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Theorizing through Metaphorical Transfer: Supply Chain Resilience as Endotherm Resilience

Abstract

This study explores the application of formal metaphorical transfer to construct theory regarding supply chain resilience, a topic of increased significance due to rising supply chain disruptions. We propose an ecological resilience perspective to illuminate the complex, dynamic nature of supply chain systems. Our research pivots around two questions: (1) Can the resilience of endotherms (warm-blooded animals) serve as a conceptually robust source phenomenon for metaphorical transfer to the study of supply chain resilience? (2) What theory-based principles can be derived from this metaphor to enhance our understanding of supply chain resilience? After rigorously establishing the conceptual equivalence between endotherm resilience and supply chain resilience, we identify a set of theory-based principles that provide insights into the evolving field of supply chain resilience. These principles help illuminate the adaptive and predictive dimensions of supply chain resilience. This paper contributes to theory building in operations management and supply chain management while suggesting new avenues for future research.

KEYWORDS

Supply chain resilience; theory building; metaphors; metaphorical transfer; endotherm resilience

1. INTRODUCTION

This study presents an application of formal metaphorical transfer to advance theory building in the domain of supply chain resilience. The immediacy of this research is underscored by the growing imperative for supply chain resilience due to mounting vulnerabilities faced by firms due to increasingly frequent supply chain disruptions (Katsaliaki et al., 2021; Lund et al., 2020). According to recent data, more than half of U.S. firms encounter some type of supply chain disruption annually, attributable to either environmental conditions or sociopolitical factors (Katsaliaki et al., 2021). In particular, the National Oceanic and Atmospheric Administration (NOAA) documents a rise in climate-related disasters in the U.S., from an average of 2.7 events per year in the 1980s to 10.5 events per year in the 2010s. Concurrently, human-induced factors such as trade tariffs, Brexit implications, the Syrian civil war, the invasion of Ukraine, and the COVID-19 pandemic are additional catalysts for supply chain disruptions (Katsaliaki et al., 2021). These volatile dynamics bring forth calls for intensified research efforts to identify strategies that enhance supply chain resilience in the face of such disruptions (Wieland et al., 2023).

Our study aims to utilize metaphorical transfer to identify new principles that offer insightful perspectives into supply chain resilience while also corroborating established conceptualizations. In the domains of operations management and supply chain management (OM/SCM), metaphors are often casually invoked to describe complex phenomena (Chen et al., 2013; Foropon & McLachlin, 2013). These metaphors associate a familiar concept with a more complex one, thereby leveraging our understanding of the familiar one to enhance our grasp of the complex one (Cornelissen et al., 2005; Lakoff & Johnson, 1980; Morgan, 1980) Examples of casual metaphors in OM/SCM include likening operations strategy to a machine (Boyer & Lewis, 2002), comparing factories to biological cells (Demeester et al., 2003), describing high-contact service delivery as jazz improvisation (Secchi et al., 2019), and viewing strategies of operations executives through the lens of football teams or bicycle racers (Vaid et al., 2021).

Although metaphors employed casually can facilitate initial comprehension and generate mental imagery, they can also introduce ambiguities by blurring the boundaries between literal and theoretical interpretation (Ramsay, 2004). This issue became particularly salient during the COVID-19 pandemic when supply chains were metaphorically characterized as ‘ecosystems’ (Ivanov & Dolgui, 2020) and ‘networks’ (Shen & Sun, 2023), underscoring their interconnected nature. Such metaphors, however, risk oversimplifying complex dynamics (Taber, 2007) such as power imbalances and competitive tensions among stakeholders. Comprehending the intricacies in supply chain dynamics is vital for scholars aiming to enhance theoretical developments in the OM/SCM fields. Thus, the systematic application of metaphors via formal methods such as metaphorical transfer is appropriate. Chen et al. (2013) exemplify this method by likening “strategic buyer-supplier relationship dissolution” to “divorce.” In our study, we employ metaphorical transfer to deepen the theoretical understanding of supply chain resilience, capturing the

dynamism, efficiency, and control that are inherent in supply chains.

Drawing from Holling (1996), we propose the endotherm—a group of animals that includes mammals, birds, and certain reptiles such as the leatherback sea turtle (Grigg et al., 2004)—as an exemplar of naturally occurring resilience, which we call endotherm resilience, that is conceptually transferable to supply chains. Endotherms exhibit endotherm resilience through their maintenance and regulation of internal body temperature, thus demonstrating the dynamism, efficiency, and control observed in supply chains. By selecting endotherm resilience as our exemplar, we present a tangible illustration of resilience that effectively counters criticisms concerning the application of ecological concepts to economic systems (Davoudi, 2012). Such criticism centers on the lack of mechanisms for efficiency and control in natural ecosystems.

By adopting endotherm resilience as a metaphorical lens, our objective is to glean and transpose insights and principles to deepen our understanding of supply chain resilience. This approach aligns with the perspectives of eminent scholars in the field, such as Wieland and Durach (2021) and Stephens et al. (2022), who advocate for the integration of conceptual insights derived from biological resilience to enrich the analysis of resilience strategies in socio-economic systems. This metaphorical interplay, thus, not only fosters a richer understanding of socio-economic resilience but also opens avenues for innovative strategies in managing supply chain dynamics (Stephens et al., 2022).Our work brings clarity to the use of 'ecological resilience' in supply chain literature. Although this concept is commonly mentioned, it is often invoked, without specifying which ecosystems are being discussed. Our contribution precisely addresses this gap by directly aligning the sophisticated thermoregulatory capabilities of endotherms, which allow for remarkable adaptability in fluctuating environments, with attributes applicable to resilient supply chains. In doing so, we provide a metaphor that meets demands for aptness, theoretical depth, and interestingness (Stephens et al., 2022), while addressing critiques regarding vague applications of ecological models to economic structures (Carpenter et al., 2001; Davoudi, 2012; Walker et al., 2006). This approach solidifies the metaphor within a well-understood biological framework while advancing supply chain strategies against disruptions and environmental uncertainties. The results of this work offer a refined, conceptually rich, and applicable model of ecological resilience for economic systems.

This paper is structured as follows: In Section 2, we outline the formal process of metaphorical transfer and its associated theoretical implications. Section 3 establishes the conceptual equivalence between endotherm resilience and supply chain resilience through metaphorical transfer, including establishing equivalence at three levels: ontology, analogy, and identity. Notably, Section 3 extrapolates theoretical principles derived from this metaphor, underscoring their relevance in the context of contemporary supply chain dynamics. At the identity level, this metaphorical transfer unveils shared theoretical foundations spanning both phenomena. In Section 4, we assess the suitability, richness, and novelty of the "supply chain

resilience as endotherm resilience" metaphor as prescribed in Stephens et al. (2022). Finally, in Section 5, we summarize our theoretical insights and offer directions for future research.

2. METAPHORICAL TRANSFER AS THEORIZING MECHANISM

Metaphorical transfer aids in understanding complex ideas by systematically comparing an abstract 'target domain' with a concrete 'source domain'(Cornelissen et al., 2005; Morgan, 1980) (Lakoff & Johnson, 2008). In the case of the endotherm resilience metaphor, endotherms regulate body temperature internally, enabling stability against environmental changes (Labocha & Hayes, 2019). Similarly, supply chain resilience is the capability to predict, adapt to, withstand, or recover from disruptions (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009; Sheffi & Rice, 2005). Here, endotherm resilience serves as the source phenomenon and supply chain resilience is the target phenomenon.

The use of metaphorical transfer in academic research bears significant merits. It assists in constructing theories from metaphors by rendering abstract concepts into tangible terms (Morgan, 1983), enhances metaphors' communicative accuracy (Thibodeau & Boroditsky, 2013), and promotes their thorough analysis (Cornelissen, 2005). Chen et al. (2013) underscore the utility of metaphorical transfer in OM/SCM research by employing the metaphor of divorce to depict strategic buyer-supplier relationship dissolution. Their study exemplifies how casually invoked metaphors can become theory-constitutive. This transformation is achieved by ensuring an equivalence between the metaphorical domain and the target phenomenon—deriving insights that rule both realms and allowing the integration of theories external to the OM/SCM domain.

In this study, we implement a two-step approach, initially evaluating the potential effectiveness of the metaphor and subsequently establishing metaphorical equivalence. The first step concerns evaluating the metaphor for its aptness, theoretical richness, and interestingness. The second step concentrates on affirming the metaphorical equivalence across three hierarchical levels—ontology, analogy, and identity, following the structure proposed by Chen et al. (2013) and others (Garud & Kotha, 1994; Tsoukas, 1991).

