Transportation Research Interdisciplinary Perspectives 37 (2026) 101970

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Defining and assessing the structural flexibility of transportation networks

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ARTICLE INFO

Keywords:
Transportation network flexibility
Transportation flexibility
Structural flexibility
Graph theory
Complex adaptive systems theory
Simulation

ABSTRACT

International supply chains increasingly require flexibility in transportation services supplied by logistics service providers (LSPs) to deal with uncertainty and disruption. Despite the literature on transportation flexibility, current studies primarily emphasize operational service attributes or isolated node- and arc-level capacities, with limited attention to the role of the transportation network structure in enabling system-level flexibility. Consequently, the concept of transportation network flexibility and its relationship to network topology is poorly understood. This research fills these gaps by conceptualizing transportation network flexibility as an attribute of the network structure at the network level, defined as the existence of at least one feasible origin–destination itinerary under joint volume and time capacity constraints. Drawing on graph theory and complex adaptive systems theory, the study formally distinguishes between arc-, node-, mix-, and network-level flexibility and finds that only network-level flexibility can consistently handle shipper change requests. A simulation-based transportation network flexibility index, grounded in residual network theory, is developed to test seven canonical transportation network topologies under stochastic capacity degradation. The results show that network structure systematically influences flexibility outcomes: scale-free networks have much greater network-level flexibility than other network topologies, irrespective of common network metrics such as density, connectivity, or centralization. By decoupling structural flexibility from operational performance, the study establishes the unit of analysis for transportation flexibility. It provides LSPs with a principled foundation for designing, evaluating, and ranking flexible transportation services without resorting to expensive, fully flexible network designs.

1. Introduction

Shipper firms increasingly require their logistics service providers (LSPs) to provide transportation services that are more flexible in accommodating uncertainties coming from market competition or disruptive events such as the Covid-19 pandemic (Khakdaman et al., 2022; Reis, 2014; Mason and Nair, 2013). In logistics and supply chain systems, transportation networks serve as the structural backbone on which LSPs provide end-to-end transportation services to their shipper clients. Recent industry examples highlight the challenges LSPs face in providing flexible transportation services to their shipper clients. For instance, the congestion of several ships at the ports of Los Angeles and Long Beach, along with the shortage of trucks and rail capacities, increased the transportation delay for DSV, the Danish provider of worldwide transportation and logistics services, and deteriorated its ability to provide timely and flexible transportation services (DSV, 2022). A new survey of global LSPs on warehousing capacity constraints found that almost 40% of warehouses are operating at 90–99% capacity, and about 20% are operating at above 100% capacity (Extensive, 2022). The lack of sufficient terminal capacity in ten European intermodal freight transport chains (Saeedi et al., 2019) and in the Australian rail network (Shipping Australia Limited, 2011) demonstrates LSPs' challenges in providing flexible transportation services (Karam et al., 2023).

From a service perspective, the flexibility of transportation services is often defined as a logistics service provider's ability to accommodate changes to service components requested by shippers before finalizing the booking, and even while the goods are in transit. Such changes may include adjusting the time or location of delivery, shortening or extending lead times, consolidating or deconsolidating flows, or modifying volume or variety through warehouses or cross-docking terminals (Khakdaman et al., 2020). While this form of transportation service flexibility reflects LSP operational responsiveness, it is necessarily tied to the structural characteristics of the underlying transportation network. Without a network structure that provides feasible alternative routes, modes, or transhipments under capacity and time constraints, the ability to provide service-level flexibility is limited, despite operational policies and control decisions.

From a network management perspective, LSPs' managers become

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https://doi.org/10.1016/j.trip.2026.101970
Received 15 November 2024; Received in revised form 26 January 2026; Accepted 25 March 2026
Available online 31 March 2026

concerned about how insufficient capacities and capabilities of a node (for example, a warehouse or a port terminal) or an arc (for example, a transportation mode or route) in their transportation network may disrupt the provision of flexible transportation services. However, providing flexibility in a transportation network needs more than adding extra capacities and capabilities at isolated nodes or arcs. It requires a more comprehensive understanding of how the overall *structure* of the transportation network enables or constrains the accommodation of change.

Inefficiencies and disruptions in transportation networks have been primarily investigated in the literature, with most studies focusing on identifying the factors that cause them or on developing mitigation strategies (for example, Farahani et al., 2013; Zhang et al., 2015). In many cases, however, disruption or inefficiency is not a result of individual facilities but a consequence of the structural connections of logistical resources within the network. Furthermore, insufficient resources at the local level, i.e., at a node or an arc, do not necessarily lead to a network-level disruption. As a result, an LSP's inability to offer flexible transportation services is often due to a lack of understanding of flexible network structures rather than isolated capacity shortages.

Chandra et al. (2005) highlight the critical role of structural factors, such as network topology, in providing flexibility in transportation networks. It is often implicitly assumed that transportation networks with higher connectivity, density, or concentration around a few central nodes are better able to provide flexibility; however, whether such structural characteristics enable transportation networks to accommodate change under capacity and time constraints remains poorly understood. While many scholars assessed the impact of network topology in different contexts (for example, Perera et al., 2017 (supply chain network topologies), Lin and Ban, 2013; Zhang et al., 2015 (transportation network structures), Kim et al., 2015 (supply network structures)), the question of which transportation network structure(s) could better enable provision of flexible transportation services remains underexplored. Moreover, the existing literature lacks a formal definition of transportation network flexibility (Naim et al., 2006) and provides little guidance to LSPs on identifying the appropriate level of flexibility needed to fulfill shipper change requests effectively. Could extra capacity in warehouses or transportation modes provide the required flexibility? Providing a fully flexible transportation network – where all arcs and nodes are flexible – would incur huge costs, while having no flexibility is ineffective in addressing customers' requests. Prior research suggests that little flexibility in the system would provide most benefits of a fully flexible system at substantially lower cost (Yan et al., 2017). While Yan et al. (2017) demonstrate this principle in the context of process flexibility and airport operations, what constitutes "little yet effective flexibility" for a transportation network structure remains unclear. This study takes a structural, network-level perspective to address this gap. Specifically, the following research questions are examined: *how does the structure of a transportation network influence an LSP's ability to provide flexible transportation services, and how can the flexibility of transportation networks be assessed at the network level?*

To address these questions, this study draws on graph theory and complex adaptive systems theory to develop a structural conceptualization of transportation network flexibility, independent of routing, scheduling, or control decisions. Transportation network flexibility is discussed as a network-level capability, defined by the presence of viable origin–destination itineraries under volume and time capacity constraints, rather than as a performance result at the operational level, such as travel time or cost efficiency. The study provides a formal definition of transportation network flexibility, illustrates a spectrum of flexibility levels, and identifies the level needed to meet shipper service requirements. A simulation model is developed to evaluate the flexibility of main transportation network topologies and to examine how structural characteristics shape LSPs' capabilities to provide flexible transportation services.

The contributions of this research are fourfold. First, the study presents a network-level conceptualization of transportation network flexibility. It introduces the appropriate unit of analysis by differentiating between structural flexibility and arc-, node-, and mix-flexibilities on the one hand, and operational decision-making and performance results on the other. Second, the research proposes a probabilistic, residual-network-based flexibility index that captures a transportation network's structural flexibility under stochastic capacity degradation and combined volume-time capacity constraints. Importantly, capacity constraints are treated as exogenous feasibility conditions of nodes and arcs rather than as decision variables, and the index does not rely on routing, scheduling, flow assignment, or control policies. Third, the paper presents theory-driven evidence that transportation network topology can systematically influence network-level flexibility by illustrating that various canonical network structures can facilitate or limit the provision of flexibility regardless of operational decision-making processes. This demonstrates that flexibility is an emergent structural property of network topology, rather than an inherent outcome of network capacity or connectivity alone. Fourth, the study indicates that traditional metrics of network topology (such as density, degree, connectivity, and centralization) are inadequate indicators of transportation network flexibility and should be replaced by a probabilistic measure of structural feasibility under capacity constraints.

The remainder of the paper follows this structure. In Section 2, the literature on the flexibility of transportation networks and the corresponding network-structural views is reviewed. Section 3 conceptualizes transportation network flexibility and its levels. Section 4 assesses the effect of transportation network structure on the flexibility of seven canonical network topologies. Managerial and research implications are discussed in Section 5, and the limitations and future research directions are concluded in Section 6.

