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A dual perspective towards building resilience in manufacturing organizations

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A dual perspective towards building resilience in manufacturing organizations

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Modern manufacturing organizations exist in the most complex and competitive environment the world has ever known. This environment consists of demanding customers, enabling, but resource intensive Industry 4.0 technology, dynamic regulations, geopolitical perturbations, and innovative, ever-expanding global competition. Successful manufacturing organizations must excel in this environment while facing emergent disruptions generated as biproducts of complex man-made and natural systems. The research presented in this thesis provides a novel two-sided approach to the creation of resilience in the modern manufacturing organization. First, the systems engineering method is demonstrated as the qualitative framework for building literature-derived organizational resilience factors into organizational structures under a life cycle perspective. A quantitative analysis of industry expert survey data through graph theory and matrix approach is presented second to prioritize resilience factors for strategic practical implementation.

DEDICATION

This thesis is dedicated to my late father, Michael Fazio, who relentlessly encouraged me to write. He was always my biggest fan and the one who galvanized my decision to pursue a master’s degree. I would also like to dedicate this work to my wife Adrienne who has often felt like a single parent through the late nights and working weekends. I am deeply grateful for her dedicated love and support.

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INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Modern manufacturing organizations (MO) exist in the most complex and competitive environment the world has ever known. This environment consists of demanding customers, enabling, but resource intensive Industry 4.0 technology, dynamic regulations, geopolitical perturbations, and innovative, ever-expanding global competition. Successful MOs must excel in this environment while facing emergent disruptions generated as biproducts of complex man-made and natural systems.

Recently, the global COVID-19 pandemic has caused isolated and cascading disruptions with varying severity across the manufacturing sector. Because of the de-verticalization of production systems (especially in the United States), disruptions from the pandemic have been severe in some cases, causing supply chain breakage. This is noticed in the automotive industry constriction due to engine control system microchip shortages. Labor shortages have been another pandemic-related disruption lowering predictability and performance for organizations and consumers. Natural disasters such as Hurricane Ida have agitated logistics operations and petroleum production. These disruptions directly affect logistics and petroleum companies; they may also infect the operations of virtually every manufacturing organization from large corporations to SMEs. Events caused by climate change such as more frequent extreme weather have been linked to extended blackouts in the southern US and major losses in the lumber industry (Flavelle et al., 2021).

Large-scale environmental and epidemiological disruptions such as those mentioned above create often-existential effects on MO operations by severely constraining labor and supply chains. Smaller, more common disruptions including new competitive market entries or unchecked process variance, which are relatively manageable on their own, may combine into complex networks and seriously or even mortally drain performance.

In decades past, risk management has been a primary discipline in the pursuit of defending MO operational performance against disruption. This traditional method consists of a probabilistic evaluation of negative consequence likelihood and severity for mitigation of organizational exposure. More recently, the field of resilience engineering has emerged to develop frameworks for building absorptive, adaptive, and recoverable qualities into organizations rather than strictly developing risk mitigation strategies (Francis, 2014).

The concept of organizational resilience (OR) was developed from ecology and the study of natural systems as an advancement of organizational risk mitigation. In this paradigm, resilience transcends supposition and is recognized as a fundamental system property incorporating diversity, efficiency, adaptability, and cohesion through an evolutionary life cycle (Fiksel, 2003). Generally, resilience is defined as the property enabling a system to quickly resume standard operation following a disruption. Many, more detailed and industry-specific definitions have been offered in the literature. For example, it has been defined as the "ability of a system to withstand a major disruption within acceptable degradation parameters and to recover with a suitable time and reasonable costs and risks" (Haimes, 2009). Modifying the definition to apply specifically to organizations, Vogus and Sutcliffe offered "the ability of an organization to absorb strain and improve functioning despite the presence of adversity" (2007). The addition of system growth or improvement has been adopted by many authors. It is adopted in this research accordingly.

Much research has been conducted towards the understanding of OR. Generating a plethora of definitions and frameworks for its assessment, authors have reached little consensus as to the methods for implementation of resilience principles in practice (Francis, 2014). The aim of this research is to unravel the quandary surrounding the creation of resilience in manufacturing organizations using a novel dual perspective approach. First, manufacturing organizational resilience (MOR) is examined from a systems engineering (SE) perspective where the SE methodology is proposed as a framework for the synthesis of life cycle management and OR into a structured system design methodology. Second, OR factors derived from the literature are analyzed by implementing manufacturing industry expert opinions into the graph theory and matrix approach (GTMA) framework. This framework creates a priority structure that managers may use for strategic implementation. Additionally, GTMA creates visually intuitive networks that may be used to gain insight into the inter-relationships between OR factors and subsequent implications. The combination of GTMA OR factor analysis and SE design methodology is a new research contribution that creates a robust, dual-perspective rendering adoptable in the manufacturing industry to increase operational performance through the creation or expansion of resilience. In pursuit of these goals, the following research objectives are identified:

I. Construct a MO focused SE framework for building and managing resilience
II. Model literature-derived OR factors to construct a priority structure
III. Derive practical implications for MOs and strategies for managers

To identify OR factors, a non-exhaustive literature review was conducted, and prominent factors selected for study. Manufacturing industry experts were asked to participate in a bespoke survey for their extensive experience in organizational management. The survey data were analyzed using GTMA which outputs both single numerical values and a visual model of OR factor inter-dependence.

1.2 Literature review

1.2.1 Resilience in manufacturing

The current reality for the manufacturing industry is that customers are well informed and demanding. While navigating complexity, volatility, uncertainty, and ambiguity, MOs must satisfy customers with high quality, customization, and high reliability of delivery (Bauer et al., 2021). Inevitably, disruptions will occur, testing the resilience of manufacturing firms and their respective supply chains. The effectiveness of a firm's resilience model extends beyond these boundaries to include the communities in which they operate (Yao et al., 2008). The presence of system interdependence is not unique to the manufacturing sector. Health care, defense, food service, logistics, entertainment, and virtually all others are links in their own supply chains and influence the prosperity of the communities in which they operate. The aim of this research is to specifically examine resilience in the context of manufacturing industry idiosyncrasies.

To address the need for a practical model for responding to disruption, Sahebjamnia, Torabi, and Mansouri developed an integrated business continuity and disaster recovery planning model using multi-objective mixed-integer robust possibilistic programming to create a balanced trade-off structure between resources, recovery time, and recovery point (2018). Validation of the model was completed with a real case study involving a furniture manufacturing firm. Sampling data from 205 manufacturing firms, Bustinza et al. used Structural Equation Modelling to validate the mediating effect of OR on the impact of technological changes to overall organizational effectiveness. The authors elaborate to conclude that OR is a function of human factors enabled by firm human resource practices (2019). Many authors have noted the connections between OR and supply chain resilience. Using an integrated Delphi – fuzzy logic approach, Kumar and Anbanandam established the enhancers and inhibitors to supply chain resilience from the literature that may be used to formulate a resilience index (2019). Sourcing, manufacturing flexibility, and logistic flexibility were found to be the primary enhancers while information sharing, lack of risk management culture, inter-organizational relationships, and integration of supply chain stakeholders were noted as the primary inhibitors. Dubey et al. examined the enhancing effect of data analytics capability and organizational flexibility on supply chain resilience and competitive advantage (2021). This theoretical model is based in organizational information processing theory and the hypotheses tested using variance-based structural equation modelling.

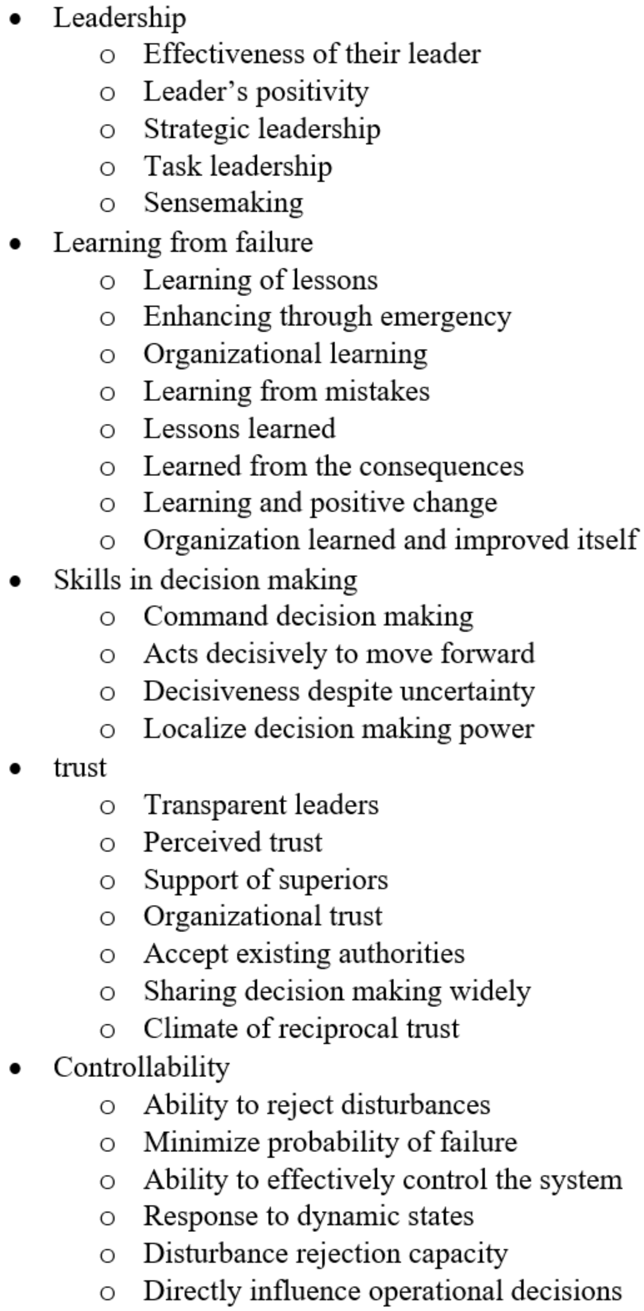
In a study of Nigerian manufacturing firms, Akpan et al. used Partial least Squares Structural Equation Modeling to validate dynamic capabilities described as sensing and reconfiguration enhancement of systemic resilience properties adaptability and agility (2021). In a case study of two manufacturing and two service firms, Borekci et al. evaluated a two-dimensional resilience model that consists of operational and relational dimensions as it related to organizational resilience in terms of survivability and sustainability (2021). This study found examples supporting the positive correlation between both resilience dimensions and survivability and sustainability.

There have been several attempts in the literature to derive sets of resilience factors. One such research generated 33 variables that were categorized under seven main OR factors and used to create a survey distributed to 159 manufacturing firms (Morales et al., 2019). The resulting information was implemented in a partial least square structural equation modelling approach to derive the primary drivers of OR and their interdependence. In Section 1.2.2, these OR factors along with others from the literature are examined and combined to contribute to the theoretical MOR evaluation framework for this research.

1.2.2 Resilience factors

1.2.2.1 Research methodology: identifying and defining resilience factors

A literature review and bibliometric analysis (shown in Figure 1.2) of 75 papers was conducted to find prominent OR factors. The factors themselves are not manufacturing industry specific due to their applicability to organizations in general. During the review, common themes were developed through coding and grouping of similar ideas. 88 codes for potential OR factors were generated and overlapping ideas either combined or used to create sub-factors. Based on low frequency of mentions or citations, some codes were discarded. Results of the bibliometric analysis were obtained using Equation 1.1 and are shown in Table 1.1. To give an example of this method, the *innovation and creativity* factor is considered. This factor or variations on it are mentioned as a main factor of resilience in 24% of the reviewed literature. Examples of different representations of this idea were coded as *bricolage*, *improvisation*, and *organizational craftsmanship*. All three of these ideas share a common theme of skill in quickly creating novel solutions to organizational disruptions. This commonality led to combining them, at the discretion of the researcher, under the most inclusive, concise, and repeated related code found in the literature: *innovation and creativity*. To further illustrate the coding method that was used to synthesize the factors and subfactors, an example from the coding of the *leadership* factor is displayed in Figure 1.1.



- Leadership
    - Effectiveness of their leader
    - Leader’s positivity
    - Strategic leadership
    - Task leadership
    - Sensemaking
- Learning from failure
    - Learning of lessons
    - Enhancing through emergency
    - Organizational learning
    - Learning from mistakes
    - Lessons learned
    - Learned from the consequences
    - Learning and positive change
    - Organization learned and improved itself
- Skills in decision making
    - Command decision making
    - Acts decisively to move forward
    - Decisiveness despite uncertainty
    - Localize decision making power
- trust
    - Transparent leaders
    - Perceived trust
    - Support of superiors
    - Organizational trust
    - Accept existing authorities
    - Sharing decision making widely
    - Climate of reciprocal trust
- Controllability
    - Ability to reject disturbances
    - Minimize probability of failure
    - Ability to effectively control the system
    - Response to dynamic states
    - Disturbance rejection capacity
    - Directly influence operational decisions

Figure 1.1 Sample codes from *leadership* OR factor

Once the review reached a point where new codes were not being generated and a sufficiently robust group of factors and sub-factors had been assembled, the review was concluded. The resulting nine factors of OR and 33 sub-factors from the literature are presented in the following sections. They are summarized in Table 1.1.

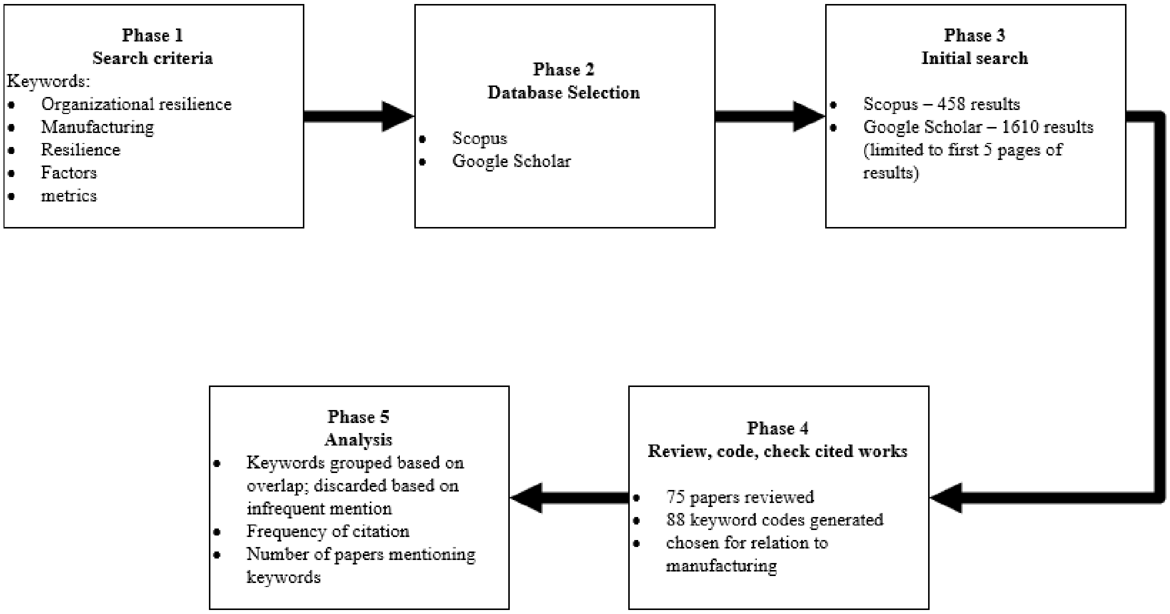


Figure 1.2 Literature review method

Table 1.1 Bibliometric analysis of resilience factors

Factor	Factor Letter	# of papers mentioning	% of papers mentioning
leadership	A	29	39%
teamwork	B	17	23%
information and knowledge management	C	21	28%
innovation and creativity	D	18	24%
coordination and monitoring	E	15	20%
planning strategies and preparedness	F	24	32%
resources	G	38	51%
flexibility	H	31	41%
minimization of silos	I	9	12%

$$\frac{X_i}{n} \tag{1.1}$$

where X_i = number of papers mentioning the i^{th} keyword,
n = total number of reviewed papers (75 in this case)

1.2.2.2 Leadership

The role of leadership in building resilient organizations is to guide and enable mechanisms understood as the OR factors. (O'Rourke, 2007) notes that, "Leadership is, perhaps, the most critical factor in promoting resilience, and also the least predictable." Effective leaders must therefore be able to expedite clear and unfettered two-way communication throughout the organization (Norman et al., 2010). The specific makeup of this communication described as *transparency*, includes openness to bi-directional feedback, openly sharing insight into decision making and other relevant information, and acting in a manner congruent with rhetoric (Norman et al., 2010).

As transparency permeates organizational culture, members develop an understanding that decisions made by leadership will generate results in alignment with their own interests, i.e., transparency builds *trust* (Driscoll, 1978). Leaders looking to build trust within organizations may find the concept to be ambiguous. For this reason, Mayer et al. constructed a trust model that disaggregated the concept into three factors: ability, benevolence, and integrity (1995). The authors discuss the potential for trust to exist with varying levels of the three factors while maintaining that high levels of all three maximize a leader's trustworthiness.

Leaders must also be able to effect change during times of dynamic uncertainty. This *controllability*, while a trait of leadership, must be built into the system during the design phase (Dinh et al., 2012). Higher levels of controllability will enhance overall OR by enabling implementation of designed flexibility. When disruptive events exceed system controllability, leaders may be faced with exceptional situations that challenge their ability to prioritize core values. This *decisiveness* in the face of uncertainty is described by Lengnick-Hall et al. as a key cognitive leadership trait contributing to resilience (2011).

Even when exceptional leadership is present, disruption may lead to system faults. For this reason, a feedback loop should exist to inform future system design and operation towards a more reliable, steady state (Crichton et al., 2009). This *learning from failure* may also occur by examining and benchmarking other firms and human response to historical events such as natural disasters.

1.2.2.3 Teamwork

The resilient organization is built on effective personnel. Beyond effective individuals, those working together with shared objectives and complimentary skills can experience a reduction in burden leading to increased organizational performance during disruption (Azadeh, Salmanzadeh-Meydani, et al., 2017). This group dynamic or teamwork and resilience potential is partly created by a workforce with the competence and motivation to achieve predetermined needs of the organization (Aleksić et al., 2013). *Human factors* are therefore the human components who enable the formation of effective teams and teamwork.

As teams are formed with strategic groupings of human factors, guiding principles can help focus effort on the needs of the organization. One such principle is the *orientation for completing tasks* (Azusa and Hiroyuki, 2013). This may help teams filled with different views to reach consensus, if not on every issue, on the importance of results. Completion of tasks is beneficial for teams and thus organizational performance. For teams and their organizations to thrive, however, it is necessary for each individual within a team to have an *orientation for interpersonal relationships*. This sub-factor prioritizes communication and an atmosphere of mutual respect for diversity in skills and strengths (Azusa and Hiroyuki, 2013).

1.2.2.4 Information and knowledge management

Organizational knowledge and information should receive treatment commensurate with its high potential value. Direction of these resources, or *knowledge management*, involves an array of tasks including acquisition, storage, organization, and dissemination (Mack et al., 2001). A firm's *awareness* is a key trait of this resilience factor in that it will yield performance drivers insight (Gonzalo et al., 2018).

Beyond the existence of general knowledge awareness, prevailing information embedded in the minds of personnel creates organizational culture. When it rejects detrimental behavior, a *just culture* results with a clear distinction between desirable and undesirable action (Gonzalo et al., 2018).

1.2.2.5 Innovation and creativity

Planning and preparing for disruption have become ordinary activities in the rapidly changing, emergent environments in which today's organizations operate. Preparedness, however, is limited by the inherent inability of leaders to consider and plan for the infinite range of disruptive possibilities. *Creativity*, or the process of generating new effective alternatives, drives several traits of the innovation and creativity resilience factor by serving to enhance adaptive capability and strengthen individual improvisational ability (Chelariu et al., 2002; Kendra and Wachtendorf, 2003).

Much of the resilience literature focuses on the need for what Grøtan et al. refer to as to as, "constant awareness and adaptation" (2008). The ubiquity of *improvisation* in the literature supports this idea and its importance. It occurs when disruption forces the instantaneous subversion of operational norms for new ideas and actions. In other words, *improvisation* exists at the intersection of creation and execution (Chelariu et al., 2002). An individual's response to an unexpected event is driven by improvisational ability. Subsequently the severity of a disruption is partially dependent on the improvisational abilities of the response group. An important distinction between improvisation and creativity is that improvisation exists post-disruption, while creativity is vital in the entire resilient system life-cycle (Kendra and Wachtendorf, 2003).

Innovation as the result of creative input and flexibility is considered a necessary component of the competitive advantage required in a sustainable business model (Christensen, 2006). This idea owes in part to the understanding that disruption may be caused by new innovative entries into the competitive landscape, requiring reciprocal innovation for survival. Unfortunately for larger organizations, managerial systems required in effectively governing their expansive operations tend to stifle the innovative process, meaning processes should be put in place to balance this effect (Christensen, 2006).

When applied to processes, innovation yields what is described in the resilience literature as *emergence*. This should not be confused with the definition imposed in SE literature which places a generally negative connotation on the term, using it to describe unexpected results arising from complexity amongst associated network components. Emergence in OR terms occurs post-disruption and involves an overhaul of the system including new or updated processes, relationships, supply chain links, and customer base (Kendra and Wachtendorf, 2003).