3. EVALUATING "ENDOTHERM RESILIENCE" AS A SOURCE DOMAIN FOR SUPPLY CHAIN RESILIENCE

Before employing metaphorical transfer, it is crucial to assess the metaphor's potential for contributing to theoretical development. Specifically, we evaluate the suitability, depth, and originality of using endotherm resilience as a metaphor for understanding the principles of supply chain resilience, following the approach outlined by Stephens et al. (2022). This process involves critical evaluation of the metaphor based on three criteria: aptness, theoretical richness, and interestingness (Stephens et al., 2022). Aptness refers to the metaphor's credibility and plausibility; absent this, the metaphor could lead to empirical inconsistencies

(Cornelissen, 2017; Stephens et al., 2022). Theoretical richness gauges the extent to which the metaphor brings a wide range of concepts, models, and theories from the source domain to the target, thereby ensuring a substantial contribution to the theoretical framework (Hunt & Menon, 1995). The criterion of interestingness evaluates the metaphor's potential to generate new and innovative hypotheses by exploring both similarities and differences between the source and target phenomena (Cornelissen, 2017; Hunt & Menon, 1995; Stephens et al., 2022). This process is shown in **Figure 1**.

3.1. Aptness: Is the source domain plausible?

In academic theorizing, metaphors derive their significance partly from *aptness*—the degree to which they represent empirical phenomena (Cornelissen, 2002). This criterion holds considerable weight in the nuanced realm of supply chain resilience, an area of ongoing scholarly exploration (Babaei et al., 2023; Karbassi Yazdi et al., 2023). Traditional interpretations of supply chain resilience tend to be considered through an engineering lens, with supply chains viewed as systems reverting to equilibrium post-disruption (Wieland & Durach, 2021). However, recent perspectives gravitate toward an ecological resilience model that contemplates multiple potential equilibria following disturbances (Pettit et al., 2010; Wieland & Durach, 2021).

Drawing parallels between natural ecosystems, such as forests and lakes, and socio-economic constructs like supply chains can present challenges. Namely, defining aspects of economic systems, including managerial control and pursuit of efficiency, are markedly absent from conventionally conceived natural ecosystems (Davoudi, 2012). Given this conceptual distance, a need for a nuanced metaphor that captures the distinct intricacies of supply chain dynamics arises. Accordingly, Holling (1996) introduces the endotherm—a specialized ecological subset—as a metaphor congruent with the control and efficiency-seeking hallmarks of supply chains. Endotherms epitomize resilience through their precise regulation of internal temperature. For instance, humans typically maintain a temperature of 97–99°F through a synergy of mechanisms—sensory input, central nervous system orchestration, and muscular and glandular responses (Osilla et al., 2018). This thermoregulatory system endows endotherms with a distinct type of resilience that we call ‘endotherm resilience,’ which fortifies them against environmental fluctuations.

With this backdrop, we champion endotherm resilience as a fitting metaphor for supply chain resilience—portraying both as dynamic and adaptive systems. After dissecting the equivalences in this metaphor in Section 3—spanning ontology, analogy, and identity—we underscore its potential in predicting supply chain dynamics (Stephens et al., 2022).

3.2. Richness: Is the source domain theoretically rich?

To facilitate robust research into supply chain resilience, the endotherm resilience metaphor must be *theoretically rich,* meaning it must be supported by a well-developed body of knowledge (Hunt & Menon, 1993, 1995). The richness of a source domain can be assessed through the variety and number of concepts,

models, and theories that offer useful extrapolations to the target of the metaphor (Stephens et al., 2022). In essence, the concepts and theories from the source domain should enrich understanding and predictive capabilities in the target phenomenon (i.e., supply chain resilience).

In this case, the extensive literature on endotherms provides valuable insights into the systems and mechanisms governing their survival and functionality. Diverse theories inform researchers about their origins, thermoregulatory processes, metabolic functions, reproductive patterns, and more (Grigg et al., 2004). The richness of the source phenomenon is further emphasized by the nuanced inclusion of certain ectotherm species like sharks and turtles, which exhibit endotherm characteristics that provide obvious evolutionary advantages (Grigg et al., 2004). Based on this vast body of empirical evidence, endotherm resilience satisfies the criterion of theoretical richness, offering fertile ground for academic exploration.

3.3. Interestingness: Does the source domain bring forth novel insights?

Interestingness in a source domain like endotherm resilience catalyzes the generation of innovative perspectives in the metaphor target (i.e., supply chain resilience). A metaphor can be interesting due to its ability to demonstrate similarity or dissimilarity, in the latter case by encouraging researchers to "rearrange their view of the target phenomenon, which may lead to new insights" (Stephens et al., 2022, p. 129). Intriguing metaphors can spark counterintuitive theories that challenge established assumptions, adding to their interestingness (Stephens et al., 2022).

Productive metaphors are interesting, in part, due to their dissonance (Cornelissen, 2006; Oswick et al., 2011). For instance, in the juxtaposition between supply chains and endotherms, the former represents networks of interrelated entities whereas the latter are singular organisms. Notably, supply chains operate as social constructs rather than living systems, underscoring the inherent difference (Wieland et al., 2023). Stephens et al. (2022) describe this divergence as the "distance between domains," with the allure of the metaphor being positively related to the magnitude of the distance. Despite overt physical differences, the resilience traits in endotherms have conceptual parallels with supply chain systems. For instance, endotherm resilience characteristics permit multiple equilibria and functional states, thereby contesting the traditional engineering perspective of supply chain resilience as a singular equilibrium and operational state (Holling, 1996). Recent OM/SCM studies reflect such a paradigm shift toward describing supply chain resilience through the multi-equilibria ecological lens (e.g., Adobor & McMullen, 2018; Ponomarov, 2012; Wieland & Durach, 2021), with the endotherm serving as a novel exemplar. Accordingly, we deem the metaphor sufficiently stimulating for further theory development.

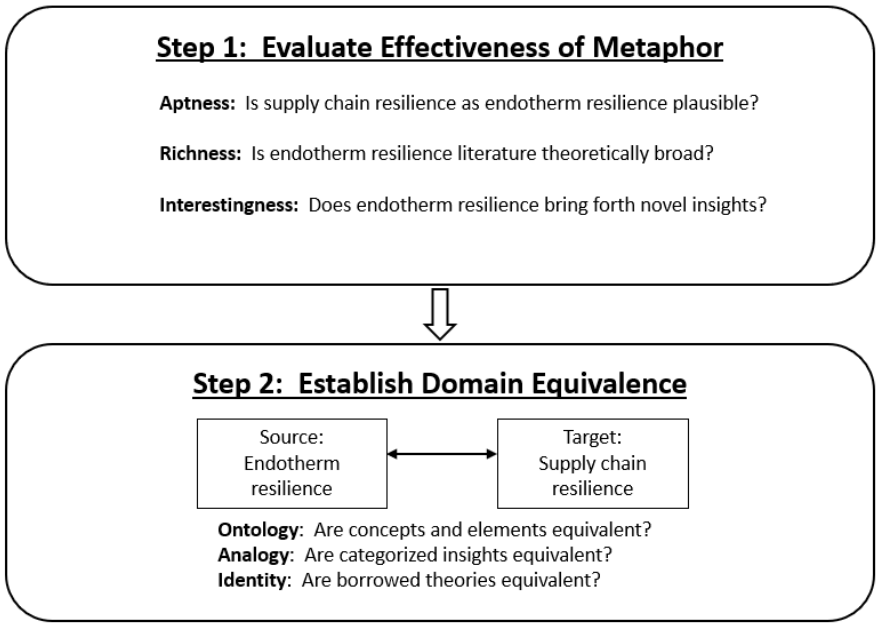

FIGURE 1. Two-step process for formal metaphorical transfer.

Metaphors do not represent complete correspondence between the domains they connect (Lakoff & Johnson, 1980). As such, the metaphorical transfer should not fixate on perfect symmetry between the source and target domains (Keil, 1986). The objective is to extract meaningful insights while recognizing and accepting inherent boundaries and limitations (Ramsay, 2004). For example, diverse interpretations of supply chain relationships, compared at times to both friendships and marriages, reflect the broad spectrum of perspectives available (Golicic et al., 2003; Sheppard & Sherman, 1998).

4. DEMONSTRATING EQUIVALENCE BETWEEN ENDOTHERM RESILIENCE AND SUPPLY CHAIN RESILIENCE

In this section, we report the formal metaphorical transfer procedure for the "supply chain resilience as endotherm resilience" metaphor. The procedure entails evaluating the source (endotherm resilience) and target (supply chain resilience) at three levels of equivalence: *ontology*, *analogy*, and *identity* (Chen et al., 2013; Tsoukas, 1991). At the ontology level, we delineate and juxtapose the core components that characterize both endotherm and supply chain resilience. Equivalence at the analogy level involves linking like relationships across the domains, while correspondence at the identity level culminates in generalizable principles.