2. Literature review on transportation network flexibility

Flexibility in transportation services enhances shipper firms' adaptability to address changing/disruptive circumstances in their business environment. In simple terms, flexibility is the capability to accommodate changes using currently available resources and capabilities without incurring additional investments or significant costs (Jordan and Graves, 1995). A substantial body of literature has developed the concept of supply chain flexibility, encompassing the flexibility of various supply chain functions, including product development, sourcing, production, transportation, and organizational design (for example, Malhotra and Mackelprang, 2012). Within this stream, Zhang et al. (2005) defined transportation flexibility as "the ability of a firm to respond quickly and efficiently to changing customer needs in inbound and outbound delivery, support, and services." Swafford et al. (2006) offered a broader definition as "the availability of a range of options and the ability to effectively exploit them to adapt the process of controlling the flow and storage of materials, finished goods, services, and related information from origin to destination in response to changing marketplace conditions." Khakdaman et al. (2020) defined transportation flexibility as "the capability of a transportation system to provide possible changes in the service components adaptive to shippers' business needs at any point in time, before and after the departure of the freight/goods towards the destination." Collectively, these definitions give a clear perspective on the transportation flexibility at the *service* level. However, they do not explicitly define and operationalize transportation *network* flexibility.

Beyond having sound managerial and organizational competencies for providing transportation flexibility (see, for example, Abrahamsson et al., 2003), LSPs also rely on the transportation network as the primary operational backbone for offering end-to-end services (Chandra et al., 2005). Accordingly, several papers examined transportation systems at the network level to understand accessibility, robustness, delay propagation, and system behavior during disruptions and interdependent failures (for example, Amirgholy et al., 2023; Rodriguez-Roman et al., 2024; Sugishita et al., 2024; Chung et al., 2025). These works underscore the importance of studying transportation systems as networks rather than as nodes or links.

Despite this growing literature, three main pitfalls can be identified in the existing literature on transportation network flexibility. The first one concerns the conceptualization and operationalization of transportation network flexibility. The research by Feitelson and Salomon (2000) is among the first to examine network flexibility in the context of transportation. They defined network flexibility as "the ease with which a network can adjust to changing circumstances and demand, both in terms of infrastructure and operation." They considered three elements for a flexible network: node flexibility (the ability to add new nodes to the network), link flexibility (the ability to add new arcs), and temporal flexibility (the ability to sequence infrastructure investment). Their approach is mainly focused on spatial modeling to compare the flexibility of rail, road, and air transportation networks. A major pitfall in their definition is treating flexibility as the capability to add extra capacity to the network, for example, extra nodes or arcs, which contrasts with popular definitions that view flexibility as using current capacity without additional investment (Jordan and Graves, 1995). In addition, their study is more focused on strategic (investment) decisions rather than on system-level requirements for accommodating customer change requests.

Related contributions by Lee (2004) and Jahre and Fabbe-Costes (2005) conceptualize transportation network flexibility or adaptability as its capacity to reshape the supply chain to accommodate future changes without being tied to legacy issues or prior operating practices. However, their research did not discuss the operationalization of transportation network flexibility and associated levels of flexibility. Lin et al. (2009) provided a clearer picture of flexibility by distinguishing direct delivery and direct shipment as key characteristics of a flexible transportation network. They defined direct delivery as delivering products from distribution centers to customers, bypassing retailers, and direct shipment as sending products from production plants to retailers, without passing through distribution centers. Although their work further developed our understanding of flexible transportation networks, it focuses mainly on arc-level flexibility. It does not provide a network-wide conceptualization that aligns with broader service-wide definitions, such as those of Swafford et al. (2006) and Khakdaman et al. (2020).

Similar questions have been tackled by other studies using reserve capacity, robustness, accessibility, and disruption analysis. As an example, Zhu and Cheng (2016) evaluated the flexibility of transport networks in terms of reserve capacity, whereas multiple network-based studies assessed the behavior of a transport network subjected to capacity degradation, disruption, and delay propagation (such as Amirgholy et al., 2023; Salvo et al., 2025; Abaza and Hegland, 2025; Sugishita et al., 2024). Nonetheless, these analyses typically measure network performance or accessibility during stress, but do not explicitly determine transportation network flexibility as a structural capacity independent of operational performance. This underscores the need to conceptualize and operationalize transportation network flexibility at the network level.

Similar to previous research on network robustness and resilience, this paper differentiates between structural feasibility (the existence of viable origin–destination itineraries within a transportation network given volume and time constraints), and operational performance (the efficiency with which those itineraries are utilized though routing, time scheduling, and control decisions) (Taylor et al., 2006; Mattsson and Jenelius, 2015). Structural feasibility is an essential requirement for any operational response to demand variability or disruption, but it has frequently been conflated with performance-based indicators in the transportation literature, such as travel time, cost, or reliability (Zhang et al., 2015; Amirgholy et al., 2023). It is imperative to clarify this distinction to conceptualize transportation network flexibility as a network-level capability rather than a result of particular operational policies.

The second pitfall is identifying the level of flexibility LSPs should maintain to provide a satisfactory service level to their customers. Barad and Sapir (2003) defined transportation network flexibility as the capability to reposition stock in the supply chain network in real time to address supply chain uncertainties. Their research contributes to an arc-level flexibility in the transportation network. In another example, Paixao and Bernard Marlow (2003) and Russell et al. (2022) considered a node-level flexible network with flexible ports within the transportation network. The arc-level flexibility is also demonstrated in the research by Morlok and Chang (2004) and Groothedde et al. (2005). The former considered the flexibility of transportation capacity along routes, and the latter focused on leveraging the capacity of parallel transportation modes to improve network flexibility. Following a similar approach to flexibility levels, Ukkusuri and Patil (2009) addressed the network design problem for strategic investment in transportation networks under uncertain, elastic demand. Building on the concept of transportation network flexibility introduced by Lin et al. (2009), Hiremath et al. (2012), and Cheshmehgaz et al. (2013) addressed the transportation network design problem in different supply chain contexts. The primary focus of these studies is flexibility at the individual node or arc level, not at the network level. This study distinguishes between the flexibility of the entire transportation network and that of individual nodes or arcs, because network-level flexibility enables a truly flexible transportation network capable of accommodating diverse customer requirements for changes in shipment volume, variety, location, storage, lead time, and more. It can also be effective during disruptions to node(s) or arc(s) to avoid network-wide disconnection across the entire supply chain.

Relevant studies on synchromodality and the Physical Internet also highlight the significance of flexibility at the network level. Synchromodality emphasizes the possibility to switch dynamically between transport modes and itineraries without committing to the implementation of transportation plans in advance(Tavasszy et al., 2010; Acero et al., 2022; Alaei et al., 2024), whereas the Physical Internet conceptualizes hyperconnected logistics networks due to the standardized interface and common infrastructure (Montreuil, 2011; Ballot et al., 2021; Matusiewicz et al., 2024). These approaches implicitly rely on the availability of structurally feasible alternative origin–destination itineraries within capacity and time limitations.

The third research gap concerns identifying the critical role of LSPs' network structures, such as network topologies, in their ability to provide flexible transportation services. Many scholars have identified different topologies to characterize network structures in their studies (for example, Rivkin and Siggelkow, 2007 (decision-making structures), Kim et al., 2015 (supply network structures), and Perera et al., 2017 (supply chain network topologies)). In transportation networks, two main research streams can be identified. The first applies operational research methods to address transportation network design problems across different business contexts (for example, see the following review papers: Wieberneit, 2008; Xie and Levinson, 2009; Farahani et al., 2013). However, their main drawback is their focus on a particular problem rather than examining the impact of different network structures on the flexibility of the transportation network. In the second research stream, a few studies classified relevant network structures. They introduced network analysis measures to assess different characteristics of the transportation network such as accessibility, efficiency, transitivity and so on (see for example, Straka and Malindzak, 2010; Ducruet and Lugo, 2013; Lin and Ban, 2013; Zanin et al., 2018, (classification and measures of transportation networks), Blumenfeld-Lieberthal, 2009; Levinson, 2012 (classification of Urban transportation networks), Bowen, 2012 (structure of UPS and FedEx transportation networks). Zhang et al. (2015) assessed the resilience of different transportation network structures, categorized into four connectivity types ranging from complete to random. According to the literature, topology can influence the behavior of systems under congestion, disruptions, and interdependent failures (for example, Amirgholy et al., 2023; Khan et al., 2025; Salvo et al., 2025). Nonetheless, there is little theory-informed evidence on the systematic effects of transportation network topology on transportation network flexibility, a structural feasibility property.

The following sections address these gaps by defining and operationalizing transportation network flexibility, clarifying the adequate level of flexibility for LSPs, and examining which network structure(s) are most effective in enabling LSP-driven flexible transportation services.

3. The concept of transportation network flexibility

To demonstrate the concept of transportation network flexibility, the supply chain network is first illustrated at a high level, and the transportation network is then depicted at more detailed levels. Fig. 1 shows a typical supply chain network that (potentially) includes suppliers, producers, distribution centers, retailers, customers, and a transportation network managing the flow of products and services among all these entities (Lin et al., 2009). Looking at the supply chain network from a structural perspective, it is a graph containing nodes (facilities, such as suppliers and manufacturers) and arcs (transportation facilities, infrastructure, modes, and so on) (Borgatti and Li, 2009). Going one layer into the details, each node and arc could potentially contain an internal network. In particular, arcs of the supply chain network include a complex network of nodes and arcs called the transportation network, typically operated by LSPs to perform (physical) transportation and inventory management, such as storage, handling, and packaging (Larson and Halldorsson, 2004; Jafari, 2015).

