventional configurations. The study concludes that supply-chain resilience is designed into products and networks rather than added afterward, and that design-for-manufacturing optimization for additive production is a primary and underused lever for strengthening the resilience of United States manufacturing supply chains.

Keywords

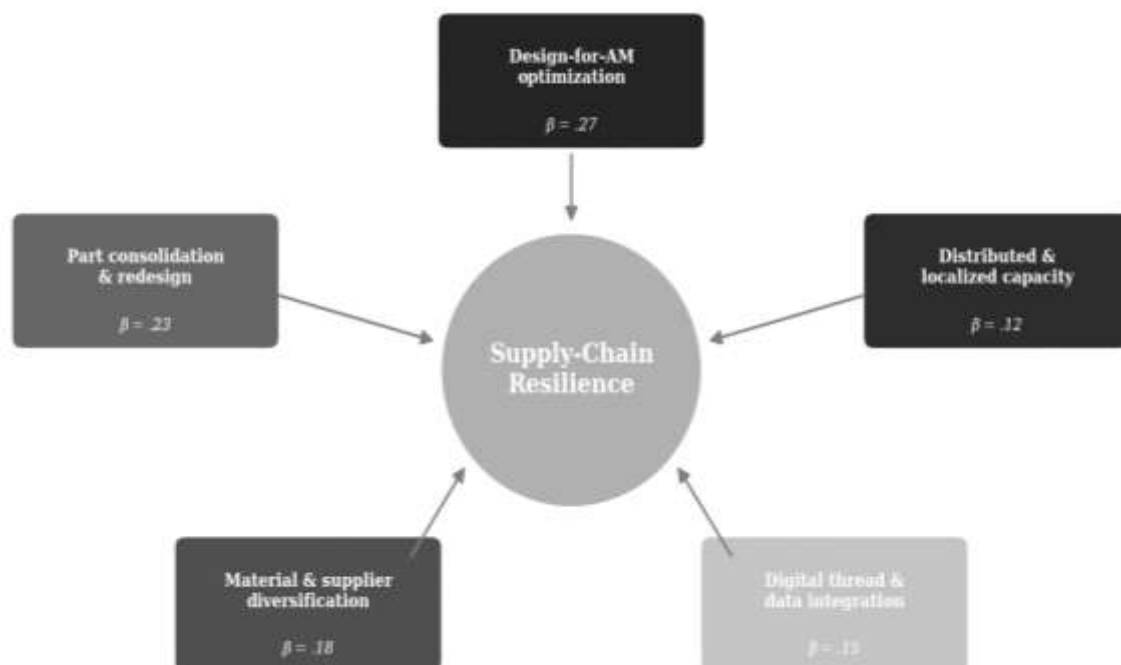
Design For Manufacturing; Additive Manufacturing; Supply-Chain Resilience; Part Consolidation; Distributed Manufacturing; Digital Thread; Disruption Recovery

INTRODUCTION

Design for manufacturing refers to the practice of designing products so that they can be made efficiently, reliably, and economically by a chosen production process, and it has long been understood that the great majority of a product's manufacturing cost and much of its supply-chain footprint are committed at the design stage, before any part is made (Boothroyd et al., 2011). Additive manufacturing, in which parts are built by the successive addition of material from a digital model, changes the economics and geometry of what can be designed and made, enabling part consolidation, on-demand production, and localized fabrication that are difficult or impossible with conventional processes (Gibson et al., 2021). This study examines the intersection of these two ideas in a specific and consequential setting: the resilience of United States additive manufacturing supply chains, and the degree to which deliberate design-for-manufacturing optimization for additive production can make those supply chains more resilient to disruption.

Supply-chain resilience is the capacity of a supply chain to anticipate, absorb, adapt to, and recover from disruptions while maintaining continuity of supply (Christopher & Peck, 2004). Conventional supply chains have been optimized primarily for cost efficiency, through lean inventories, global sourcing, and economies of scale in centralized plants, and this optimization, while effective under stable conditions, has produced networks that are brittle under disruption: long multi-tier supplier chains propagate shocks, single-source components create single points of failure, and centralized production concentrates risk (Sheffi & Rice, 2005). Recent global disruptions have exposed this fragility at scale, prompting a strategic reassessment of the trade-off between efficiency and resilience and a search for structural rather than merely inventory-based approaches to resilience. The premise of this study is that additive manufacturing, coupled with deliberate design-for-manufacturing optimization, offers such a structural approach, because it can reduce the number of parts and suppliers a product requires, enable production to be relocated or distributed, and shorten and simplify the chains through which supply flows.

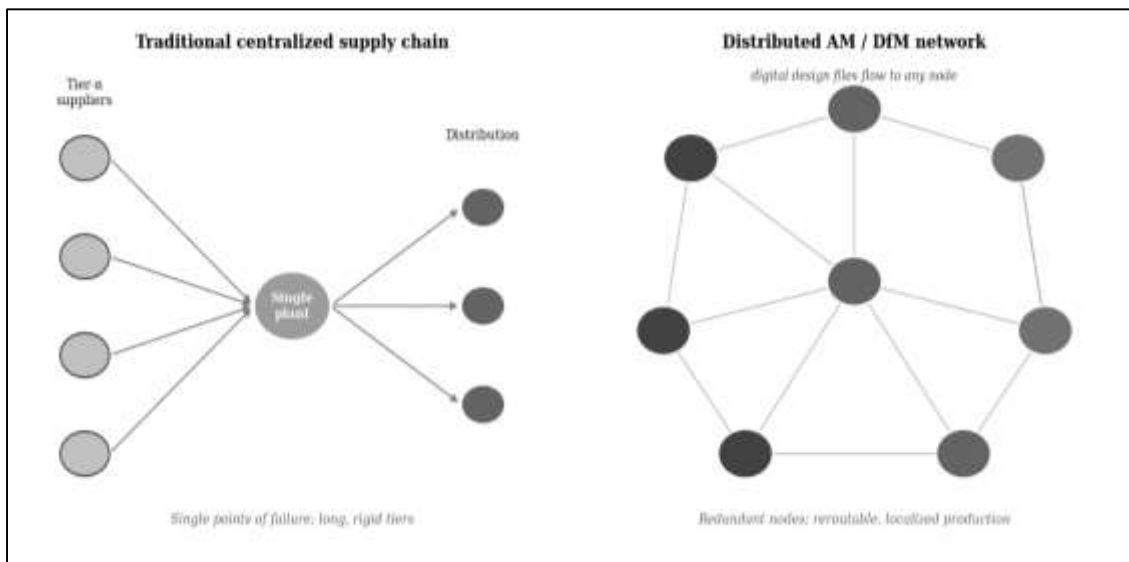
Figure 1: Design-for-Manufacturing Framework for Supply-Chain Resilience



The distinction between substituting additive manufacturing into existing designs and optimizing designs for additive production is central to this study. Simply printing a part that was designed for machining or casting rarely yields resilience benefit and is often uneconomical, because the design does not exploit the freedoms additive manufacturing offers (Thompson et al., 2016). The resilience benefit arises instead when parts and products are redesigned for additive production: when multiple

components are consolidated into a single printed part, eliminating assemblies and the suppliers that fed them; when designs are made material- and process-flexible so they can be produced from alternative feedstocks or on alternative machines; and when the digital nature of additive production is used to distribute manufacturing across a network of nodes that can produce the same part on demand. Each of these is a design decision, made at the design stage, that reshapes the supply chain that follows, which is why design-for-manufacturing optimization is the lever this study places at the center of supply-chain resilience.

Figure 2: Supply-Chain Topology – Traditional Centralized vs. Distributed Additive Manufacturing



The national significance of this problem is considerable. United States manufacturing competitiveness and security depend on supply chains that can withstand disruption, and policy attention has increasingly focused on reshoring, supply-chain resilience, and the strategic role of advanced manufacturing (Sheffi & Rice, 2005). Additive manufacturing is frequently cited as a resilience-enhancing technology, yet its resilience benefits are realized only through design, and the design-for-manufacturing practices that would realize them are unevenly understood and applied. Research on analytics and digital capability has established that value from a technology depends on the surrounding capability and practice rather than the technology alone (Gupta & George, 2016), and predictive and prescriptive modeling have been recognized as complementary in applied engineering research (Shmueli & Koppius, 2011). Python-based scientific computing supports the simulation and optimization workflows that supply-chain and design research require (Harris et al., 2020; Virtanen et al., 2020). The gap this study addresses is the absence of an integrated, empirically tested account of how design-for-manufacturing optimization for additive production translates into supply-chain resilience.