4.1. Equivalence at the level of ontology

Ontology is the first level of equivalence, capturing the conceptual congruence between fundamental elements of source and target phenomena (Chen et al., 2013; Tsoukas, 1991). These elements, the "what"

as termed by Whetten (1989), form the foundation of the theory underlying a given phenomenon. **FIGURE 2** illustrates equivalence at the level of ontology through the example of *functional redundancy*, a core element in the respective domains. In endotherm resilience, functional redundancy (a_1) manifests as a set of overlapping systems—sweating and shivering, vasoconstriction and vasodilation, hair, and heart functionality—which contribute to thermoregulation. Each contributes to body temperature maintenance specifically and endotherm resilience more broadly, in cooperation with the others. In supply chain resilience, functional redundancy (b_1) consists of optionality (alternatives) consisting of redundant (multiple) suppliers, routing options, and multiple production sites either individually or in concert with one another.

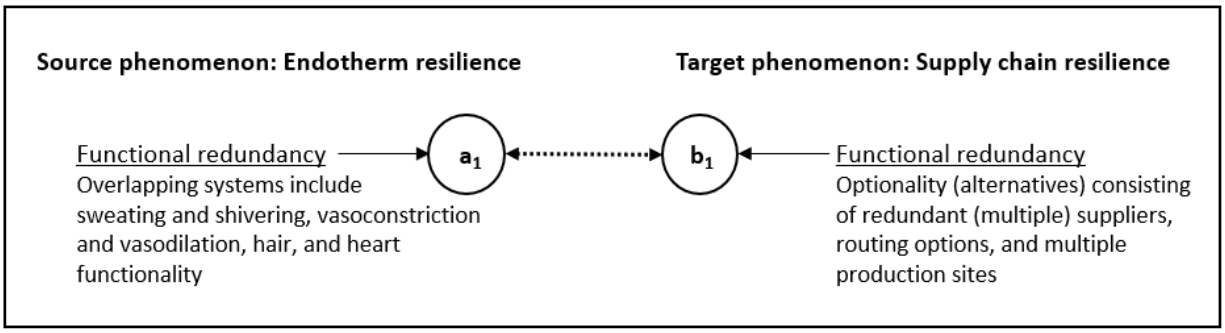

FIGURE 2. Example of equivalence at level of ontology.

As a second illustration, the *centralized signaling system* in endotherm resilience involves the central nervous system (a_3) which integrates sensory cues from the neural warning system (a_4) and emits messages through the neural emitting system (a_5) to modulate thermal states. This is conceptually analogous to a centralized information management system in supply chain resilience (b_3), which coordinates supply chain activities by receiving and disseminating information (Böcker & Hanf, 2000). The *system alert mechanisms* for supply chain resilience also include predictive and real-time warning systems, consisting of devices (e.g., IoT devices) or mechanisms (e.g., data analytics) for sensing and transmitting relevant information (b_4). Supply chain resilience includes managerial *directives to act* via decision implementation systems and outgoing messages for supply chain entities to act upon (b_5). Thus, the three core ontological elements—*centralized signaling system*, *system alert mechanisms*, and *directives to act*—are mutually prevalent in both endotherm resilience and supply chain resilience, substantiating the metaphorical congruence between the two (Chen et al., 2013; Hunt & Menon, 1995).

In examining the adaptive systems that bolster supply chain functionality during disruptions, we find similarities with the endotherm's homeostatic mechanisms. These include *long-term resource reserves*, *short-term deployable resources*, and *goal pursuit* for survival (endotherms) or satisfying stakeholders (supply chains). A dominant or influential focal firm in the supply chain can be equated to the endotherm

hypothalamus in terms of powerful *central command and control* and *data interpretation and analysis*. The supply chain's external business environment can be likened to the endotherm's external natural environment, both functioning in their *environmental conditions* and *within a defined boundary*.

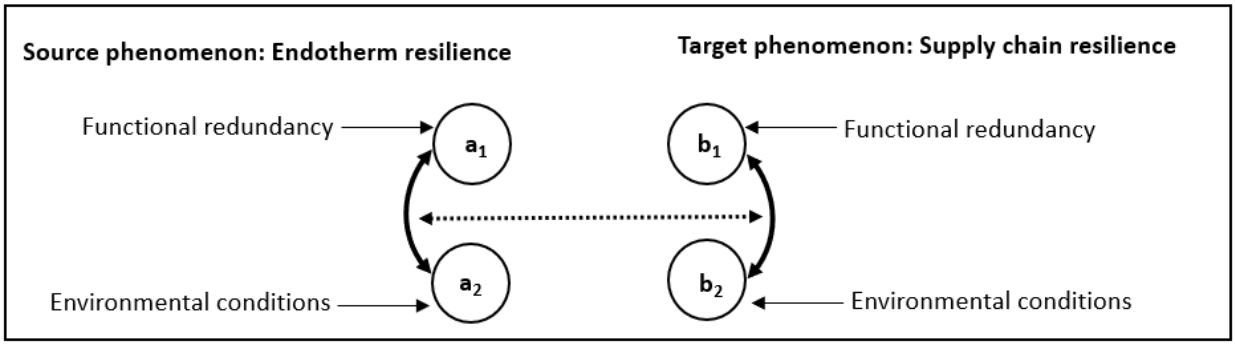

FIGURE 3. Equivalence at the level of analogy.

summarizes the one-to-one mapping between ontological elements of endotherm resilience and supply chain resilience. We conclude that the coordinated systems and mechanisms that allow endotherms to maintain stable internal body temperature exhibit abstract equivalence to the control and coordination within supply chains, and thus demonstrate equivalence at the level of ontology.

TABLE 1. Equivalence at the level of ontology: Endotherm resilience and supply chain resilience.

Endotherm Resilience as Source Phenomenon		**Shared conceptual foundation**		**Supply Chain Resilience as Target Phenomenon**
Overlapping systems include sweating and shivering, vasoconstriction and vasodilation, hair, and heart functionality	(a_1)	*Functional redundancy*	(b_1)	Optionality (alternatives) consisting of redundant (multiple) suppliers, routing options, and multiple production sites, and the like
External environment (temperature and weather)	(a_2)	*Environmental conditions*	(b_2)	External environment (market volatility, competitive landscape, geopolitical issues)
Central nervous system (CNS)	(a_3)	*Centralized signaling system*	(b_3)	Information management system (ERP, OM/SCM tools)
Neural warning system (sensory input to CNS)	(a_4)	*System alert mechanisms*	(b_4)	Predictive and real-time warning system (IoT devices, data analytics)
Neural emitting system (CNS messaging to muscles and glands)	(a_5)	*Directives to act*	(b_5)	Decision implementation system (managerial directives)
Defined spatial boundary (skin)	(a_6)	*Defined boundary*	(b_6)	Operational boundary (contracts, supply agreements, supply chain mapping)
Energy stores (fats)	(a_7)	*Long-term resource reserves*	(b_7)	Strategic reserves (cash reserves, inventory reserves, capacity reserves)
Immediate energy source (glucose)	(a_8)	*Short-term deployable resources*	(b_8)	On-demand resources (cross-trained personnel, versatile machinery, on-hand inventory)

Energy used to support metabolism (proteins)	(a_9)	*Growth and maintenance resources*	(b_9)	Operational and strategic resources (employee skills, technology, supplier relationships)
Sensory input analysis (brain function)	(a_{10})	*Data interpretation and analysis*	(b_{10})	Data analytics (Business Intelligence tools)
Purposeful goal to survive	(a_{11})	*Goal pursuit*	(b_{11})	Business goal (ensure business continuity and stakeholder satisfaction)
Central control (hypothalamus)	(a_{12})	*Central coordination and control*	(b_{12})	Central coordination and control (focal firm)

Note: Table 1 format is similar to Chen et al. (2013).

4.2. Equivalence at the level of analogy

Equivalence at the level of analogy serves as an advanced correspondence linking relationships within each domain's constituent elements, for example, $a_1 \leftrightarrow a_2$ in the source phenomenon and $b_1 \leftrightarrow b_2$ in the target phenomenon.

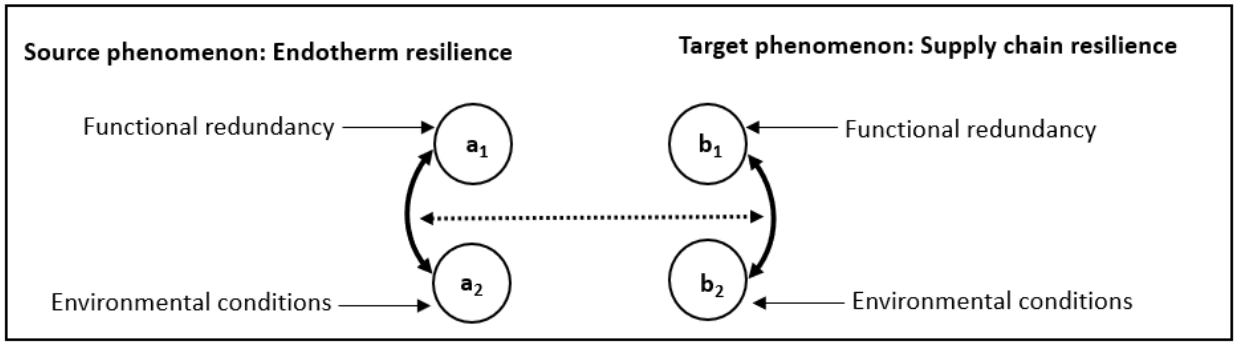

FIGURE 3 depicts an analogical relationship between endotherm resilience and supply chain resilience, namely the parallel relationships between *functional redundancy* and *environmental conditions*. In the endotherm, overlapping systems (a_1) respond to variations in environmental conditions (a_2) such as changes in temperature, weather, season, or climate. This adaptability enables endotherms to thrive across diverse geographical and climatic conditions. Analogously, supply chain functional redundancy (i.e., optionality) (b_1) supports continuity to operate within a range of business environmental conditions (b_2) including disruptions such as loss of a supplier, delayed deliveries, or shifting customer preferences. Showing this parallel across the two domains substantiates the notion of equivalence at the level of analogy.