1.2.2.6 Coordination and monitoring

Dependent on the actions of team members, the preparedness for and response to a disruptive crisis relies heavily on *dissemination of information* and following up on its use (Gomes et al., 2014). These activities are noted under the factor moniker coordination and monitoring.

Performance coordinating individuals and teams during and after a disruption is time dependent. Leaders and managers must therefore eschew ambiguity and deliver instructions with *task clarity*. This trait helps to maximize coordination and minimize vital resources spent in corrective monitoring (Azusa & Hiroyuki, 2013). As tasks are handed down and implemented through the organization and over time, new information is generated that should be fed back through the system to benefit future decisions (Grøtan et al., 2008). The effectiveness with which this sharing occurs can be captured and measured within the *dissemination of information* trait (Chelariu, Johnston, and Young, 2002).

As system inputs and resources vary during disruption, close monitoring of those variables enables adjustments to be made prior to unacceptable performance loss or even system failure.

This trait of the coordination and monitoring OR factor is described in the literature as *fault tolerance* (Azadeh, Roudi, et al., 2017).

1.2.2.7 Planning strategies and preparedness

Confronting vulnerabilities is key to developing OR but can be an unpleasant task for managers (Brown et al., 2017). The task, however, can only be completed if information is available after completing regular *risk assessments*. In addition to a specific awareness of potential disruptions, formal risk assessments negate biased human tendencies such as skewing probabilities toward serious but unlikely disruptions like earthquakes and away from less serious, more probable events like floods (Alcayna et al., 2016). Once potential risks and their likelihoods have been evaluated, the organization must develop a mitigation plan that accounts for its strengths, weaknesses, and level of preparedness (Brown et al., 2017).

Strategic planning and preparedness must also encompass *recognition of critical interdependencies*, a trait that involves awareness of the internal and external relationships that are vital to OR (Lee et al., 2013). In fact, from a supply chain system perspective, perfectly optimized processes may be wholly ineffective if supported by a network of sub-optimal links and nodes (Christopher and Peck, 2004). Such relationships may include those with external vendors, logistics providers, or even internal departments. While some may consider these as dependent relationships, basic sustainability principles prescribe that linkage built from mutual benefit will yield a more resilient system, thus dictating recognition of interdependence in the development and management of win-wins in such connections (Fiksel, 2003).

Planning and preparedness can be supported and strengthened by *scenario analysis, testing, and simulation*. The activities comprised in this trait have been partly enabled by the advancement of computing technology that can model complex networks with realistic detail and infinite variability, enabling system designers and operators to virtually experience varied input-response relationships (Lee et al., 2013; O'Rourke, 2007). In this fashion, an iterative planning and analysis strategy is developed to rehearse scenarios and validate plans.

The ultimate success of a planning strategy is dependent on it incorporating the entire relevant system scope. *Risk assessments* and *recognition of critical interdependencies* along with their implementation into *scenario analysis, testing and simulation* form the basis of effective resilience strategy. As strategies are developed, managers must consider the traits of planning and preparedness on both the organization and business process levels (Tadić et al., 2014).

1.2.2.8 Resources

A variety of external resources ranging from suppliers to logistics providers are important components of OR during disruption. These resources were discussed from a relational perspective in the previous sub-section under the critical interdependency factor heading. Managers must also consider the resource perspective to address contingencies for obtaining the resources necessary in maintaining acceptable operational performance (Brown et al., 2017). Alternative to maintaining the flow of resources into the organization, managers may choose to mitigate disruption by implementing plans for budgeting limited available resources (Sahebjamnia et al., 2018). In either scenario this trait is defined as *resource supply*.

Availability of specialized or cross-trained disruption support staff is an internal resource that can help strengthen OR. Whether through planned roles or crisis management, internal resources must be divided during disruption between maintaining acceptable operational performance and crisis response, i.e., there must be *emergency personnel available* beyond that which is required for nominal operation (O'Rourke, 2007).

Supplementing both in terms of resource supply and emergency personnel is likely to incur additional costs to the organization. For this reason, there must exist the *financial capacity* to subsume this economic liability. The inability to cope with the formidable financial burden of crisis-level disruption may render recovery completely out of reach (Alcayna et al., 2016). Maintaining a network of accessible financial resources to be leveraged is an acceptable solution; however, history has proven in the case of Toyota following the earthquake and tsunami of 2011, that, when possible, ability to self-finance recovery can lead to competition vanquishing advantage (Canis, 2011). During this disaster, Toyota suppliers were crippled leaving assembly-plant workers without work. Toyota was able to pay worker salaries and deploy them with various suppliers, helping the company resume acceptable operation levels much more quickly than had these resources not been available.

Cash resources are another important driver of resilience that may at times, especially for SMEs laden with short-term cash flow concerns, be the sole determining factor of OR (Ates, 2011). Cash resource limitations of SMEs translate into a culture of reactivity and firefighting rather than one of long-term resilience building strategy (Ates, 2011; Van Gils, 2005). The goal of every manufacturing organization in terms of financial resources should be to at least maintain sufficient cashflow for continuous operation. The goal of the resilient organization, however, should be to create an adaptive cash-management strategy that exceeds the capability of its competition.

With the increasing technical complexity of manufacturing systems, the need for a network of support personnel well-versed in relevant knowledge is a key driver of resilience. This sub-factor, known as *technical professional network support*, affords technology-rich industry 4.0 manufacturing firms absorptive ability by deploying subject matter experts to troubleshoot and improve advanced systems (Alcayna et al., 2016).

1.2.2.9 Flexibility

Perhaps one of the most important OR factors, the ability of the organization to remain flexible during and after disruption is reliant on many of the other factors. Flexibility, enabled by factors such as planning and resources, in this sense is a mechanism by which the organizational system absorbs or transfers disruptive shock, restoring nominal operation without crashing. *Adaptability* is the trait focused on processes that enable the organization to monitor system parameters and quickly implement resilience model changes if needed (Gonzalo et al., 2018; Woods, 2012).

When a need for system changes is identified, the *reorganization* trait describes a potential approach. Reorganization or restructuring is a design element enabling the system architecture to be modified at any point on the disruption continuum (Jackson & Ferris, 2013). Because disruptions are critical by nature, reorganization effectiveness is largely contingent on the speed at which it is realized, making it a good way to measure organizational flexibility. The specific nature of restructuring may be related to a wide array of organizational elements including structure of the organization chart, supply chain, and resource usage (Boin and van Eeten, 2013; Jackson and Ferris, 2013).

The resilient organization must be able to quickly resume normal operations post disruption. The approach may involve on-line and/or off-line repairs, but restorative capacity and the rate at which repair is achieved is defined as *repairability* (Jackson & Ferris, 2013).

Another trait of flexibility involves alleviating one of the primary attributes of modern systems: complexity. As systems increase in size and scope, people, processes, and technology are added to meet proportionally increasing demands on them. The *reduction of complexity* trait deals with the need to maintain or obtain simplicity in these aspects wherever possible (Jackson and

Ferris, 2013). An example of this can be seen as small businesses grow and require processes to effectively manage an expanding workforce. The solution in such a case may exist outside of stringent and convoluted human resource policies and processes. Collins argues that the presence of such practice is indicative of employees who are mis-aligned with company culture, i.e., replacing culturally-mis-aligned employees with aligned employees may serve to reduce overall system complexity (2001).

1.2.2.10 Minimization of silos

Complexity in manufacturing often creates the need for highly specialized functions spread across large organizations. The tendency in this case is for individuals and teams to subjugate the organization's agenda to their specific needs, making decisions based on their own goals (Fenwick and Brunsdon, 2009). The resulting decentralized units are known as silos and the non-communicative reductionist approach as silo mentality (Mcmanus, 2008). As this mentality is counter-productive to the previously outlined OR factors and traits, minimization of silos should be a goal of resilient organization managers.

Individuals who consider the gamut of factors including social, organizational, policy, political, technical, and informational to achieve a global perspective are said to have a *holistic view* (Hossain et al., 2020). This trait ensures that the attention to internal and external relationships necessary for OR will be paid by team members (Fenwick and Brunsdon, 2009).

Dissemination of information was discussed under the coordination and monitoring factor as a measure of general information sharing throughout the organization. In the case of silo minimization, the specific information sharing concern deals with the effectiveness of *cross functional communication*. This deals with the creation and utilization of conduits between functions that enable clear, expedient information flow (Mcmanus, 2008). This organization-spanning communication will lead naturally to the creation of internal agility and collaboration in competency and function-diverse social networks (Bouwer et al., 2021; Ferraz and Pimenta, 2020).

Table 1.2 Organizational resilience factors and traits

	OR Factor		Sub-factor	Description
A	**Leadership**			**Guidance of OR factor implementation**
		A_1	Transparency	Open sharing of relevant information and feedback
		A_2	Trust	Assumption that leadership will generate results in alignment with stakeholder interests
		A_3	Controllability	Ability to effect change during dynamic uncertainty
		A_4	Learning from failure	Using experience to inform future system iterations toward a more reliable, steady state
		A_5	Decisiveness	Ability to quickly prioritize core values in the face of uncertainty
B	**Teamwork**			**Increasing organizational performance through individuals working together with shared objectives and complimentary skills**
		B_1	Human factors	Human components who enable the formation of effective teams and teamwork
		B_2	Orientation for completing tasks	Ability of a leader-coordinated team to work in concert toward the successful completion of goals.
		B_3	Orientation for interpersonal relationships	Beneficial interconnectivity among team members enabling response to and recovery from disruption
C	**Information and knowledge management**			**Controlled use, storage, and transfer of information for the benefit of organizational performance**
		C_1	Knowledge management	Acquisition, storage, organization, and dissemination of information resources
		C_2	Awareness	Insight into specific information that drives organizational performance
		C_3	Just culture	Prevailing information embedded in the minds of personnel supporting a clear distinction between desirable and undesirable action
D	**Innovation and creativity**			**Ability to generate solutions as new disruptions occur**
		D_1	Creativity	Process of generating new effective alternatives

Table 1.2 (continued)

	OR Factor		**Sub-factor**	**Description**
		D_2	Improvisation	Instantaneous subversion of operational norms for new ideas and actions
		D_3	Innovation	Generation of effective new ideas as a result of creativity and flexibility
		D_4	Emergence	Process and business model changes made after disruption
E	**Coordination and monitoring**			**The useful distribution of information and oversight of its effective use**
		E_1	Task clarity	Maximizing coordination of the workforce with clear and concise instructions
		E_2	Dissemination of information	Effective sharing of new information generated during system operation
		E_3	Fault tolerance	Processes allowing adjustment prior to unacceptable performance loss or system failure
F	**Planning strategies and preparedness**			**Assessment of risk and development of mitigation plans that account for strengths, weaknesses, and levels of preparedness**
		F_1	Risk assessments	Processes designed to create specific awareness of potential disruptions and their likelihood of occurrence
		F_2	Recognition of critical interdependencies	Awareness of the internal and external relationships that are critical to OR
		F3	Scenario analysis, testing, and simulation	Iterative, technology-driven analysis strategy for rehearsal of scenarios and validation of plans
G	**Resources**			**The roles, materials, supplies, machinery, funds, and technology required for operation of the organization**
		G_1	Resource supply	Maintenance of the flow of resources into the organization
		G_2	Emergency personnel available	Availability of adequate internal resources to simultaneously maintain acceptable performance during disruption and respond to crisis.
		G_3	Financial capacity	Availability of funds or economic resources to subsume the economic burden of disruption

Table 1.2 (continued)

	OR Factor		Sub-factor	Description
		G_4	Technical professional network support	Access to critical infrastructure technical subject matter experts
H	**Flexibility**			**Mechanism by which the organizational system absorbs or transfers disruptive shock, allowing return to nominal operation without crashing.**
		H_1	Adaptability	Processes that enable the organization to monitor system demands and boundaries to quickly implement needed resilience model changes
		H_2	Reorganization	Process enabling system architecture modification around or during disruption
		H_3	Repairability	The rate at which return to normal operation is or may be achieved
		H_4	Reduction of complexity	The need to maintain or obtain system simplicity
I	**Minimization of silos**			**Reduction or elimination of decentralized organizational units enabling implementation of OR factors**
		I_1	Holistic view	Consideration of global system perspective including social organizational, policy, political, technical, and informational factors
		I_2	Cross-functional communication	Creation and utilization of conduits between functions that enable clear, expedient information flow
		I_3	Cross-functional integration	Creation of internal agility and collaboration through cohesive organization-spanning social networks

1.2.3 Organizational resilience and multi-criteria decision making

Myriad problems face decision makers working in the complexity of today’s organizations. As such, a great deal of research has been conducted concerning the development of effective methods for devising and selecting optimal solutions. Some solutions involve probability theory as a means of mitigating risk among alternatives, while others use a statistical approach. Multiple criteria decision making (MCDM) methods or multiple attribute decision making (MADM) methods have been shown in the literature to be effective tools in solving problems where diametric relationships exist among alternative criteria.

There exist several prevalent MCDM methods in the literature. Each of these methods has been extensively evaluated through research to determine strengths and weaknesses as well as demonstrate potentially useful applications. One study by Kumar et al. compared eight of the most prominent MCDM methods in a review focused on the development of sustainable renewable energy (2017). These methods include Weighted Sum Method, Weighted Product Model, Analytical hierarchy process (AHP), Elimination and Choice Translating Reality (ELECTRE), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), VlseKriterijumskaOptimizacija I KompromisnoResenje (VIKOR), Preference Ranking Organization Method (PROMETHE), and Multi Attribute Utility Theory (MAUT). The authors note that MAUT, AHP, Weighted Sum Method, and Weighted Product Method are suitable for prioritization problems (Kumar et al., 2017). Another research used a two-step fuzzy AHP and fuzzy TOPSIS combined approach to rank organizational resilience factors (Tadic et al., 2014). The evaluation of supply chain resilience has been a common MCDM application. One example exists in (Sahu, Datta, and Mahapatra, 2017) where a fuzzy-based approach was used to create a resilience performance index based on linguistic inputs from experts. Another supply chain related research used Grey DEMATEL and Fuzzy Best-Worst methods to assess the barriers to resilience-generating cooperation among supply chain links (Mahmud et al., 2021). This study found that barriers related to communication and information were the most significant.

When selecting an MCDM method for this research, the advantages and disadvantages of the many available methods were considered. The primary motivator behind the selection of

GTMA exists in the foundations of SE as described by Deming (1994) as the recognition that effective management is contingent on systems thinking or awareness of interdependencies between components and sub-systems that make up whole systems and drive them toward—or hinder them from—reaching their aim. The key idea here is *interdependence*. If analysis of any system is limited to a single component or even a set of its sub-systems, without consideration of the interdependencies between all related components and sub-systems—and so the entire system—is an analysis that will yield unsatisfactory, incomplete information. The same logic applies to a decision making tool like GTMA that captures the information generated from interdependent relationships and incorporates it into a holistic problem solution.

1.2.4 Graph theory and matrix approach

Graph theory and matrix approach (GTMA), though it was not called such, was developed by Gandhi et al. for analyzing the reliability of mechanical systems (1991). The need as described by the authors was for a more accurate method of determining system reliability. At that time statistical and modeling methods were state of the art but yielded results incongruent with reality. By combining graph theory for developing structural system models with MCDM methods and matrix algebra, the authors were able to mathematically incorporate component and sub-system interdependencies, yielding a more accurate quantitative description of system reliability. The specific metrics are the matrix determinant (VCM-r) and matrix permanent (VPF-r) which are each useful dependent on the type of system data that is available (Gandhi et al., 1991).

Furthering the above research, Gandhi and Agrawal combine the then novel GTMA concept with failure modes and effects analysis (FMEA) toward better understanding of hydraulic system reliability (1992). The authors note that digraphs and matrices are conducive to computer analysis, making this method more attractive to designers dealing with complex interactions and emergent sources of mechanical failure.

This section presents an overview of GTMA applications from a review of 82 papers where GTMA was implemented as an MCDM method. Figure 1.3 shows the distribution of these applications.

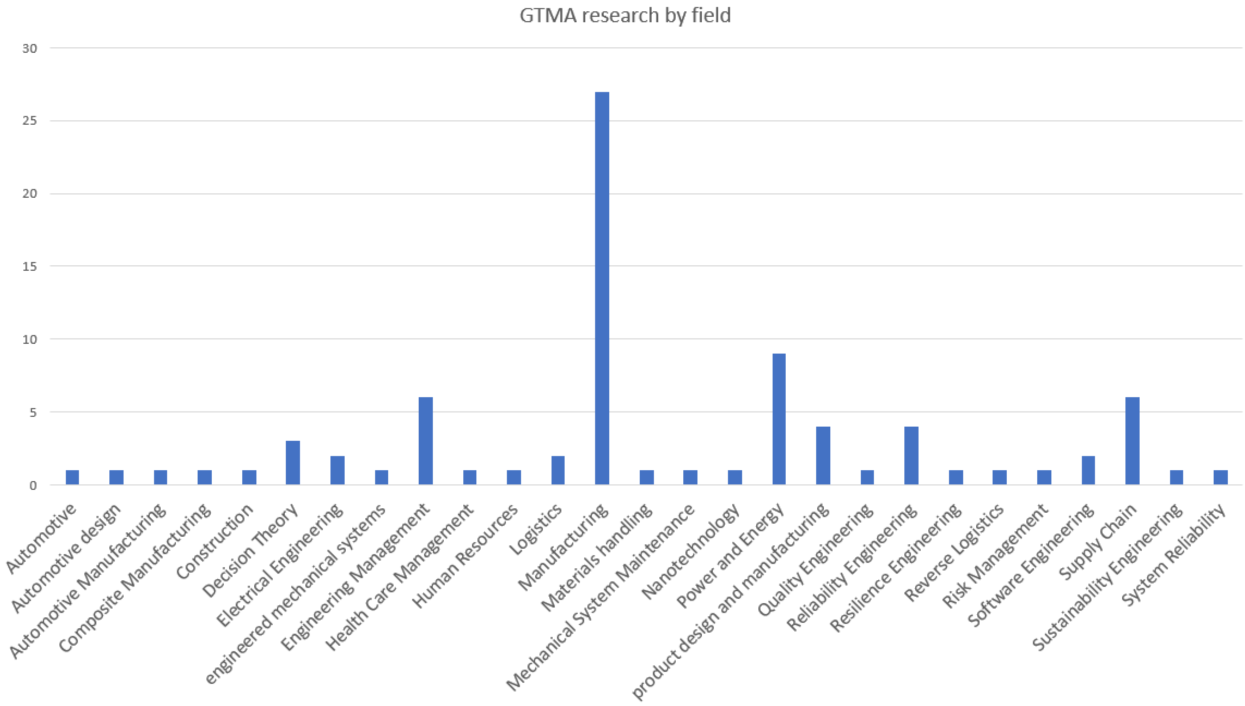


Figure 1.3 GTMA implementation frequency by field

The founding authors of GTMA used relatively simple examples to demonstrate the method's efficacy. Venkatasamy and Agrawal tested the method in the significantly more complex application of an automobile system (1995). This paper decomposes the detailed, but well-understood automobile into a four-tiered tree diagram, then into digraphs followed by matrices that yield, dependent on the parameters examined by researchers, indices for the entire automobile structure.

Venkatasamy and Agrawal continue this work in tuning the GTMA tool towards automobile quality analysis (1997). A detailed theoretical framework is constructed combining the work of quality gurus Juran, Crosby, and Taguchi with the eight quality dimensions developed by Garvin (1984) and the multi-faceted GTMA. The matrix permanents in this research yield quality indices for subsystems up to the total vehicle system level. The authors note that the development of subsystem indices may aid in evaluating quality trade-offs in the design phases. This approach also mitigates the complexity of such a large system.

The implementation of GTMA in system design phases is prevalent in the literature. Wani and Gandhi show the effectiveness of this approach by using GTMA to analyze maintainability of mechanical systems via their tribology characteristics (2002). In this work, five system features are identified—1) life-time/long-life lubrication 2) wear compatibility 3) tribo-compatibility 4) design parameters 5) tribo diagnostics—and installed in the GTMA method to generate a maintainability index. The authors contend that this approach employed in the design stage of mechanical systems will yield increased friction-wear performance through more robust evaluation of alternatives than traditional design methods.

While much of the early applications of GTMA involved mechanical systems, power and energy systems quickly drew attention as critical infrastructure of sufficient complexity. Mohan et al. suggest that at the time of publication, no mathematical model had been created to evaluate the performance with consideration of holistic system architecture of a steam power plant (2003). GTMA was available to fill this gap by creating detailed models of what the authors refer to as macro systems, e.g., boilers, turbines, turbogenerators, up to the plant or system level. This approach, believed to be less complicated than alternatives historically applied in the power and energy sector, yields a concise index for performance evaluation and comparison of steam power plants (Mohan et al., 2003).

Several other GTMA implementation papers regarding evaluation of steam power plants have been published. Interested readers are directed to the following works by topic:

Coal power plant equipment maintenance (Mohan et al., 2004), steam power plant performance evaluation (Mohan et al., 2006), power plant evaluation and selection, (Garg et al., 2006), power plant performance monitoring (Mohan et al., 2007), thermal power plant quality evaluation and selection (Garg et al., 2007), steam power plant reliability (Mohan et al., 2008).

In addition to the study of physical systems, GTMA has also been shown to be effective applied to theoretical concepts and soft-systems. One such application by Grover et al. was to create a framework for assessing the total quality management (TQM) environment of a firm, i.e. how conducive the environment is to performance excellence through the implementation of TQM ideals (2004). This differs from previous studies not only in its concern of soft versus hard systems. It also addresses a topic that has been described differently by many authors in the literature, showing that GTMA is well suited to modeling a wide variety of systems.