Fig. 2 shows a typical LSP-driven transportation network. Arcs of the transportation network are different transportation modes (for example, rail, road, air, water, and so on) and transportation routes connecting transportation network nodes, which are typically warehousing/cross-docking facilities in different locations of the transportation network (for example, ports, terminals, and warehouses). The transportation network in Fig. 2 depicts links from upstream to downstream supply chain nodes and vice versa to represent product (or material) returns. In the following sections, a graph-theoretic representation of the transportation network is introduced, followed by definitions and characterization of transportation network flexibility. Graph theory supports the analysis of the underlying structure of flexible transportation networks by enabling the description of flexibility at different levels, the identification of the configurations of flexible arcs and nodes, and the demonstration of their ability to address changes across the supply chain.

3.1. Graph-theoretic perspective of the transportation network

In graph theory, a transportation network is a set of arcs connecting nodes (Gross and Yellen, 2005). Graph-theoretic notions (Diestel, 2005) are applied to represent the transportation network (see Fig. 3). A graph is denoted by $G = (N, A)$, where N represents the set of nodes, and A represents the set of arcs. If arcs of a graph have orientations, they make a directed graph or digraph where each arc has a tail and a head (see Fig. 3). The transportation network is modeled as a digraph because product flows in typical supply chains predominantly occur from upstream to downstream nodes. The transportation network in Fig. 3 is denoted by TN (transportation network) $= (N, A)$, where $N = \{n1, \ldots, n4\}$ shows transportation nodes (for example, warehouses and terminals), and $A = \{a1, \ldots, a16\}$ represents transportation arcs (for example, transportation modes and routes). Two sets of arcs exist in this transportation network: $Set1 = \{a1, \ldots, a7, a13, \ldots, a16\}$ connects supply chain nodes directly together (for example, *a7*) or to the transportation nodes (for example, a3), and $Set2 = \{a8, \ldots, a12\}$ connects only the transportation nodes together.

To understand the structure of a transportation network and the concept of transportation network flexibility, several graph-theoretic concepts are introduced. The number of arcs attached to a node is called its degree. The out-degree is the number of arcs outgoing from a node, and the in-degree is the number of arcs incoming to the node. For instance, in Fig. 3, the out-degree of node *n2* is 2, and the in-degree is also 2. This means that node *n2* sends goods to transportation node *n4* via arc *a9* and to supply chain node *D1* via arc *a13*, and receives goods from transportation node *n1* and supply chain node *P1* via arcs *a8* and *a2*, respectively. A source node has positive out-degree and zero in-degree (for example, *P2*), and a sink node has positive in-degree and zero out-degree (for example, *D1*). In a transportation network, source and sink nodes are supply chain nodes that function as suppliers, producers, distribution centers, retailers, or customers. A walk in a digraph (or directed walk) is an alternating sequence of arcs and nodes departing from the source node(s) towards a sink node, where arcs' heads indicate the flow direction. For example, in Fig. 3, $W = \{P1, a3, n1, a10, n4, a15, D2\}$ is a walk from source node *P1* to the sink node *D2* where goods are transported from producer *P1* to the transportation node *n2* passing through arc *a3* first, then stored/cross-docked in transportation node *n2*, then shipped to node *n4* via arc *a10*, and finally delivered at the distribution center node *D2* through arc *a15*. In this context, a walk represents a transportation itinerary between an origin and a destination.

Connected graph, capacitated network, feasible flow, and residual network are other concepts from graph theory that need to be applied in this study. The original definition of a connected graph in graph theory – where at least one walk exists between any pair of nodes in the graph

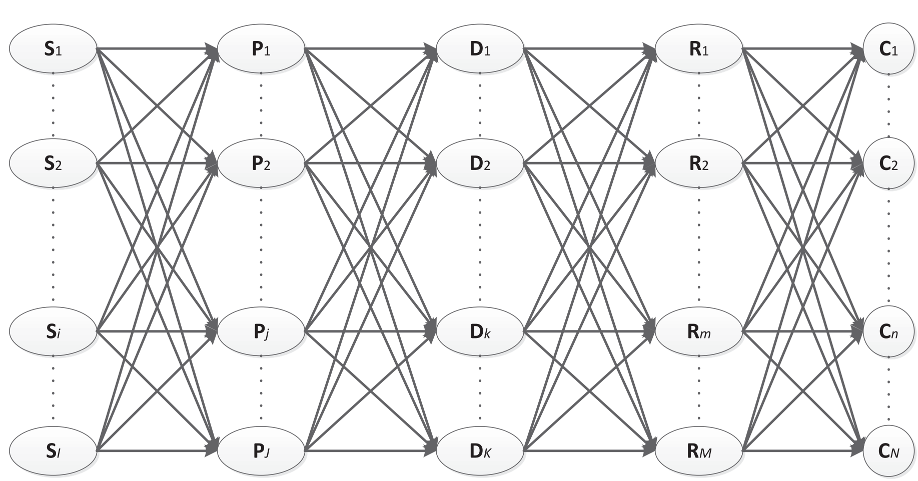

Fig. 1. The structure of the traditional supply chain network (adapted from Lin et al. 2009).

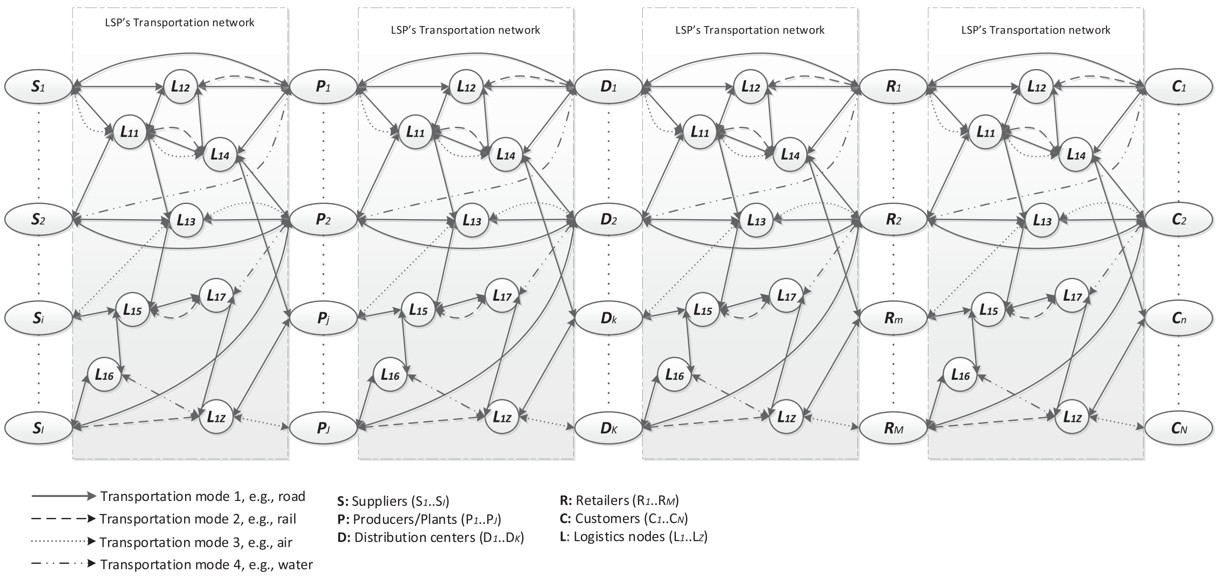

Fig. 2. The structure of the LSP-driven transportation network (authors).