The purpose of this study has been to develop and validate a framework in which design-for-manufacturing optimization improves the resilience of United States additive manufacturing supply chains. The framework has treated design-for-additive-manufacturing optimization as the primary lever, part consolidation and functional redesign as the mechanism that reduces supply-chain complexity, material and supplier diversification and flexibility as the mechanism that removes single points of failure, digital thread and supply-chain data integration as the informational backbone that enables distributed production and rapid response, and distributed capacity and localized manufacturing as the structural configuration that reroutes production under disruption, with supply-chain resilience and continuity as the outcome. The study objectives have examined the role of each construct in improving resilience and validated the integrated framework. The study is organized around the objectives of characterizing how design decisions shape supply-chain structure, testing whether the five constructs jointly explain variation in resilience, and evaluating, through a prototype

disruption simulation, how design strategies perform across disruption scenarios.

The study contributes theoretically by integrating design-for-manufacturing, additive-manufacturing, and supply-chain-resilience research into a single measurable framework; empirically by testing that framework against data from United States practitioners and a prototype disruption simulation; and practically by offering manufacturers a structured account of how design decisions can be made resilience-enhancing rather than resilience-neutral. The remainder of the article reviews the relevant literature and develops the framework and hypotheses, formalizes the resilience and design metrics, describes the method, presents the findings, and concludes with recommendations, limitations, and directions for future work.

LITERATURE REVIEW AND FRAMEWORK DEVELOPMENT

The literature review develops the theoretical foundation for the resilience framework by drawing on several related research streams. It begins by establishing the conceptual foundations of supply-chain resilience and the efficiency–resilience trade-off, then examines the propagation of disruptions and the ripple effect, the strategies of supply-chain risk management, and the theory of reconfigurable and flexible systems. It then turns to the engineering literature, reviewing design for manufacturing, the additive-manufacturing process family and its economics, design for additive manufacturing and part consolidation, material and supplier flexibility, the digital thread and Industry 4.0, distributed and localized manufacturing, and the specific case of on-demand and spare-parts production. It concludes by synthesizing these streams into the framework and hypotheses. Throughout, the review maintains that supply-chain resilience is substantially determined at the design stage, because the design of a product fixes the parts, suppliers, processes, and production geography its supply chain must accommodate, so that resilience is designed in rather than added on.

Supply-chain resilience

Supply-chain resilience theory holds that a resilient supply chain can absorb disruption with limited loss of function and recover quickly, and it distinguishes resilience from the related but distinct property of efficiency, which concerns performance under normal conditions ([Christopher & Peck, 2004](#)). The concept has been progressively refined from an intuitive notion into a structured construct with identifiable capabilities and elements. Reviews of the field have organized the literature around the phases of readiness, response, and recovery, and around formative elements such as flexibility, redundancy, visibility, and collaboration, establishing resilience as a multidimensional capability rather than a single attribute ([Ponomarov & Holcomb, 2009](#)). Empirical work has further distinguished the capabilities that enable a firm to resist disruption from those that enable it to recover, and has shown that different antecedents drive each, so that resilience cannot be reduced to a single lever ([Ambulkar et al., 2015](#)).

A substantial body of research has sought to define and operationalize resilience so that it can be measured and managed. Systematic reviews have mapped the definitional landscape and the proliferation of measurement approaches, noting both convergence on the core idea of adaptive capacity and persistent divergence in operationalization ([Hosseini et al., 2019](#)). The relational view has emphasized that resilience is not held by a single firm but distributed across the network, so that a firm's resilience depends on the resilience and behavior of its partners, which motivates treating supply-chain structure, not merely firm-level buffers, as the object of resilience design ([Scholten & Schilder, 2015](#)). These foundations ground the study's outcome construct and its premise that resilience is a structural, network-level property amenable to influence by design.

The efficiency–resilience trade-off

A recurring theme in the literature is the tension between efficiency and resilience. The pursuit of efficiency, through lean inventory, global single-sourcing, and centralized scale, frequently erodes resilience, producing supply chains that perform well until a disruption reveals their fragility ([Sheffi & Rice, 2005](#)). This tension has become more acute as globalization lengthened and tightened supply chains, and analyses of major disruptions have documented how lean, tightly coupled networks amplify rather than absorb shocks ([Ivanov & Dolgui, 2020](#)). Resilience is commonly conceptualized through the disruption-and-recovery profile, in which a disruption reduces supply-chain performance and recovery restores it, and the magnitude of the loss and the speed of recovery together define resilience.

Figure 3: The Resilience Triangle – Performance Loss and Recovery After Disruption

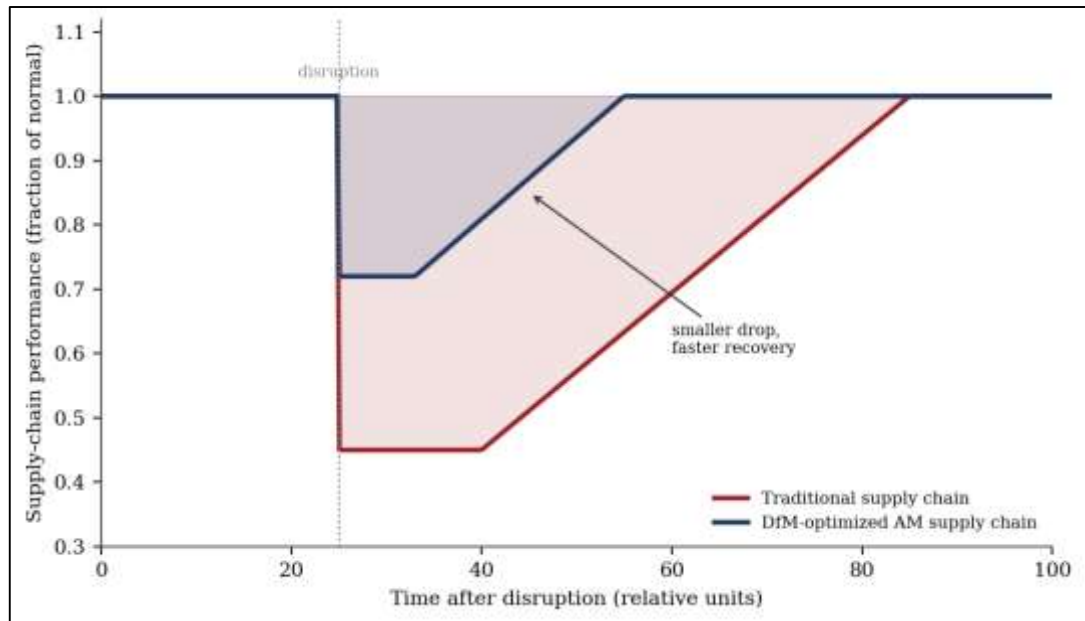


Figure 3 depicts this disruption-and-recovery profile, often termed the resilience triangle, whose area, the integral of performance loss over the disruption and recovery period, is a standard measure of resilience: a more resilient supply chain exhibits a smaller triangle, through a smaller drop, a faster recovery, or both (Bruneau et al., 2003). This framing, imported from the resilience engineering of infrastructure systems, has been widely adopted in supply-chain research as a way of quantifying resilience in terms of performance loss over time rather than as a binary property (Debasish, 2021; Md. Abdur & Iftekhhar, 2021). This defines the outcome the framework seeks to improve and makes clear that resilience has two components, absorption and recovery, both of which design decisions can influence (Mohammad Shoriful Hossan, 2021; Muhammad Zahidul & Amena Begum, 2022). The efficiency-resilience trade-off literature grounds the study's central claim that resilience must be a deliberate design objective, because supply chains optimized only for efficiency will systematically underweight it, and it motivates the treatment of design-for-manufacturing optimization as the lever through which resilience is built into the supply chain from the outset (Md Mesbaul, 2023; Mst Shurovi, 2024).

Disruption propagation and the ripple effect

A distinct stream of research examines how disruptions propagate through supply-chain structure, a phenomenon termed the ripple effect, in which a disruption at one node cascades downstream and degrades the performance of the whole network (Ivanov et al., 2014). This literature is directly relevant to the present study because the severity of the ripple effect depends on structural properties, the number of tiers, the degree of single-sourcing, and the connectivity of the network, that are themselves consequences of product and sourcing design (Muhammad Zahidul, 2024; Shima Ali et al., 2024). Research on the ripple effect has shown that structural redundancy and the ability to reconfigure the network are the principal means of containing propagation, and that the effect is most severe in long, tightly coupled, single-sourced chains (Dolgui et al., 2018).