In their study, Grover et al. review TQM literature to aggregate the many factors for TQM success into five groupings dubbed critical elements (2004). These critical elements and their sub-factors are then used as the basis for development a GTMA model resulting in the TQM performance index.

GTMA has been applied to the product design process in a paper by Prabhakaran et al. that examines the design and manufacture of composite products through a resin transfer molding process (2006). The authors describe the uses of such composite products as being suited to aerospace and automotive applications that have stringent design and performance requirements. For this reason, several design aspects must be considered and optimized concurrently, making GTMA an ideal solution. The resulting analysis provides designers with assurance that stakeholder requirements along with their interactions are fully considered and an optimal balance of interdependent elements is achieved (Prabhakaran et al., 2006).

The complexity present in the manufacture of composites exists in many modern manufacturing processes. For example, machining of engineered materials with exceptional hardness such as ceramics requires an optimal balance of machining parameters that may demand knowledge beyond that of a skilled machinist. Zhong et al. present a GTMA-based paper that considers four different advanced ceramic materials (2006). Three mechanical properties are chosen and used to evaluate each ceramic for its machinability index. This value gives the manufacturer valuable information that can be used to determine machining parameters such as material removal rate and grinding force. The authors state that the results of this study are commensurate with known properties of the materials investigated, validating the efficacy of GTMA in the application.

This sort of subtractive manufacturing process has long been a mainstay of modern manufacturing. The relatively new additive manufacturing technologies have created new possibilities, among them, rapid prototyping. Rao and Padmanabhan acknowledge that firms face complex decisions when evaluating rapid prototyping processes (2007). Given that speed-to-market of new products along with life-cycle quality developed in product design stages are critical to success among ever-increasing competition, the authors developed a GTMA based methodology for evaluation and selection of rapid prototyping processes suited to a given application based on six product attributes. These attributes ranging from part cost to various mechanical properties are evaluated on an eleven-point fuzzy scale that, when installed in the matrix yields a process selection index.

Selection problems similar to those described in the previous paragraphs are common targets for GTMA. Several similar studies have been made as follows:
Industrial robot selection (Rao and Padmanabhan, 2006), selection of third party logistics providers (Qureshi et al., 2009), selection of contractors (Darvish et al., 2009), selection of non-traditional machining processes (Chakladar et al., 2009), selection of jigs and fixtures (Paramasivam et al., 2010), equipment selection (Paramasivam et al., 2011), selection of supply chain risk mitigation strategy (Rajesh et al., 2015).

Another important consideration in the MCDM ecosystem is the hybrid approach that combines two or more methods to enhance effectiveness in a given study. This aggregation can address interesting new applications and create more functionality than would be available with single methods. Thakkar et al. used a GTMA-interpretive structural modeling (ISM) hybrid approach in developing a framework for evaluation of supply chain relationship strength (2008).
The authors are faced with the challenge of differing realities when analyzing a large firm versus a small-to-medium-sized firm. Qualitative, in addition to quantitative information from field experts is included in the model to account for the various elements of supply chain relationships (Thakkar et al., 2008). This study, significant for its evaluation of a largely human-element system, demonstrates further usefulness of GTMA.

A GTMA model for assessing manufacturing system flexibility, an increasingly necessary ingredient for success, is developed by (Baykasoğlu, 2009). This research considers flexibility to be a function of versatility and efficiency or capability and capacity in more standard industry terms. While GTMA can be easily used to produce an index value indicative of system flexibility, the authors admit that acquiring accurate probabilities of occurrences (necessary for computation of flexibility index) is challenging at best and flawed at worst. This highlights the fact that elicitation of accurate information from experts is an important consideration in any MCDM endeavor.

The full list of papers included in the literature review is contained in the appendix. Since all are not noted in Section 1.2.4, they are presented in Table A.1 for the sake of interested readers.

GTMA implementations over the last thirty years have been collected and reviewed. The literature shows that applicability of the method has been wide. The literature also shows its effectiveness in dealing holistically with complex systems of interdependencies. Often times the application is directly linked to a decision or selection problem. It is, however, also effective in analysis of system architecture for optimization of any number of parameters.

The same challenges of eliciting accurate and meaningful information from experts is present in all MCDM methods, GTMA notwithstanding. This is perhaps an instance where the intuitive graphical nature of digraphs may benefit analysts in the form of improved communication with decision makers, experts, and system practitioners.

Though it has been used in research for some time now, GTMA is still in the beginning stage of world implementation. Past success suggests that new applications, new hybrid approaches, and new research will incorporate GTMA and rank it among effective SE tools.

CHAPTER II

THEORETICAL FRAMEWORK

2.1 Manufacturing organizations and systems engineering

A foundational concept of this research is the system definition presented by Deming (1994). This work states that any organization meeting certain criteria is a system; namely that it consists of a network of interdependent components working in concert towards a mutual aim. In this configuration, organizational components subjugate local efficiency to holistic system performance, creating an operational mandate that extends beyond the organization to the larger system-of-systems structure of value chains and ultimately the global economy (Deming, 1994, pp. 49-91).

The associated discipline of SE is a product of the post-World War II engineering environment defined by increasing complexity of military technology and rapid advancement of nascent space industry in the United States and the Soviet Union. While complexity and the need for interdisciplinary cooperation existed prior, these endeavors warranted a new systems thinking approach that gave way to recognition of the SE discipline (Weigel, 2000).

The SE method that evolved out of the need to solve complex system problems is well suited to addressing resilience needs in the large-scale complexity of today's manufacturing organizations and the environments in which they operate. This research proposes the SE methodology (Figure 2.5) as the framework for the synthesis of life cycle management, OR factors, and established industrial and systems engineering tools to help manufacturing organizations build more resilient systems.

2.2 The life cycle perspective

The benefits of holistic considerations that exist in managing systems, can be extended beyond the instantaneous to entire life cycles. Whether this involves product or process life cycles or that of the entire organization, the effect on overall resilience can be great, i.e., resilience extended through the events of the next three days is more effective than resilience today only. This life cycle perspective may be used in the methods and strategies of system design to enhance holism and create a more systematic approach to building resilient manufacturing organizations (Fet et al., 2013). The specific nature of life cycle perspective implementation manifests in the use of tools for forecast, measurement, and control of resilience across the various stages of product, process, and organization life cycles. These practices are described as life cycle management (LCM) by Fet et al. (2013) in relation to environmental sustainability. Jensen calls LCM a “flexible management framework” that lends organizations to systematically and holistically incorporate sustainability concerns (2003). The inherent overlap of resilience and sustainability makes the extension of the LCM framework to serve OR principles easily.

Several organizational life cycle (OLC) models were proposed in the latter 20th century literature (Mosca et al., 2021). Rooted in biology, these models range from three to ten stages and are designed to uncover the linkages between business stages, strategy, and performance (Lester et al., 2003). A brief overview of extant models is presented in Table 2.1. This research adopts the model proposed by Lester et al. (2003), which is displayed in Fig. 2.1, for its consideration and synthesis of prior models, its relevance to both SMEs and large corporations, and empirical validation for multi-industry applicability (Al-Taie & Cater-Steel, 2020). Details of the model are outlined in section 2.2.2.

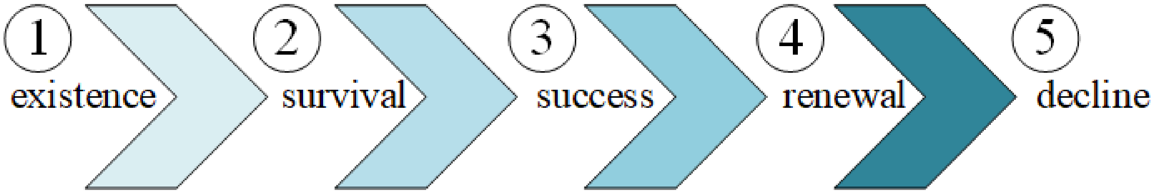


Figure 2.1 Organizational life cycle model adapted from (Lester et al., 2003)

Table 2.1 Organizational life cycle models

Paper	# of stages	Stages				
		1	2	3	4	5
Lippitt & Schmidt (1967)	3	Birth	Youth	Maturity	n/a	n/a
Churchill & Lewis (1983)	5	Conception	Survival	Profitability	Take-off	maturity
Quinn & Cameron (1983)	4	Entrepreneurial	Collectivity	Control	Decline	n/a
Miller & Friesen (1984)	5	Birth	Growth	Maturity	Revival	Decline
Lester (2003)	5	Existence	Survival	Success	Renewal	Decline

2.2.2 Organizational life cycle model stages

2.2.2.1 Stage one – existence

This beginning stage is characterized by the creativity and innovation of the entrepreneurial approach. An organization must make a case for its existence and connect with customers in such a way as to initialize operations. Decision making is centralized.

2.2.2.2 Stage two – survival

The second stage is initiated as the organization grows and seeks to differentiate itself from competition. Organizational structure becomes more complex and defined (Quinn and Cameron, 1983). Revenue as the enabler of growth is a primary concern, so goal setting and analysis are typical activities in the survival stage that lead to successful or mediocre entry into stage three. The financial stress of growth at this point creates a formidable probability of failure.

2.2.2.3 Stage three – success

Structural complexity and bureaucracy are the result of organizations maturing to stage three. Innovation and creativity are replaced with formal job descriptions, policies, and processes. Hierarchical management structures are in place with big picture strategy at the top and day-to-day operations in the middle.

2.2.2.4 Stage four – renewal

The structures created to manage the organization built in stages two and three are modified or remade to re-prioritize innovation and creativity, customer needs, and a flattened organizational structure. This may be characterized as a return-to-roots or return-to-core competencies with a decentralized decision-making structure.

2.2.2.5 Stage five – decline

There is an infinite number of mortal pitfalls awaiting organizations along the OLC. For organizations reaching the decline stage, however, it may or may not serve as the catalyst towards demise. The success of the firm has created opportunities for individuals to prioritize their own success over that of the organization. This combined with a prolonged lack of innovation and creativity may create revenue deficits that drag operational performance and market share to untenable levels.

2.2.3 Product life cycle

Expanding the product focus of manufacturing organizations from production processes to the multi-dimensional life cycle is understood as product life cycle thinking (Jensen, 2003). In the case of OR, this means understanding the impacts and drivers of product attributes such as quality not only at the time of delivery, but also during use and disposal. This is challenging in that it requires firms to predict how the role of products will change as time passes and customer demands on the product change due to concerns ranging from competing products to environmental (Tipnis, 1994). Another facet of this reality has been described as the “product life cycle trap” which describes that success lies in a firm’s ability to serve opposing operational directives: the first that prioritizes existing products and customers; the second that focuses on the creation of new products and acquisition of new customers (Bennett and Cooper, 1984).

2.3 Measuring resilience

2.3.1 Classification of resilience performance levels

Consideration of the manufacturing organization from the lifecycle perspective is necessary to achieve true resilience as ignoring any stage may result in system failure. This is displayed in Figure 2.2 where organization lifecycle is situated on the x-axis and organization scope on the y-axis. The idea behind this model is that the organizational system scope generally increases over the OLC (section 2.2.2) and creates levels on which certain resilience factors (section 1.2.2) are more suited to building resilience than others. As organizations move in the positive y direction, they are incorporating more holistic concerns with the likelihood of greater resilience. Typical business growth occurs along the x-axis through the OLC.

During the beginning of organizational development, entrepreneurs create startup firms, the success of which are driven by the *resources* and *innovation and creativity factors*. These two are most critical at this existence stage due the need for differentiation from or disruption of competition (*innovation and creativity*) and the need to survive the highly volatile environment of startup (*resources*).

The second band in Figure 2.2 features the intersection of small teams and the survival or growth stage populated by the *leadership* and *coordination and monitoring* factors. At this stage, organizations have created a successful product along with an efficient manner of production. Growth defines this stage, so dissemination of information and effective oversight (*coordination and monitoring*) along with the culture building of effective *leadership* are paramount for gaining buy-in from a core workforce.

The third stage in the OLC model that aligns with the intersection of success and divisions is referred to in some models as maturity. In this stage organizational structures become larger, much more developed, and more complex. As such, information and its management and use in long term strategy are primary considerations for resilience building. In terms of the OR factors, these activities align with *information and knowledge management* and *planning strategies and preparedness*.

Growth of the organization becomes less predictable as time progresses. The choices made by manufacturing firms as they struggle to grow through organizational creation in a turbulent environment may take them in wildly varied directions, away from one another and away from their initial purpose. While this path is unpredictable, the likelihood of a generalized renewal stage is high. Thus, new sources of value will be identified during the renewal stage of the OLC model. One form this may take is in diversification by acquisition or strategic partnership across internal divisions or outside the organization in the larger value chain. Facilitating this growth through renewal will require *minimization of silos* and *teamwork* to create resilient, novel organizational structures.

Organizations that reach the final stage of the OLC model face the challenge of an expansive and complex system beyond their prior experience. Simplification of this reality might presume a choice: continue to innovate, extending the renewal phase and re-entering the OLC model at a previous stage, or fail to innovate and decline into irrelevance or closure. *Innovation and creativity* is the key OR factor in realizing the preferred former.

Each performance level presents unique challenges for resilience creation. Graduation from one level to the next, while being a measure of resilience in and of itself, is cause for caution. Transitory firms will experience uncertainty in their ability to implement new OR factors into an organization gaining in complexity and facing a broader range of threats from a growing environment.

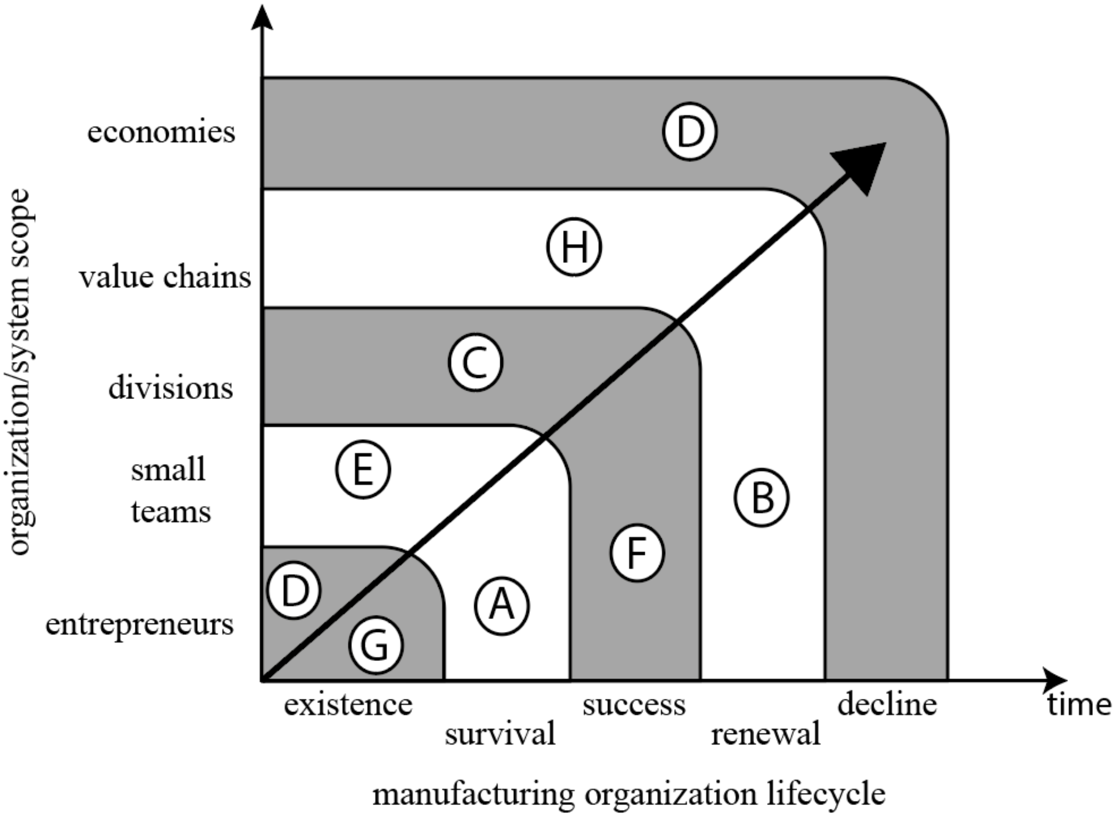


Figure 2.2 Classification of resilience performance levels

2.3.2 Resilience metrics

The complexity involved in mechanisms of manufacturing organizations presents managers with a mandate to incorporate the abundance of methodologies and tools for controlling and enhancing operational performance. Firms are likely to have internal dashboards devoted to performance monitoring metrics. Resilience metrics, being less prevalent and perhaps less straight forward are also required for successful decision support and resilient system design. Such metrics can be divided into static and dynamic, as well as probabilistic and deterministic varieties (Hosseini et al., 2016). Though the consideration of uncertainty and stochastic system behavior is relevant in many situations, the deterministic approach is adequate for the demonstration of the SE

MOR framework in this research. A simple static metric (Eq.2.1) was proposed by Bruneau et al. for the assessment of resilience lost from community infrastructure after suffering an earthquake (2003). This metric—visualized in figure 2.3—measures the loss in performance over the time period beginning at a disruption and ending at the point of recovery. Initial system performance is assumed to be maximized and the function $Q(t)$ may be a wide variety of performance measurement functions.

$$RL = \int_{t_0}^{t_1} [100 - Q(t)]dt \tag{2.1}$$

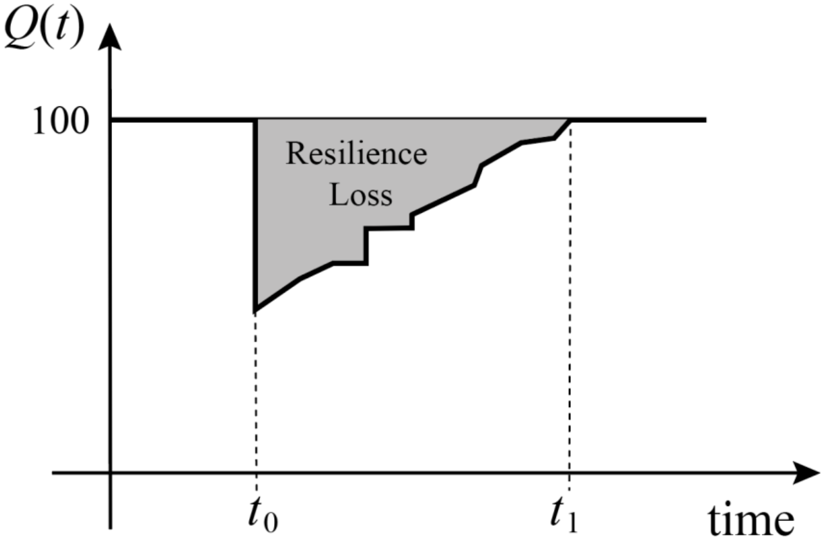


Figure 2.3 Graph of resilience loss known as the resilience triangle

Adapted from Bruneau et al., (2003)

Another analysis framework and dynamic resilience metric was proposed by Francis and Bekera which is briefly outlined below (2014). This framework recognizes resilience as a function of three qualities: absorption, adaptation, and restoration. Other involved variables include the speed of recovery S_p , the system performance level during stable operation F_o , the performance level immediately following disruption F_d, the transitional performance level generated by the system reaching an equilibrium state post-disruption F_d^*, and the performance level of the system once it has reached a stable state following all recovery efforts F_r. Incorporating these variables, a resilience factor ρ_i is defined as follows in Eq. 2.2:

$$\rho_i(S_p, F_r, F_d, F_o) = S_p \frac{F_r}{F_o}\frac{F_d}{F_o}$$

$$\text{where } S_p = \begin{Bmatrix} (t_\delta/t_r^*)\exp\left[-a(t_r - t_r^*)\right] \quad \text{for } t_r > t_r^* \\ \\ t_\delta/t_r^* \text{ otherwise} \end{Bmatrix} \tag{2.2}$$

The variable t_δ is defined by each firm as slack time or the maximum allowable time elapsed prior to beginning recovery efforts. t_r and t_r^* are defined as elapsed time until final recovery and initial recovery are each completed respectively. The final variable a represents the resilience loss attributable to time elapsed before reaching the new stable state. Resilience is displayed graphically in Figure 2.4.

By incorporating historical or published industry data as benchmark values for recovery speed, managers and system architects may incorporate resilience principles and tools into new system design endeavors with an understanding of what must be improved upon or where advantage may exist. Further analysis potential is provided in the framework by decomposing the equation. In doing so, metrics for absorptive capacity (F_d/F_o), or the immediate post-disruption system performance relative to the stable state, and adaptive capacity (F_r/F_o), or the system performance of the new stable state also relative to the original stable state. This adaptive capacity ratio may be larger than one enabling the framework to characterize post-disruption system improvement during the restoration phase.

The above framework describes the consequences of a disruptive event *i* . To fully assess the resilience performance of a system during the design phase, simulation must be used to model the system by incorporating probabilities of disruptive events along with a weighting structure. Francis and Bekera provide for this in their resilience metric framework; however, these formulations are not discussed here as the specifics of system simulation models are outside the scope of this research (2014).