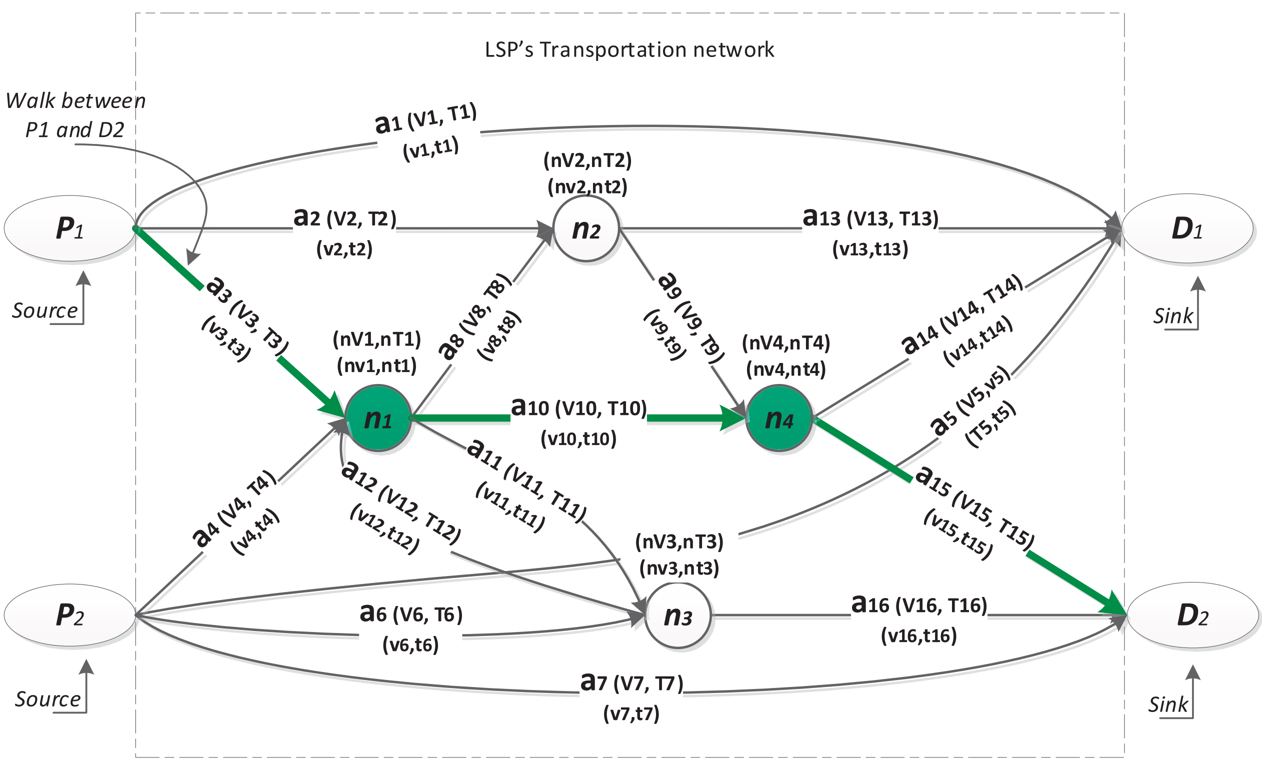

Fig. 3. (Graph-theoretic) representation of a transportation network (authors).

(Gross and Yellen, 2005) – is modified by Kim et al. (2015) for supply chain settings. They define a connected supply chain network as a digraph with at least one walk from the source to the sink. Using this definition, a connected transportation network is one in which at least one walk exists between the source node(s) and a target sink node, enabling the movement of physical goods. Connectivity of a transportation network is defined as the minimum number of arcs and/or nodes whose removal disconnects the network (Gross and Yellen, 2005; Kim et al., 2015). For example, in Fig. 3, considering *P1* and *P2* as source nodes and *D2* as the sink node, the associated transportation network has connectivity of 3. This means that disconnecting the network needs eliminating at least three entities, such as three arcs, for example, (*a7, a15,* and *a16*), or a mixture of arcs and nodes, such as one arc and two nodes, for example, (*a7, n3,* and *n4*) or one node and two arcs, for example, (*n3, a7,* and *a15*) or (*n4, a7* and *a16*).

A capacitated transportation network is defined as a connected digraph in which nonnegative weights are assigned to arcs and nodes, representing capacities. In graph theory, a capacitated network is a connected digraph in which each arc has a nonnegative weight called arc capacity (Gross and Yellen, 2005). However, to represent a capacitated transportation network, node capacities are also considered. Thus, the notions of the maximum flow problem with node capacities are adopted (Ford and Fulkerson, 1962), where the objective is to find the maximum feasible flow through a network with capacity constraints on both arcs and nodes.

In a transportation network, two main capacity types for each arc and node should be considered: volume capacity and required operation time capacity. Volume capacity is the maximum volume that a transportation node (for example, a warehouse/terminal) can store/cross-dock/operate, or a transportation arc (for example, a transportation mode) can carry between adjacent nodes. Time capacity is the maximum time required to carry or store/cross-dock the maximum volume capacity in arcs or nodes, respectively. For instance, in Fig. 3, T2 indicates the time capacity required (for example, in days) to carry *V2* units of goods (for example, in TEU or Tonnes) from node *P1* to node *n2* via arc *a2*. Similarly, *nT2* shows the time capacity required to store/cross-dock/operate *nV2* volume of goods in node *n2*. In considering time capacity, the required operation time comprises two components: a fixed operation time, which is a volume-independent time needed to set up the operation regardless of the volume to be served, and a variable operation time, which is a volume-dependent time that increases with volume. To maintain tractability, time capacity is represented using the dominant component for nodes and arcs. Fixed operation time is ignored for nodes (for example, setup times in a warehouse/terminal), while variable operation time is retained for storage/cross-docking/processing. For arcs, variable operation time (for example, loading/unloading) is not considered, and the fixed transportation time between nodes is retained. Based on these assumptions, the maximum required operation time to handle the volume capacity at each node/arc is used as the time capacity dimension. So, each node has a maximum time limit for performing the operations. Thus, handling any volume less than the capacity would take less time than the maximum time required to handle the capacity. For arcs, the same time is needed to transport any volume (from one unit to the volume capacity), since it depends only on the distance between the two nodes. Thus, the time capacity in arcs is the same for maximum volume, the flow volume, and the residual volume capacity.

Now, a feasible flow in a capacitated transportation network is defined. According to Gross and Yellen (2005), a feasible flow f is a function in a capacitated network N that assigns a nonnegative number $f(e)$ to each arc e such that:

(i) $f(e) \leq Capacity(e)$, for every arc e in the network N
(ii) $\sum_{e \in Inflow(v)} f(e) = \sum_{e \in Outflow(v)} f(e)$, for every node v in network N except source and sink nodes

The definition of feasible flow in graph theory applies only to arc capacities, whereas transportation networks require node capacities as well. Accordingly, a feasible flow in a capacitated transportation network is defined here as a walk that assigns a nonnegative flow to each node and arc such that:

(iii) The flow volume/time $\leq$ volume/time capacity for each node and arc
(iv) The sum of inflow volume $=$ the sum of outflow volume for each node and each set of arcs between two adjacent nodes

In graph theory, the available residual capacity for each node or arc is the difference between its flow at each point in time and its capacity. A residual network is thus constructed from the available capacities of arcs and nodes and has no flow (Cormen et al., 2001). Consequently, a residual transportation network is a transportation network formed by available capacities on arcs and nodes, where: for each node, the available volume/time capacity is less than or equal to the volume/time capacity, and for each arc, available volume capacity is less than or equal to the volume capacity, while available time capacity is equal to the time capacity. Using small letters, Fig. 3 shows the residual capacities in nodes and arcs where *v* and *nv* indicate available volume in arcs and nodes, and *t* and *nt* show required time in arcs and nodes, respectively. For example, *v2* and *t2* indicate the available volume and time capacities in arc *a2*, meaning that *v2* containers can be transported via arc *a2* in *t2* days.

In a residual transportation network, a residual walk is a walk with residual capacities that starts at a source node and ends at a sink node. Thus, the volume and time capacities of a residual walk are obtained as follows:

(v) The time capacity: the sum of the time capacities of nodes and arcs in the walk
(vi) The volume capacity: the minimum of the volume capacities of arcs and nodes in the walk

Now that the required graph-theoretic concepts have been introduced, transportation network flexibility is characterized in the next section. To simplify visualization, residual transportation networks are used to represent available capacities.

3.2. Transportation network flexibility

Transportation network flexibility allows the ability to change logistical sources, for example, transportation modes/routes, stock volume/warehouses, and so on. When the transportation network is only arc-flexible (for example, modes/routes with flexible transport capacity and alternative modes/routes for the time of disruption) or node-flexible (for example, warehouses to consolidate/disaggregate goods' volume and alternative nodes for disruption times), it may not be ready to accommodate the full range of shippers' requested changes. In contrast, combined arc and node flexibility would provide a network that proactively supports seamless connectivity among supply chain nodes. Transportation network flexibility is defined here as the existence of a range of options between source(s) and sink(s) nodes that enables efficient and effective changes in the flow and storage of products/services in response to disruptive and changing marketplace conditions, thereby maintaining the level of service committed to clients. This definition includes changes originating from the demand side, the supply side, and the middle-stage facilities in the supply chain. It also includes reverse transportation operations in which source and sink nodes are from downstream and upstream supply chains, respectively. This definition encompasses key logistics operations associated with demand fluctuations, warehousing, distribution network, delivery, packaging, and reverse transportation (Jafari, 2015, Table IX).

To provide a more realistic perspective on the transportation network depicted in Fig. 3, Fig. 4 shows different transportation modes on arcs with associated residual capacities, and this representation is applied in Fig. 6. For example, arc *a13* in Fig. 3 comprises two transportation modes, shown as *a16* and *a17* in Fig. 4. The volume capacity (time capacity) of arc *a13* in Fig. 3 is the total volume capacity (the maximum of time capacities) of arcs *a16* and *a17* in Fig. 4. A further modeling choice in Fig. 4 is treating arcs between transportation nodes (for example, *{a9, …, a15}*) as two-way links, allowing goods to move in both directions between transportation warehouses/terminals. This is illustrated for nodes *n1* and *n3*, where arc *a14* carries goods from *n1* to *n3*, and arc *a15* performs the return flow. To avoid unnecessary complexity, the other two-way arcs among transportation nodes are not explicitly represented.