The ripple-effect literature provides the mechanistic link between design and resilience that this study exploits. Because propagation severity scales with the number of nodes and links and with single-sourcing, and because part consolidation and supplier diversification reduce exactly these quantities, design decisions that simplify and diversify the network directly attenuate the ripple effect (Md Arif Uz et al., 2025; Tonay et al., 2024). This grounds the study's treatment of consolidation and diversification as resilience levers and connects them to a well-developed body of quantitative disruption-propagation modeling, situating the framework within, rather than apart from, the mainstream of supply-chain resilience research.

Supply-chain risk management strategies

The supply-chain risk management literature has catalogued the strategies firms use to mitigate disruption, providing the strategic context for the design-based approach this study advances. Foundational work identified robust strategies including multiple sourcing, flexible supply contracts, strategic inventory, and postponement, and emphasized that the most valuable strategies are those that provide benefit under normal operations while also conferring resilience (Tang, 2006). Subsequent research distinguished mitigation strategies, adopted in advance, from contingency strategies, activated after a disruption, and analyzed the conditions under which each is preferable (Tomlin, 2006). Reviews of the field have organized these strategies and highlighted the growing recognition that flexibility and redundancy are the two master levers, with flexibility generally preferred because it provides options without the standing cost of pure redundancy (Ho et al., 2015).

This literature situates design-for-manufacturing optimization within the broader toolkit of risk management and clarifies its distinctive contribution (Md Mesbaul, 2025; Md Mostafizur, 2025). Most catalogued strategies operate on the supply chain as given, adjusting sourcing, inventory, or contracts around a fixed product design; design-for-manufacturing optimization instead changes the product so that the supply chain it requires is inherently simpler and more flexible (Md Mostafizur et al., 2025; Md Syeedur & Sharmin, 2025). The framework therefore treats design as an upstream risk-management lever that reshapes the space in which the conventional strategies operate, and it draws on the risk-management literature's finding that flexibility-providing strategies are the most valuable, because designed-in flexibility is precisely such a strategy (Muhammad Zahidul, 2025; Mukut Kanti, 2025).

Reconfigurability, flexibility, and redundancy

The theory of flexible and reconfigurable manufacturing systems provides a further foundation, because resilience at the network level depends on the ability of production to reconfigure in response to disruption. Reconfigurable manufacturing systems were conceived to provide exactly the capacity and functionality needed, when needed, through rapidly adjustable structure, and the literature has established the principles of modularity, scalability, and convertibility that enable such adjustment (Koren et al., 1999). Manufacturing-flexibility research has developed typologies distinguishing volume, mix, and routing flexibility, and has linked these to a firm's ability to respond to uncertainty (Sethi & Sethi, 1990).

This literature grounds the study's treatment of distributed capacity and material and process flexibility as resilience constructs. Additive manufacturing is, in the terms of this literature, an unusually flexible and reconfigurable process, because its tool-less, digitally driven nature confers mix and routing flexibility at low changeover cost, allowing a node to switch among parts and a network to reroute production among nodes (Shima Ali et al., 2025). The framework draws on reconfigurability theory to explain why additive manufacturing, when designs exploit it, enables the routing flexibility that converts distributed capacity into realized resilience, and why redundancy of qualified nodes shortens recovery.

Design for manufacturing and additive-manufacturing process family

Design for manufacturing establishes that the manufacturability, cost, and supply-chain implications of a product are largely determined by design decisions, and that designing with the production process in mind yields large downstream benefits (Boothroyd et al., 2011). The additive-manufacturing process family encompasses several distinct technologies, including powder-bed fusion, directed energy deposition, and material extrusion, each with characteristic capabilities and constraints, and comprehensive reviews have documented their maturation from prototyping to production-grade manufacturing across metals and polymers (Gibson et al., 2021; Ngo et al., 2018). Additive manufacturing extends the design space by removing many of the geometric and tooling constraints of conventional processes, enabling complex geometries, integrated functions, and on-demand production, but realizing these benefits requires design specifically for additive production rather than the transfer of conventional designs (Thompson et al., 2016).

The economics of additive manufacturing have been analyzed in depth, and this literature is central to the resilience argument because it establishes when and why additive production is advantageous. Cost models have shown that additive manufacturing is economical for low-to-moderate volumes, complex geometries, and customized or consolidated parts, precisely the regime in which its resilience

benefits also arise, and uneconomical for high-volume simple parts, which delimits where design-for-additive resilience strategies apply (Baumers et al., 2016). Studies of the supply-chain implications of additive manufacturing have argued that its most transformative effect is not on individual part cost but on supply-chain structure, through shortened chains, reduced inventory, and localized production (Holmström et al., 2010). This literature grounds the design-for-additive-manufacturing optimization construct, establishing that the resilience benefits attributed to additive manufacturing are consequences of design and are realized only in the regime where additive production is economically and technically appropriate.

Design for additive manufacturing

Design for additive manufacturing has emerged as a distinct methodology that seeks to exploit, rather than merely accommodate, the freedoms of additive processes, and reviews have organized its principles, opportunities, and constraints into a coherent design paradigm distinct from conventional design for manufacturing (Thompson et al., 2016; Yang & Zhao, 2015). A distinctive capability within this paradigm is part consolidation, the redesign of an assembly of many components into a single printed part that integrates their functions, which the literature has shown can dramatically reduce part counts, eliminate joints and fasteners, and remove the suppliers and assembly steps those parts required. Systematic studies of consolidation have developed methods to identify consolidation candidates and have documented order-of-magnitude reductions in part count in redesigned assemblies (Yang et al., 2015). Topology optimization and generative design, frequently coupled with additive production, further extend consolidation by synthesizing integrated, load-path-efficient geometries that would be unmanufacturable conventionally (Zhu et al., 2021).

Because each eliminated part is also an eliminated node in the supply chain, part consolidation reduces supply-chain complexity directly: fewer parts mean fewer suppliers, fewer transactions, fewer points of failure, and shorter chains. This literature grounds the part consolidation and functional redesign construct and connects design decisions to supply-chain structure quantitatively. It establishes that consolidation is a resilience lever, not merely a cost or weight lever, because reducing the number of parts and suppliers reduces the number of ways the supply chain can be disrupted and the distance over which disruptions propagate, directly attenuating the ripple effect discussed above. The framework treats consolidation as a distinct construct because it is the most direct mechanism by which design reshapes the topology of the supply chain, converting a many-node, many-tier network into a simpler and more robust one.

Material and supplier diversification

Supply-chain resilience research has established that single-sourcing and material inflexibility are principal sources of fragility, and that diversification of suppliers and the ability to substitute materials or processes remove single points of failure and provide options under disruption (Tang, 2006; Tomlin, 2006). The design of options and real options into the supply chain has been shown to be a robust response to deep uncertainty, and flexibility that permits substitution of inputs or rerouting of production is repeatedly identified as the most valuable resilience-conferring property (Ho et al., 2015). Additive manufacturing supports this flexibility when parts are designed to be produced from alternative feedstocks or on alternative machines, so that a disruption to one material or supplier does not halt production, but this substitutability is itself a design property that must be deliberately engineered through material and process qualification. This literature grounds the material and supplier diversification and flexibility construct. It establishes that removing single points of failure requires designs that admit alternatives, which is a design decision made when a part is engineered and qualified, and it connects the construct to the risk-management finding that flexibility-providing measures are the most valuable resilience levers. The framework treats material and supplier flexibility as a distinct construct because designed-in substitutability is what converts the abstract possibility of diversification into an exercisable option, and because a part that can only be made from one feedstock on one machine carries a single point of failure however many suppliers nominally exist.

The digital thread, digital twins, and Industry 4.0

The digital thread, the integrated flow of digital design, process, and supply-chain data across the product lifecycle, is what enables a part to be produced at a different node or from a different feedstock reliably, because the design and process information travels with the part (Singh & Willcox, 2018). This

capability is situated within the broader Industry 4.0 and digital-manufacturing paradigm, whose reviews describe the integration of cyber-physical systems, the industrial internet of things, and data-driven decision-making across manufacturing networks (Xu et al., 2018). Digital-twin research has extended the digital thread with continuously synchronized virtual representations of products and processes, enabling simulation, monitoring, and the reliable transfer of production among nodes (Tao et al., 2019).