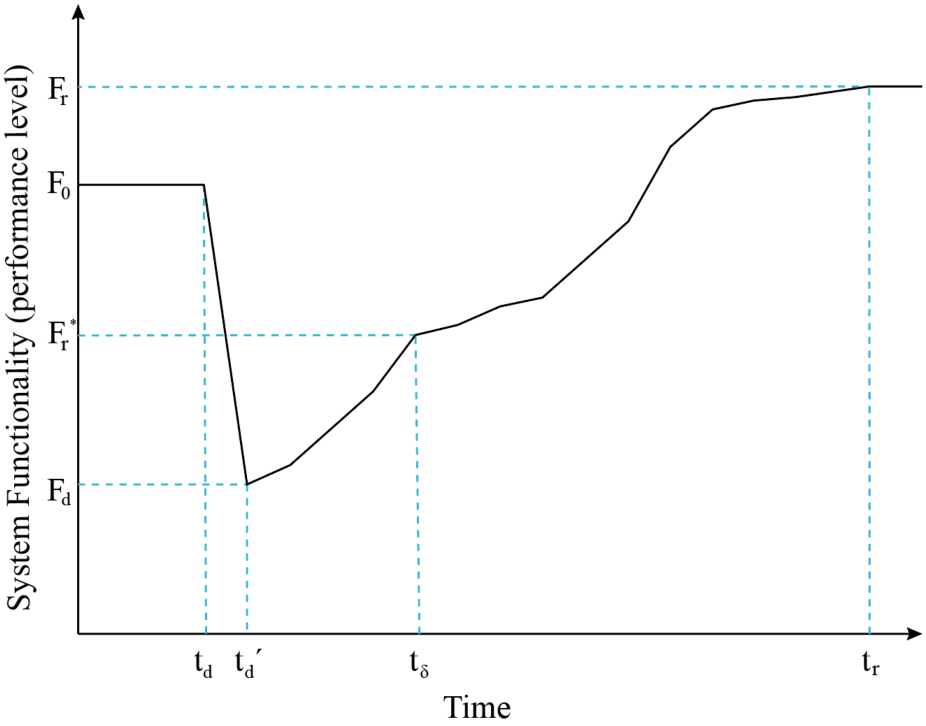


Figure 2.4 Resilience graph

Resilience is shown as system performance is plotted as a time-series. Adapted from Francis and Bekera (2014)

2.4 Tools for resilience improvement

Tools for resilience improvement are those geared towards assessing and improving performance on OR factors of *leadership, teamwork, information and knowledge management, innovation and creativity, coordination and monitoring, planning strategies and preparedness, resources, flexibility, and minimization of silos*. The following section presents a brief overview of the myriad tools that can be useful in resilience analysis and improvement with respect to organizational processes, products, and management. These tools are also shown in Table 2.2.

2.4.1 Process oriented tools

Organizational processes are the engine powering resilience performance. In the process design phase, FMEA may be used to assess risk associated with different options. It may also be used as an on-line tool for dynamic analysis of risk in support of increased resilience performance (Alyami et al., 2014). As processes develop through organizational growth and team member turnover, waste will develop, draining operational efficiency. Spanning processes from suppliers to end-users, value stream mapping presents an industry-proven tool for the reduction of process waste and therefore system reliability through increased resources, flexibility, and information and knowledge management (Vinodh et al., 2011).

Predicting and detecting failures are also important skills within organizations. The root cause of failure must be understood so that corrective actions can be applied to processes and systems (Ates, 2011). This is a common and well understood approach through popular methodologies such as Six Sigma, DMAIC, PDCA, and 8D that were developed for the purpose of isolating and correcting root causes of process variations (Aichouni et al., 2021). Extending these tools to envelop the life cycle perspective of processes is the adjustment necessary to transform them into resilience tools.

A more general, holistic approach to creating and managing resilient processes is demonstrated in change management which helps firms confront the persistent presence of change inside and outside the organization, in the needs of customers, and from competitive pressures (By, 2005). These mandates for change are added to those mentioned in this section previously. Resilient processes, though, may be best created by applying failure and root cause detection tools within a larger change management and life cycle perspective structure to create an organizational culture of resilience-centric process improvement (Ates, 2011).

2.4.2 Product oriented tools

A systematic evaluation of a manufacturing organization's product portfolio, the relationships between products and customers, and detailed financial information gives valuable insight into a wealth of resilience-impacting information (Ismail et al., 2011).

Life cycle costing at the outset of product development provides organizations with a holistic understanding of the costs associated with a product from development to disposal (Janz et al., 2005). Detailed implementation of this tool will also include evaluation of costs down to the component level. Vital linkages between cost, value, and product functionality will be assessed to identify needs for redesign of product or marketing strategy (Janz et al., 2005).

Review of available product-related information is likely to reveal uncertainty in the form of missing information or forecasting. Various tools have been developed to help decision makers navigate these situations. One such tool is decision tree analysis that uses a structured approach to quantify a complex network of decisions and unknown outcomes. This helps managers develop risk mitigation strategies as part of the product development process (Shafqat et al., 2019).

An appropriate framework in which these product tools may be nested can amplify their effectiveness. Such a framework exists in the eight-dimensional strategic quality model presented by Garvin (Kumar et al., 2021). Garvin’s eight dimensions disaggregate quality into distinct components managers may use to build a prioritized structure that most effectively targets specific customers. In this manner, the efficacy of the product-related resilience tools may be increased by their application to more robust products.

2.4.3 Management oriented tools

The tools at this level are largely associated with the development of competitive business strategy as it relates to the largest applicable scope. In the modern manufacturing industry, this scope is often global. Firm managers engaged in this strategic planning may implement a variety of tools such as Nominal Group Technique, Forecasting/Trend Analysis, or SWOT analysis (Webster et al., 1989). In order to specifically build resilience, however, a focus on agility, varied growth opportunities, and a culture of predictive strategy must be developed. This is achieved by employing minor modifications to the traditional tools mentioned above, resulting in *assessment of strategic growth opportunities*, *industry trends and impacts analysis,* and *industry leadership factors* (Ismail et al., 2011).

Once resilience-based strategies have been developed, managers must find effective means of implementation. Objectives and key results (OKRs) meet this mandate through a simple structure of goal setting and accountability that has successfully driven sustained growth in the turbulent tech industry among others (Doerr, 2017). One of the primary features of OKRs is silo-minimizing transparency. Team members are encouraged not only to set concise, aggressive goals and quantify them with measurable results. They must also publish objectives as a means of cross-functional alignment and hierarchy-free accountability (Doerr, 2017).

A tool for developing the *information and knowledge management* and *coordination and monitoring* factors combined with the above practices creates a well-rounded management system.

Such a tool is widely used in the health care industry as a formal structure for documentation and analysis of team member communication. This tool is called *WalkRounds* and generates a cyclical flow of information geared towards transparency and openness between management and team members (Frankel et al., 2006). Building on the management-by-walk-around concept *WalkRounds* formalize elicitation of useful information from conversation. Collected information is documented and analyzed with respect to other reported information and presented to executive leadership who then generate change initiatives and/or responses for return to originators.

Table 2.2 Organizational resilience tools

Level	**Tool**	**Description**	**Reference**
Process	Root Cause Analysis	Identify root causes of system failures	Ates (2011)
	Change management	Innovative responses to the market through continuous change and improvement	Ates (2011)
	FMEA	Dynamic analysis of risk	Alyami (2014)
	Value stream mapping	Process waste reduction from end to end in the product value stream.	Vinodh (2011)
Product	Portfolio analysis adaptation	Provide understanding of attractiveness factors from a customer and company POV	Hussey (1997)
	Life cycle costing	Evaluation of product costs and revenues from development to disposal	Janz (2005)
	Decision tree analysis	Assess risk in product life cycle	Shafquat (2019)
	Quality strategy	Build competitive advantage through strategic implementation of specific quality dimensions	Garvin (1984)
Organization	Assessment of strategic growth options	Assess growth options based on potential contribution to financial performance and growth	Ismail (2011)
	Industry trends and impacts analysis	Examination of trends and effects likely to impact on the company	Ismail (2011)
	Industry leadership factors	Understand key differentiators and perceived performance WRT competitors	Ismail (2011)
	OKRs	Goal setting methodology for cultural alignment towards sustained, elevated results	Doerr (2017)
	WalkRounds	Formal structure for documentation and analysis of team-member communication in a cyclical flow leading to transparency and openness	Frankel (2006)

2.5 Systems engineering and organizational resilience

2.5.1 The systems engineering methodology

The SE approach to the design, management, and improvement of systems is unique in its appropriateness for dealing holistically with large, complex systems over their entire lifecycles. In the case of resilience, manufacturing organizations face the need to address vertical production and horizontal value chain systems as well as product and organizational lifecycles. In this section, the steps of the SE method (Fet et al., 2013) are examined in combination with the OR tools as they relate to the OR factors.

The six steps of the SE method are shown in Fig. 2.5. These steps outline a complete engineering solution; however, a general understanding of system structure and concerns associated with various life cycle stages is integral to successful implementation (Fet et al., 2013).

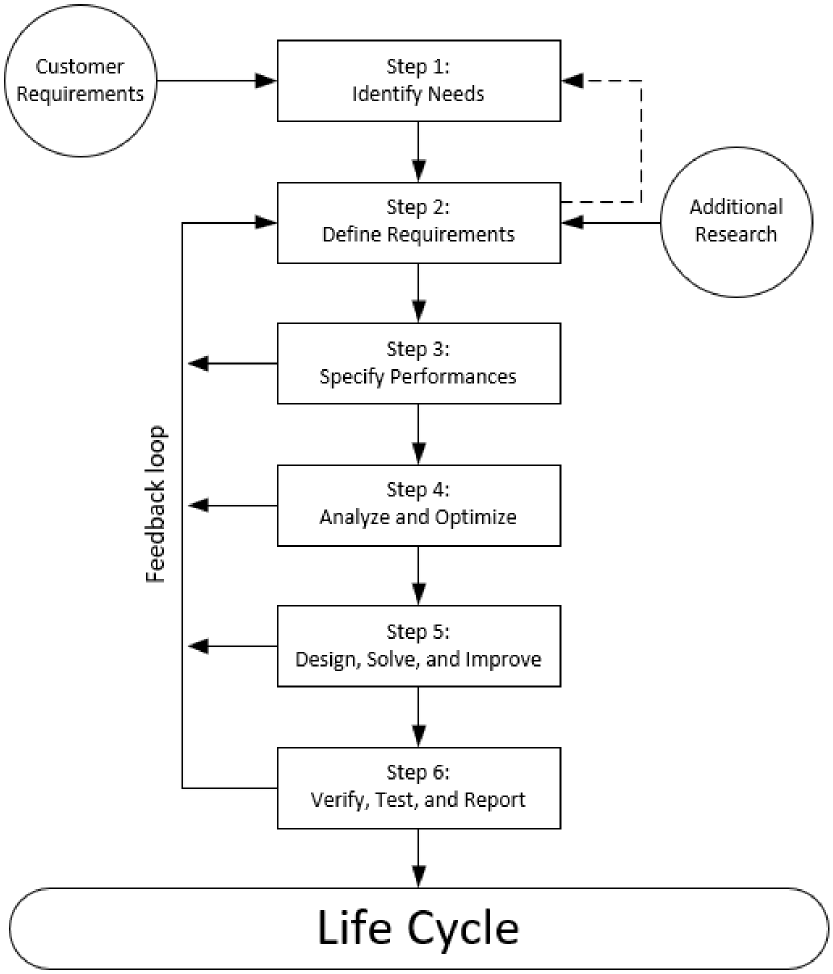


Figure 2.5 The Systems Engineering method

Adapted from (Fet et al., 2013)

2.5.1.2 Identify needs

Understanding the needs of the organization's stakeholders is the first step towards building a resilient manufacturing system and organization. The most relevant stakeholders may include employees, vendors, strategic partners, customers, shareholders, etc.… In order to elicit resilience needs, interviews with stakeholders should be conducted. Sample queries are presented below:

- What is the negative response threshold for performance impact due to instability or lack of resilience?
- Are there multiple points of resilience degradation at which benefits erode?
- What benefits may be realized through higher resilience than competitors?

Different stakeholders are likely to display disparate needs or perspectives of similar needs. For example, employees may be primarily concerned with efficient systems for completion of their responsibilities, while vendors are focused on robust information sharing. Other needs may be more similar as displayed in the example of strategic product quality (Section 2.4.2) being a primary concern of both employees and customers.

2.5.1.3 Define requirements

Once the needs have been established, requirements must be defined to scope the performance required to satisfy each need. Whether qualitative—install an integrated ERP system to coordinate supply chain organizations—or quantitative—reduce lead time between supply chain links by 50 percent—requirements should be specified at the discretion of stakeholders such that meeting them will create satisfactory results.

2.5.1.4 Specify performances

In this stage, narrative and qualitative information must be developed into quantitative description of performance for the various alternatives being considered. By quantifying and normalizing the data, accurate comparisons can be made. Many of the OR tools outlined in section 2.4 are well suited to this purpose. For example, value stream mapping may be used to link specific metrics such as process velocity or queue length to strategic resilience-generating performances like competitive product delivery time. The OR tools in section 2.4 are merely examples and should be expanded or replaced by industry practitioners to suit specific needs. The applicability of this research is captured in holistic SE methodology as a generalized qualitative framework for resilience building.

2.5.1.5 Analyze and optimize

In this stage, engineers, managers, and decision makers face a multi-criteria decision problem in which trade-offs must be considered to optimize entire systems for resilience over their lifecycles. Precise data captured in the previous step is used at this stage in any number of SE analysis methods to gain detailed insight into system performance parameters. Of those chosen and/or available for optimization, a vast array of parameter combinations may exist for exploration. As such, modeling and simulation techniques are available to develop a comprehensive understanding of the interactions between parameters as well the resilience performance generated through varied system model iterations. As overall system performance is a function of complex, emergent parameter interaction, a priority or weight structure may need to be imposed on the requirements to achieve optimal balance. This priority structure is developed from the information gathered during requirements definition. Assumptions made during the analyze and optimize stage along with subsequent uncertainties should be clearly noted and transferred into the design stage.

2.5.1.6 Design and solve

Using all the information gathered prior to this stage, new system designs or optimizations are created and implemented. As manufacturing systems and needs vary widely, so will resilience solutions. In addition to satisfying elicited needs and requirements, the most effective solutions will be novel and incorporate both product and organizational life cycle perspectives.

2.5.1.7 Verify, Validate, and Report

Solutions must be tested to verify that they perform their intended design functions. Those design functions must also be compared with the initial requirements to verify that requirements have been satisfied. Performance indicators developed in coordination with the OR tools in the specify performances stage serve as the testing protocol for verification and validation.

2.5.2 Systems engineering management

Because manufacturing organizations are dually concerned with product and manufacturing process lifecycles, there exists a need for integration of product and process lifecycle concerns. This cross-functional team coordination is realized in most organizations by project or program managers while the aerospace and defense sectors employ systems engineers for the same role. This difference in approach sheds light on the confusion surrounding SE that if better understood, could facilitate increased resilience levels across the manufacturing sector.

One of the prevailing themes in literature investigating the nature of the SE discipline describes systems engineers as integrators or “glue” that binds together subsystems (Sheard, 1996). With respect to OR creation, this description is fitting of SE managers with the *leadership* resilience factor. Indeed, SE practitioners may serve as the enablers of OR building by integrating the OR factors through expert implementation of the SE method. In other words, if the OR factors are the vehicle on the SE method roadmap to resilience, systems engineers and others embodying SE attributes are the drivers.

2.6 Process, product, and organization (PPO) design principles

2.6.1 Systems engineering and PPO design

Design principles effect manufacturing organizations at three levels of decreasing scope. These are organization, process, and product levels. Each level is associated with specific needs and functions. At the organization level design considerations are focused on organizational structure and a series of systems for management, planning, information and communication, and evaluation and rewarding (Hax and Majluf, 1981). Design at the process level has received a great deal of attention with methodologies including Lean, Six Sigma, Lean Six Sigma, DMAIC, PDCA, Process Reengineering, TQM, and Theory of Constraints to name a few. The nature of manufacturing processes with their often high volume, rapid product turnover, and large scale has led to a general favor of these continuous improvement methodologies over design. Products, while they must be considered within the scope of OR, may be designed using system, configuration, catalogue, decision, building block, or risk based design methodologies (Fet et al., 2013).

The broad range of perspectives across the three levels creates the need for a more generic approach into which practitioners may fit tools and methodologies that are most relevant to the creation of resilience in each specific application. Such a generic framework exists in three phases: divergence, transformation, and convergence (Rawson, 1979). The divergence phase is relatively unstructured with high levels of creativity and broad consideration of ideas intended to explore system boundaries and functionality. Next is the transformation phase when concepts are distilled into proposals, synthesized into working systems, and modeled to tune their performance. In the final phase, convergence, all previously considered concepts and models coalesce under scrutiny to isolate the optimal choice.

The complexity generated by diversity, abundance, and interdependence of variables in these endeavors necessitates a systematic design approach, as initial requirements and perspectives may be altered by information generated during the design process. The SE method is thus superimposed on the generic design phases to create a robust approach capable of fitting a wide variety of applications when paired with proven specific design methodologies. This is shown in Table 2.3.

Table 2.3 SE method and generic design phases

SE Method	Generic design phases
1. Identify needs	Divergence
2. Define requirements	
3. Specify performance	Transformation
4. Analyze and optimize	
5. Design and solve	
6. Verify and test	Convergence

2.6.2 The divergence phase

The divergence phase primarily involves determination of function and problem boundaries so that broad-ranging ideas and concepts may be creatively considered towards meeting objectives. The first two steps in the SE method align with this phase as is outlined in the following sections using a hypothetical example of a small manufacturing firm production line.

2.6.2.1 SE method-step 1: identify needs

There are many stakeholders of the production line, but the operators of that line along with the larger organization are primary. The organization needs the production line to function with high efficiency on a prescribed schedule. Operators need the flow of products through the line to be consistent, so their jobs are fulfilling and secure. The boundaries for this example are within the organization, i.e., they do not extend to external supply chain elements.

2.6.2.2 SE method-step 2: define requirements

Before the resilience characteristics of the system can be understood, the production line performance must be evaluated on basic functional, operational, and physical levels. Creation of targets for these requirement parameters establishes the basis for resilience as systems engineers then understand the precise nature of the steady state which must be maintained. Requirements are given for each level in Table 2.4.

Table 2.4 Performance requirements for production line

Requirement category	Performance requirements
Functional	The production line produces products to fill orders generated by the sales system.
Operational	Maximize production efficiency and quality while minimizing costs. • The operational scope includes variable products, production volumes, staffing, and raw materials quality. Adjustable parameters: • SOPs • Operator training • Information system design and functionality • Quality control system
Physical	Maintain safe and ergonomically optimized conditions Adjustable parameters: • Facility layout • Workstation design and organization Set parameters: • Facility size • Physical characteristics of product to be manufactured

2.6.3 The transformation phase

In this phase, the broad ideas and concepts are documented to generate proposals for evaluation. Proposals at this stage may be scrapped or slated for deeper study based on perceived merit. These elements are synthesized into systems that may be iteratively modeled and tuned for optimal performance. Steps three through five of the SE methodology align with this phase.

2.6.3.1 SE method-step 3: specify performances

Resilience performance of the production line can be quantified using resilience indicators. Table 2.5 shows examples of resilience indicators across phases of the life cycle.

Table 2.5 Resilience indicators and performance goals for production line

Life cycle stage	Resilience indicator	Resilience indicator goal
startup	• Speed of –	
	○ Employee training	90 days
	○ Equipment installation	30 days
	• Time to stable operation	120 days
Stable operation	• System output variance (normalized to demand)	< 5%
	• Employee turnover	0
Product changeover	• Down time	1 day
	• Time to stable operation	5 days

2.6.3.2 SE method-step 4: analyze and optimize

Once resilience performance requirements are established, they may be used to evaluate system performance with respect to the indicator goals. Alternative configurations of the production line may be proposed and considered in turn. A primary function of considering alternatives is evaluating the effects of trade-offs which are likely to be necessary for problem optimization. In the production line example trade-offs between disruption of the training process from construction and the performance of construction must be evaluated. The firm has set a resilience goal of 120 days to arrive at a stable production process. Developing a priority and trade-off structure between training and construction through evaluating several variations will allow the highest likelihood of success. Each resilience indicator is evaluated in turn within the multiple-alternative framework until management is satisfied with an optimal solution. For a small firm with limited resources and historical data, elicitation of qualitative information from subject matter experts for use in AHP may prove to be sound approach.

2.6.3.3 SE method-step 5: design and solve

The results of the AHP or other analysis from the previous step are now ready to be implemented. Keeping in mind that a holistic, life-cycle perspective approach should be maintained throughout system construction will allow any new information that arises to be considered within the design framework. In our production line example, this may exist as the unpredictability of human elements in the recruiting and training processes or construction or machinery changes that occur between the design and construction phases.

2.6.4 The convergence phase

This phase completes design selection and extends towards verification and validation of the generated system.

2.6.4.1 SE method-step 6: verify and test

Resilience indicators developed in earlier stages of the project serve as the basis for evaluating whether the chosen solutions meet the initial needs and requirements of stakeholders. Explanation and discussion of the results with stakeholders is an important aspect of this step as they can clarify any misunderstandings that may have been built into the system. In other words, system designers are ultimately beholden to stakeholders, not the elicited requirements. Managers in the production line example might ask whether the devised training program can meet the targeted production line resilience goal. Testing the system to generate quantitative data will be helpful to demonstrate efficacy.