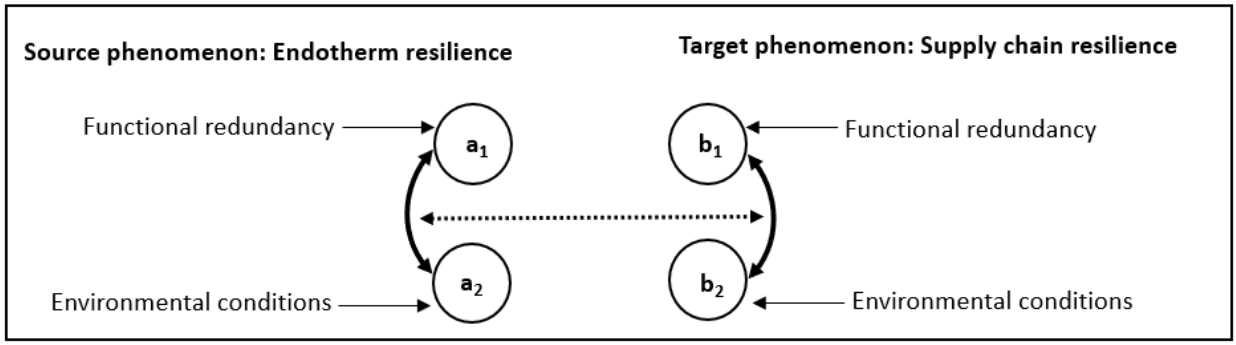

FIGURE 3. Equivalence at the level of analogy.

Another illustration is the relationship between the *centralized signaling system* and *system alert mechanisms*. In endotherms, the central nervous system (a_3) receives alerts from the neural warning system that senses changes in external temperature (a_4). Supply chain resilience and the capability to respond to disruptions are dependent on warning systems (b_4) that are supported by supply chain visibility and data transmissions from real-time signals to supply chain members through a centralized information system (b_3). For instance, food supply chains employ technologies like smartphones or RFID networks for real-time tracking of critical events affecting food perishability (Alfian et al., 2017). Just as endotherms can sense even small environmental temperature changes, supply chains with visibility and scanning systems in place can detect changes in real time. Equivalence at the level of analogy is thus confirmed as both endotherms and supply chains demonstrate similar causal interplay between their respective elements. Equivalence at the level of analogy confirms that, in addition to *looking like* the source phenomenon (ontological equivalence), the target phenomenon *behaves* like the source phenomenon (Chen et al., 2013; Hunt & Menon, 1995).

Given the 12 ontological elements of endotherm resilience and supply chain resilience reported in **Table 1**, the possible number of relationship combinations is 4147. Achieving precise equivalence among relationships involving these elements is thus understandably impractical. Alternatively, as proposed by Garud and Kotha (1994), these lower-level relationships among ontological elements can be succinctly encompassed by carefully selected higher-level categorizations. For our exploration, *System Design*, *Adaptive Response*, *Resource Management*, *Information Processing*, and *Purpose and Boundaries* serve as these categorizations. Equivalence at the level of analogy for endotherm resilience and supply chain resilience is established by demonstrating congruence to these five aspects, which we describe in detail.

4.2.1. System Design aspect

The *System Design* aspect involves system design and complexity, and subsumes ontological elements that pertain to functional redundancy, environmental adaptability, and centralized coordination.

Endotherm perspective. Endotherms such as mammals and birds exhibit functional redundancy

through systems like sweating and shivering, or vasoconstriction and vasodilation to regulate body temperature (a_1) (McGlone & Spence, 2010). Continuous adjustment to external environmental conditions, including a broad range of temperatures (a_2), is coordinated by the central nervous system (a_3) (Jablonski, 2017).

Supply chain perspective. Modern supply chains establish functional redundancy by creating and maintaining optionality, demonstrated through the strategic placement of hubs, nodes, and redundant suppliers (b_1) (Choi et al., 2001; Doukidis et al., 2020). Supply chains operate within complex business environments that necessitate response to environmental factors such as market volatility or geopolitical issues (b_2). Centralized information management systems, including ERP and SCM tools, are utilized to enable coordinated responses (b_3) (Qi et al., 2009).

4.2.2. Adaptive Response aspect

The *Adaptive Response* aspect involves changes made in response to external stimuli and encapsulates ontology elements linked to system alert mechanisms, directives to act, and central coordination and control.

Endotherm perspective. Endotherms adapt to their habitats by developing mechanisms, e.g., fur thickening in colder regions or fur thinning in warm regions (Jablonski, 2017). Their neural warning system transmits sensory input to the central nervous system (a_4), and subsequent directives to muscles and glands (a_5) ensure survival. The hypothalamus plays a pivotal role in central coordination and control (a_{12}), directing a variety of system mechanisms.

Supply chain perspective. Supply chains enact changes in response to alerts from real-time warning systems (b_4) (Cachon & Olivares, 2010). Once alerted, managerial directives (b_5) can be swiftly implemented. A supply chain focal firm can serve the role of central coordination (b_{12}). Several studies substantiate this conceptualization of central control in supply chains. Crook and Combs (2007) suggest that supply chain leaders determine power dynamics by controlling crucial resources, whereas Huo et al. (2017) conceptualize power configurations that drive operational performance. Bhardwaj and Ketokivi (2021) describe bilateral dependency and cooperation in reinforcing the leader's role as enforcer. Moreover, Wilhelm and Villena (2021) demonstrate the leader's influence on sustainable practices, and Wang et al. (2023) highlight the leader's influence on smaller firms' resilience initiatives.

4.2.3. Resource Management aspect

The *Resource Management* aspect involves the pursuit of operations efficiency and includes ontology elements concerning long-term resource reserves, short-term deployable resources, and growth and maintenance resources.

Endotherm perspective. Efficiently balancing consumption with energy conservation, endotherms use fats as long-term energy reserves (a_7), glucose for immediate energy needs (a_8), and proteins for ongoing

metabolic processes (a_9) (Hill et al., 2021).

Supply chain perspective. Supply chains maintain strategic reserves such as cash, inventory, and capacity (b_7). They also harness on-demand resources such as cross-trained personnel and flexible equipment (b_8), and deploy operational and strategic resources like technology and supplier relationships when needed (b_9) (Knight, 2022).

4.2.4. Information Processing aspect

The *Information Processing* aspect involves the use of information to support decision-making. This pertains to ontology elements of data interpretation and analysis, system alert mechanisms, and directives to act.

Endotherm perspective. Demonstrating ability in sensory information processing, endotherms leverage inputs for navigation, foraging, or threat avoidance (a_{10}) (Osilla et al., 2018). With their neural warning system as their alert mechanism (a_4), directives to act can very swiftly follow the interpretation of sensory inputs (a_5) (Osilla et al., 2018).

Supply chain perspective. Supply chains operationalize data analytics by leveraging analytics tools for interpreting diverse and extensive data sets (b_{10}). Integrated with predictive and real-time warning systems (b_4), data analytics support rapid decision-making followed by managerial directives (b_5) (Qi et al., 2009).

4.2.5. Purpose and Boundaries aspect

The *Purpose and Boundaries* aspect focuses on ontology elements surrounding goal pursuit, defined boundaries, and resource management for growth.

Endotherm perspective. All species, endotherms included, function with the purposeful goal of survival and propagation (a_{11}) while maintaining ecological existence within defined spatial boundaries (a_6), with these being interspersed with phases of growth (and decline) (Noble & Noble, 2023)

Supply chain perspective. Mirroring these characteristics in the ontology elements, supply chains strive for continuity or survival, while accounting for potential interests in growth and stakeholder satisfaction (b_{11}). Despite these interests, the supply chain may be bound by legalities such as contracts and supply agreements (b_6). Often balancing expansion and consolidation, they must effectively manage resources to ensure sustainable growth (Wu & Pagell, 2011).

4.3. Equivalence at the level of identity

Continuing the methodological process of metaphorical transfer, we next address equivalence at the level of identity by emerging nine principles that apply equally to the source and the target phenomena (Chen et al., 2013).