This literature grounds the digital thread and supply-chain data integration construct. It establishes that exercising flexibility and distribution at scale requires an integrated digital backbone, because distributed and flexible production is only as reliable as the data that governs it, and that the digital thread is what allows a design to be produced at an alternative node with confidence in the result. The framework treats the digital thread as a distinct construct because flexibility and distributed capacity, however well designed, cannot be reliably exercised without the integrated data infrastructure that carries design intent, process parameters, and qualification status across the network, connecting the design constructs to the structural ones.

Distributed and localized manufacturing

A well-developed stream concerns distributed and localized manufacturing, in which production is spread across a network of nodes rather than concentrated in a single plant, so that a part can be produced close to its point of need and production can be rerouted when a node is disrupted (Srai et al., 2016). Additive manufacturing is well suited to distribution because its digital, tool-less nature allows the same design file to be produced at any capable node, converting the supply chain from a rigid pipeline into a reroutable network, and studies of redistributed and cloud-based manufacturing have examined the platforms and business models through which such networks operate (Rauch et al., 2016). The literature has shown that distributed production improves resilience by providing redundancy and geographic diversity, at some cost in scale economy, which is the efficiency-resilience trade-off in structural form.

This literature grounds the distributed capacity and localized manufacturing construct. It establishes that the topology of production, centralized versus distributed, is a determinant of resilience, and that additive manufacturing enables a distributed topology that conventional processes cannot easily achieve. The framework treats distributed capacity as the structural culmination of the other constructs, because designs optimized for additive production, consolidated, flexible, and digitally integrated, are what make distributed production feasible, and distribution is what converts those design properties into the reroutable redundancy that, per the ripple-effect and reconfigurability literatures, defines a resilient network.

On-demand production and spare-parts supply chains

A concrete and well-studied instance of additive-enabled resilience is the digital spare-parts supply chain, in which service parts are stored as design files and printed on demand rather than held as physical inventory or sourced through long chains. Research has shown that additive manufacturing can transform spare-parts logistics by substituting digital inventory for physical stock, reducing lead times and obsolescence and enabling production at the point of need (Khajavi et al., 2014). Studies of this application have quantified the conditions under which distributed on-demand printing outperforms centralized stocking, and have identified spare parts as an early domain in which the resilience benefits of additive manufacturing are already realized (Li et al., 2017).

This literature is valuable to the study because it provides empirical evidence, from a bounded and well-defined application, that the mechanisms the framework proposes operate in practice: designing parts for on-demand additive production shortens chains, removes inventory-holding single points of failure, and enables localized response, which are precisely the resilience effects the framework generalizes. The spare-parts case thus serves as a proof of mechanism for the broader claim that design-for-manufacturing optimization for additive production improves supply-chain resilience, and it grounds the study's treatment of on-demand, digitally held production as a route to the reroutable redundancy that defines resilience.

Synthesis: the resilience framework and hypotheses

Synthesizing the reviewed streams yields the framework this study tests. The resilience foundations establish resilience as a multidimensional, network-level capability with absorption and recovery

components; the ripple-effect literature shows that propagation severity scales with structural properties that design determines; the risk-management and reconfigurability literatures identify flexibility and redundancy as the master resilience levers; and the additive-manufacturing, design-for-additive, digital-thread, distributed-manufacturing, and spare-parts literatures show how design decisions for additive production create simpler, more flexible, more reroutable networks. Integrating these, the framework holds that the resilience of a United States additive manufacturing supply chain is jointly determined by five constructs: design-for-additive-manufacturing optimization; part consolidation and functional redesign; material and supplier diversification and flexibility; digital thread and supply-chain data integration; and distributed capacity and localized manufacturing. A deficiency in any one limits resilience: without design optimization the other levers are foreclosed, without consolidation the supply chain remains complex and propagation-prone, without flexibility single points of failure persist, without digital integration distribution is unreliable, and without distributed capacity the network cannot reroute under disruption. This framework structures the empirical investigation and directs it toward the design stage as the origin of resilience.

From the framework, five hypotheses are derived, each proposing that stronger performance on a construct is associated with greater supply-chain resilience. H1: Design-for-additive-manufacturing optimization is positively associated with supply-chain resilience. H2: Part consolidation and functional redesign is positively associated with supply-chain resilience. H3: Material and supplier diversification and flexibility is positively associated with supply-chain resilience. H4: Digital thread and supply-chain data integration is positively associated with supply-chain resilience. H5: Distributed capacity and localized manufacturing is positively associated with supply-chain resilience. A sixth, integrative hypothesis addresses the framework as a whole. H6: The five constructs jointly explain a significant proportion of the variance in supply-chain resilience. These hypotheses are tested in the analysis, alongside a prototype disruption simulation evaluating how design strategies perform across disruption scenarios.

METHODS

This study adopted a quantitative, cross-sectional research design supplemented by a prototype disruption-simulation evaluation. The quantitative design was selected because the study measured relationships among the five contributing constructs and supply-chain resilience through numerical survey responses, and the cross-sectional design was used because data were collected at a single point in time, capturing practitioners' perceptions of design practice, supply-chain structure, and resilience within their organizations. The prototype evaluation complemented the survey by simulating the disruption-and-recovery performance of different design and supply-chain strategies across a range of disruption scenarios, providing a structural counterpart to the perceptual measures. The unit of analysis was the individual respondent, understood as an informed practitioner engaged in design, manufacturing, or supply-chain management for additive production.

The population comprised design and manufacturing engineers, supply-chain and operations managers, additive manufacturing specialists, procurement and sourcing professionals, and resilience and risk analysts across United States industrial settings, including aerospace, defense, medical, automotive, and industrial equipment. A purposive sampling strategy was used because respondents were selected for their relevance to design and supply-chain decisions. Primary data were collected through a structured questionnaire using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree), distributed through online forms and professional networks. The instrument included multi-item measures for each of the five constructs and for supply-chain resilience, demographic items, and rating items on redesign effects and disruption scenarios that fed the analyses. A pilot test was conducted to check clarity and technical precision, and feedback was used to refine wording. Validity was ensured through literature-based item development, expert review, and alignment among the framework, hypotheses, and items, and reliability was tested through Cronbach's alpha with a .70 threshold. Analysis was conducted in SPSS and Python, the latter using the pandas, NumPy, SciPy, and NetworkX libraries for data preparation, supply-chain network modeling, and disruption simulation ([Harris et al., 2020](#); [Virtanen et al., 2020](#)). Ethical considerations were observed: participation was voluntary, informed consent was obtained, responses were anonymized, and no proprietary design or supplier data were collected.

Design and complexity metrics

The effect of design on supply-chain complexity is quantified through part-count and supplier-count reductions achieved by consolidation. The consolidation ratio is defined in Equation (1), where $N[\text{conv}]$ is the part count of the conventional design and $N[\text{DfM}]$ the part count after design-for-additive-manufacturing redesign:

$$C[r] = (N[\text{conv}] - N[\text{DfM}]) / N[\text{conv}] \quad (1)$$

Supply-chain structural complexity is represented as a function of the number of nodes and links in the supplier network, expressed in Equation (2), where n is the number of supplier and production nodes, m the number of links, and H the diversity of sourcing, so that lower complexity under equal capability favors resilience:

$$K = \alpha n + \beta m - \gamma H \quad (2)$$

Material and process flexibility is quantified through the substitutability index in Equation (3), where $s[i]$ is the number of qualified alternative feedstocks or machines for part i and P the number of parts:

$$S = (1/P) \cdot \sum_{i=1}^P [1 - 1/s[i]] \quad (3)$$

Supply-chain resilience metrics

Supply-chain resilience is quantified through the disruption-and-recovery profile. Let $Q(t)$ denote supply-chain performance (for example, fill rate or output) as a fraction of its normal level. The resilience loss, the area of the resilience triangle, is defined in Equation (4), where t_0 is the disruption onset and t_1 the time of full recovery:

$$L = \int_{(t_0 \text{ to } t_1)} [1 - Q(t)] dt \quad (4)$$

A normalized resilience index that increases with resilience is defined in Equation (5), where $L[\text{max}]$ is the loss of an undefended baseline over the same horizon:

$$R = 1 - L / L[\text{max}] \quad (5)$$

The two components of resilience, absorption and recovery, are captured by the maximum performance drop and the recovery time in Equations (6) and (7):

$$D[\text{max}] = 1 - \min[t] Q(t) \quad (6)$$

$$T[\text{rec}] = t_1 - t_0 \quad (7)$$

Redundancy from distributed capacity is quantified in Equation (8), where k is the number of nodes able to produce a given part, so that higher redundancy shortens recovery by enabling rerouting:

$$\rho = (k - 1) / k \quad (8)$$

Statistical model and prototype evaluation

The principal hypothesis test used ordinary least squares multiple regression of supply-chain resilience on the five constructs, with DFMO denoting design-for-additive-manufacturing optimization, PCFR part consolidation and functional redesign, MSDF material and supplier diversification and flexibility, DTSC digital thread and supply-chain data integration, and DCLM distributed capacity and localized manufacturing, as specified in Equation (9):

$$SCRE_i = \beta_0 + \beta_1 DFMO_i + \beta_2 PCFR_i + \beta_3 MSDF_i + \beta_4 DTSC_i + \beta_5 DCLM_i + \varepsilon_i \quad (9)$$