2.7 Conclusion

Integration of resilience factors into the SE methodology as a holistic approach to resilient PPO design is a novel concept not previously presented in the literature. Within current reality where manufacturing firms face turbulent uncertainty, the need to build absorptive, adaptive, and recoverable systems rather than simply mitigate damage is urgent. The field of resilience engineering, however, is still in its infancy. Moreover, systems engineers or practitioners possessing the intrinsic attributes of SE may not be available in many organizations. This is why the simple and concise SE methodology has been demonstrated enabling managers from diverse backgrounds to implement resilience ideals into their organizations. Further quantitative analysis of the OR factors is presented in Chapter III.

CHAPTER III

GRAPH THEORY AND MATRIX APPROACH PRIORITIZATION OF ORGANIZATIONAL RESILIENCE FACTORS

3.1 Proposed research framework

A critical, but non-exhaustive literature review was conducted to identify prevalent factors of resilience in manufacturing organizations. These factors were used in designing and distributing a survey tool to manufacturing industry experts. Using GTMA, the survey data was analyzed with respect to OR factor priority and interdependence. The proposed research framework is shown in Fig 3.1. Results and implications of this research are as follows:

- Survey of data from manufacturing industry experts in the United States
- Resilience factor analysis through GTMA establishment of a priority and inter-relationship structure
- Examining the state of industry resilience factor prioritization from expert feedback

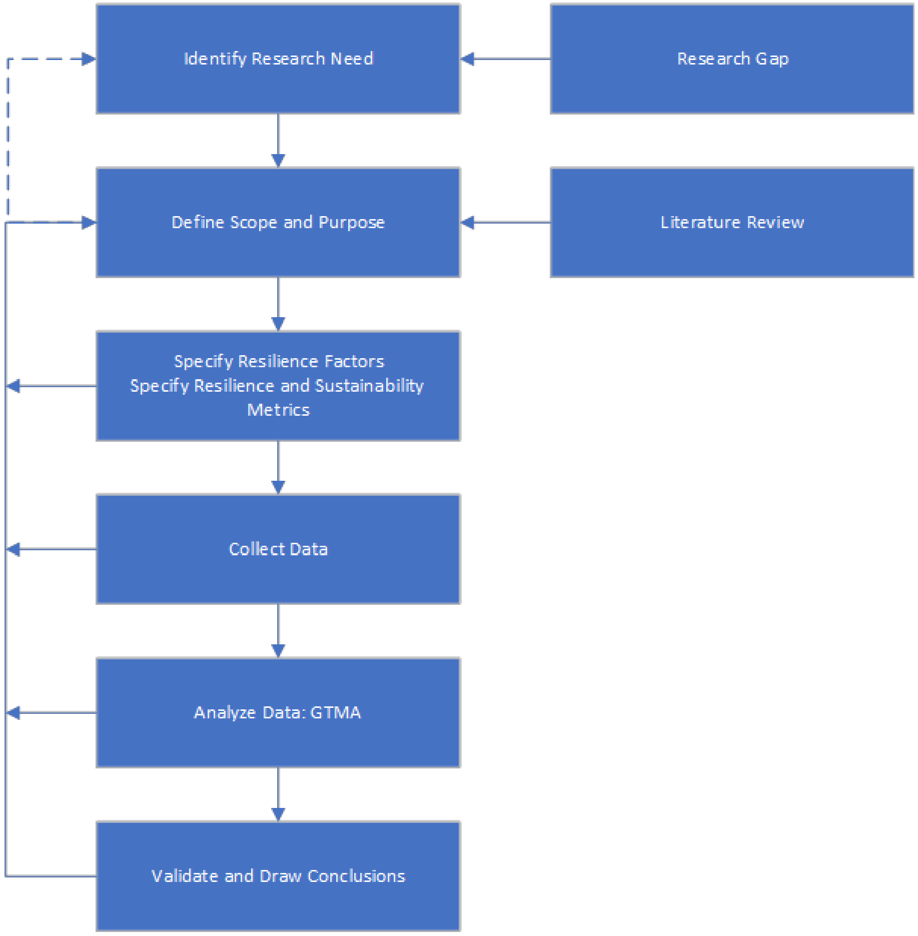


Figure 3.1 Proposed quantitative research framework

3.2 Solution methodology

To assess the priority of OR factors for manufacturing organizations while maintaining the integrity of their interdependence, graph theory and matrix approach (GTMA) is used. It is noted that a vast number of MCDM methods exist for developing criteria weight or priority structures. GTMA is favored in this research for its ability to develop an understanding of the relationships between factors and sub factors that may lead to a more holistic and effective implementation of the results in practical SE applications. The following section 3.2.1 includes an overview of the method and fundamentals of its implementation in decision making problems.

3.2.1 Graph theory and matrix approach overview

GTMA combines graph theory, combinatorial mathematics, and matrix algebra to create system models which account for interdependence and hierarchy of components and sub-systems (Gandhi et al., 1991; Gandhi and Agrawal, 1992). These traits, along with the use of directed graphs or digraphs for constructing graphical models, make GTMA a powerful tool for system design and optimization in addition to decision making.

As is the case in the analysis of any system, the analyst must first define the system using either a top-down or bottom-up approach. Once the system, its sub-systems, and all its individual components are defined, they can be visually modeled using a node-directed edge graph known as a digraph. This approach borrowed from graph theory, uses nodes to represent system entities—anything from subsystem to component—and edges to represent relationships between entities. Each edge is marked with an arrow indicating the direction of information flow or influence.

To demonstrate the construction of a GTMA digraph, the simple system of a person reading a book under a lamp is examined. Figure 3.2 displays the three system components of *person*, *book*, and *lamp* as nodes along with five directed edges labeled a, b, c, d, e. The graph is represented mathematically as $G = [V, E]$ with the vertices or nodes being $V = [Person, Book, Lamp]$ and edges $E = [a, b, c, d, e]$.

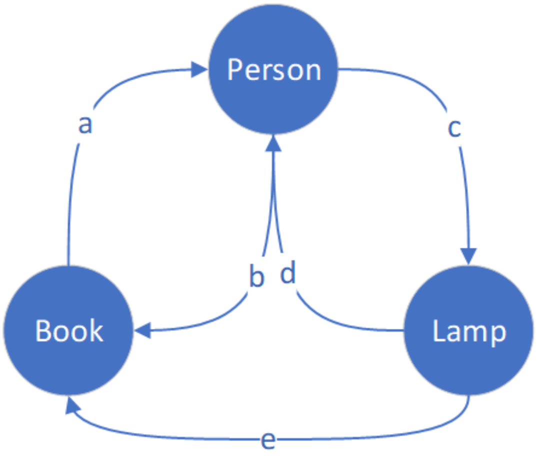


Figure 3.2 Example digraph

The directed edges of the graph indicate the relationship between system components, e.g., the mutual influence between the person and the book. This relationship also exists between the person and the lamp as each influences the other. The book, however, does not influence the lamp and so the book node is connected to the lamp node with a single edge that signifies this relationship.

A digraph is useful for system representation in this simple example. As the number of nodes and complexity of the system increases, digraphs become cumbersome. In this case it may be helpful to generate subsystem graphs while dealing with high-level modeling in matrix form only.

Adjacency matrices are useful for modeling the graph edges or system interdependencies, but GTMA method prescribes the construction of a variable permanent matrix (VPM). This matrix for a system of N nodes is an N x N asymmetric matrix with diagonal elements N_i representing nodes and off-diagonal elements represent the strength of dependency on other nodes.

The computation of matrix determinants is likely to be familiar to most readers. GTMA, however, employs the far less common matrix permanent as it is calculated using only positive signs, leaving all system information in the resulting value. This main feature of GTMA means that while all relationships are accounted for, computation is only reasonably completed with the use of a computer (Baykasoglu, 2014).

3.2.2 Implementation of methodology

The primary steps of the methodology implementation are as follows:

Step 1. Expert evaluation of OR factors and sub-factors

Step 2. Construction of the digraph

Step 3. Construction of the matrix – conversion of the digraphs into matrices is realized by replacing matrix variable with the values given by experts. These potential values are shown in Table 3.1

Step 4. Theoretical best and worst values – these values are calculated to define the scale for final factor permanent values

Step 5. Calculation of matrix permanent values. Formulation of the matrix permanent function is displayed in Appendix B.1

Table 3.1 Relative importance of OR factor – qualitative measures

	Relative importance of attributes	
Definition	d_{xy}	$d_{yx} = 10\text{-}d_{xy}$
Comparing sub-factors are equally important	5	5
One sub-factor is moderately more important than the other	6	4
One sub-factor is strongly more important than the other	7	3
One sub-factor is very strongly more important than the other	8	2
One sub-factor is extremely more important than the other	9	1
One sub-factor is completely more important than the other	10	0

3.3 Problem context – experts' organizations

The rise of industrial production capabilities in developing countries around the world has created competition for the United States, dominating the market for much of the 20th century. The aggregate output of US manufacturing in 2018 was $2.33 trillion, according to figures published by the National Association of Manufacturers, which accounted for 11.39% of GDP (2021). These figures had been rising overall following the recession of 2008 until the onset of the global pandemic that has majorly disrupted the industry once again. Building resilience into manufacturing firms will benefit their strategic positions in the domestic and global markets as well as create a more stable global economy for those firms participating in the growing ubiquity of global supply chains.

Five experts were selected from a variety of manufacturing firms in the United States. This research is meant to demonstrate the potential value of OR factor analysis for the manufacturing industry. The experts' job titles are noted along with their level of experience in the manufacturing industry in Table 3.2. Details of experts' organizations are withheld.

Table 3.2 Manufacturing industry expert information

Expert	Job Title	Manufacturing Experience
1	Operations Manager	More than 15 years
2	Production Lead	5-9 years
3	Executive Vice President, Technology	5-9 years
4	General Manager	More than 15 years
5	Senior Manager Health and Safety	More than 15 years

3.4 Application of GTMA

3.4.1 Collection of data

Data was collected from manufacturing industry experts with at least five years of professional experience. Job titles included Production Lead, Operations Manager, Executive Vice President, Technology, General Manager, and Senior Manager Health and Safety. In addition to extensive manufacturing industry experience, experts were chosen for their familiarity with management and decision making in the dynamic turbulence of the modern manufacturing environment.

A survey instrument was designed to elicit experts' opinions on the ranking and importance of literature-derived OR factors and sub factors. The survey instrument was created using Google Forms and delivered electronically to experts. Appendix C shows the complete survey.

3.4.2 Resilience factors

Nine OR factors and 32 sub-factors were derived from a non-exhaustive literature review. The chosen factors and sub-factors are meant to build an accurate, not definitive, model for the drivers of MOR. The first part of the survey asks experts to rate the importance of the sub-factors to the main factor on a scale from one-to-seven (one being completely unimportant to seven being extremely important). This serves to both validate the relevance of the sub-factors to the main factors as well as generate weight data to be used later in the GTMA analysis.

3.4.3 Evaluating priority and relationships among factors

Digraphs are created to help visualize the relationships between factors and sub-factors. These digraphs consist of nodes which represent factors and sub-factors and directed edges which represent the relationships between factors. If nodes *x* and *y* are connected by edges *d*, these may be described as d_{xy} in the event that x is relatively more important than y or d_{yx} in the event that the opposite relationship exists.

The general matrix representation of the main OR factors is shown in Eq. 3.1 where A, B, C, D, E, F, G represent the permanent values of the main OR factor nodes and q_{xy} is the relative importance of factor x over factor y. The digraph displaying the relationships between main OR factors is shown in Fig. 3.3. This visualization is helpful for conveying the idea of interdependence. It can, however, be difficult to locate specific relationships quickly. The digraph can also be represented in matrix form (Eq. 3.2) which is used in calculation of the permanent value but may also more clearly convey relationship information. The permanent values for each factor and expert are calculated using Eq. A.1 in Appendix B.1. Digraphs are also created for each factor that show sub-factors as nodes. These OR factor digraphs have a full complement of directed edges, meaning that interdependence within each factor is universally present between main-factor related sub-factors. The leadership digraph is shown in Fig. 3.4 with the remaining OR factor digraphs in Appendix B. The matrices and related permanent values for the *leadership* factor are given as examples in Eq. 3.3-3.6 below. These outputs represent the index values that may be used to create a priority structure of the factors with respect to each expert. This calculation is not provided here as is not relevant to this research. It could be used, for example, within an organization to evaluate the performance of different resilience models prior to implementation.

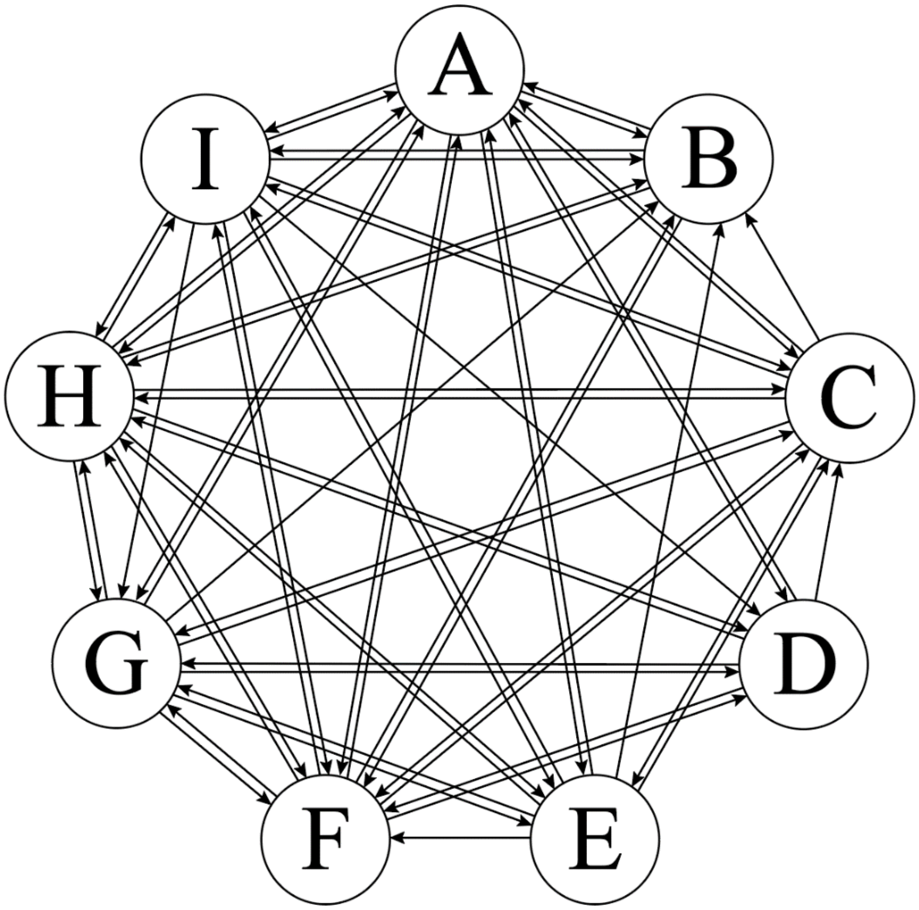


Figure 3.3 Main organizational resilience factor digraph

$$Main\ OR\ factors\ (Q) = \begin{bmatrix} A & q_{12} & q_{13} & q_{14} & q_{15} & q_{16} & q_{17} & q_{18} & q_{19} \\ q_{21} & B & q_{23} & q_{24} & q_{25} & q_{26} & q_{27} & q_{28} & q_{29} \\ q_{31} & q_{32} & C & q_{34} & q_{35} & q_{36} & q_{37} & q_{38} & q_{39} \\ q_{41} & q_{42} & q_{43} & D & q_{45} & q_{46} & q_{47} & q_{48} & q_{49} \\ q_{51} & q_{52} & q_{53} & q_{54} & E & q_{56} & q_{57} & q_{58} & q_{59} \\ q_{61} & q_{62} & q_{63} & q_{64} & q_{65} & F & q_{67} & q_{68} & q_{69} \\ q_{71} & q_{72} & q_{73} & q_{74} & q_{75} & q_{76} & G & q_{78} & q_{79} \\ q_{81} & q_{82} & q_{83} & q_{84} & q_{85} & q_{86} & q_{87} & H & q_{89} \\ q_{91} & q_{92} & q_{93} & q_{94} & q_{95} & q_{96} & q_{97} & q_{98} & I \end{bmatrix} \tag{3.1}$$

$$Per(Q) = \begin{bmatrix} A & q_{12} & q_{13} & q_{14} & q_{15} & q_{16} & q_{17} & q_{18} & q_{19} \\ q_{21} & B & 0 & 0 & 0 & q_{26} & 0 & q_{28} & q_{29} \\ q_{31} & q_{32} & C & 0 & q_{35} & q_{36} & q_{37} & q_{38} & q_{39} \\ q_{41} & 0 & q_{43} & D & 0 & q_{46} & q_{47} & q_{48} & 0 \\ q_{51} & q_{52} & q_{53} & 0 & E & q_{56} & q_{57} & q_{58} & q_{59} \\ q_{61} & q_{62} & q_{63} & q_{64} & 0 & F & q_{67} & q_{68} & q_{69} \\ q_{71} & q_{72} & q_{73} & q_{74} & q_{75} & q_{76} & G & q_{78} & 0 \\ q_{81} & q_{82} & q_{83} & q_{84} & q_{85} & q_{86} & q_{87} & H & q_{89} \\ q_{91} & q_{92} & q_{93} & q_{94} & q_{95} & q_{96} & q_{97} & q_{98} & I \end{bmatrix} \tag{3.2}$$

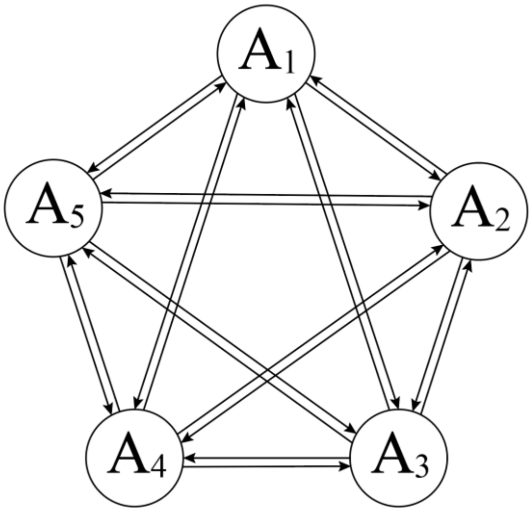


Figure 3.4 Leadership sub-factor digraph

$$Per^{E1}(A) = \begin{bmatrix} A_1 & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & A_2 & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & A_3 & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & A_4 & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & A_5 \end{bmatrix} = \begin{bmatrix} 7 & 6 & 3 & 5 & 3 \\ 4 & 7 & 4 & 6 & 4 \\ 7 & 6 & 6 & 7 & 4 \\ 5 & 4 & 3 & 7 & 3 \\ 7 & 6 & 6 & 7 & 6 \end{bmatrix} = 450540 \tag{3.3}$$

$$Per^{E3}(A) = \begin{bmatrix} 7 & 5 & 7 & 3 & 7 \\ 5 & 7 & 8 & 5 & 8 \\ 3 & 2 & 5 & 3 & 3 \\ 7 & 5 & 7 & 7 & 5 \\ 3 & 2 & 7 & 5 & 7 \end{bmatrix} = 409824 \tag{3.4}$$

$$Per^{E4}(A) = \begin{bmatrix} 7 & 6 & 6 & 5 & 6 \\ 4 & 7 & 8 & 4 & 4 \\ 4 & 2 & 7 & 5 & 3 \\ 5 & 6 & 5 & 7 & 5 \\ 4 & 6 & 7 & 5 & 7 \end{bmatrix} = 526028 \tag{3.5}$$

$$Per^{E5}(A) = \begin{bmatrix} 6 & 5 & 4 & 2 & 2 \\ 5 & 6 & 7 & 5 & 4 \\ 6 & 3 & 5 & 5 & 1 \\ 8 & 5 & 5 & 7 & 5 \\ 8 & 6 & 9 & 5 & 7 \end{bmatrix} = 381154 \tag{3.6}$$

The permanent values for all expert-OR factor combinations are calculated in this fashion and are shown in Appendix B.2. For reference, the theoretical best and worst values are calculated for each OR factor. Eqs. 3.7 and 3.8 demonstrate this technique for the *leadership* factor. The aggregated results from GTMA implementation are presented in Table 3.3. Because the number of sub-factors differs between main factors, the theoretical best and worst values serve as normalizing guides for each resilience priority index value. These theoretical values assume that all sub-factors are rated as being equally important in pairwise comparison while being labeled at extremes of the importance scale relative to their respective main factors.

$$Per(A)^{Best} = \begin{bmatrix} 7 & 5 & 5 & 5 & 5 \\ 5 & 7 & 5 & 5 & 5 \\ 5 & 5 & 7 & 5 & 5 \\ 5 & 5 & 5 & 7 & 5 \\ 5 & 5 & 5 & 5 & 7 \end{bmatrix} = 559432 \tag{3.7}$$

$$Per(A)^{Worst} = \begin{bmatrix} 1 & 5 & 5 & 5 & 5 \\ 5 & 1 & 5 & 5 & 5 \\ 5 & 5 & 1 & 5 & 5 \\ 5 & 5 & 5 & 1 & 5 \\ 5 & 5 & 5 & 5 & 1 \end{bmatrix} = 168376 \tag{3.8}$$

Table 3.3 Index values of organizational resilience factors for manufacturing industry experts