4.3.1. Operating near the edge of instability

Principle 1**.** For any given endotherm or supply chain, operating near the edge of instability enhances resilience**.**

This principle asserts that resilience, whether for an endotherm or supply chain, is enhanced when navigating within unstable conditions, specifically at the "edge of instability" (Holling, 1996, p. 41). This conceptualization posits that optimal adaptability, innovation, and responsiveness are not fostered in a purely stable environment; rather, they develop and thrive under conditions teetering toward chaos (Pascale, 1999). Supply chains operating in this zone of instability will more quickly adapt to changes, seize emerging opportunities, and enhance overall resilience against unforeseen events, thus demonstrating agility to maintain a competitive advantage in rapidly evolving markets (Kocabasoglu-Hillmer et al., 2023).

This principle encompasses the analogy aspects of *System Design, Adaptive Response, Resource Management, Information Processing,* and *Purpose and Boundaries.* These aspects collectively reflect an intricate balance between stability and adaptability. Endotherms exemplify this by surviving and maintaining homeostasis amidst severely adverse conditions, exposing them to stress which may in fact enhance their resilience and longevity (Epel & Lithgow, 2014). In supply chains, these aspects translate into design complexities, adaptive strategies, and information management that jointly uphold a state of controlled instability while relying on agility and responsiveness. This delicate state that exists between order and disorder requires systems—whether ecological, social, or organizational—that contribute toward developing capabilities that are responsive to external changes, thereby enabling timely and pertinent adjustments (Holling, 1996).

Endotherm equivalence. Holling (1996) identifies a paradox: engineering resilience models, which prioritize control and efficiency, may produce short-term operational consistency but ultimately result in rigid, slow-to-adapt management structures. The endotherm metabolic process serves as a metaphorical counterpoint to this paradox. Endotherms are notable for maintaining physiological homeostasis despite environmental fluctuations. They maintain internal body temperature within a very narrow range, achieved through metabolic processes that can ramp up to 5–10 times their base rate (Labocha & Hayes, 2019). This relatively precise regulation, however, situates endotherms at the edge of instability in which even minor internal temperature fluctuations can trigger severe health crises such as hypothermia or heatstroke (Yildiz et al., 2020). Diverse mechanisms are utilized for internal temperature regulation, each employed over particular ranges and with varying efficiencies. This redundancy from overlapping systems results in a system that is both robust and sensitive to changes. Despite the risk to survival, endotherms exposed to extreme conditions appear to benefit in terms of metabolic resilience and longevity (Epel & Lithgow, 2014; Rattan, 2008). Animal studies (including human studies) record such benefits from cold exposure (e.g., ice bath), heat exposure (e.g., sauna), and intermittent fasting (Rattan, 2008).

Supply chain equivalence. From an engineering perspective, maintaining a system near the edge of instability might initially seem to deviate from conventional wisdom (Holling, 1996). However, there is precedent within the engineering discipline that affirms the efficacy of this approach. In aeronautical

engineering, high-performance aircraft jet engines are intentionally designed to operate perilously close to thresholds that might induce failure (Saxena et al., 2008). Functionality is sustained via intricate, layered control systems, underscoring the principle of balancing on the cusp of instability for optimized performance and safety. We consider the broader applicability of this aspect of system design and complexity. Holling's (1996) notion of operating on the edge of instability finds a parallel in Pascale's argument for operating supply chains on the "edge of chaos" (1999). This suggests a pivotal reconceptualization, namely the amalgamation of dynamic equilibrium and instability to inform a more resilient supply chain strategy.

Contrary to paradigms that champion static equilibrium in systems (Sheffi, 2005; Wieland & Durach, 2021), the concept of operating on the edge of instability accentuates a viewpoint capturing the resilience-building value of endotherm resilience. This principle is illustrated when a buyer switches from a single supplier to multiple suppliers, thereby increasing both the complexity and volatility of the supply chain (Kocabasoglu-Hillmer et al., 2023; Li et al., 2023). Additionally, the contemporary shift toward near-shoring to gain more control of the supply chain, catalyzed by recent disruptions, inadvertently feeds the possibility of unforeseen counter-reactions that may lead to system rigidity and, ultimately, less resilience. Supply chain modeling has traditionally been driven by the engineering view where the aim was to achieve a static optimal equilibrium (i.e., seeking a singular perfect balance). However, adopting a perspective for operating on the edge of instability acknowledges that supply chains are ever-evolving, influenced by factors that include changes in demand or technologies. The edge of instability view likens managing the supply chain to balancing on a moving platform, emphasizing adaptability. Notably, Kocabasoglu-Hillmer et al. (2023) apply paradox theory to highlight the significance of balancing stability and change in addressing modern supply chain complexities.

4.3.2. Sequential resource utilization

Principle 2**.** For any given supply chain, sequentially structured resource allocation aligned with the duration of disruptions enhances its resilience.

This principle integrates the analogy aspects of *System Design, Resource Management,* and *Information Processing.* These aspects reflect, respectively, the hierarchical organization of resources, the balance between consumption and conservation, and the data-driven decision-making necessary for sequentially allocating resources during disruptions. Endotherms hierarchically and sequentially deploy energy sources—from proteins to fats—in response to varying demands (Hill et al., 2021). Supply chains can employ a multilayered strategic blueprint for fortifying supply chain resilience through tiered and sequential allocation of resources. Initial responses to disruption begin with utilization of operational and strategic resources for maintaining standard operations. As disruptions persist, deployment of on-demand reserves addresses short-term disruptions. For moderate disturbances, tactical assets are employed, while strategic reserves are preserved for severe, prolonged disruptions (Jüttner & Maklan, 2011). This structured approach

ensures control, agility, and stability in response to disruptions, optimizing resource utilization and bolstering supply chain resilience (Jüttner & Maklan, 2011).

Endotherm equivalence. This principle finds a conceptual foundation in the energy sources utilized by endotherms, where proteins, glucose, glycogen, and fat serve as sequentially leveraged energy substrates (Hill et al., 2021). Proteins fuel routine metabolic activities, whereas glucose acts as a rapid energy source during acute energy needs. Glycogen serves as an intermediate reserve, mobilized during sustained exertion, and fat functions as a long-term energy store for extended periods of scarcity (Hill et al., 2021). These four energy sources are utilized by the endotherm in a manner that is both hierarchical and sequential.

Supply chain equivalence. This principle translates to operational and strategic resource deployment for supply chain disruptions. Initially, "growth and maintenance resources" (see

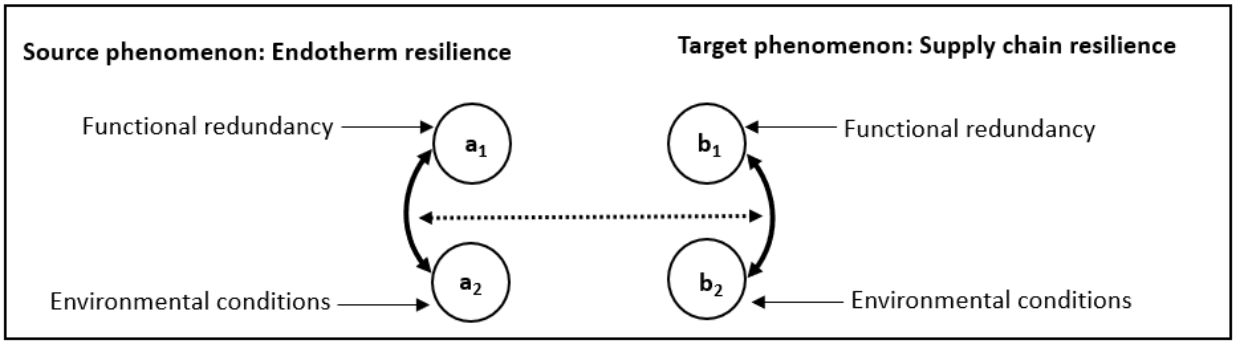

FIGURE 3. Equivalence at the level of analogy.

) can be utilized for immediate needs to continue operations during disruption. Subsequently, flexible on-demand resources like cross-trained employees, multipurpose equipment, and available inventory are deployed to ensure medium-term operational continuity. Ultimately, strategic reserves are activated for enduring high-impact, low-frequency disruptions. These reserves may include excess capacity, inventory reserves, and financial buffers (Zhao et al., 2019).

The 2011 Fukushima disaster serves as an instructive case study of how some firms sequentially activated resources to mitigate supply chain disruptions (Jüttner & Maklan, 2011). Initial resilience was afforded by mobilizing operational and strategic resources such as workforce skills, technological frameworks, and stakeholder relationships. As disruptions escalated, flexible on-demand resources like versatile machinery and inventory were engaged (Blackhurst et al., 2011). As the disruption continued over a prolonged period, tactical reserves such as alternative suppliers and temporary surges in production capacity were activated. Finally, in the face of extensive and ongoing disruption, firms drew on strategic reserves, including cash reserves, surplus inventory, and spare production capacity to ensure business continuity (Jüttner & Maklan, 2011).