3.2.1. Arc, node, and mix level flexibility

From a graph-theoretic perspective, a flexible arc or node can allocate sufficient capacity to accommodate changes in the transportation network while maintaining normal flow. For instance, a shipper requests a change in the duration and/or destination of a transportation order initially planned from production plant *P1* (source node) to distribution center *D2* (sink node). Fig. 5 shows a spectrum of flexibility levels in a transportation network for a change request, ranging from zero flexibility (Fig. 6(a)) to full flexibility (Fig. 6(f)). A rigid network is a network

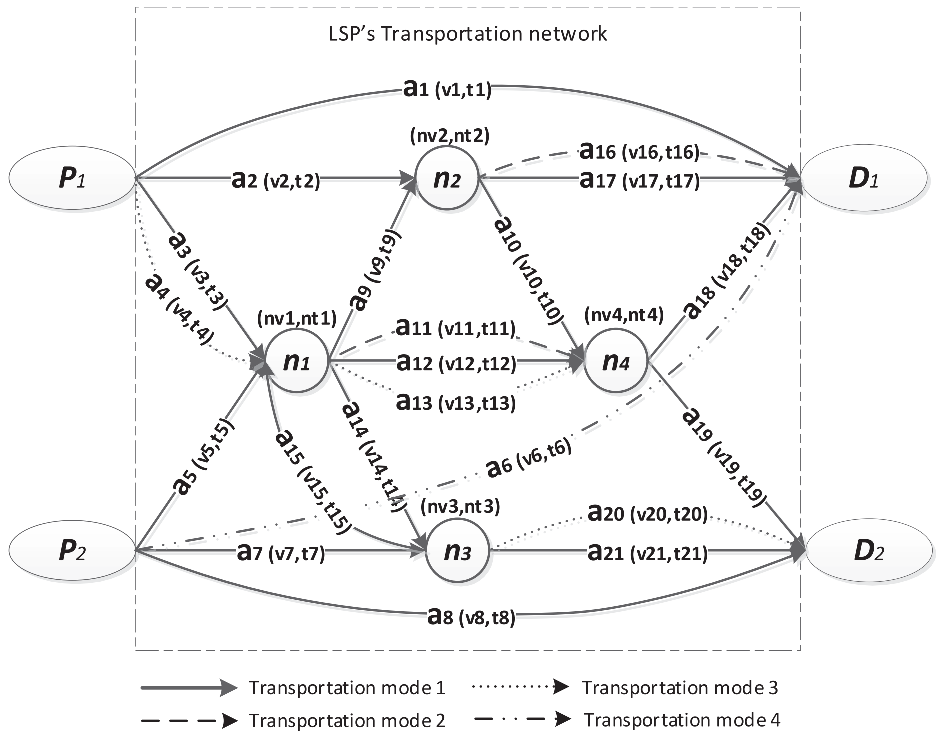

Fig. 4. (Graph-theoretic) Transportation network with differentiated transportation modes (authors).

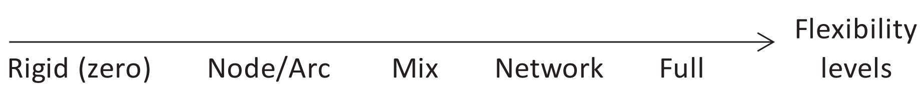

Fig. 5. (Gragh-theoretic) Spectrum of flexibility levels in a transportation network (authors).

that cannot accommodate a change request when it arrives in the network (Fig. 6(a)) due to the incapability of all nodes and arcs in the potential walks from the source to the sink; in graph theory, a rigid structure is a structure that won't bend or swivel under an applied force (it may break with higher force levels) (Gross and Yellen, 2005), a definition that is adapted to the transportation network setting.

Arc-level and node-level transportation flexibilities are depicted in Fig. 7(b) and 7(c), respectively. The arc(node)-level flexibility occurs when there is at least one flexible arc (node) within potential walks that are supposed to handle a shipper's change request. As an illustration, going from source node P1 to sink node D2, there are 13 possible walks, for example, *W1 = {P1, a2, n2, a10, n4, a19, D2}* (1 walk), *W2 = {P1, a3/a4, n1, a9, n2, a10, n4, a19, D2}* (2 walks), *W3 = {P1, a3/a4, n1, a11/a12/a13, n4, a19, D2}* (6 walks) and *W4 = {P1, a3/a4, n1, a14, n3, a20/a21, D2}* (4 walks). In Fig. 6(b), the transportation network has arc-level flexibility, where the walk *W3* and *W4* arc sets *{a3, a11, a19}* and *{a3, a21}*, respectively, are flexible. Please note that arcs/nodes exclusive to the walk sets *W1* to *W4*, i.e., *{a1, a5, …, a8, a16, …, a18}*, are not relevant for fulfilling the demand request from *P1* to *D2*.

Mix-level flexibility (Fig. 6(d)) happens when some flexible nodes and arcs exist in the network, but they cannot form a completely flexible walk capable of meeting the shipper's change request. In Fig. 6(d), if node *n1* and arc *a19* were flexible, walk *W3* would become a completely flexible walk, enabling network-level flexibility. A fully flexible network is a transportation network where all possible walks from the source node to the sink node are flexible. Fig. 6(f) shows that all possible walks from *P1* to *D2* are flexible. When a feasible walk with required capacities is not possible at the network level, the network becomes disconnected flexibly, i.e., its flexibility is disrupted. Thus, a network may remain physically connected while becoming flexibly disconnected. LSPs need to distinguish between network-level transportation flexibility and node/arc/mix-level flexibility, which may only satisfy their internal needs (for instance, internal inventory aggregation, disaggregation, and relocation) rather than customer change requests.

3.2.2. *Network level flexibility*

From a graph-theoretic lens, network-level transportation flexibility is defined as a situation where the capacity of each node (and arc) can be utilized continuously so that its residual capacity does not deteriorate the available capacity of the adjacent arcs (and nodes) for the entire walk intended to accommodate a change in transportation demand (Fig. 6(e)). In other words, there exists a (combination of) residual walk (s), corresponding to feasible origin–destination itineraries, between associated source node(s) and sink node that is targeted to handle a customer's change request such that:

(vii) The (sum of the) volume capacity of the residual walk(s) associated with the change request ≥ required volume capacity to meet the change request.

(viii) The (sum of the) required time of walk(s) associated with the change request ≤ required time to meet the change request.

In simpler terms, the transportation network remains flexible enough to accommodate a change in transportation demand by admitting at least one feasible transportation itinerary. The network-level flexibility in Fig. 6(e) provided via walk *W4* could also have been provided by alternative feasible itineraries corresponding to walks *W1, W2,* and *W3,* if they had sufficient capability. Having more than one flexible walk, i.e., alternative feasible itineraries, won't increase the flexibility level of the transportation network for a change request; however, it could