	OR factors								
Expert	A	B	C	D	E	F	G	H	I
E1	450540	1065	989	16820	1087	959	16494	16266	942
E2	543853	1037	1111	21961	1087	1038	20866	21915	926
E3	409824	1066	652	2236	828	586	20688	17524	1044
E4	526028	963	1094	17608	882	1111	18994	21530	1111
E5	381154	780	914	16593	574	923	22080	13831	892
Best Value	559432	1118	1118	22376	1118	1118	22376	22376	1118
Worst Value	168376	326	326	6776	326	326	6776	6776	326

It is noted that the theoretical worst values used are *not* the lowest possible permanent values. For this reason, the normalized output is constrained to non-negative values with the lower limit being 0. Each output value's proximity to the best and worst values gives normalized values that may be directly compared with every other output value regardless of the number of sub-factors evaluated by experts. The normalization method is shown in Eq. 3.9 followed by the normalized index values of OR factors for manufacturing industry experts in Table 3.4.

$$\varphi_A = \frac{(Per^{E1}(A) - Per(A)^{Worst})}{(Per(A)^{Best} - Per(A)^{Worst})} = \frac{(450540 - 168376)}{(559432 - 168376)} = 0.72154 \tag{3.9}$$

Table 3.4 Normalized index values of organizational resilience factors for manufacturing industry experts

	OR factors								
Expert	φ_A	φ_B	φ_C	φ_D	φ_E	φ_F	φ_G	φ_H	φ_I
E1	0.72154	0.93308	0.83712	0.64385	0.96086	0.79924	0.62295	0.60833	0.77778
E2	0.96016	0.89773	0.99116	0.97340	0.96086	0.89899	0.90321	0.97045	0.75758
E3	0.82456	0.93434	0.41162	0	0.63384	0.32828	0.89179	0.68897	0.90657
E4	0.91458	0.80429	0.96970	0.69436	0.70202	0.99116	0.78321	0.94577	0.99116
E5	0.54411	0.57323	0.74242	0.62929	0.31313	0.75379	0.98103	0.45224	0.71465

Normalized index values for all experts within each OR factor are averaged according to Eq. 3.10 and labeled with the added priority column to give the GTMA analysis prioritization results in Table 3.5. Normalized result values for each expert can be found in Appendix B.4.

$$\bar{\varphi}_X = \frac{1}{5}\sum_{i=1}^{5} Per^{Ei}(\varphi_X) \tag{3.10}$$

Table 3.5 Averaged, normalized GTMA results

OR factor	Symbol	$\bar{\varphi}_X$	Priority
Leadership	A	0.79299	4
Teamwork	B	0.82853	3
Information and knowledge management	C	0.79040	5
Innovation and creativity	D	0.58818	9
Coordination and monitoring	E	0.71414	8
Resources	F	0.83644	1
Planning strategies and preparedness	G	0.75429	6
Flexibility	H	0.73315	7
Minimization of silos	I	0.82955	2

3.5 Discussion of GTMA results

The overall priority ranking structure generated by the expert survey results and GTMA analysis is F>I>B>A>C>G>H>E>D. A graphical representation of the results is shown in Figure 3.5. These results were not generated through expert consensus as no expert results were exactly the same; instead, the mean was calculated for each expert-spanning set of OR factor results to combine the inputs into a single generalized output. This strengthens the GTMA output by lowering the weight of outlying expert opinions.

Resources (A) was the top-ranked factor with a final MOR factor index value of 0.83644. This suggests that resilience is a property of relatively mature organizations which have had the time to stabilize operations to the point where resource capacity is both robust and predictable.

Infrastructure including emergency personnel and a technical professional network in addition to a well-developed supply chain maintaining resource-flow are also hallmarks of larger, established firms. This being said, startups and younger SMEs may be able to overcome these challenges by means including the development of strategic relationships with investors and more established resource and supply chain providers. This result is validated by a study of textile manufacturing firms that found cash flow and resourcefulness were among the top contributors to economic resilience (Pal et al., 2014). This is perhaps intuitive when evaluating SMEs due to the need for healthy cash flow to serve in place of unlikely cash reserves. In terms of larger businesses, however, financial resources have proven to be the stuff of which resilience is made. This is illustrated in the symbiotic relationship built between Toyota and its supplier networks in which these groups have remained partially insulated from volatile outside financing concerns by Toyota acting as the bank to fund new product tooling (Womack et al., 2007). In a two-step Fuzzy AHP and Fuzzy TOPSIS analysis of resilience factors, Tadic et al. evaluated a set of 11 factors with a similar structure to those in this research (2014). This study found resources to be more important to resilience than any other similar factor. Another similar MCDM approach by Marcuzic et al. found coordination and monitoring to be the least important resilience factor (2016).

Figure 3.5 Graph of GTMA OR factor prioritization

3.5.2 Minimization of silos

With a GTMA final OR factor index value of 0.82955, minimization of silos (I) was rated as the second highest priority in MOR generation. This ideal tracing back to Deming's 14 points has been approached by myriad authors and practitioners as a driver of organizational performance. It is perhaps not surprising then, that it should be linked to an organization's ability to avert, absorb, or recover from debilitating disruptions. The decentralization of organizational units and firm-wide embodiment of systems thinking are not just organizational performance enhancers, they are so robust in creating effectiveness as to strengthen that organization against turmoil.

3.5.3 Teamwork

With a GTMA final OR factor index value of 0.82853, teamwork (B) was rated as the third highest priority in MOR generation. Interdependence exists between most of the factors as can be seen in Figure 3.3. The relationship between teamwork and minimization of silos is a good example of this interdependence and an explanation for their close proximity in priority. The essence of teamwork is combining the efforts of diverse individuals with complimentary skills towards the elevation of organizational performance. In order to assemble teams with the diversity in skills and knowledge necessary to realize maximum effectiveness, functional barriers must often be erased, thus making the connection between these two high-ranked OR factors.

3.5.4 Leadership

With a GTMA final MOR factor index value of 0.79299, leadership (A) was rated as the fourth highest priority in MOR generation. Leadership has been linked to high-level organizational functions such as determination of overall purpose and development of long-term strategy. In relation to OR, it serves the supporting function of OR factor implementation. It is fitting, then, that experts ranked it in the middle of the factors below specific resilience-creating factors such as resources but still high enough to prioritize expert guidance. The many linkages between leadership and the other factors as well as subfactors such as transparency and trust suggest that this factor has a strong connection to the building of resilience factors into firm culture. This reality will allow creation of better and more permanent resilience results.

3.5.5 Information and knowledge management

With a GTMA final OR factor index value of 0.79040, information and knowledge management (C) was rated as the median priority in MOR generation. Though it is not rated as highly as some other factors, its effect on the efficacy of other higher-ranked factors may be substantial. This is visualized by the number of influence edges shown in Figure 3.3. It may also be intuitively understood by imagining leadership or teams attempting to work effectively without the aid of well-developed information and knowledge management systems.

3.5.6 Planning strategies and preparedness

With a GTMA final MOR factor index value of 0.75429, planning strategies and preparedness (G) was rated as the sixth highest priority in MOR generation. A possible explanation for the low ranking of this factor is that expert opinions are focused more on the organizations short term flexibility and adaptability generated by effective personnel rather than long-term strategy. This factor, though, is clearly still important as it is linked to resisting potentially catastrophic disruptions such as extreme competition and disasters.

3.5.7 Flexibility, coordination and monitoring, and innovation and creativity

With GTMA final OR factor index values of 0.73315, 0.71414, and 0.58818, flexibility (H), coordination and monitoring (E), and innovation and creativity (D) were rated as the seventh, eighth, and last priority respectively in MOR generation. These three factors, while clearly important if for no other reason that their relationships to other, more highly rated factors, should not be prioritized by managers and practitioners. The low prioritization of innovation and creativity suggests that the expert view of resilience creation has more to do with system design and operation based on established principles rather than generation of new ideas. This, however, may prove to be ill-conceived when faced with the reality that the most severe disruptions tend to have little or no precedent and therefore may be immune to extant resilience approaches.

3.6 Implications to practice

The creation of resilience as a system property is likely to be a daunting task for managers and industry practitioners. It is often relegated to secondary status behind more immediate organizational concerns that generate quick results or solve pressing concerns. For these reasons and others, the dual qualitative and quantitative perspectives outlined in this research present a novel, holistic framework that may be systematically implemented by non-expert practitioners in manufacturing organizations to build robust systems that are adaptable, fault-tolerant, and recoverable in the face of disruption.

Resilience engineering requires cross-functional cooperation and long-term strategic thinking for maximum effectiveness. The SE method offers a simple yet robust framework to guide practitioners in a concerted effort towards this end from elicitation of requirements through deployment and verification of finished systems. Great utility may be realized by the applicability of the SE method to soft systems such as business processes as well as hard systems such as production lines and value chains. Additionally, its iterative nature encourages creation of optimal solutions that may only be accessible to those willing to honestly answer the questions of whether the system was built to specification and whether those specifications meet the elicited needs. Managers may benefit from applying the standardized resilience engineering approach to other aspects of business systems as it compliments and bolsters the proven effectiveness of continuous improvement culture.

The SE method is a generalized approach to system design that has been tooled in this research for resilience building. More specifically, resilience factors have been distilled from the literature and presented to bridge the gap between the qualitative SE method and the quantitative nature of GTMA. These nine factors and 32 sub-factors, if viewed without the benefit of the

GTMA matrix permanent values, may lend to self-evaluation within organizations for determining areas for improvement via the SE method. When both the GTMA method and results are applied, managers add further dimensions to their resilience engineering programs.

The prioritization of resilience factors in this research offer manufacturing firms a hierarchical structure to guide efforts toward building more effective resilience strategies than if they were faced with strengthening all OR factors simultaneously. The resources required for this would likely prove to be unavailable. As the resources OR factor was chosen by experts through the GTMA analysis to be the primary driver of OR, this could prove entirely counterproductive.

3.7 Implications to theory

The field of SE is, at least partially, shrouded in confusion with regards to its definition and the composition of its practicing base. The SE method and its application as a perspective towards the building of resilient manufacturing systems in this research may serve as foothold towards the further understanding of SE as a component of industrial and systems engineering.

Resilience in manufacturing organizations is the focus of this research; however, the concepts put forth, primarily the dual perspective approach of SE and GTMA, may be extended beyond the boundaries of manufacturing systems into many other organizational systems. The resilience factors have been geared for manufacturing, but could be reworked, expanded, or truncated to fit varied applications. It is further noted that the intention of this research was to demonstrate a novel framework through a reasonable factor-set rather than create a determinant rendering of resilience. One of the possibilities for further research would be to create a more generalized and complete set of resilience factors. Further research may also include a case study for validation of the dual perspective framework as well as an extension of the survey instrument to more and varying industry experts.

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APPENDIX A

GRAPH THEORY MATRIX APPROACH LITERATURE REVIEW REFERENCE

Table A.1 Full list of reviewed GTMA papers

	Author/Paper	**Field**	**Use**
1	Agrawal (2016)	Reverse Logistics	Evaluation of dispostion alternatives in reverse logistics
2	Ahmad (2015)	Reliability Engineering	Evaluation of complex mechatronic systems
3	Attri (2014)	Manufacturing	Evaluation of barriers to total productive maintenance implementation
4	Babu (2008)	Manufacturing	Quality evaluation of resin transfer molded products
5	Baykasoglu (2009a)	Manufacturing	Evaluation of manufacturing system flexibility; selection of system configuration
6	Baykasoglu (2009b)	Manufacturing	Modeling and quantifying manufacturing system flexibility (fuzzy method)
7	Baykasoglu (2014)	Decision Theory	MADM; review of 80 GTMA papers
8	Chakladar (2009)	Manufacturing	Selection of non-traditonal machining methods
9	Darvish (2009)	Construction	Contractor ranking and selection
10	Faisal (2007)	Risk Management	Supply chain risk evaluation and mitigation
11	Farrokhi (2018)	Engineering Management	Evaluating factors for organization readiness for implementing business intelligence project
12	Gadakh (2011)	Manufacturing	Selection of machining parameters
13	Gandhi (1991)	Manufacturing	reliability of mechanical and hydraulic systems
14	Gandhi (1992)	product design and manufacturing	FMEA approach to reliability of mechanical and hydraulic systems
15	Gandhi (1996)	System Reliability	Weld failure analysis
16	Ganhdi (1994)	engineered mechanical systems	System wear evalutation and analysis
17	Garg (2006)	Power and Energy	Power plant evaluation and selection
18	Garg (2007)	Reliability Engineering	Development of reliability index for journal bearing oil supply system
19	Garg (2007b)	Power and Energy	Thermal power plant quality evaluation and selection
20	Geetha (2016a)	Automotive	Optimization of diesel engine operating parameters
21	Geetha (2016b)	Decision Theory	Concise review of GTMA method and applications
22	Ghosh (2018)	Electrical Engineering	Optimizing phasor measurement unit placement in power systems
23	Grover (2004)	Engineering Management	TQM evaluation
24	Grover (2005)	Engineering Management	Evaluation of HR contribution to TQM
25	Grover (2006)	Human Resources	Evaluation of human factors in TQM implemetation
26	Gupta (2020)	Logistics	Evaluation of sustainability performance
27	Jain (2015)	Manufacturing	Evaluation of intensity of variables affecting flexibility in FMS
28	Jain (2018)	Engineering Management	Analysis of factors contributing to medical tourism in India
29	Jangra (2011a)	Manufacturing	Evaluation of tungsten carbide composite machinability
30	Jangra (2011b)	Manufacturing	Evaluation of die performance
31	Kaur (2006)	Supply Chain	Evaluation of supply chain coordination
32	Kavilal (2018)	Supply Chain	Evaluation framework for supply chain complexity
33	Kiran (2011)	product design and manufacturing	Concurrent design of mechatronic systems
34	Kulkarni (2005)	Engineering Management	Evaluation of TQM performance
35	Kumar (2010)	Manufacturing	Structural modeling and analysis of electroplating effluent treatment process
36	Kumar (2011)	Manufacturing	Design of optimal electroplating system
37	Kumar (2016)	Manufacturing	Evaluation of lean manufacturing attributes
38	Kumar (2017)	Manufacturing	Evaluation of manufacturing system agility
39	Kumar (2018)	Manufacturing	Evaluation of ultrasonic vibration assisted EDM process parameters
40	Kumar (2019)	Manufacturing	modeling and analysis of electroplating systems
41	Maharani (2017)	Power and Energy	Analysis of steam power plant reliability

Table A.1 (continued)

	Author/Paper	**Field**	**Use**
42	Mishra (2019)	Health Care Management	Evaluation of health care unit waste management performance
43	Mohan (2003)	Power and Energy	Coal power plant system optimization
44	Mohan (2004)	Power and Energy	Coal power plant equipment maintenance
45	Mohan (2006)	Power and Energy	Steam power plant performance evaluation
46	Mohan (2007)	Power and Energy	Power plant performance monitoring
47	Mohan (2008)	Power and Energy	Steam power plant reliability evaluation
48	Paramasivam (2009)	product design and manufacturing	Evaluation and analysis of product design alternatives
49	Paramasivam (2010)	Manufacturing	Evaluation and selection of jig/fixture
50	Paramasivam (2011)	Manufacturing	Equipment selection
51	Prabhakaran (2006)	product design and manufacturing	Resin transfer molding product design and development
52	Prabhakaran (2008a)	Composite Manufacturing	Composite manufacturing system design and evaluation
53	Prabhakaran (2008b)	Quality Engineering	Quality modeling and analysis of composite products
54	Prince (2009)	Nanotechnology	Structural analysis of microelectromechanical systems
55	Qureshi (2009)	Logistics	Evaluation and selection of third party logistics providers
56	Rabbani (2019)	Resilience Engineering	Evaluation of resilience performance, petrochemical plant case study
57	Raj (2010)	Engineering Management	Evaluation of barriers to TQM implementation
58	Rajesh (2015)	Supply Chain	Supply chain risk evaluation and mitigation
59	Rao (2002)	manufacturing	Material machinability evaluation
60	Rao (2006)	Materials handling	Industrial robot selection
61	Rao (2006a)	Manufacturing	Materials selection
62	Rao (2006b)	Manufacturing	Evaluation and selection of flexible manufacturing systems
63	Rao (2007a)	Manufacturing	Rapid prototyping process selection
64	Rao (2008)	Sustainability Engineering	Environmental impact assessment of manufacturing processes
65	Rao (2018)	Manufacturing	Evaluation of process parameters in micro machining
66	Seghal (2000)	Reliability Engineering	Bearing selection
67	Singh (1996)	Manufacturing	optimization of material usage in metal stamping process
68	Singh (2008)	Manufacturing	Structural analysis of manufacturing system performance
69	Singh (2019)	Supply Chain	Evaluation of supply chain flexibility and agility
70	Thakkar (2008)	Supply Chain	Evaluation of automotive supply chain relationships; SME focus
71	Upadhyay (2008)	Software Engineering	Structural design and analysis of object oriented system architecture
72	Upadhyay (2010)	Software Engineering	Development of software maintainability index
73	Venkatasamy (1995)	Automotive design	System and structural analysis
74	Venkatasamy (1997)	Automotive Manufacturing	Automotive product quality analysis
75	Virmani (2021)	Manufacturing	Evaluation of factors impeding Industry 4.0 implementation
76	Wagner (2010)	Supply Chain	Assessing vulnerability of supply chains
77	Wani (1999)	Mechanical System Maintenance	mechanical system maintainability evaluation
78	Wani (2002)	Reliability Engineering	maintainability of mechanical systems based on tribology
79	Yadav (2009)	Power and Energy	Evaluation and selection of power plants
80	Zhang (2019)	Electrical Engineering	Optimization of power conversion architectures
81	Zhong (2006)	Manufacturing	Ceramics machinability evaluation
82	Zhuang (2017)	Decision Theory	Evaluation and selection of paper shredder alternatives

APPENDIX B

MATRIX PERMANENT FORMULATION, ORGANIZATIONAL RESILIENCE SUB-FACTOR DIGRPAHS, AND ADDITIONAL CALCULATIONS

B.1 General formulation of matrix permanent

$$
\begin{aligned}
Per\,(F) = {} & \prod_{x=1}^{6} F_x + \sum_{x=1}^{5}\sum_{y=x+1}^{6}\sum_{z=1}^{3}\sum_{a=z+1}^{4}\sum_{b=p+1}^{5}\sum_{c=q+1}^{6} (d_{xy}d_{yx})\,F_zF_aF_bF_c + \sum_{x=1}^{4}\sum_{y=x+1}^{5}\sum_{z=y+1}^{6}\sum_{a=1}^{4}\sum_{b=a+1}^{5}\sum_{c=b+1}^{6} (d_{xy}d_{yz}d_{zx} + d_{xz}d_{zy}d_{yx})\,F_aF_bF_c \\
& + \left(\begin{array}{l}
\displaystyle\sum_{x=1}^{3}\sum_{y=x+1}^{6}\sum_{z=x+1}^{5}\sum_{a=x+2}^{6}\sum_{b=1}^{5}\sum_{c=b+1}^{6} (d_{xy}d_{yx})(d_{za}d_{az})\,F_bF_c + \\
\displaystyle\sum_{x=1}^{3}\sum_{y=x+1}^{5}\sum_{z=x+1}^{6}\sum_{a=y+1}^{6}\sum_{b=1}^{5}\sum_{c=b+1}^{6} (d_{xy}d_{yz}d_{za}d_{ax} + d_{xa}d_{az}d_{zy}d_{yx})\,F_bF_c
\end{array} \right) \\
& + \left(\begin{array}{l}
\displaystyle\sum_{x=1}^{4}\sum_{y=x+1}^{5}\sum_{z=y+1}^{6}\sum_{a=1}^{5}\sum_{b=a+1}^{6}\sum_{c=1}^{6} (d_{xy}d_{yz}d_{zx} + d_{xz}d_{zy}d_{yx})(d_{ab}d_{ba})\,F_c + \\
\displaystyle\sum_{x=1}^{2}\sum_{y=x+1}^{5}\sum_{z=x+1}^{6}\sum_{a=x+1}^{5}\sum_{b=y+1}^{6}\sum_{c=1}^{6} (d_{xy}d_{yz}d_{za}d_{ab}d_{bx} + d_{xb}d_{ba}d_{az}d_{zy}d_{yx})\,F_c
\end{array} \right) \\
& + \left(\begin{array}{l}
\displaystyle\sum_{x=1}^{3}\sum_{y=x+1}^{5}\sum_{z=x+1}^{6}\sum_{a=y+1}^{6}\sum_{b=1}^{5}\sum_{c=b+1}^{6} (d_{xy}d_{yz}d_{za}d_{ax} + d_{xa}d_{az}d_{zy}d_{yx})(d_{bc}d_{cb}) \quad + \\
\displaystyle\sum_{x=1}^{1}\sum_{y=x+1}^{5}\sum_{z=y+1}^{6}\sum_{a=1}^{4}\sum_{b=a+1}^{5}\sum_{c=b+1}^{6} (d_{xy}d_{yz}d_{zx} + d_{xz}d_{zy}d_{yx})(d_{ab}d_{bc}d_{ca} + d_{ac}d_{cb}d_{ba}) + \\
\displaystyle\sum_{x=1}^{1}\sum_{y=x+1}^{6}\sum_{z=x+1}^{3}\sum_{a=x+2}^{6}\sum_{b=z+1}^{5}\sum_{c=z+2}^{6} (d_{xy}d_{yx})(d_{za}d_{az})(d_{bc}d_{cb}) \quad + \\
\displaystyle\sum_{x=1}^{1}\sum_{y=x+1}^{5}\sum_{z=x+1}^{6}\sum_{a=x+1}^{6}\sum_{b=x+1}^{6}\sum_{c=1}^{6} (d_{xy}d_{yz}d_{zp}d_{ab}d_{bc}d_{cx} + d_{xc}d_{cb}d_{ba}d_{az}d_{zy}d_{yx})
\end{array} \right)
\end{aligned}
\tag{B.1}
$$