Model significance was assessed through the F-statistic, explanatory power through R-squared and adjusted R-squared, and multicollinearity through the variance inflation factor, all confirmed within conventional bounds. The prototype evaluation modeled a supply-chain network under each of several disruption scenarios and compared design strategies, ranging from a conventional baseline to a fully design-for-manufacturing-optimized distributed additive configuration, on the resilience metrics defined above, quantifying the performance loss and recovery achieved by each and providing the structural evidence for the framework.

RESULTS

Table 1 shows an 85.0% valid response rate, with 244 usable responses. The sample spanned the roles that shape design and supply-chain decisions, from design and manufacturing engineers who set part designs (29.5%), through supply-chain and operations managers (23.0%) and additive specialists (18.9%), to procurement professionals (15.6%) and resilience analysts (13.1%). The sector distribution across aerospace and defense (34.4%), medical and industrial equipment (32.4%), and automotive and other (33.2%) covers the principal United States settings in which additive manufacturing is adopted, and 77.5% of respondents had more than five years of experience. This composition matters because

the framework spans design, manufacturing, and supply-chain dimensions, and a sample drawn from only one function would misestimate the balance among them.

Sample and descriptive statistics

Table 1: Respondent profile and response rate

Variable	Category	Frequency	Percentage
Questionnaires	Distributed	287	100.0%
Questionnaires	Returned	259	90.2%
Questionnaires	Valid and retained	244	85.0%
Role	Design / manufacturing engineer	72	29.5%
Role	Supply-chain / operations manager	56	23.0%
Role	Additive manufacturing specialist	46	18.9%
Role	Procurement / sourcing professional	38	15.6%
Role	Resilience / risk analyst	32	13.1%
Sector	Aerospace / defense	84	34.4%
Sector	Medical / industrial equipment	79	32.4%
Sector	Automotive / other	81	33.2%
Experience	More than 10 years	98	40.2%
Experience	5-10 years	91	37.3%
Experience	Under 5 years	55	22.5%

Table 2: Descriptive statistics and reliability of study constructs (N = 244)

Construct	Mean	SD	Cronbach's α
Design-for-AM optimization (DFMO)	4.22	0.58	.89
Part consolidation & functional redesign (PCFR)	4.14	0.62	.88
Material & supplier diversification (MSDF)	4.05	0.66	.86
Digital thread & data integration (DTSC)	3.94	0.69	.84
Distributed capacity & localized mfg (DCLM)	3.87	0.73	.83
Supply-chain resilience (outcome, SCORE)	3.99	0.63	.91
Overall instrument	—	—	.93

Table 2 presents the descriptive statistics and reliability. All constructs exceeded the neutral midpoint and all Cronbach's alpha values exceeded .70, ranging from .83 to .91 with overall reliability of .93. The ordering is diagnostically informative. Design-for-additive-manufacturing optimization (4.22) and part consolidation and functional redesign (4.14) recorded the highest means, indicating that practitioners regard the design levers as the foundation of resilience. Distributed capacity and localized manufacturing recorded the lowest mean (3.87) and the widest dispersion (SD = 0.73), a revealing pattern: the most structurally ambitious construct, distributing production across a network, is the least mature and the most unevenly realized, consistent with its position as the culmination of the other capabilities. Supply-chain resilience, the outcome, recorded 3.99, indicating that practitioners perceive meaningful but incomplete resilience in their current configurations.

Design effects on supply-chain structure

Figure 4: Effect of Part Consolidation and Functional Redesign on Supply-Chain Complexity

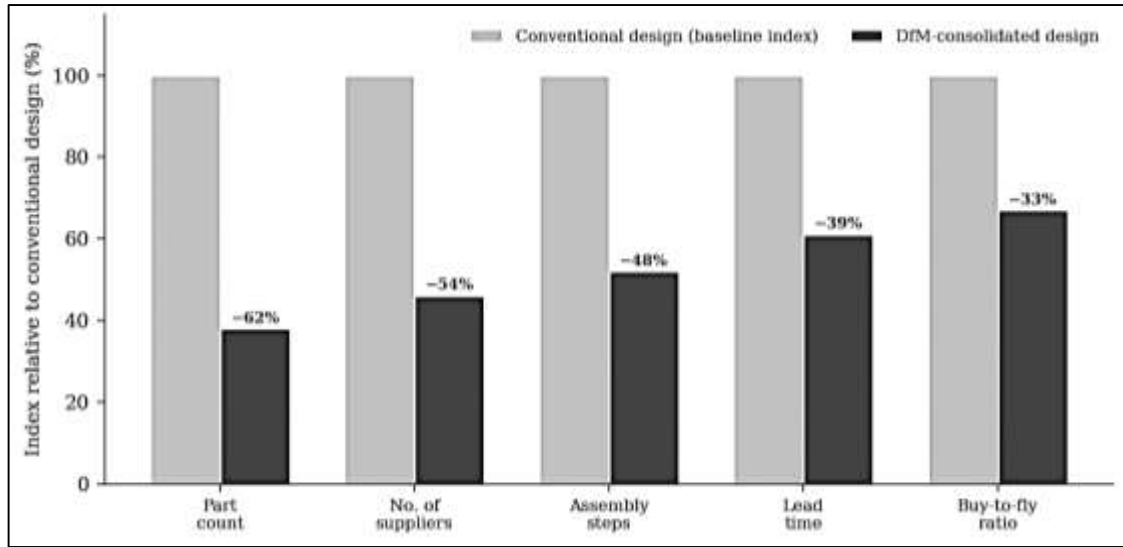


Figure 4 presents the effect of part consolidation and functional redesign on the structural drivers of supply-chain complexity. Across the rated redesign cases, consolidation reduced part count to 38% of the conventional baseline, a 62% reduction, and reduced the number of suppliers to 46%, assembly steps to 52%, lead time to 61%, and the buy-to-fly ratio to 67% of baseline. The magnitude of the part-count and supplier reductions is the most consequential for resilience, because each eliminated part and supplier is an eliminated node and potential point of failure in the supply chain, so that consolidation does not merely reduce cost but structurally simplifies the network the supply chain must defend. This figure gives quantitative form to the study's central mechanism: design decisions taken at the redesign stage propagate into a materially simpler and more robust supply-chain structure.