More recently, microchip shortages highlight the complex vulnerabilities affecting multiple industries, from automotive to electronics (Knight, 2022). The situation, exacerbated by increased demand, geopolitical tensions, and supply chain bottlenecks, shows the pressing need for strategically layered resource management. Ad-hoc crisis-driven strategies—akin to the frenzied hoarding of toilet paper during the early days of the pandemic (Knight, 2022)—underlie a significant lesson: the value of preplanned, hierarchical, and sequential resource allocation.

4.3.3. Proportionate response

Principle 3. For any given endotherm supply chain, aligning the intensity of response with the magnitude of a disruption enhances resilience [1]

This principle offers an adaptive framework for enhancing supply chain resilience. Responses should be meticulously scaled to the magnitude of disruptions by judiciously balancing flexibility and stability. Through this calibrated approach, organizations can improve their resilience to navigate the landscape of supply chain disruptions more effectively. The principle subsumes the analogy aspects of *Adaptive Response, Resource Management,* and *Information Processing*. These aspects highlight the alert mechanisms and action directives used to adjust to changing scenarios, the balance between conservation and consumption of resources in response to disruption, and the importance of data interpretation in guiding these responses. Specifically, the principle asserts that supply chain resilience is enhanced when the intensity and nature of responses are tailored to the disruption magnitude. This mirrors endotherm adaptive strategies—ranging from minor metabolic changes to hibernation—in reaction to external stimuli (Labocha & Hayes, 2019). For supply chains, minor disruptions necessitate measured responses, whereas severe events can prompt extensive overhauls (Ellis et al., 2010; Thibodeau, 2017), echoing the depth and scale of responses seen in endotherms. By emphasizing reaction proportionality, the principle underscores the importance of matching response to disruption scale.

Endotherm equivalence. Endotherms maintain internal stability in response to external perturbations through both incremental adjustments and profound adaptations (Ruf & Geiser, 2015). This includes utilizing minor metabolic system changes or behavioral adjustments when small responses suffice (Frappell & Butler, 2004). Significant metabolic alterations or physiological transformations may be needed to enact a moderate response (Ruf & Geiser, 2015). During extreme conditions, endotherms may enter a state of hibernation (Labocha & Hayes, 2019).

Supply chain equivalence. The Proportionate Response Principle emphasizes actions aligned with the magnitude of the disruption. Minor disruptions warrant mild corrective measures, which are responses

[1] Notably, although this principle shares some conceptual similarities with the Sequential Resource Utilization Principle, it additionally specifies that the response to disruption should not merely follow a particular sequence but should be carefully gauged to match the disruption's scale. This principle therefore complements and extends the scope of the previous principle by layering on the proportionality of resource allocation and response mechanisms.

aimed at restoring stability. Moderate disruptions necessitate more sweeping changes, whereas major disruptions may require an operational paradigm shift and may compel a fundamental operational overhaul, analogous to the endotherm's state of hibernation (Labocha & Hayes, 2019). Severely disruptive events may require radical supply chain reconfigurations (Ellis et al., 2010; Thibodeau, 2017).

The 2014 truck drivers' strike at the ports of Los Angeles and Long Beach caused many firms to reroute shipments or shift to temporary alternative transportation modes (Gorman et al., 2014). By contrast, the monumental disruptions from the COVID-19 pandemic led to radical supply chain restructuring. Apple and Tesla, for example, diversified their supply sources during this timeframe (SinghKang et al., 2023; Xu et al., 2020). The counterbalancing effects of flexibility and stability are at play. Flexibility facilitates adaptive and proportionate responses to disruptions of varying magnitudes (Sodhi & Tang, 2012). Stability, on the other hand, involves re-establishing operational norms and preserving pre-existing supply chain configurations (Wu & Barnes, 2011). Whereas preserving and restoring were achievable in the case of the truck drivers' strike, the pandemic disruption presented starkly greater challenges.

4.3.4. Regulated collective action

Principle 4**.** For any given endotherm supply chain, balanced use of central control and emergent collective action enhances resilience.

This principle proposes a framework that emphasizes the balance between focal firm authoritative roles and collaborative capacities of other supply chain entities. By adapting insights from biological resilience within a multilevel commons framework (Chopra et al., 2021), this principle emphasizes the role of coordinated, regulated actions in mitigating supply chain vulnerabilities. Regulated collective action advocates for a balanced approach to supply chain resilience, emphasizing the harmonization between centralized oversight and the emergent actions of diverse stakeholders. This principle subsumes the analogy aspects of *System Design*, and *Information Processing*. The analogy aspect of *System Design* underscores the significance of adaptability through centralized coordination, as observed in both endotherms (Holling, 1996) and supply chains (Choi et al., 2001; McGlone & Spence, 2010). *Information Processing* accentuates the critical role of data interpretation, evident when comparing the sensory processing of endotherms (Aslam et al., 2018) with business intelligence tools leveraged in supply chains (Qi et al., 2009). Regulated Collective Action accentuates the need to synergize central governance with decentralized, informed actions to fortify supply chain resilience. Ultimately, this principle underscores the core facets of control, emergence, flexibility, and stability (Choi et al., 2001).

Endotherm equivalence. The endotherm hypothalamus provides the centralized control that regulates body temperature, both receiving and sending messages to other systems in response to environmental conditions. When external conditions such as extreme cold stress the ability to internally regulate temperature, endotherms may resort to emergent collective action, such as penguins huddling to conserve warmth (Labocha & Hayes, 2019). Huddling as a social thermoregulatory behavior reduces the need for

food intake (by 26–39%) and resting metabolism (by 36–37%) (Sukhchuluun et al., 2018). Thus, huddling is a 'low-cost' collective action that supports endotherm resilience (Gilbert et al., 2010).

Supply chain equivalence. The endotherm example demonstrates the essential role collective action plays in specific circumstances. In the supply chain context, strategies such as Collaborative Forecasting, Planning, and Replenishment (CPFR) enable firms to jointly navigate volatile market conditions (Holmström et al., 2002). However, unregulated collective action can engender problems such as free-rider issues and opportunistic behaviors (Ketokivi & Mahoney, 2020). Consequently, supply chain resilience hinges on a well-managed and balanced regulated collective action.

The balance between control and emergent collective action is exemplified in the multilevel "commons" framework introduced by Chopra et al. (2021), which guides firms on concurrently maintaining efficiency and resilience, even during disruptions. The first level of commons comprises the focal firm maintaining control and providing direction for other supply chain entities, mirroring the function of the endotherm hypothalamus. This includes the focal firm setting rules and contractual agreements with suppliers, establishing standards, and guiding operations. For instance, Walmart has stringent supplier agreements that establish clear rules for coordination and cooperation (Chopra et al., 2021).

The second level of commons emphasizes regulated collective action, fostering relationships that incentivize alignment with resilience objectives. Although retaining control, the focal firm encourages collective actions such as information sharing or joint problem-solving. Procter & Gamble's adoption of a web-based vendor-managed inventory system to facilitate real-time data sharing with worldwide suppliers serves as an example (Grossman & Shapiro, 1984). This system addresses the bullwhip effect (Croson & Donohue, 2006) and enhances overall supply chain resilience (Oliveira & Handfield, 2017; Yu et al., 2018).

The third level of commons emerges when central control by the focal firm or industry is insufficient, necessitating broader regulatory interventions (Chopra et al., 2021). Here, the role of governments or supranational bodies is crucial, creating shared platforms or legislation to enhance overall resilience. For instance, during the recent health pandemic, some governments intervened to regulate the supply of essential commodities and support logistics infrastructure. The collaborative initiative for COVID-19 vaccines for Southeast Asia by the group known as "Quad" demonstrates such a shared resource system: the U.S. and Japan contributed financing, India provided manufacturing, and Australia handled distribution logistics (Chopra et al., 2021). The role of NATO in determining weapons and supplies for the current war in Ukraine is another example.

4.3.5. Expedited response

Principle 5**.** For any given endotherm or supply chain, reducing reaction time between system alerts and directives to act enhances resilience.

This principle underscores the integration of analogy aspects of *System Design, Adaptive Response,* and *Information Processing* as vital elements for fortifying supply chain resilience. By leveraging rapid

detection and response mechanisms, supply chains with these capabilities are equipped to adapt and thrive in the face of disruptions. The facet of *System Design* underscores centralized coordination (Choi et al., 2001), akin to endotherm adaptability to shifting climates (Choi et al., 2001; McGlone & Spence, 2010). The domain of *Adaptive Response* accentuates swift disruption detection, reminiscent of endotherm adjustment mechanisms like rapid vasodilation and vasoconstriction which occur in less than one minute (McGlone & Spence, 2010), and the real-time alert mechanisms in supply chains (Cachon & Olivares, 2010). *Information Processing* in this discourse addresses data interpretation (Aslam et al., 2018)—echoing both endotherm sensory processing (Osilla et al., 2018) and supply chain utilization of business intelligence tools (Qi et al., 2009).