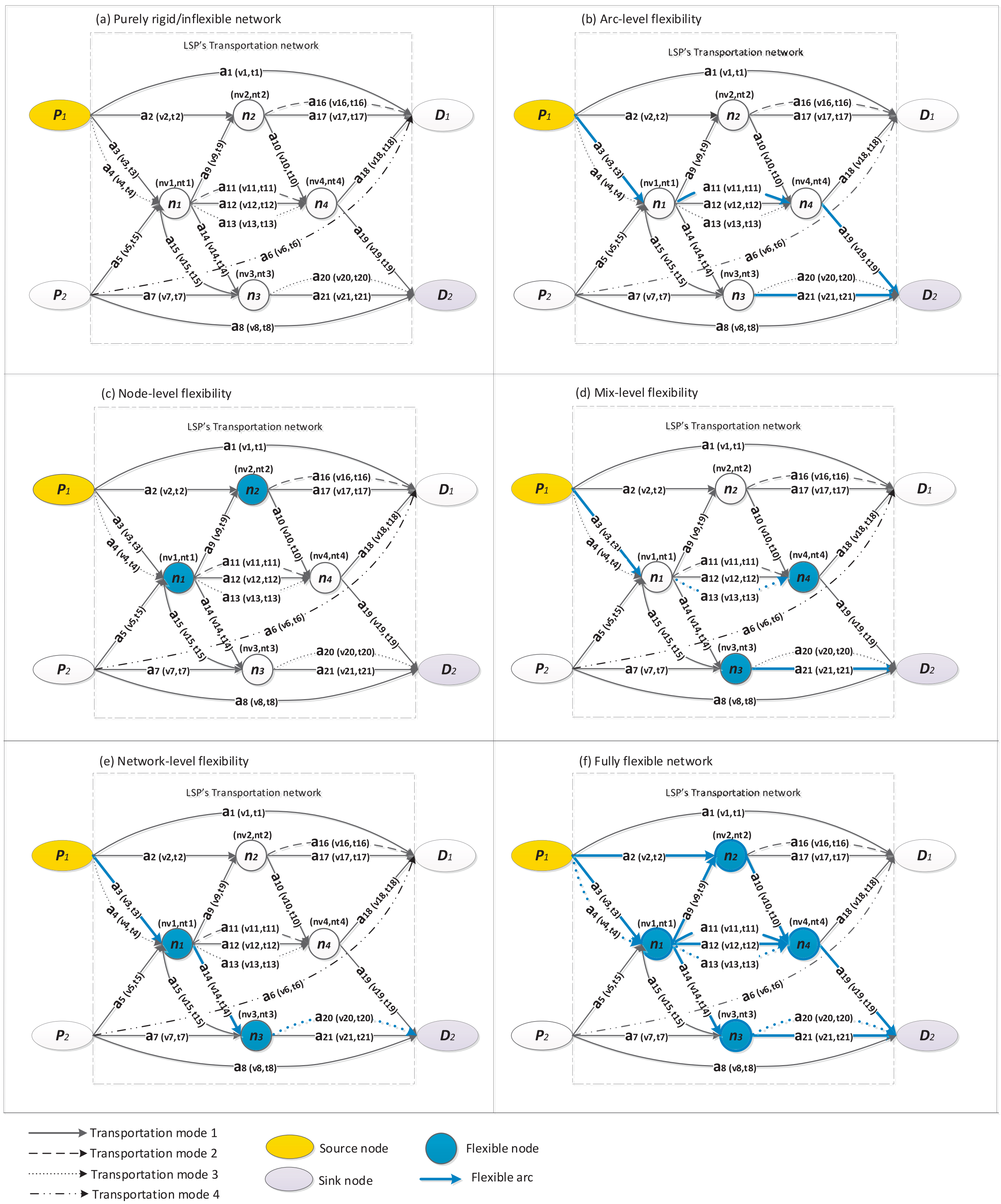

Fig. 6. Flexibility levels in a transportation network at arc, node, mix, network, and full-level flexibility for a given source (*P1*) and sink node (*D2*) (authors).

potentially provide cheaper service fulfillment options by enabling alternative itineraries (see section 5 for a detailed discussion). Please note that the concept of a flexible graph is slightly different in graph theory, and the definition is adapted here for the transportation network setting. Graph theory defines a flexible graph as a graph where "its nodes can be moved continuously so that (1) the distances between adjacent nodes are unchanged, and (2) at least two nonadjacent nodes change their mutual distances" (Maehara, 1992).

Overall, these illustrations highlight the need to distinguish network-level transportation flexibility as an effective *threshold* from lower flexibility levels (for example, node/arc/mix-level) and higher ones (for example, full flexibility level). The configuration of the transportation network structure – in terms of the number, position, and capacity of arcs and nodes – affects an LSP's ability to provide network-level flexibility (Chandra et al., 2005). For instance, having nodes with higher degrees (out-degree plus in-degree) can increase the likelihood of maintaining network-level flexibility under demand changes. The following section, therefore, examines how the transportation network's structure influences network-level flexibility.

4. Transportation network structure and flexibility

This section discusses the impact of network structure on network-level transportation flexibility. Building on the conceptual framework established in Section 3, the analysis compares a set of canonical topologies of transportation networks to determine the impact of structural connectivity patterns on the existence of feasible origin–destination itineraries under capacity constraints. The section starts by introducing the network structures used in this study, then explains the analytical scope and experimental design characteristics, and ultimately assesses network flexibility using a proposed simulation-based index of flexibility.

4.1. Transportation network structures

To examine the impact of network structure on transportation flexibility, concepts from complex adaptive systems theory are applied to formalize structural complexity (Langton, 1990; Kauffman, 1993). In this perspective, interactions of system elements can be represented using an *NK* model to understand their system-wide impact (Kauffman, 1993). In the *NK* model, a system consists of *N* elements (for example, nodes) with *K* interactions among them (for example, arcs). Illustratively, in a transportation network with $N = 12$ and $K = 3$, each node has an average of 3 arcs, yielding a network with 12 nodes and 36 arcs.

Many scholars identified different types of topologies to characterize network structures in their studies (see, for example, Rivkin and Siggelkow, 2007 (decision-making structures), Lin and Ban, 2013; Zhang et al., 2015 (transportation network structures), Kim et al., 2015 (supply network structures) and Perera et al., 2017 (supply chain network topologies)). Zhang et al. (2015) assessed the resilience of 17 types of transportation network structures, categorized into four connectivity types ranging from complete to random. Kim et al. (2015) applied four network topologies (from Rivkin and Siggelkow, 2007) to characterize resilience in supply network structures. Drawing on these structures, seven main transportation network topologies are identified: chain, small-world, cluster, hub-and-spoke, scale-free, grid, and random (Fig. 7).

The selection of seven structures from the broader set of candidate topologies (17 from Zhang et al., 2015, and 10 from Rivkin and Siggelkow, 2007) is based on two main criteria: distinct structural characteristics and relevance to real-world freight transportation networks. In each of these two studies, equivalent structures exempted first (in Rivkin and Siggelkow (2007), dependent, hierarchical, and preferential attachment are structurally akin to the centralized, diagonal, and scale-free, respectively, and in Zhang et al. (2015) central ring, double tree and complete grid, are structurally akin to converging tails, hub-and-spoke and complete network, respectively). Then, similarities among the remaining structures of the two studies are removed. Finally, the relevance of the remaining unique structures to real-world transportation networks is evaluated, and the seven most practical network topologies are identified.

These seven canonical network structures are adapted to the transportation network context, where goods flow from the source node to the other nodes and finally reach the sink node via directed arcs (digraph). This yields comparable *NK* representations across structures by keeping the number of nodes *N* constant and allowing limited variation in the number of arcs *K* consistent with each topology. Following Zhang et al. (2015), $N = 10$ is set for each transportation network, including a source node and a sink node from the shippers' supply chain, to isolate the analysis for meaningful comparison across seven structures (Borgatti and Li, 2009). Fixing *N* across topologies is a design decision that allows the observed variation in flexibility to be attributed to structural connectivity patterns rather than network-scale effects. Additional constraints are that every intermediate node has to be linked (positive in-degree and out-degree) so that no isolated nodes occur. Transportation nodes are labeled from n1 to n8, while the number of arcs varies by topology (from 9 in the chain structure to 21 in the hub-and-spoke structure). This design maintains comparable complexity while retaining unique structural patterns. Fig. 7 depicts the structures and their degree distributions. Each topology is described below with an illustrative real-world example.

4.1.1. Canonical transportation network structures

The chain or local structure (Fig. 8a) is the most basic form of a transportation network, in which a linear chain of nodes connects the source and sink nodes. It resembles a ring network structure where two consecutive nodes are source and sink nodes (Zhang et al., 2015). The chain and ring freight transportation networks (for example, roads or railways) are usually part of a larger transportation network.

The Small-world network structure (Fig. 8b) is formed when nodes are clustered locally and connected by a few long-distance links that bridge clusters (Zhang et al., 2015; Rivkin and Siggelkow, 2007). A real-world example is the worldwide maritime transportation network with container liners functioning as network arcs (Hu and Zhu, 2009).

In the cluster (or block-diagonal) network structure (Fig. 8c), nodes are connected only within each cluster, and each cluster connects the source to the sink independently (Kim et al., 2015; Rivkin and Siggelkow, 2007). Examples include transportation clusters in the Rotterdam-Antwerp-Duisburg triangle and the Singapore port area (Sheffi, 2012).

The hub-and-spoke (or centralized) structure (Fig. 8d) is a star topology in which most nodes connect to a central hub. It resembles a winner-take-all pattern (Barabási, 2002), in which the degree of the central hub(s) is significantly higher than that of other nodes (Barabási, 2002; Zhang et al., 2015). Typical examples include air freight networks and LSP networks such as DHL and UPS (Rodrigue et al., 2016).

In the scale-free network structure (Fig. 8e), most nodes have few connections. In contrast, a small number of nodes have excessively many connections, where the most prominent hub is closely followed by a smaller one with almost the same number of connections (Barabási, 2002; Rivkin and Siggelkow, 2007). This results in a highly skewed distribution of node degrees, representing a power-law or Pareto distribution. Barabási (2002: page 103) shows this as the rich-get-richer pattern, where the hierarchy of node degrees distinguishes this network structure from the highly centralized hub-and-spoke structure. Xu et al. (2007) demonstrated China's ship transportation network (including 42 seaports and 120 river ports) as a scale-free structure, where seaports have extensive hinterland connections following an approximate power-law degree distribution.

In the grid (mesh or distributed) structure (Fig. 8f), each node connects to a small set of neighbors, representing a relatively uniform degree distribution in the network (Barabási, 2002; Zhang et al., 2015). Examples include railway and road networks in different countries (for example, the US highway network) (Barabási, 2002; Rodrigue et al., 2016).