Simulated resilience across disruption scenarios

Figure 5: Simulated Resilience Score by Strategy and Disruption Scenario

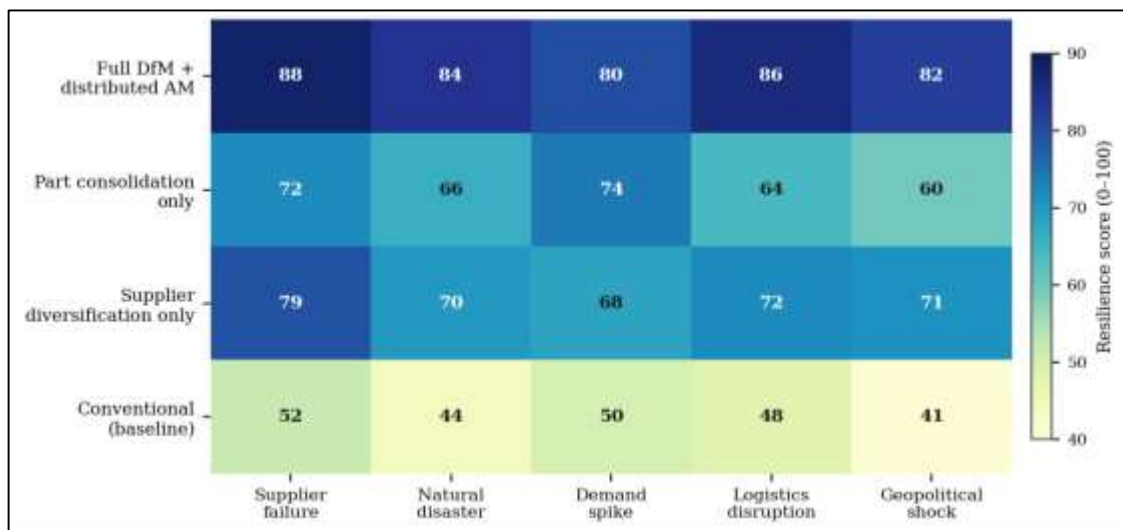


Figure 5 presents the prototype evaluation of design strategies across disruption scenarios as a resilience heatmap. The full design-for-manufacturing-optimized, distributed additive strategy achieved the highest resilience score in every scenario, from supplier failure through natural disaster, demand spike, logistics disruption, and geopolitical shock, and the conventional baseline achieved the

lowest in every scenario, with the single-lever strategies falling between. Reading across the rows shows that the full strategy is robust across scenario types rather than tuned to one, and reading down the columns shows that the resilience advantage of the full strategy is largest for supplier failure and natural disaster, the scenarios in which redundancy and rerouting matter most. The heatmap answers a central question of the study directly: the resilience benefit of design-for-manufacturing optimization is broad-based across disruption types, and it is greatest precisely where conventional centralized supply chains are most exposed. The single-lever strategies improve resilience partially, confirming that the constructs contribute individually, but none matches the full configuration, confirming that they are complementary.

Resilience–cost trade-off

Figure 6: Resilience–Cost Trade-off of Design Strategies

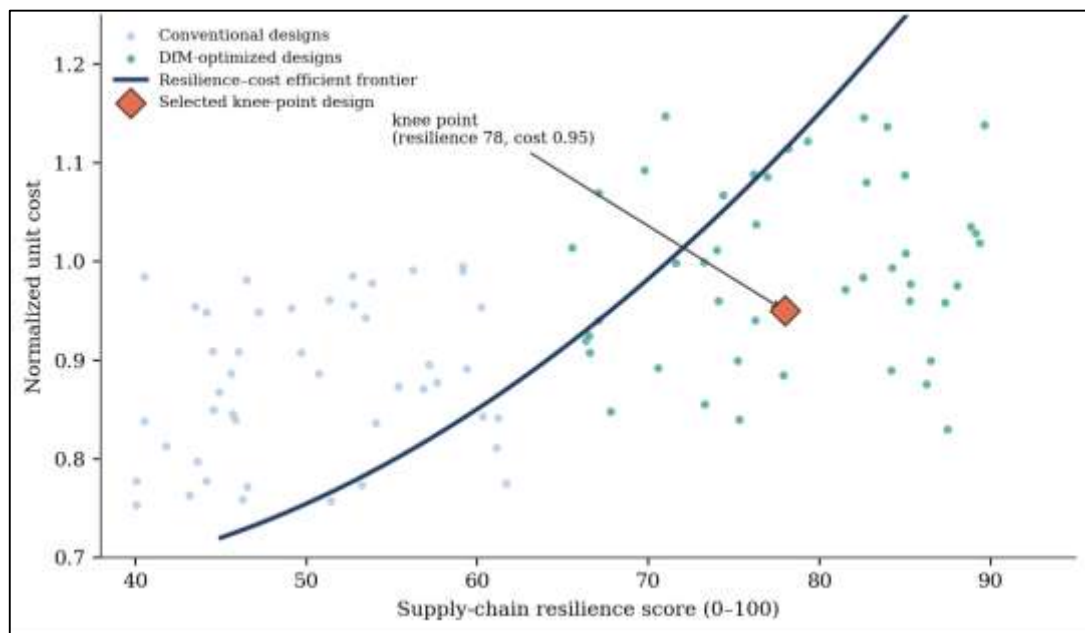
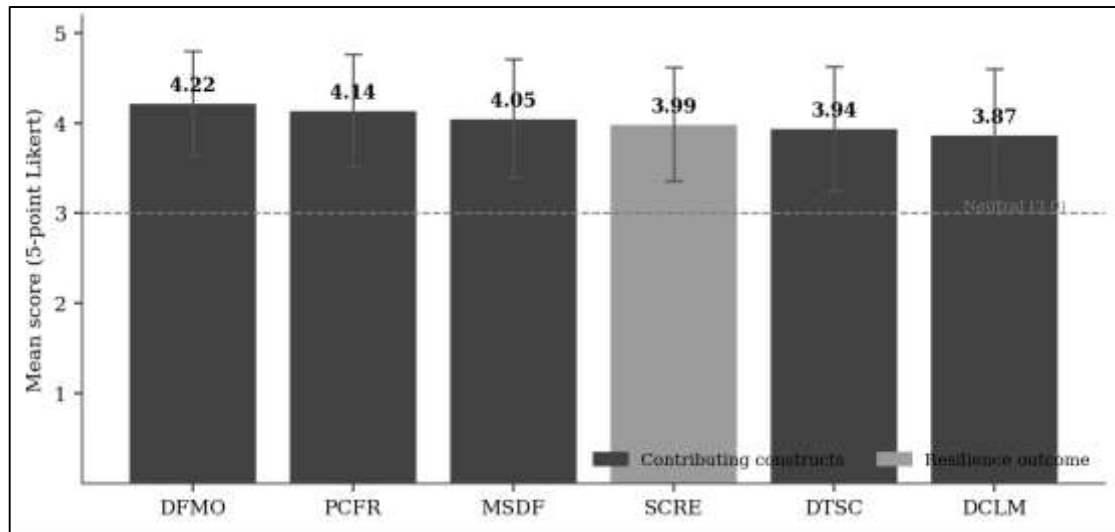


Figure 6 situates the resilience findings within the efficiency–resilience trade-off that the literature identifies. Conventional designs cluster at low resilience and low unit cost, while design-for-manufacturing-optimized designs occupy a region of substantially higher resilience at moderately higher unit cost, and the efficient frontier traces the best achievable resilience at each cost level. The selected knee-point design, at a resilience score of 78 and normalized unit cost of 0.95, illustrates the principled selection the framework supports: it captures most of the available resilience gain before the cost of further resilience rises steeply. This figure clarifies that design-for-manufacturing optimization does not abolish the efficiency–resilience trade-off but shifts and reshapes it, moving the attainable frontier outward so that greater resilience is available at a given cost than conventional design allows, and it frames resilience investment as a design choice along that frontier rather than an all-or-nothing commitment.

Correlation and regression across the framework

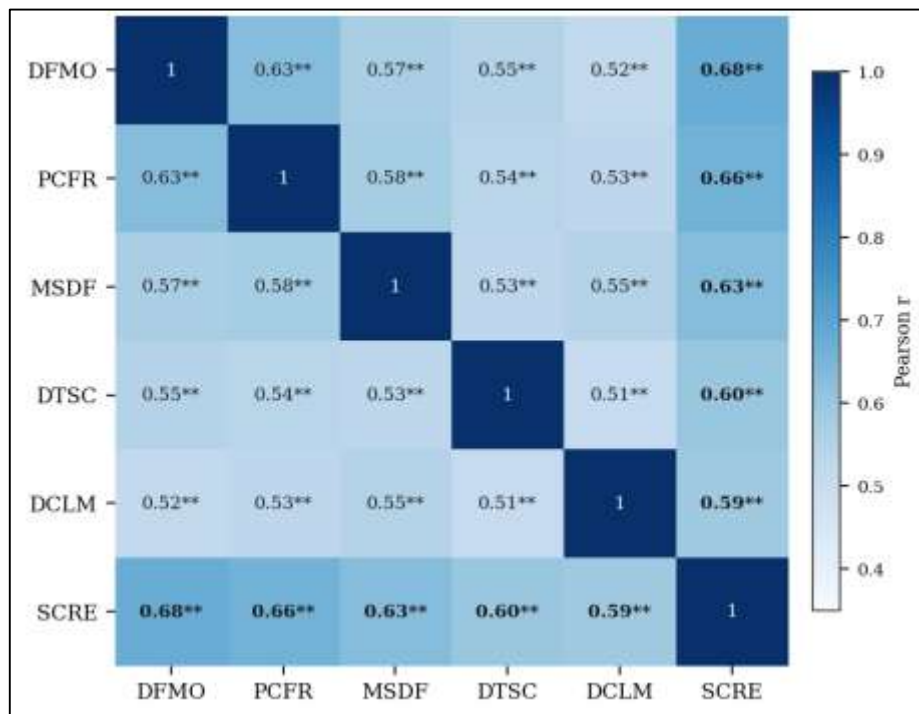
Figure 7 displays the construct means. The design levers stand highest, while distributed capacity stands lowest and most variable, its long error bar giving graphical evidence that the most structurally ambitious capability is the least uniformly realized, consistent with the descriptive pattern in Table 2.