Endotherm equivalence. Endotherms possess highly evolved mechanisms for facilitating rapid internal temperature regulation, bestowing on them a distinctive advantage across multifarious environmental challenges (Osilla et al., 2018). Sensory input about external environment conditions almost instantly transfers to the central nervous system, which immediately sends directives to various mechanisms to begin responding. Changes in heart rate, blood pressure, and blood vessels can occur in less than one minute (McGlone & Spence, 2010), whereas other mechanisms, such as shivering and sweating, may commence more slowly.

Supply chain equivalence. The emphasis on swift responsiveness is pivotal for supply chain resilience, a sentiment echoed in pioneering works (Bode & Macdonald, 2017; Fine et al., 2002; Rungtusanatham & Johnston, 2022). Advanced monitoring systems, coupled with effective communication channels, enable rapid detection of disruptions (DuHadway et al., 2019). (Ivanov, 2022) underscores the instrumental role of real-time data analytics, digitalization, and technological advancements in rapid response capabilities. These capabilities aid supply chain managers in early disruption identification and facilitate the formulation of appropriate response strategies (Iftikhar et al., 2022). In parallel, management structures must empower supply chain managers with the authority to act (Sheffi & Rice, 2005).

Faced with abrupt demand surges for medical supplies and ventilators during the recent pandemic, some organizations reconfigured production lines and supply networks, expediting deliveries of these essential items (Shih, 2020). Developing supply chain capabilities to swiftly respond to disruptions supports such agility and responsiveness (Barhmi, 2019). Agile supply chain practices such as collaboration and rapid decision-making, akin to adaptive endotherm systems, contribute to expedited response capabilities.

4.3.6. Strategic deployment of dormancy

Principle 6. For any given endotherm or supply chain, setting the degree of dormancy to match the extent of a disruption enhances resilience.

This principle provides a practical framework for enhancing supply chain resilience. Tailoring decisions regarding dormancy to the scope of disruption empowers supply chains to fortify adaptability, setting the stage for post-disruption resurgence and ingenuity. The principle embodies the analogy aspects

of *System Design, Resource Management,* and *Information Processing*. Like endotherms utilizing a variety of dormancy states, disrupted supply chains may benefit from strategically chosen dormancy. The decision regarding supply chain dormancy depends on effectively balancing resource conservation against operational needs (Bode et al., 2011) along with interpreting situational market information to determine the appropriate depth and duration of dormancy (Qi et al., 2009).

Endotherm equivalence. Some endotherms exhibit metabolic "torpor," characterized by diminished metabolic rates and physiological slowdowns, to traverse environmental adversities (Ruf & Geiser, 2015). Two forms surface:

1. *Partial dormancy (hypometabolism):* Characterized by a temporary decrease in metabolic rate, this state permits some level of functionality. For instance, hummingbirds enter partial dormancy at night to conserve energy while maintaining basic activities (Ruf & Geiser, 2015).
2. *Complete dormancy (hibernation):* This extended state lasts for days or weeks and entails complete metabolic suppression. Bats, for example, accumulate fat reserves and enter hibernation, surviving for prolonged periods without food (Ruf & Geiser, 2015).

Supply chain equivalence. The adoption of either partial or complete dormancy in a supply chain is guided by a confluence of strategic considerations, ranging from disruption intensity and expected duration to the available resources, particularly cash reserves (Kulchania & Thomas, 2017). Supply chain decisions concerning dormancy also depend on the assessment of future capability to mobilize from a dormant to an active state (Kovács & Tatham, 2009). Importantly, the systemic implications of a disruption need to be assessed. If the disruption is industry-wide, affecting not just the individual supply chain but also its competitors, the strategic decision to enter a state of dormancy may be tied to decisions made by other entities. In this case, dormancy may provide an opportunity to conserve resources and plan for resurgence once the disruption subsides. However, if the disruption is unique to a particular supply chain and does not affect competitors, the dormancy decision must balance other strategic considerations such as resource conservation versus loss of market share. The scale of the disruption will also influence the decision, for instance, if the supply chain disruption is only partial, a state of partial dormancy may be the optimal approach.

Supply chains mirror these dormancy forms:

1. *Partial dormancy:* During the 2008 financial crisis, Ford Motor Company lowered production volumes, essentially reducing its operational pace without a full halt (Vlasic, 2009).
2. *Complete dormancy:* The COVID-19 pandemic caused sectors such as global cruise lines to suspend operations and draw on cash reserves while awaiting the opportunity to resume operations (Kamal et al., 2022).

4.3.7. Persistent adaptation

Principle 7**.** For any given endotherm or supply chain, developing increasingly sophisticated mechanisms for sensing and responding enhances resilience.

The analogy aspects of *System Design* and *Adaptive Response* underlie persistent adaptation*. System Design is* exemplified by both endotherms (Holling, 1996) and supply chains (McGlone & Spence, 2010) leveraging functional redundancy and centralized coordination for adaptability. This principle is also related to *Adaptive Response*, where endotherms have developed a variety of sophisticated mechanisms for advancing their likelihood of survival, and supply chains may be similarly impacted via co-evolving networks (Ivanov & Dolgui, 2020).

Endotherm equivalence. The transition from ectothermy to endothermy stands out as a paramount example of persistent adaptation. This evolutionary shift provided crucial adaptive advantages such as resilience against cold temperatures through sustained metabolic activity. This adaptation includes innovations like fur insulation, a four-chambered heart, and efficient oxygen transport systems (Frappell & Butler, 2004). In addition to the specific mechanisms of complex organ systems, adaptive behaviors like hibernating and sophisticated social behaviors such as huddling contribute to endotherm resilience (Labocha & Hayes, 2019).

Supply chain equivalence. Drawing from this biological metaphor, supply chains similarly evolve by developing and integrating advanced mechanisms, progressively moving from reactivity to proactivity in the face of challenges. This includes adopting real-time tracking (Gunasekaran et al., 2017), employing data analytics for predictive market insights (Mandl & Minner, 2023), and diversifying supplier networks to enhance resilience (Hu & Kostamis, 2015). These adaptations play a pivotal role in enabling supply chains to survive and thrive amid market volatility (Ivanov & Dolgui, 2020).

Originally focused on efficiency through conventional retail stores and inventory practices (Basker, 2007), Walmart revamped its strategy due to changing consumer habits and rising competition. This transformation included the incorporation of omnichannel retailing, advanced analytics, and blockchain for enhanced transparency (Kucukaltan et al., 2022). Through persistent adaptation, supply chains can fortify their resilience against unforeseen business challenges (Ivanov & Dolgui, 2020).

4.3.8. Shared collective anticipation

Principle 8**.** For any given endotherm or supply chain, increased agreement among partners on perceptions of disruption risk enhances resilience.

This principle provides a foundation for supply chain resilience through shared anticipation by fostering collaboration and transparent information exchange among supply chain partners. Through these means, partners improve their capability to anticipate, prepare for, and manage prospective disruptions, thus enhancing the resilience of the supply chain. Anchored in core analogy aspects of *Adaptive Response, Resource Management, Information Processing,* and *Purpose and Boundaries,* this principle posits that

collective foresight enables more effective risk management and fosters the development of coordinated response strategies. Such communal anticipation heightens decision-making agility, allowing for quick and streamlined responses to unexpected situations while also supporting longer-term flexibility. It prompts stakeholders to adapt their approaches based on mutually acknowledged risk projections, thereby strengthening the overall stability and resilience of the supply chain.

Endotherm equivalence. Endotherms exhibit anticipatory physiological adaptations, like fur shedding or fat accumulation, in preparation for changing environmental conditions (Sherwood et al., 2012). Such changes occur under the centralized control of the hypothalamus which also coordinates other functionally redundant (overlapping) systems and mechanisms involved in endotherm resilience.

Supply chain equivalence. In supply chains, this principle suggests that a unified perception of potential disruption risks among partners enhances the likelihood of a cohesive resilience strategy. Although extant literature does not explicitly refer to shared collective anticipation, there is a heavy emphasis on information sharing as a cornerstone of supply chain resilience (Scholten & Schilder, 2015). When supply chain entities share information, they achieve a more nuanced understanding of the broader risks among partners, motivating collaborative and coordinated risk management strategies (Scholten & Schilder, 2015). Such synchronized anticipation lays the groundwork for proactive measures aimed at mitigating supply chain disruptions (Ambulkar et al., 2015), thereby supporting agile responsiveness and supply chain stability (Kim et al., 2015).