In the random network structure (Fig. 8g), most nodes have a similar number of arcs, and no node has a high number of arcs. The degree distribution of the random network follows a bell curve, i.e., a normal distribution with a small standard deviation (Barabási, 2002). A typical example is road transportation networks. Barabási (2002) describes the US National Highway network as a random network in which arcs

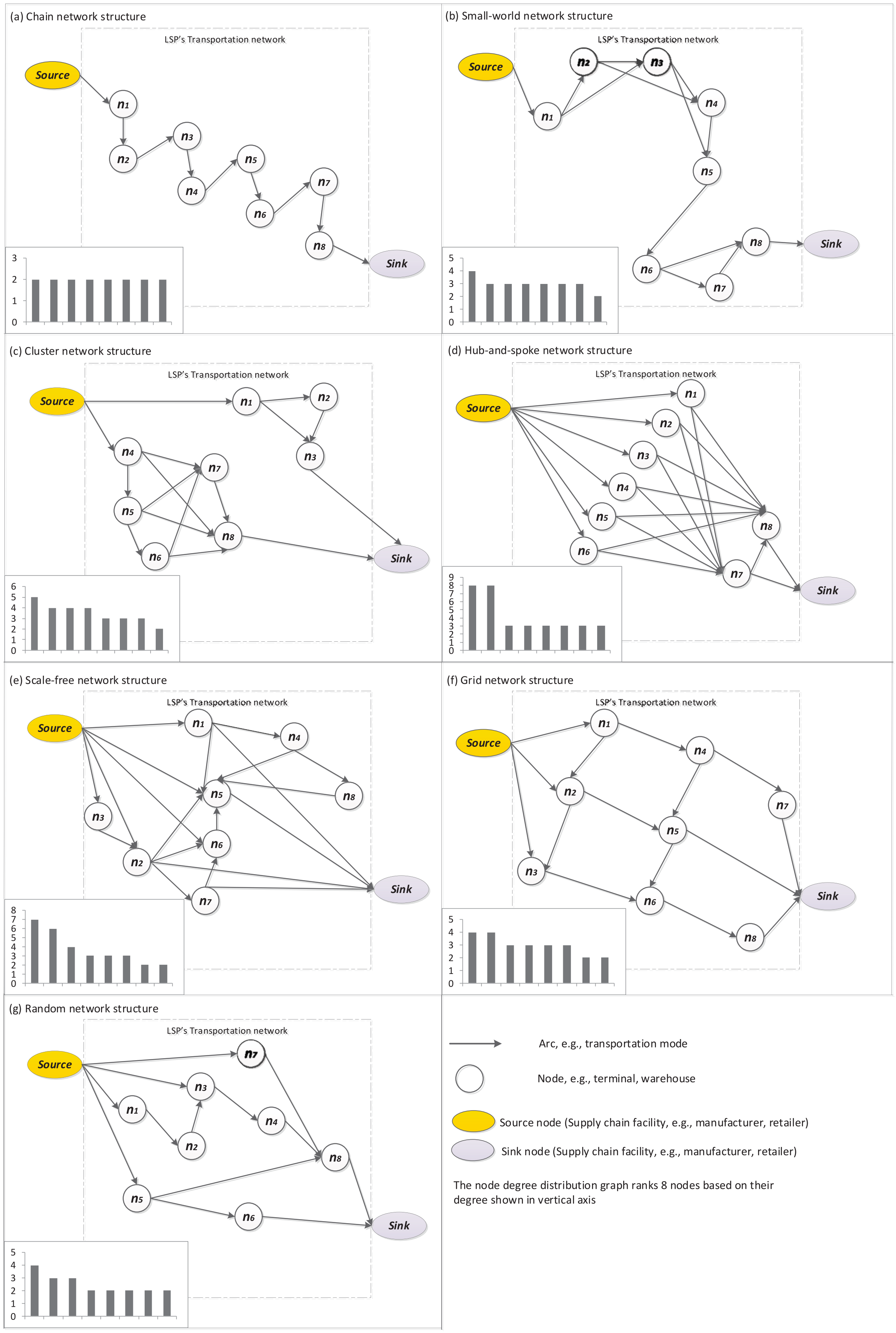

Fig. 7. Seven canonical transportation network structures with their node degree distributions (authors).

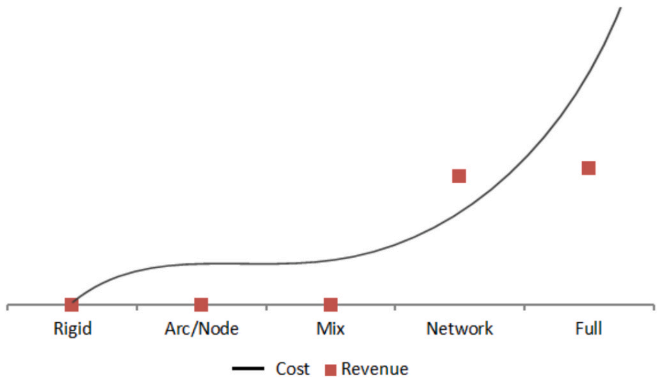

Fig. 8. A conceptual understanding of cost and revenue trade-offs for flexibility levels (authors).

represent major highways connecting nodes (for example, cities).

Although any combination of these structures may exist in the real world, they are compared independently here to isolate structural effects.

4.2. Analytical scope and experimental design

This section explains the methodological scope of this study. Transportation network flexibility is considered a structural, network-level capability, defined by the existence of at least one feasible origin–destination itinerary that satisfies joint volume and time capacity constraints. Capacity constraints are treated as exogenous feasibility conditions of nodes and arcs rather than as decision variables. This viewpoint intentionally abstracts from operational performance outcomes, including travel time, service frequency, reliability, and cost-effectiveness, that result from routing, scheduling, and control decisions implemented on a particular network. These operational decisions operate at a different level of analysis than network structure, as they describe how a given structure is utilized rather than whether that structure admits feasible alternatives in the first place. The simultaneous modeling of structural feasibility and operational performance would thus confound the two different explanatory processes: structural constraints and operational control, hence changing the unit of analysis and obscuring the independent influence of network topology. The analysis isolates the structure of the transportation network as a key precondition for operational responses to changes in demand or disruptions, focusing on structural feasibility rather than operational utilization. This abstraction permits a theory-driven comparison of network architectures and allows the examination of structural patterns that affect network-level flexibility independently of short-term operational control mechanisms.

Based on this structural view, the study's computational experiments use hypothetical transportation network topologies of stylized sizes to isolate the influence of network topology on transportation network flexibility. This design decision is indicative of the study's theory-building aim: to determine structural tendencies and comparative insights across canonical networks, rather than to simulate, calibrate, or predict the behavior of particular real-world transportation systems. Applying size-controlled networks does not allow confounding structural effects with network size, geographic embedding, data-specific idiosyncrasies, or operational control policies – issues that, in empirical contexts, are usually highly intertwined and make the attribution of observed flexibility outcomes to network structure alone unattainable. By keeping network size constant and varying only the connectivity pattern, the experiments enable a principled comparison of network structures and support causal inference on how topology shapes the probability that at least one feasible origin–destination itinerary exists under stochastic capacity degradation. The results are therefore not to be interpreted as predictive of the behaviour of specific transportation networks; instead, they are intended to elicit general structural properties and tendencies related to various transportation network topologies. This abstraction is in line with theory-oriented work in network science (for example, Perera et al., 2017) and transportation research (for example, Zhang et al., 2015; Kim et al., 2015), where stylized models are then used to discover underlying relationships that can be used to inform a future empirical study or practical network design.

4.3. Flexibility of main transportation networks

In this section, a transportation network flexibility index and a simulation model are developed to compare the seven network structures in terms of flexibility. Moreover, popular network analysis metrics are computed to determine whether they can explain differences in flexibility among topologies. The comparison assesses the ability of conventional metrics to forecast transportation network flexibility compared with the proposed index of network flexibility.

4.3.1. Transportation flexibility index measure and other network metrics

Several network analysis measures for assessing transportation network flexibility have been introduced in the literature. Network metrics such as Cyclomatic number, network diameter, Alpha index, Gamma index (Rodrigue et al., 2016), network density, average degree (or Beta index), number of walks, average walk length, minimum walk length, maximum walk length, network connectivity (Wasserman and Faust, 1994), average clustering coefficient (Albert and Barabási, 2002) and network centralization (Freeman, 1978) are used. Table 1 shows the definitions and formulas for these metrics. Using Microsoft Excel and Gephi software for network analysis, these metrics are calculated for each topology and presented in Table 2.

The final measure is the transportation network flexibility index computed via a simulation model. The proposed index is a probabilistic measure of structural feasibility under joint volume and time capacity constraints. A transportation network is considered structurally flexible when at least one residual walk exists between the source and sink nodes with sufficient capacity (volume and time) to meet customer demand. In this formulation, route constraints and capacity limits are addressed directly through the residual network: an origin–destination itinerary is possible only when there exists at least one directed path in the residual network for which every arc and intermediate node has sufficient residual volume and time capacity to satisfy the required shipment.