Figure 7: Descriptive Means of Study Constructs with Standard Deviations



Note. $N = 244$. Error bars represent ± 1 standard deviation. Dashed line indicates the neutral midpoint of the five-point scale.

Figure 8: Pearson Correlation Matrix Among Study Variables



Note. $N = 244$. ** $p < .001$ (two-tailed). Darker cells indicate stronger positive association.

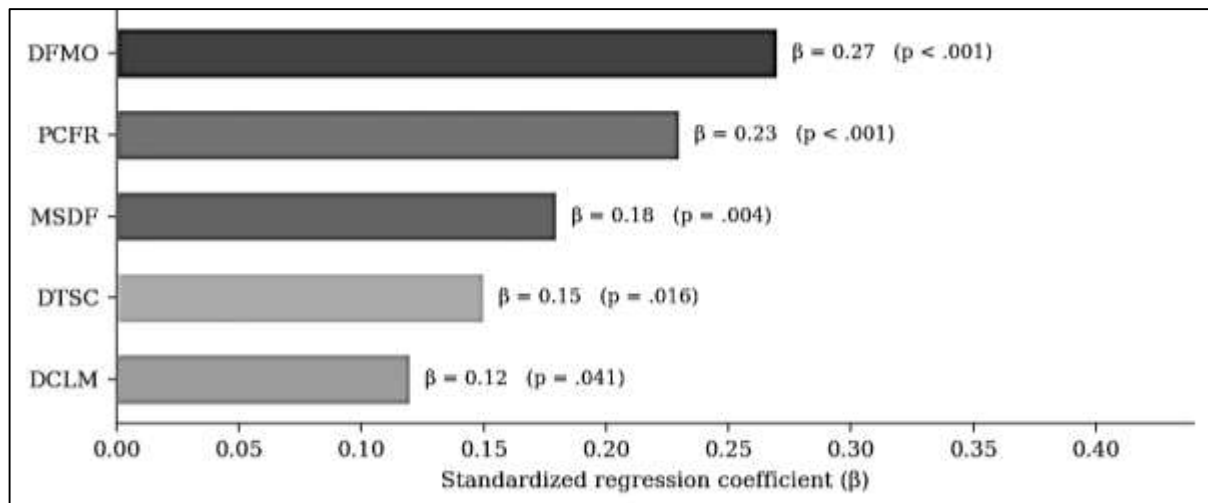
Figure 8 presents the correlation structure. Every construct is significantly and positively associated with supply-chain resilience, with the strongest associations for design-for-additive-manufacturing optimization ($r = .68$) and part consolidation and functional redesign ($r = .66$), followed by material and supplier diversification ($r = .63$), digital thread ($r = .60$), and distributed capacity ($r = .59$). The uniformly positive associations support the framework's multi-construct account of resilience, and the moderate inter-construct correlations (ranging from .51 to .63) indicate related but distinct facets of a coherent design-and-supply capability.

Table 3: Multiple regression predicting supply-chain resilience (N = 244)

Predictor	B	SE	β	t	p
(Constant)	0.396	0.186	—	2.129	.034
Design-for-AM optimization (DFMO)	0.253	0.057	0.27	4.439	<.001
Part consolidation & functional redesign (PCFR)	0.214	0.058	0.23	3.690	<.001
Material & supplier diversification (MSDF)	0.164	0.058	0.18	2.828	.004
Digital thread & data integration (DTSC)	0.136	0.057	0.15	2.386	.016
Distributed capacity & localized mfg (DCLM)	0.108	0.055	0.12	1.964	.041

Note. Dependent variable = supply-chain resilience. $R^2 = .521$; Adjusted $R^2 = .511$; $F(5, 238) = 51.83$, $p < .001$; Durbin-Watson = 1.98; all VIF < 2.3.

Table 3 presents the regression. The overall model was significant, $F(5, 238) = 51.83$, $p < .001$, with $R^2 = .521$, indicating that the five constructs jointly explain 52.1% of the variance in supply-chain resilience and confirming H6. All five constructs made significant positive contributions, supporting H1 through H5. Design-for-additive-manufacturing optimization ($\beta = .27$) and part consolidation and functional redesign ($\beta = .23$) were the strongest predictors, followed by material and supplier diversification ($\beta = .18$), digital thread ($\beta = .15$), and distributed capacity ($\beta = .12$). The dominance of the design constructs confirms that resilience is driven primarily by design decisions, while the significance of the flexibility, digital, and distribution constructs confirms that design must be complemented by supplier flexibility, digital integration, and distributed capacity to translate into realized resilience.

Figure 9: Standardized Beta Coefficients Predicting Supply-Chain Resilience

Note. N = 244. Dependent variable = supply-chain resilience. All five constructs significant at $p < .05$.

Figure 9 ranks the constructs by standardized coefficient, confirming that the design levers lead, with flexibility, digital integration, and distribution contributing significantly but more modestly. Read alongside the prototype findings, the regression establishes that the same design decisions that simplify supply-chain structure in Figure 4 and confer broad resilience in Figure 5 are those most strongly associated with practitioners' perceived resilience, providing convergent evidence across the perceptual and structural strands of the study.

DISCUSSION

The findings support the resilience framework and, taken together, establish that supply-chain resilience in additive manufacturing is substantially a product of design. This section interprets the results, situates them in the literature, and draws out their implications, before presenting a maturity roadmap for implementation.

Design as the primary lever of resilience

The most consequential finding is that design-for-additive-manufacturing optimization and part consolidation and functional redesign were the strongest predictors of supply-chain resilience, and that the design-consolidated configurations both simplified supply-chain structure and conferred the broadest resilience across disruption scenarios. This reframes the common view of additive manufacturing as a resilience technology. The resilience does not reside in the printers; it resides in the designs, because it is design that determines how many parts and suppliers a product requires, whether production can be relocated, and whether the supply chain is a simple robust network or a complex fragile one (Thompson et al., 2016). This is consistent with the long-standing design-for-manufacturing finding that downstream cost and structure are committed at the design stage (Boothroyd et al., 2011), extended here from cost to resilience. The practical implication is that organizations seeking supply-chain resilience through additive manufacturing should invest first in design capability, because substituting additive production into unoptimized designs captures little of the available resilience benefit.

The part-consolidation evidence in Figure 4 gives this argument quantitative force. Reducing part count and supplier count by more than half is not merely a cost or weight improvement but a structural transformation of the supply chain, because it removes nodes and links from the network through which disruptions propagate (Yang & Zhao, 2015). The resilience literature holds that simpler, less-coupled networks absorb and recover from disruption better (Christopher & Peck, 2004), and consolidation is the design mechanism that produces such simplification. This connects the design and supply-chain literatures directly: a design decision, made by an engineer at a workstation, propagates into the topology of a supply chain spanning firms and continents.