At the operational level, shared collective anticipation can be nurtured through mechanisms such as collaborative forecasting, information sharing, and collective risk assessments. CPFR serves as one such framework that synergizes forecasting and planning activities across supply chain entities (Sherman, 1998). Additionally, emerging digital technologies like blockchain and IoT offer real-time visibility into supply chain operations, thereby enabling quicker and more informed responses to disruptions (Balakrishnan & Ramanathan, 2021).

The global supply chain crisis triggered by the recent health pandemic underscores the importance of shared collective anticipation. As the severity and extent of the pandemic became apparent, some supply chain entities anticipated risks related to transportation disruptions, labor shortages, and changing consumer behaviors (Ivanov & Dolgui, 2020). Consequently, some initiated collaborative efforts to mitigate these risks, including enhancing digital capabilities for remote work, jointly lobbying for government support, and pooling resources to ensure continuity of operations (Reeves et al., 2020).

4.3.9. Beneficial complexity

Principle 9**.** For any given endotherm or supply chain, increased complexity enhances resilience.

This principle proposes that complexity, when managed effectively, can serve as a strategic asset for boosting supply chain resilience. This encourages a shift in perception—from viewing complexity as an

obstacle to be minimized to recognizing it as a potential asset to be strategically harnessed for superior resilience. This principle focuses on strategic decisions to increase complexity as a pathway to enhanced supply chain resilience. Complexity can be increased through decisions to create diversity, interconnectivity, and redundancy. The principle encompasses the aspects of *System Design, Resource Management,* and *Information Processing*. *System Design* underscores the merits of functional redundancy and centralized coordination for fostering adaptability (McGlone & Spence, 2010). *Resource Management* emphasizes a calibrated balance between conservation and consumption, reflecting the supply chain's balance amid complexity and operational efficiency (Knight, 2022). Concurrently, *Information Processing* delineates the need for adept data interpretation, echoing the intricate task of decoding embedded patterns within expansive supply chain structures (Aslam et al., 2018; Qi et al., 2009).

Endotherm equivalence. Drawing parallels from biology, the complexity inherent within endotherms is illustrative. Endotherms have myriad mechanisms involved in regulating body temperature, spanning from hormonal to muscular systems. Such systems create an intricate network characterized by organ redundancies and multiple metabolic routes, hence reinforcing resilience (Labocha & Hayes, 2019).

Supply chain equivalence. Supply chain complexity is often associated with increased risk (Craighead et al., 2007) and thus, might predict reduced resilience. For example, Bode and Wagner (2015) attribute increased disruption frequency to upstream supply chain complexity. Similarly, (Bozarth et al., 2009) show that both upstream and downstream complexity can negatively affect manufacturing plant performance. However, an emerging body of research points to complexity being a double-edged sword that, if successfully harnessed, can benefit supply chain resilience. Complexity, in this context, encompasses the dynamic interplay of diverse elements, their interconnectivity, and redundancy. Supply chains can "gain from disorder" (Nikookar et al., 2021, p. 3), and intentional, well-managed complexity can foster enhanced supply chain resilience.

Diversity in supply chains, represented by varied products, technologies, or personnel, increases capability to respond to unforeseen disruptions. Redundancy, typically in the form of duplicate resources, assets, or processes, allows for fallback options and buffering capacity during disruptions (Song et al., 2020). Moreover, interconnectivity among these diverse and redundant supply chain elements allows for coordination and promotes collective security. The core premise of this principle lies in managing complexity effectively (Sá et al., 2020). Although uncontrolled complexity may lead to inefficiencies, misunderstandings, and unpredictable outcomes, well-managed complexity, with a clear understanding of network intricacies, becomes a source of competitive advantage that is hard to replicate and confers flexibility and adaptability (Reeves et al., 2020).

As an example of this principle, global retailer Zara, operating in an environment marked by rapidly changing consumer trends, rapidly cycles through large numbers of diverse styles, identifying popular items

and trends, and quickly adapts its inventory to meet customer demand (Cohen & Kouvelis, 2021). The firm positions its complex, interconnected supply chain as a source of resilience and competitive advantage, enabling it to respond to market changes more quickly than competitors (Reeves et al., 2020). Similarly, Apple's supply chain is a complex network of hardware, software, and services. Diversity and interconnectivity among products, coupled with redundancy in supply and manufacturing processes, create a complex but agile network that is difficult for competitors to replicate (Gligor et al., 2015). When one element of the system is disrupted, Apple typically utilizes redundancies to maintain operational continuity (Choudhary et al., 2021; Choudhary et al., 2022). Integration of advanced analytics and data-driven decision-making at companies such as Netflix are another example of beneficial supply chain complexity. Leveraging diverse data sources and predictive modeling, sophisticated analytical approaches enable companies to harness the advantages of complex supply chain networks, optimize inventory, personalize offers, and implement dynamic pricing strategies (Caro et al., 2020).

5. DISCUSSION

This study represents a significant contribution to the literature on supply chain resilience by leveraging metaphorical transfer as a potent tool to aid theoretical development. Drawing insights from the ecological domain, we establish conceptual equivalence between endotherm resilience and supply chain resilience, validated across ontology, analogy, and identity dimensions (Chen et al., 2013; Garud & Kotha, 1994; Tsoukas, 1991).(Stephens et al., 2022)

In the face of the rising frequency of supply chain disruptions—exemplified by recent events such as Brexit (2020), the Suez Canal blockage (2021), the COVID-19 pandemic (2020–present), and the global chip shortage (2020–present)—the significance of this research resonates. These disruptions, with vast economic and operational ramifications (Hendricks, 2007), underscore the necessity for scholars to refine our understanding of supply chain resilience. Minimizing supply chain vulnerabilities remains paramount for management advancement (Melnyk et al., 2014). The catastrophic consequences of supply chain disruptions, ranging from economic setbacks to geopolitical instability (Khan et al., 2022; Tukamuhabwa et al., 2017), emphasize the urgency for firms to prioritize resilience enhancement.

Endotherms and supply chains share the trait of stabilizing systems. Whereas endotherms maintain stability through controlled internal body temperature, supply chains historically reverted to their original operational state post-disruption (Wieland & Durach, 2021). Our research advocates for an adaptive model of supply chain resilience, suggesting that supply chains may gain an advantage by adopting a "new normal" operational state following disruption.

Using the endotherm resilience body of knowledge in this study, we help to deepen the understanding of supply chain resilience while providing new avenues for exploration. Both entities rely on adaptive

capacities that enable them to thrive within their respective ecosystems. By integrating the lens of endotherm resilience, we infuse fresh theoretical perspectives into the study of supply chain resilience. In essence, this research sets the stage for transformative hypotheses and solutions, enhancing management practices to support supply chain resilience, and providing a foundation for an array of innovative empirical studies.

5.1. Limitations and future research

This investigation, while thorough in its approach, is not devoid of limitations that warrant recognition. Despite the conceptual rigor embodied in our metaphorical framework, the conclusions drawn remain predominantly theoretical, calling for empirical substantiation. Moreover, a pivotal query pertains to the viability of transposing the endotherm resilience model onto supply chains, especially considering the diverse stakeholders and regulatory intricacies inherent to such networks. These stakeholders encompass a broad spectrum, ranging from investors and partners to customers, communities, and beyond.

The endeavor to extrapolate principles from biological ecosystems (specifically, endotherms) to socio-economic constructs (like supply chains) introduces an additional stratum of complexity. This study does not exhaustively delineate the potential hurdles that may arise from this cross-disciplinary application. Furthermore, while the endotherm resilience metaphor offers an insightful perspective for understanding supply chain resilience, it is not without its intrinsic constraints. Analogous to how endotherms necessitate constant sustenance, supply chains are subject to distinctive challenges, such as the escalated expenditures associated with sustaining redundancy and flexibility within the system. Consequently, a plurality of metaphors may be needed to encapsulate the full spectrum of intricacies present in supply chain dynamics.

Acknowledging these limitations not only delineates the scope of this study but also unveils a plethora of intriguing prospects for subsequent inquiries. Future research could meticulously examine both nascent and established supply chain frameworks to evaluate the applicability of endotherm resilience tenets. An additional captivating research direction is the formulation of adaptive algorithms that replicate endothermic regulatory processes. This line of inquiry could explore the feasibility of training supply chain systems to autonomously adjust, akin to how endotherms respond to environmental variations. A timely pivotal question is whether supply chain systems can integrate machine learning or other self-regulatory technologies to adeptly adapt to evolving conditions.

5.2. Conclusion

In line with the overarching objective of this study—to pioneer innovative theory-building for exploring the development of supply chain resilience through metaphorical transfer—this paper successfully introduces a set of principles that can serve as the foundation for testable hypotheses in future research endeavors. Our utilization of the endotherm metaphor adds nuanced layers to the existing discourse on supply chain resilience while underscoring the necessity for a multifaceted, strategic approach to resource

management and allocation.

In conclusion, this study stands as a catalytic agent to inspire future research on supply chain resilience. It beckons scholars and practitioners to transcend traditional paradigms and embrace an adaptive approach to navigating the complexities of supply chain resilience.

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