B.2 Calculation of OR factor permanent values

Below are the individual calculations of permanent values for each expert-OR factor combination. Calculations were completed using the BosonSampling package in R (P. Clifford & R. Clifford, 2021). An example of the implemented code is displayed in Fig. B.1.

~~~
```{r}
x <- c(7,2,3,1,8,5,5,5,7,5,6,5,9,5,5,6)
E5H <- matrix(x, nrow = 4, ncol = 4)
rePerm(E5H)
~~~
```

```
[1] 13831
```

Figure B.1 Screenshot from RStudio showing the permanent calculation
```

The generalized forms of each main OR factor digraph are shown in Eqs. B.2 – B.9.

$$Per(B) = \begin{bmatrix} B_1 & b_{12} & b_{13} \\ b_{21} & B_2 & b_{23} \\ b_{31} & b_{32} & B_3 \end{bmatrix} \tag{B.2}$$

$$Per(C) = \begin{bmatrix} C_1 & c_{12} & c_{13} \\ c_{21} & C_2 & c_{23} \\ c_{31} & c_{32} & C_3 \end{bmatrix} \tag{B.3}$$

$$Per(D) = \begin{bmatrix} D_1 & d_{12} & d_{13} & d_{14} \\ d_{21} & D_2 & d_{23} & d_{24} \\ d_{31} & d_{32} & D_3 & d_{34} \\ d_{41} & d_{42} & d_{43} & D_4 \end{bmatrix} \tag{B.4}$$

$$Per(E) = \begin{bmatrix} E_1 & e_{12} & e_{13} \\ e_{21} & E_2 & e_{23} \\ e_{31} & e_{32} & E_3 \end{bmatrix} \tag{B.5}$$

$$Per(F) = \begin{bmatrix} F_1 & f_{12} & f_{13} \\ f_{21} & F_2 & f_{23} \\ f_{31} & f_{32} & F_3 \end{bmatrix} \tag{B.6}$$

$$Per(G) = \begin{bmatrix} G_1 & g_{12} & g_{13} & g_{14} \\ g_{21} & G_2 & g_{23} & g_{24} \\ g_{31} & g_{32} & G_3 & g_{34} \\ g_{41} & g_{42} & g_{43} & G_4 \end{bmatrix} \tag{B.7}$$

$$Per(H) = \begin{bmatrix} H_1 & h_{12} & h_{13} & h_{14} \\ h_{21} & H_2 & h_{23} & h_{24} \\ h_{31} & h_{32} & H_3 & h_{34} \\ h_{41} & h_{42} & h_{43} & H_4 \end{bmatrix} \tag{B.8}$$

$$Per(I) = \begin{bmatrix} I_1 & i_{12} & i_{13} \\ i_{21} & I_2 & i_{23} \\ i_{31} & i_{32} & I \end{bmatrix} \tag{B.9}$$

## B.3 Permanent values

Permanent calculations used in obtaining resilience factor index values for each expert are shown below. Matrices are grouped by factor so that each expert's index value is shown for one OR factor before moving to the next group.

### B.3.1 Teamwork calculations

$$Per^{E1}(B) = \begin{bmatrix} 7 & 6 & 3 \\ 4 & 6 & 7 \\ 7 & 3 & 7 \end{bmatrix} = 1065$$

$$Per^{E2}(B) = \begin{bmatrix} 7 & 5 & 6 \\ 5 & 7 & 5 \\ 4 & 5 & 6 \end{bmatrix} = 1037$$

$$Per^{E3}(B) = \begin{bmatrix} 7 & 4 & 4 \\ 6 & 7 & 3 \\ 6 & 7 & 7 \end{bmatrix} = 1066 \qquad \text{(B.10)}$$

$$Per^{E4}(B) = \begin{bmatrix} 7 & 6 & 5 \\ 4 & 5 & 5 \\ 5 & 5 & 7 \end{bmatrix} = 963$$

$$Per^{E5}(B) = \begin{bmatrix} 6 & 7 & 5 \\ 3 & 5 & 5 \\ 5 & 5 & 5 \end{bmatrix} = 780$$

### B.3.2 Information and knowledge management calculations

$$\begin{gathered}
Per^{E1}(C) = \begin{bmatrix} 7 & 5 & 7 \\ 5 & 7 & 6 \\ 3 & 4 & 6 \end{bmatrix} = 989 \\
Per^{E2}(C) = \begin{bmatrix} 7 & 5 & 6 \\ 5 & 7 & 5 \\ 4 & 5 & 7 \end{bmatrix} = 1111 \\
Per^{E3}(C) = \begin{bmatrix} 5 & 2 & 2 \\ 8 & 5 & 5 \\ 8 & 5 & 7 \end{bmatrix} = 652 \\
Per^{E4}(C) = \begin{bmatrix} 7 & 5 & 6 \\ 5 & 7 & 6 \\ 4 & 4 & 7 \end{bmatrix} = 1094 \\
Per^{E5}(C) = \begin{bmatrix} 6 & 6 & 4 \\ 4 & 6 & 5 \\ 6 & 5 & 6 \end{bmatrix} = 914
\end{gathered} \tag{B.11}$$

### B.3.3 Innovation and creativity calculations

$$Per^{E1}(D)=\begin{bmatrix}7 & 5 & 3 & 4\\ 5 & 7 & 2 & 3\\ 7 & 8 & 7 & 8\\ 6 & 7 & 2 & 6\end{bmatrix}=16820$$

$$Per^{E2}(D)=\begin{bmatrix}7 & 5 & 5 & 4\\ 4 & 7 & 4 & 4\\ 5 & 6 & 7 & 6\\ 6 & 6 & 4 & 7\end{bmatrix}=21961$$

$$Per^{E3}(D)=\begin{bmatrix}7 & 10 & 5 & 5\\ 0 & 2 & 0 & 0\\ 5 & 10 & 7 & 5\\ 5 & 10 & 5 & 7\end{bmatrix}=2236$$

$$Per^{E4}(D)=\begin{bmatrix}7 & 7 & 4 & 4\\ 3 & 5 & 3 & 3\\ 6 & 7 & 7 & 5\\ 6 & 7 & 5 & 7\end{bmatrix}=17608 \tag{B.12}$$

$$Per^{E5}(D)=\begin{bmatrix}7 & 8 & 5 & 5\\ 2 & 5 & 4 & 4\\ 5 & 6 & 6 & 7\\ 5 & 6 & 3 & 6\end{bmatrix}=16593$$

### B.3.4 Coordination and monitoring calculations

$$
\begin{aligned}
Per^{E1}(E) &= \begin{bmatrix} 7 & 6 & 4 \\ 4 & 7 & 4 \\ 6 & 6 & 7 \end{bmatrix} = 1087 \\
Per^{E2}(E) &= \begin{bmatrix} 7 & 6 & 6 \\ 4 & 7 & 6 \\ 4 & 4 & 7 \end{bmatrix} = 1087 \\
Per^{E3}(E) &= \begin{bmatrix} 7 & 5 & 8 \\ 5 & 7 & 8 \\ 2 & 2 & 6 \end{bmatrix} = 828 \\
Per^{E4}(E) &= \begin{bmatrix} 7 & 7 & 7 \\ 3 & 6 & 4 \\ 3 & 6 & 6 \end{bmatrix} = 882 \\
Per^{E5}(E) &= \begin{bmatrix} 7 & 9 & 9 \\ 1 & 6 & 5 \\ 1 & 5 & 5 \end{bmatrix} = 574
\end{aligned}
\tag{B.13}
$$

### B.3.5 Planning strategies and preparedness calculations

$$Per^{E1}(F) = \begin{bmatrix} 7 & 3 & 3 \\ 7 & 7 & 8 \\ 7 & 2 & 7 \end{bmatrix} = 959$$

$$Per^{E2}(F) = \begin{bmatrix} 7 & 4 & 5 \\ 6 & 7 & 5 \\ 5 & 5 & 6 \end{bmatrix} = 1038$$

$$Per^{E3}(F) = \begin{bmatrix} 5 & 1 & 1 \\ 9 & 7 & 5 \\ 9 & 5 & 7 \end{bmatrix} = 586 \tag{B.14}$$

$$Per^{E4}(F) = \begin{bmatrix} 7 & 6 & 5 \\ 4 & 7 & 5 \\ 5 & 5 & 7 \end{bmatrix} = 1111$$

$$Per^{E5}(F) = \begin{bmatrix} 7 & 8 & 5 \\ 2 & 6 & 5 \\ 5 & 5 & 6 \end{bmatrix} = 923$$

### B.3.6 Resources calculations

$$Per^{E1}(G) = \begin{bmatrix} 7 & 7 & 4 & 4 \\ 3 & 6 & 1 & 6 \\ 6 & 9 & 7 & 9 \\ 6 & 4 & 1 & 6 \end{bmatrix} = 16494$$

$$Per^{E2}(G) = \begin{bmatrix} 7 & 8 & 5 & 4 \\ 2 & 7 & 3 & 6 \\ 5 & 7 & 7 & 7 \\ 6 & 4 & 3 & 7 \end{bmatrix} = 20866$$

$$Per^{E3}(G) = \begin{bmatrix} 7 & 5 & 5 & 4 \\ 5 & 7 & 7 & 8 \\ 5 & 3 & 7 & 3 \\ 6 & 2 & 7 & 7 \end{bmatrix} = 20688 \qquad (B.15)$$

$$Per^{E4}(G) = \begin{bmatrix} 7 & 8 & 5 & 6 \\ 2 & 7 & 3 & 4 \\ 5 & 7 & 7 & 7 \\ 4 & 6 & 3 & 7 \end{bmatrix} = 18994$$

$$Per^{E5}(G) = \begin{bmatrix} 7 & 5 & 5 & 5 \\ 5 & 7 & 5 & 5 \\ 5 & 5 & 7 & 7 \\ 5 & 5 & 3 & 7 \end{bmatrix} = 22080$$

### B.3.7 Flexibility calculations

$$Per^{E1}(H) = \begin{bmatrix} 7 & 6 & 2 & 4 \\ 4 & 7 & 2 & 3 \\ 8 & 8 & 7 & 7 \\ 6 & 7 & 3 & 6 \end{bmatrix} = 16266$$

$$Per^{E2}(H) = \begin{bmatrix} 7 & 5 & 5 & 6 \\ 5 & 7 & 4 & 5 \\ 5 & 6 & 7 & 6 \\ 4 & 5 & 4 & 7 \end{bmatrix} = 21915 \qquad (B.16)$$

$$Per^{E3}(H) = \begin{bmatrix} 5 & 5 & 6 & 6 \\ 5 & 5 & 6 & 6 \\ 4 & 4 & 7 & 5 \\ 4 & 4 & 5 & 7 \end{bmatrix} = 17524$$

$$Per^{E4}(H) = \begin{bmatrix} 7 & 6 & 6 & 6 \\ 4 & 7 & 6 & 5 \\ 4 & 4 & 7 & 4 \\ 4 & 5 & 6 & 7 \end{bmatrix} = 21530$$

$$Per^{E5}(H) = \begin{bmatrix} 7 & 8 & 7 & 9 \\ 2 & 5 & 5 & 5 \\ 3 & 5 & 6 & 5 \\ 1 & 5 & 5 & 6 \end{bmatrix} = 13831$$

### B.3.8 Minimization of silos calculations

$$\begin{gathered} Per^{E1}(I) = \begin{bmatrix} 6 & 3 & 3 \\ 7 & 7 & 6 \\ 7 & 4 & 7 \end{bmatrix} = 942 \\ Per^{E2}(I) = \begin{bmatrix} 6 & 3 & 4 \\ 7 & 7 & 5 \\ 6 & 5 & 6 \end{bmatrix} = 926 \\ Per^{E3}(I) = \begin{bmatrix} 7 & 5 & 5 \\ 5 & 7 & 5 \\ 5 & 5 & 6 \end{bmatrix} = 1044 \\ Per^{E4}(I) = \begin{bmatrix} 7 & 5 & 6 \\ 5 & 7 & 5 \\ 4 & 5 & 7 \end{bmatrix} = 1111 \\ Per^{E5}(I) = \begin{bmatrix} 6 & 7 & 5 \\ 3 & 6 & 5 \\ 5 & 5 & 6 \end{bmatrix} = 892 \end{gathered} \tag{B.17}$$

### B.4 Normalized results by expert

Table B.1 Expert 1 normalized results

| priority | OR factor | Normalized values |
|---|---|---|
| 1 | E | 0.96086 |
| 2 | B | 0.93308 |
| 3 | C | 0.83712 |
| 4 | F | 0.79924 |
| 5 | I | 0.77778 |
| 6 | A | 0.72154 |
| 7 | D | 0.64385 |
| 8 | G | 0.62295 |
| 9 | H | 0.60833 |

Table B.2 Expert 2 normalized results

| priority | OR factor | Normalized values |
|---|---|---|
| 1 | C | 0.99116 |
| 2 | D | 0.9734 |
| 3 | H | 0.97045 |
| 4 | E | 0.96086 |
| 5 | A | 0.96016 |
| 6 | G | 0.90321 |
| 7 | F | 0.89899 |
| 8 | B | 0.89773 |
| 9 | I | 0.75758 |

Table B.3 Expert 3 normalized results

| priority | OR factor | Normalized values |
|---|---|---|
| 1 | B | 0.93434 |
| 2 | I | 0.90657 |
| 3 | G | 0.89179 |
| 4 | A | 0.82456 |
| 5 | H | 0.68897 |
| 6 | E | 0.63384 |
| 7 | C | 0.41162 |
| 8 | F | 0.32828 |
| 9 | D | 0 |

Table B.4 Expert 4 normalized results

| priority | OR factor | Normalized values |
|---|---|---|
| 1 | F | 0.99116 |
| 2 | I | 0.99116 |
| 3 | C | 0.9697 |
| 4 | H | 0.94577 |
| 5 | A | 0.91458 |
| 6 | B | 0.80429 |
| 7 | G | 0.78321 |
| 8 | E | 0.70202 |
| 9 | D | 0.69436 |

Table B.5 Expert 5 normalized results

| priority | OR factor | Normalized values |
|---|---|---|
| 1 | G | 0.98103 |
| 2 | F | 0.75379 |
| 3 | C | 0.74242 |
| 4 | I | 0.71465 |
| 5 | D | 0.62929 |
| 6 | B | 0.57323 |
| 7 | A | 0.54411 |
| 8 | H | 0.45224 |
| 9 | E | 0.31313 |

### B.5 Sub-factor digraphs

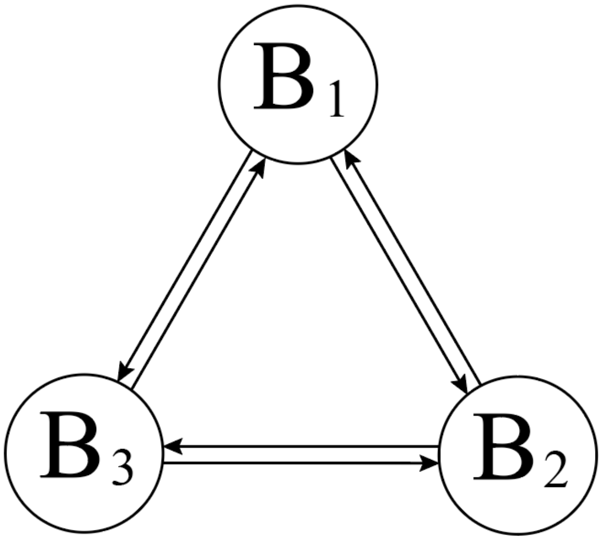

Figure B.2 Teamwork digraph

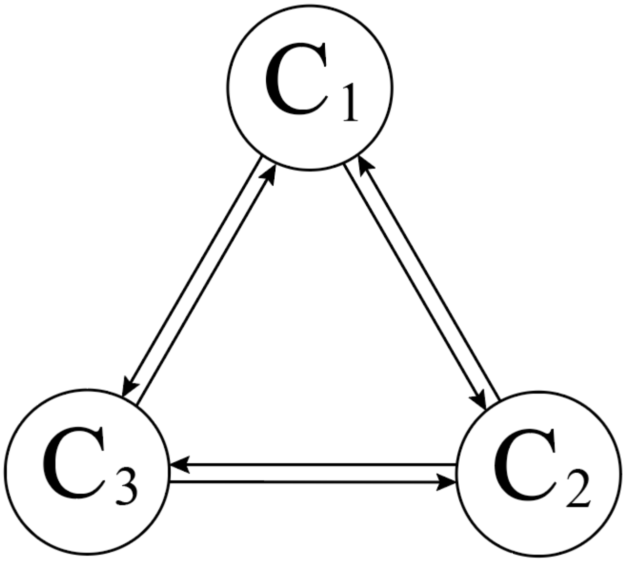

Figure B.3 Information and knowledge management digraph

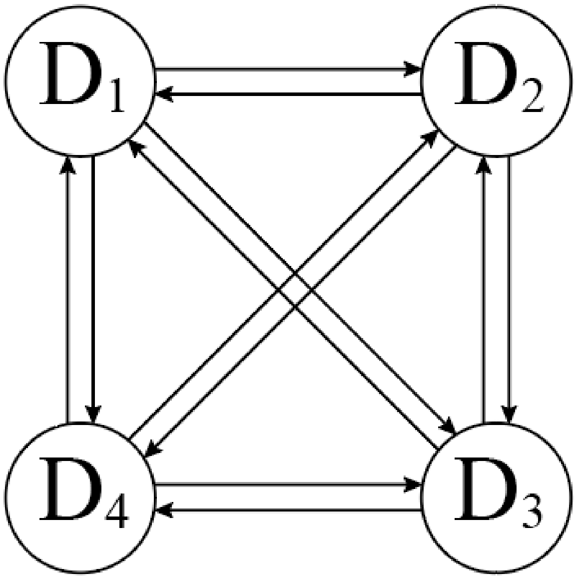

Figure B.4 Innovation and creativity digraph

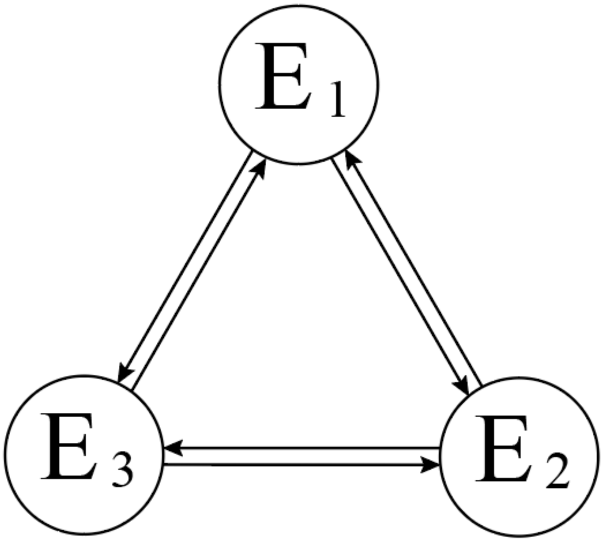

Figure B.5 Coordination and monitoring digraph

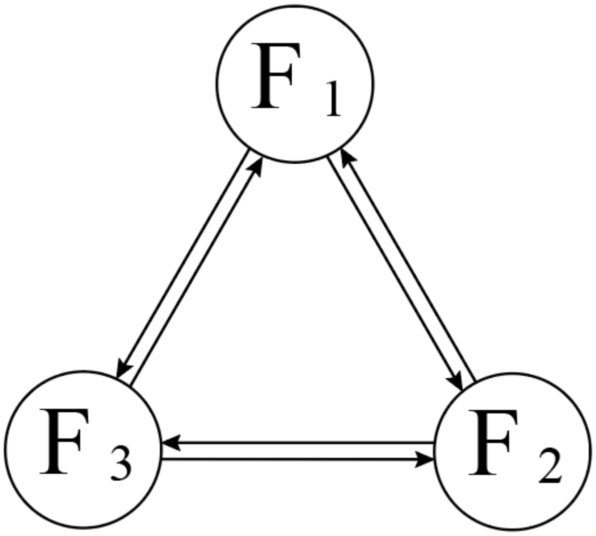

Figure B.6 Planning strategies and preparedness digraph

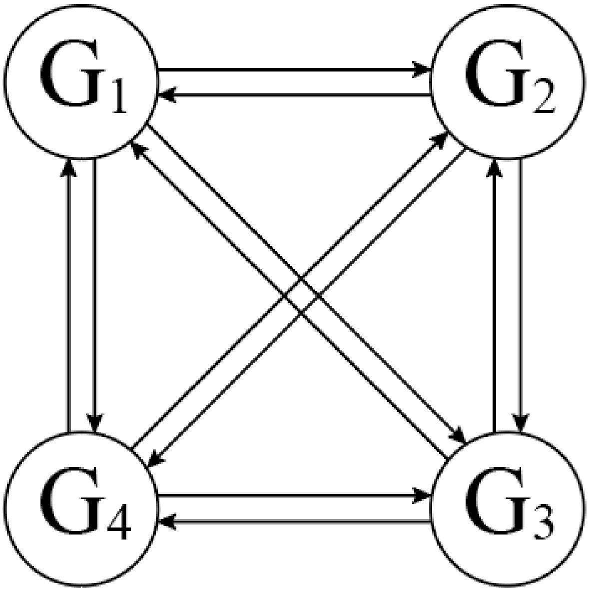

Figure B.7 Resources digraph

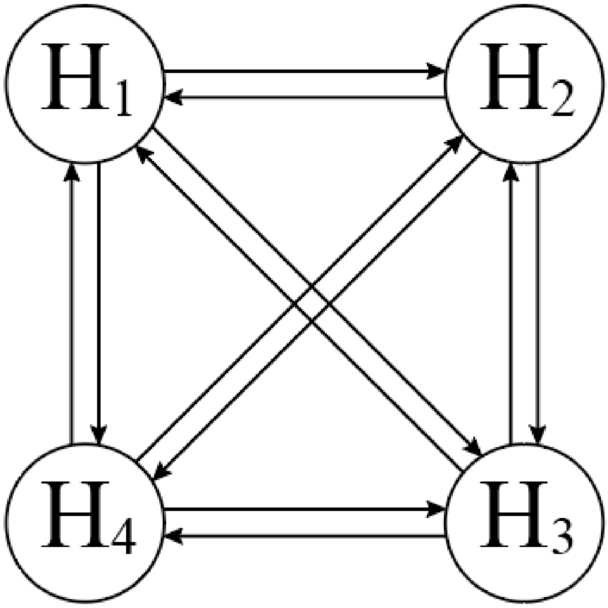

Figure B.8 Flexibility digraph

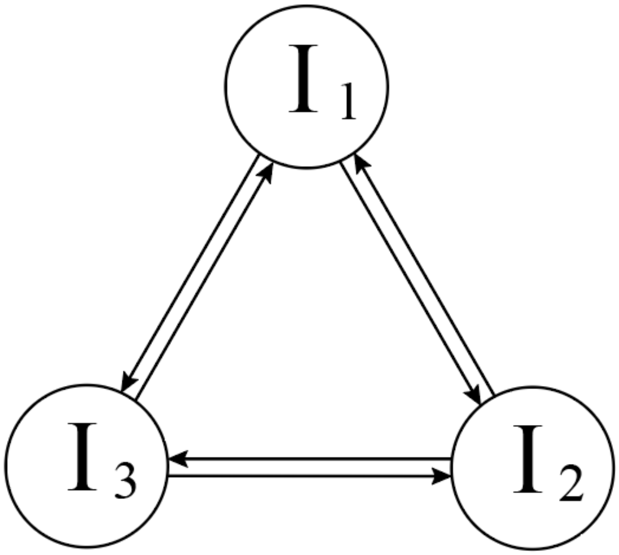

Figure B.9 Minimization of silos digraph

# APPENDIX C

# MANUFACTURING ORGANIZATIONAL RESILIENCE SURVEY

## C.1 Objective:

This survey as part of research project is designed to assess the relative importance of literature-derived resilience factors in building, maintaining, and improving the resilience of manufacturing organizations (i.e., how can such organizations survive and thrive amidst disruptions ranging from natural disasters to innovative competition to global pandemics). Resilience is defined generally as the property allowing a system to recover from disruption quickly and without critical harm.

## C.2 Procedures:

If you agree to participate, completion of the survey will take approximately 15-25 minutes. Following some basic questions about your position in industry and experience level, you will be presented with 75 resilience-related questions consisting of -

1) rating the literature-derived factors' importance on a linear scale

2) rating sub-factors relative importance to one another.

## C.3 Risks:

This is a survey study. There are no possibilities of risk or harm to participants as a result of participation in the study.

## C.4 Anonymity:

Responses will remain completely anonymous. This survey is designed to collect expert opinions for the purpose of academic research only. No personal information other than employer name, job title, and experience level will be collected. Employer names will not be published.

### C.5 Questions:

If you have questions about this research project, please feel free to contact Steven A. Fazio, Mississippi State University graduate researcher at saf8@msstate.edu

VOLUNTARY PARTICPATION:

Your participation in this study is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You may discontinue participation at any time.

1. By entering the survey area, you indicate that you are at least 18 years old and giving informed consent to participate in this study.
2. What is the name of your employer?
3. What is your job title?
4. How many years of manufacturing industry experience do you have?

#### C.5.1 Leadership factor

Leadership is defined in the literature as guidance of OR factor implementation. The following questions will assess the relative importance of each leadership trait to the main factor.

5. In relation to LEADERSHIP: How important is TRANSPARENCY, or the open sharing of relevant information and feedback?
6. In relation to LEADERSHIP: How important is TRUST, or the assumption that leadership will generate results in alignment with stakeholder interests?
7. In relation to LEADERSHIP: How important is CONTROLLABILITY, or the ability to effect change during dynamic uncertainty?

8. In relation to LEADERSHIP: How important is LEARNING FROM FAILURE, or using experience to inform future system iterations toward a more reliable, steady state?
9. In relation to LEADERSHIP: How important is DECISIVENESS, or the ability to quickly prioritize core values in the face of uncertainty?
10. In relation to LEADERSHIP: How would you rank the importance of TRANSPARENCY (open sharing of relevant information and feedback) over TRUST (assumption that leadership will generate results in alignment with stakeholder interests)?
11. In relation to LEADERSHIP: How would you rank the importance of TRANSPARENCY (open sharing of relevant information and feedback) over CONTROLLABILITY (ability to effect change during dynamic uncertainty)?
12. In relation to LEADERSHIP: How would you rank the importance of TRANSPARECNY (open sharing of relevant information and feedback) over LEARNING FROM FAILURE (using experience to inform future system iterations towards a more reliable, steady state)?
13. In relation to LEADERSHIP: How would you rank the importance of TRANSPARENCY (open sharing of relevant information and feedback) over DECISIVENESS (ability to quickly prioritize core values in the face of uncertainty)?
14. In relation to LEADERSHIP: How would you rank the importance of TRUST (assumption that leadership will generate results in alignment with stakeholder interests) over CONTROLLABILITY (ability to effect change during dynamic uncertainty)?
15. In relation to LEADERSHIP: How would you rank the importance of TRUST (assumption that leadership will generate results in alignment with stakeholder interests) over LEARNING FROM FAILURE (using experience to inform future system iterations toward a more reliable, steady state)?

16. In relation to LEADERSHIP: How would you rank the importance of TRUST (assumption that leadership will generate results in alignment with stakeholder interest) over DECISIVENESS (ability to quickly prioritize core values in the face of uncertainty)?
17. In relation to LEADERSHIP: How would you rank the importance of CONTROLLABILITY (ability to effect change during dynamic uncertainty) over LEARNING FROM FAILURE (using experience to inform future system iterations toward a more reliable, steady state)?
18. In relation to LEADERSHIP: How would you rank the importance of CONTROLLABILITY (ability to effect change during dynamic uncertainty) over DECISIVENESS (ability to quickly prioritize core values in the face of uncertainty)?
19. In relation to LEADERSHIP: How would you rank the importance of LEARNING FROM FAILURE (using experience to inform future system iterations toward a more reliablie, steady state)? Over DECISIVENESS (ability to quickly prioritize core values in the face of uncertainty)?

### C.5.2 Teamwork factor

TEAMWORK is defined as increasing organizational performance through individuals working together with shared objectives and complimentary skills.

20. In relation to TEAMWORK: how important is HUMAN FACTORS, or the human components who enable the formation of effective teams and teamwork?
21. In relation to TEAMWORK: How important is ORIENTATION FOR COMPLETING TASKS, or the ability of a leader-coordinated team to work in concert toward the successful completion of goals?

22. In relation to TEAMWORK: How important is ORIENTATION FOR INTERPERSONAL RELATIONSHIPS, or the beneficial interconnectivity among team members enabling response to and recovery from disruption?
23. In relation to TEAMWORK: How would you rank the importance of HUMAN FACTORS (human components who enable the formation of effective teams and teamwork) over ORIENTATION FOR COMPLETING TASKS (ability of a leader-coordinated team to work in concert toward the successful completion of goals)?