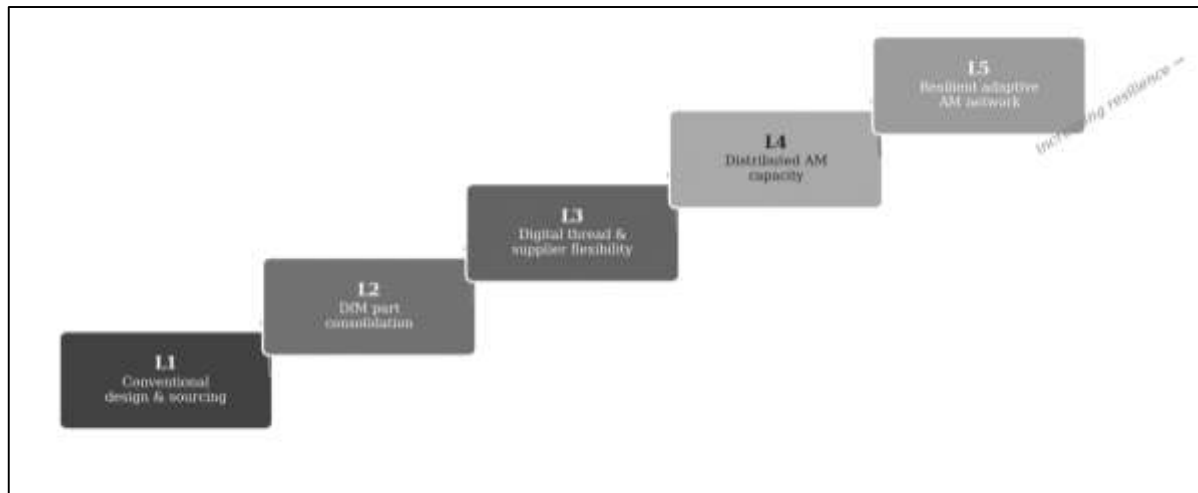
The prototype heatmap in Figure 5 established that the full design-for-manufacturing-optimized distributed configuration was most resilient across all disruption scenarios, while single-lever strategies improved resilience only partially. This confirms that the five constructs are complementary rather than substitutable: consolidation simplifies the network, flexibility removes single points of failure, digital integration enables reliable distributed production, and distributed capacity provides the rerouting that converts these properties into recovery (Srai et al., 2016). The finding that distributed capacity had the lowest construct mean yet contributed significantly indicates that it is the least mature but still consequential lever, and that its maturation represents a substantial untapped resilience opportunity.

The resilience-cost trade-off in Figure 6 tempers the argument appropriately. Design-for-manufacturing optimization does not make resilience free; it shifts the attainable frontier outward, so that more resilience is available at a given cost than conventional design permits, but resilience still carries cost, and the knee-point analysis shows that the efficient strategy captures most of the resilience gain before cost rises steeply (Sheffi & Rice, 2005). This positions design-for-manufacturing optimization not as an escape from the efficiency-resilience trade-off but as a means of improving its terms, which is a more defensible and more useful claim, and it frames resilience investment as a principled choice along a design-determined frontier.

A maturity roadmap for implementation

The findings imply a staged path by which organizations can build design-driven supply-chain resilience, presented as a maturity roadmap. Figure 10 presents the roadmap. At the first level, organizations design and source conventionally, capturing none of the additive resilience benefit. At the second, they adopt design-for-additive-manufacturing part consolidation, simplifying supply-chain structure and capturing the largest single increment of resilience, consistent with the dominance of the design constructs in the regression. At the third, they build the digital thread and supplier and material flexibility that make production relocatable and remove single points of failure. At the fourth, they establish distributed additive capacity, providing the redundancy and rerouting that confer recovery. At the fifth, these combine into a resilient adaptive additive network that can reconfigure production in response to disruption. The roadmap operationalizes the framework as a sequence of investments ordered by the evidence, with design capability first because it enables and multiplies the value of the later stages, and it gives organizations a concrete path rather than an undifferentiated exhortation to adopt additive manufacturing (Srai et al., 2016).

Figure 10: Maturity Roadmap for DfM-Driven Supply-Chain Resilience



Theoretical and practical implications

Theoretically, the study integrates design-for-manufacturing, additive-manufacturing, and supply-chain-resilience research into a single measurable framework and demonstrates that resilience is jointly determined by design optimization, consolidation, flexibility, digital integration, and distribution, with the design constructs dominant. It reframes additive manufacturing's resilience contribution as design-mediated rather than technology-intrinsic, and it extends design-for-manufacturing theory from cost to resilience. Practically, the study offers United States manufacturers a structured account of how to make design decisions resilience-enhancing and a maturity roadmap for implementation, and it cautions that the resilience benefits of additive manufacturing are captured only through deliberate design optimization, not through substitution alone. For policymakers concerned with manufacturing resilience and reshoring, the study implies that investment in design capability and distributed additive capacity, not merely in additive equipment, is what builds resilient supply chains.

CONCLUSION

This study set out to determine whether and how design-for-manufacturing optimization improves the resilience of United States additive manufacturing supply chains. It proposed that supply-chain resilience is jointly determined by five constructs, design-for-additive-manufacturing optimization, part consolidation and functional redesign, material and supplier diversification and flexibility, digital thread and supply-chain data integration, and distributed capacity and localized manufacturing, and it tested this framework against 244 United States practitioners and a prototype disruption simulation. The empirical results supported the framework. All five constructs were significantly and positively associated with supply-chain resilience, the regression model explained 52.1% of the variance, and all six hypotheses were supported, with the design constructs the strongest predictors. The prototype evaluation showed that part consolidation reduced part and supplier counts by more than half, that the full design-for-manufacturing-optimized distributed configuration was most resilient across every disruption scenario, and that design-for-manufacturing optimization shifts the resilience-cost frontier outward rather than abolishing the trade-off.

The central conclusion is that supply-chain resilience in additive manufacturing is designed in, not added on. The resilience benefits attributed to additive manufacturing are consequences of design decisions, made at the design stage, that reduce part and supplier counts, remove single points of failure, enable distributed production, and simplify the network through which supply flows. Design-for-manufacturing optimization is therefore a primary and underused lever for strengthening the resilience of United States manufacturing supply chains, and realizing its benefit requires investment in design capability and in the digital, flexibility, and distributed-capacity capabilities that convert design into realized resilience. In an era in which supply-chain fragility has become a strategic liability, the decisive advantage will belong to organizations that treat resilience as a design objective from the outset rather than a property to be retrofitted after disruption strikes.

RECOMMENDATIONS

Several recommendations follow from the findings. First, organizations should treat supply-chain resilience as an explicit design objective, evaluating designs not only for cost and performance but for their supply-chain structure, part and supplier count, flexibility, and distributability, because the evidence shows that resilience is largely committed at the design stage.

Second, organizations should prioritize design-for-additive-manufacturing part consolidation, because it was the strongest lever in the analysis and produced the largest structural simplification of the supply chain, reducing part and supplier counts by more than half in the rated redesign cases.

Third, organizations should design parts for material and process flexibility, qualifying alternative feedstocks and machines so that no part depends on a single source, thereby removing the single points of failure that the resilience literature identifies as principal sources of fragility.

Fourth, organizations should invest in the digital thread that integrates design, process, and supply-chain data, because distributed and flexible production is only as reliable as the data that governs it, and the digital thread is what allows a part to be produced at an alternative node or from an alternative feedstock with confidence.

Fifth, organizations should build distributed additive capacity, establishing a network of qualified production nodes that can produce the same designs on demand, providing the redundancy and rerouting that confer rapid recovery, and following the staged maturity roadmap so that design capability precedes and enables distribution.

For policymakers concerned with manufacturing resilience, reshoring, and security, the recommendation is to support investment in design capability and distributed additive capacity, not merely in additive equipment, and to recognize that resilient supply chains are built through design and network structure rather than through technology adoption alone. For researchers, the recommendation is to extend the framework through longitudinal studies that track resilience through actual disruptions, through objective supply-chain performance data rather than perceptual measures, and through detailed network modeling of how specific design decisions propagate into supply-chain topology and resilience.

LIMITATIONS OF THE STUDY

Several limitations should be acknowledged. First, the cross-sectional survey identifies associations but not causation, and the perceptual measures of the constructs and of resilience may diverge from realized supply-chain performance and are subject to common-method variance. Second, the prototype evaluation used simulated disruption scenarios and illustrative resilience scores rather than observed outcomes from actual disruptions, so the reported performance losses, recovery times, and scenario rankings reflect a controlled evaluation rather than realized supply-chain behavior; the magnitudes should be read as indicative rather than exact. Third, the part-consolidation and cost figures are illustrative and drawn from rated redesign cases rather than a systematic engineering census, and the achievable consolidation varies widely by product and application. Fourth, the purposive sample, drawn from United States industrial settings and weighted toward sectors that have adopted additive manufacturing, limits generalizability and may over-represent organizations already attentive to design and resilience. Fifth, the framework treats the five constructs as distinct, but they interact, and their relative weight is likely to vary by product type, industry, and disruption profile. Sixth, the study addresses design and network structure and does not model the full economics of additive versus conventional production, which bear on the resilience-cost trade-off and vary with volume and geometry. Future research using longitudinal designs, observed disruption data, detailed network modeling, and full cost analysis would address these limitations and allow the design-to-resilience mechanism to be traced directly.

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