24. In relation to TEAMWORK: How would you rank the importance of HUMAN FACTORS (human components who enable the formation of effective teams and teamwork) over ORIENTATION FOR INTERPERSONAL RELATIONSHIPS (beneficial interconnectivity among team members enabling response to and recovery from disruption)?
25. In relation to TEAMWORK: How would you rank the importance of ORIENTATION FOR INTERPERSONAL RELATIONSHIPS (beneficial interconnectivity among team members enabling response to and recovery from disruption) over ORIENTATION FOR COMPLETING TASKS (ability of a leader-coordinated team to work in concert toward the successful completion of goals)?

### C.5.3 Information and knowledge management factor

INFORMATION AND KNOWLEDGE MANAGEMENT is defined as controlled use, storage, and transfer of information for the benefit of organizational performance

26. In relation to INFORMATION AND KNOWLEDGE MANAGEMENT: How important is KNOWLEDGE MANAGEMENT, or the acquisition, storage, organization, and dissemination of information?

27. In relation to INFORMATION AND KNOWLEDGE MANAGEMENT: How important is AWARENESS, or insight into specific information that drives organizational performance?
28. In relation to INFORMATION AND KNOWLEDGE MANAGEMENT: How important is JUST CULTURE, or prevailing information embedded in the minds of personnel supporting a clear distinction between desirable and undesirable action?
29. In relation to INFORMATION AND KNOWLEDGE MANAGEMENT: How would you rank the importance of KNOWLEDGE MANAGEMENT (Acquisition, storage, organization, and dissemination of information resources) over AWARENESS (insight into specific information that drives organizational performance)?
30. In relation to INFORMATION AND KNOWLEDGE MANAGEMENT: How would you rank the importance of KNOWLEDGE MANAGEMENT (Acquisition, storage, organization, and dissemination of information resources) over JUST CULTURE (prevailing information embedded in the minds of personnel supporting a clear distinction between desirable and undesirable action)?
31. In relation to INFORMATION AND KNOWLEDGE MANAGEMENT: How would you rank the importance of AWARENESS (insight into specific information that drives organizational performance) over JUST CULTURE (prevailing information embedded in the minds of personnel supporting a clear distinction between desirable and undesirable action)?

### C.5.4 Innovation and creativity factor

INNOVATION AND CREATIVITY is defined as ability to generate solutions as new disruptions occur.

32. In relation to INNOVATION AND CREATIVITY: How important is creativity, or the process of generation new effective alternatives?
33. In relation to INNOVATION AND CREATIVITY: How important is IMPROVISATION, or the instantaneous subversion of operation norms for new ideas and actions
34. In relation to INNOVATION AND CREATIVITY: How important is INNOVATION, or generation of effective new ideas as a result of creativity and flexibility?
35. In relation to INNOVATION AND CREATIVITY: How important is EMERGENCE, or process and business model changes made after disruption?
36. In relation to INNOVATION AND CREATIVITY: How would you rank the importance of CREATIVITY (the process of generating new effective alternatives) over IMPROVISATION (instantaneous subversion of operation norms for new ideas and actions)?
37. In relation to INNOVATION AND CREATIVITY: How would you rank the importance of CREATIVITY (the process of generating new effective alternatives) over (INNOVATION (generation of new effective ideas as a result of creativity and flexibility)?
38. In relation to INNOVATION AND CREATIVITY: How would you rank the importance of CREATIVITY (the process of generating new effective alternatives) over EMERGENCE (process and business model changes made after disruption)?
39. In relation to INNOVATION AND CREATIVITY: How would you rank the importance of IMPROVISATION (instantaneous subversion of operational norms for new ideas and actions) over INNOVATION (generation of effective new ideas as a result of creativity and flexibility)?

40. In relation to INNOVATION AND CREATIVITY: How would you rank the importance of IMPROVISATION (instantaneous subversion of operational norms for new ideas and actions) over EMERGENCE (process and business model changes after disruption)?
41. In relation to INNOVATION AND CREATIVITY: How would you rank the importance of INNOVATION (generation of effective new ideas as a result of creativity and flexibility) over EMERGENCE (process and business model changes made after disruption)?

### C.5.5 Coordination and monitoring factor

COORDINATION AND MONITORING is defined as the useful distribution of information and oversight of its effective use

42. In relation to COORDINATION AND MONITORING: How important is TASK CLARITY, or maximizing coordination of the workforce with clear and concise instructions?
43. In relation to COORDINATION AND MONITORING: How important is DISSEMINATION OF INFORMATION, or effective sharing of new information generated during system operation?
44. In relation to COORDINATION AND MONITORING: How important is FAULT TOLERANCE, or processes allowing adjustment prior to unacceptable performacen loss or system failure?
45. In relation to COORDINATION AND MONITORING: How would you rank the importance of TASK CLARITY (maximizing coordination of the workforce with clear and concise instructions) over DISSEMINATION OF INFORMATION (effective sharing of new information generated during system operation)?

46. In relation to COORDINATION AND MONITORING: How would you rank the importance of TASK CLARITY (maximizing coordination of the workforce with clear and concise instructions) over FAULT TOLERANCE (processes allowing adjustment to unacceptable performance loss or system failure)?
47. In relation to COORDINATION AND MONITORING: How would you rank the importance of DISSEMINATION OF INFORMATION (effective sharing of new information generated during system operation) over FAULT TOLERANCE (processes allowing adjustment prior to unacceptable performance loss or system failure)?

### C.5.6 Planning strategies and preparedness factor

PLANNING STRATEGIES AND PREPAREDNESS is defined as assessment of risk and development of mitigation plans that account for strengths, weaknesses, and levels of preparedness.

48. In relation to PLANNING STRATEGIES AND PREPAREDNESS: How important is RISK ASSESSMENT or processes designed to create specific awareness of potential disruptions and their likelihood of occurrence?
49. In relation to PLANNING STRATEGIES AND PREPAREDNESS: How important is RECOGNITION OF CRITICAL INTERDEPENDENCIES, or awareness of the internal and external relationships that are critical to organizational resilience?
50. In relation to PLANNING STRATEGIES AND PREPAREDNESS: How important is SCENARIO ANALYSIS, TESTING, AND SIMULATION, or iterative, technology-driven analysis strategy for rehearsal of scenarios and validation plans?
51. In relation to PLANNING STRATEGIES AND PREPAREDNESS: How would you rank the importance of RISK ASSESSMENTS (processes designed to create specific awareness

of potential disruptions and their likelihood of occurrence) over RECOGNITION OF CRITICAL INTERDEPENDENCIES (awareness of the internal and external relationships that are critical to organizational resilience)?

52. In relation to PLANNING STRATEGIES AND PREPAREDNESS: How would you rank the importance of RISK ASSESSMENTS (processes designed to create specific awareness of potential disruptions and their likelihood of occurrence) over SCENARIO ANALYSIS, TESTING, AND SIMULATION (iterative, technology-driven analysis strategy for rehearsal of scenarios and validation of plans)?
53. In relation to PLANNING STRATEGIES AND PREPAREDNESS: How would you rank the importance of RECOGNITION OF CRITICAL INTERDEPENDENCIES (awareness of the internal and external relationships that are critical to organizational resilience) over SCENARIO ANALYSIS, TESTING, AND SIMULATION (iterative, technology-driven strategy for rehearsal of scenarios and validation of plans)?

### C.5.7 Resources factor

RESOURCES are defined as the people, materials, supplies, machinery, and technology required for operation of the organization

54. In relation to RESOURCES: How important is RESOURCE SUPPLY, or maintenance of the flow of resources into the organization?
55. In relation to RESOURCES: How important is EMERGENCY PERSONNEL AVAILABLE, or availability of adequate internal resources to simultaneously maintain acceptable performance during disruption and respond to crisis?
56. In relation to RESOURCES: How important is FINANCIAL CAPACITY, or availability of funds or economic resources to subsume the economic burden of disruption?

57. In relation to RESOURCES: How important is TECHNICAL PROFESSIONAL NETWORK SUPPORT, or access to critical infrastructure technical subject matter experts?
58. In relation to RESOURCES: How would you rank the importance of RESOURCE SUPPLY (maintenance of the flow of resources into the organization) over EMERGENCY PERSONNEL AVAILABLE (availability of adequate internal resource to simultaneously maintain acceptable performance during disruption and respond to crisis)
59. In relation to RESOURCES: How would you rank the importance of RESOURCE SUPPLY (maintenance of the flow of resources into the organization) over FINANCIAL CAPACITY (availability of funds or economic resources to subsume the economic burden of disruption)?
60. In relation to RESOURCES: How would you rank the importance of RESOURCE SUPPLY (maintenance of the flow of resources into the organization) over TECHNICAL PROFESSIONAL NETWORK (internal or external access to critical infrastructure technical subject matter experts)?
61. In relation to RESOURCES: How would you rank the importance of EMERGENCY PERSONNEL AVAILABLE (availability of adequate internal resources to simultaneously maintain acceptable performance during disruption and respond to crisis) over FINANCIAL CAPACITY (availability of funds or economic resources to subsume the economic burden of disruption)?
62. In relation to RESOURCES: How would you rank the importance of EMERGENCY PERSONNEL AVAILABLE (availability of adequate internal resources to simultaneously maintain acceptable performance during disruption and respond to crisis) over

TECHNICAL PROFESSIONAL NETWORK (access to critical infrastructure technical subject matter experts)?

63. In relation to RESOURCES: How would you rank the importance of FINANCIAL CAPACITY (availability of funds or economic resources to subsume the economic burden of disruption) over TECHNICAL PROFESSIONAL NETWORK (access to critical infrastructure technical subject matter experts)?

### C.5.8 Flexibility factor

FLEXIBILITY is defined as the mechanism by which the organizational system absorbs or transfers disruptive shock, allowing return to nominal operation without crashing.

64. In relation to FLEXIBILITY: How important is ADAPTABILITY, or processes that enable the organization to monitor system demands and boundaries to quickly implement needed resilience model changes?
65. In relation to FLEXIBILITY: How important is REORGANIZATION, or the design element enabling system architecture modification around or during disruption?
66. In relation to FLEXIBILITY: How important is REPAIRABILITY, or the rate at which return to normal operation is or may be achieved?
67. In relation to FLEXIBILITY: How important is REDUCTION OF COMPLEXITY, or the need to maintain or obtain system simplicity?
68. In relation to FLEXIBILITY: How would you rank the importance of ADAPTABILITY (processes that enable the organization to monitor system demands and boundaries to quickly implement needed resilience model changes) over REORGANIZATION (processes enabling system architecture modifications around or during disruption)?

69. In relation to FLEXIBILITY: How would you rank the importance of ADAPTABILITY (processes that enable the organization to monitor system demands and boundaries to quickly implement needed resilience model changes) over REPAIRABILITY (rate at which return to normal operation is or may be achieved)?
70. In relation to FLEXIBILITY: How would you rank the importance of ADAPTABILITY (processes that enable the organization to monitor system demands and boundaries to quickly implement needed resilience model changes) over REDUCTION OF COMPLEXITY (the need to maintain or obtain system simplicity)?
71. In relation to FLEXIBILITY: How would you rank the importance of REORGANIZATION (processes enabling system architecture modification around or during disruption) over REPAIRABILITY (the rate at which return to normal operation is or may be achieved)?
72. In relation to FLEXIBILITY: How would you rank the importance of REORGANIZATION (processes enabling system architecture modification around or during disruption) over REDUCTION OF COMPLEXITY (the need to maintain or obtain system simplicity)?
73. In relation to FLEXIBILITY: How would you rank the importance of REPAIRABILITY (the rate at which return to normal operation is or may be achieved) over REDUCTION OF COMPLEXITY (the need to maintain or obtain system simplicity)?

### C.5.9 Minimization of silos factor

MINIMIZATION OF SILOS is defined as reduction or elimination of decentralized organizational units enabling implementation of organizational resilience factors.

74. In relation to MINIMIZATION OF SILOS: How important is HOLISTIC VIEW, or consideration of global system perspective including social, organizational, policy, political, technical, and informational factors?
75. In relation to MINIMIZATION OF SILOS: How important is CROSS-FUNCTIONAL COMMUNICATION, or creation and utilization of conduits between functions that enable clear, expedient information flow?
76. In relation to MINIMIZATION OF SILOS: How important is CROSS-FUNCTIONAL INTEGRATION, or creation of internal agility and collaboration through cohesive organization-spanning social networks?
77. In relation to MINIMIZATION OF SILOS: How would you rank the importance of HOLISTIC VIEW (consideration of global system perspective including social, organizational, policy, political, technical, and informational factors) over CROSS-FUNCTIONAL COMMUNICATION (creation and utilization of conduits between functions that enable clear, expedient information flow)?
78. In relation to MINIMIZATION OF SILOS: How would you rank the importance of HOLISTIC VIEW (consideration of global system perspective including social, organizational, policy, political, technical, and informational factors) over CROSS-FUNCTIONAL INTEGRATION (creation of internal agility and collaboration through cohesive organization-spanning social networks)?
79. In relation to MINIMIZATION OF SILOS: How would you rank the importance of CROSS-FUNCTIONAL COMMUNICATION (creation and utilization of conduits between functions that enable clear, expedient information flow) over CROSS-

FUNCTIONAL INTEGRATION (creation of internal agility and collaboration through cohesive organization-spanning social networks)?

THANK YOU!!!

Your time in completing this survey is greatly appreciated. The data you have provided will contribute to the better understanding of strengthening organizations against disruption and crisis.