To compute the proposed transportation network flexibility index, the probability of finding at least one residual walk between source and sink, i.e., one feasible transportation itinerary, is estimated under dynamically changing residual capacities. Each node/arc is considered available if it has enough capacity (i.e., remaining volume and time capacity) to meet a customer request. Thus, random deactivation of arcs and/or nodes between the source and sink generates scenarios that represent the likelihood of finding a residual walk in the network. This stochastic mechanism represents time-dependent operational stressors (such as congestion, demand surges, temporary service unavailability, or localized disruptions) that decrease adequate capacity availability over time without explicitly modeling routing, scheduling, or delay processes.

Each simulation run determines if a combination of available residual nodes/arcs could contribute to a network-level residual walk. For each topology, the total number of combinations of arc/node deactivations that make a valid residual walk from source to sink is calculated. Dividing this number by the total number of possible combinations of arc/node deactivations, i.e., the total number of simulation runs, yields the probability of finding a residual walk in each network structure. In other words, the numerator is the total number of node/arc deactivations that still leave one network-level residual walk in the network, and the denominator is the total number of possible arc/node deactivations. In formal,

Table 1
Definition and formulas of common network metrics.

Network metrics	Expression	Definition
Cyclomatic number	$a - n + G$	The maximum number of independent circuits in a network
Diameter	$\max_{i \neq j} p_{ij}$	The maximum of all shortest paths (i.e., number of nodes) of all OD pairs in the network
Density	$a/n(n-1)$	The ratio of the total number of existing arcs to the total number of possible arcs
Avg. degree	$\frac{1}{n}\sum_{i=1}^{n} a_i$	The average number of arcs incident across all nodes
Alpha index	$\frac{a-n+G}{2n-5}$	The ratio of the number of cycles to the maximum possible number of cycles
Gamma index	$\frac{a}{3(n-2)}$	The ratio of the number of arcs to the maximum possible number of arcs
Walks	–	Number of possible walks from source to sink
Avg. walk length	–	The average of the walks' length (i.e., number of arcs and nodes along the walk)
Max. walk length	–	The highest walk length, i.e., the longest walk
Min. walk length	–	The lowest walk length, i.e., the shortest walk
Connectivity	–	The minimum number of arcs and/or nodes that need to be removed from the network to disconnect it
Avg. clustering coefficient	$\frac{1}{n}\sum_{i=1}^{n} \frac{y_i}{d_i(d_i-1)}$	Indicates the degree of clustering of a graph and demonstrates the probability that two neighbors of a node are neighbors themselves
Centralization (%)	$\frac{\sum_{i=1}^{n} C(n^*) - C(n_i)}{max\sum_{i=1}^{n} C(n^*) - C(n_i)}$	Measures the structural centrality of a network or how network connections are concentrated around a few nodes

Note: a: number of arcs in the graph, n: number of nodes in the graph, G: number of sub-graphs in the graph, p_{ij}: the distance (i.e., the number of nodes) of the shortest path between OD pair (i,j), a_i: number of arcs incident on node i, d_i: the degree of node i, y_i: the number of arcs among neighbors of node i, $C(n_i)$ is the degree centrality of node i, and $C(n^*)$ is the maximum value of $C(n_i)$ in the network.

Transportation network flexibility = total number of network-level flexibility scenarios/total number of flexibility scenarios (from rigid flexibility to full flexibility).

Because volume and time capacities can vary across arcs and nodes, a node or arc is considered available only if both capacity dimensions are sufficient to meet the demand request. A simulation model is implemented in Visual Basic. In each simulation run, arcs, nodes, or their combination (between source and sink nodes) are randomly deactivated. To focus on structural differences, a uniform deactivation probability is used across arcs and nodes. The model then checks whether at least one network-level residual walk exists with sufficient capacity to meet the customer's demand; i.e., the network is flexible at least at the network level. The simulation is iterated for sample sizes of 5000, 10,000, 25,000, and 50,000 for each topology. The flexibility index for each sample size is computed as the proportion of runs in which a network-level residual walk exists. Table 2 shows the flexibility indices for 50,000 iterations. The rankings are entirely consistent across the sample sizes, which is a strong check of their validity.

4.3.2. *Comparing the flexibility of transportation networks*

The diverse scores in Table 2 indicate the substantial impact of network structures on LSP's ability to provide transportation flexibility. In particular, the scale-free structure shows the highest flexibility (0.369), followed by hub-and-spoke (0.256). The cluster structure ranks third (0.096), well below the top two. These results provide a baseline for examining how well traditional network metrics predict transportation network flexibility.

A larger number of cycles (a higher cyclomatic number) or a higher density (more arcs) might be expected to increase flexibility. However, the hub-and-spoke network has more cycles and arcs than a scale-free network but does not achieve the highest flexibility. Similarly, connectivity-related measures (average degree, alpha index, gamma index) are highest for the hub-and-spoke topology, yet it is not the most flexible. A higher number of walks or a lower average walk length might intuitively be considered for identifying flexibility, but, again, these measures incorrectly predict the hub-and-spoke structure as the most flexible topology. Maximum and minimum walk lengths are also not reliable predictors of network flexibility. Another assumption is greater concentration on a few nodes in a network (for example, a higher centralization score), which recognizes only the second-highest flexible structure.

A high connectivity measure (when disconnection requires deactivating more nodes/arcs) does not imply high flexibility; for example, the grid structure has the highest connectivity but is among the least flexible structures. Although the average clustering coefficient correctly identifies scale-free as the most flexible topology, it incorrectly suggests cluster rather than hub-and-spoke as the second-highest. Even combining metrics (for instance, high clustering coefficient, high connectivity, and low diameter) fails to correctly predict the second-highest flexible structure. Overall, these comparisons indicate that common network analysis measures are not sufficiently consistent and reliable predictors of transportation network flexibility. Moreover, it should be

Table 2
Network metrics and proposed flexibility index for canonical transportation network structures.

Network Metrics	Network type						
	Chain	Small-world	Cluster	Hub-and-spoke	Scale-free	Grid	Random
Node/Arcs	10/9	10/16	10/16	10/21	10/20	10/15	10/13
Cyclomatic number	0	7	7	12	10	6	4
Diameter	8	5	2	2	2	3	4
Density	0.10	0.18	0.18	0.23	0.21	0.17	0.14
Avg. degree	1.8	2.6	3.2	4.2	3.8	3	2.6
Alpha index	0.00	0.47	0.47	0.80	0.67	0.40	0.27
Gamma index	0.38	0.67	0.67	0.88	0.79	0.63	0.54
Walks	1	10	10	18	15	10	5
Avg. walk length	17	12.8	7.2	5.4	6.3	8.4	6.6
Max. walk length	17	16	10	7	11	11	11
Min. walk length	17	8	4	5	3	5	5
Connectivity	1	1	2	2	3	3	2
Avg. clustering coefficient	0.00	0.19	0.27	0.18	0.31	0.08	0.00
Centralization (%)	0.03	0.19	0.25	0.53	0.44	0.14	0.19
Flexibility index	0.000	0.002	0.096	0.256	0.369	0.057	0.091

noted that the transportation network flexibility index is intended to be a relative measure of structural flexibility across network topologies when capacity is stochastically degraded, rather than a measure of actual or forecasted performance in the real world.

5. Discussions and implications

While transportation flexibility has been studied in the literature, the lack of a system-wide perspective on the network-level operations of a flexible transportation network has hindered further development of the transportation and supply chain management literature, particularly given the emerging role of flexible transportation services in improving the flexibility and resilience of global supply chains. Complexity theory has established that a system's emergent behavior arises from its components' actions and interactions. Adopting a network-level perspective on transportation flexibility clarifies how flexibility emerges from the structural configuration of transportation networks, rather than from individual arcs or nodes alone. This perspective provides a stronger foundation for both scholarly research and managerial decision-making regarding transportation flexibility.

5.1. Implications for practice

This study offers several insights for LSP managers, highlighting their role in designing flexible transportation networks as the backbone of flexible transportation services. The most crucial implication is changing the attitude of LSP managers towards a system perspective to flexible transportation networks as a whole, rather than a mixture of flexible arcs and nodes. It leads to a better understanding of the vital role of network structure and the position of nodes and arcs in building network-level flexibility in the transportation network. The relative positions of individual nodes and arcs, and how they are linked to form the transportation network, need to be carefully considered.

LSP managers can significantly improve the flexibility of a transportation network by managing its structure. In particular, adopting a network connectivity structure consistent with a scale-free (Power-law) network topology increases the likelihood of achieving network-level flexibility. LSP managers can investigate how much their network structure follows a Power-law or Pareto distribution (Mitzenmacher, 2004). For example, when about 20% of the warehouses and terminals are connected to 80% of the other facilities via transportation modes, the network structure follows a Pareto distribution. The closer to a power-law distribution, the higher the flexibility index is expected to be. It highlights that the position of a warehouse or a terminal in the network matters more than its high storage and/or cross-docking capacity. Consequently, infrastructure investment decisions should place greater emphasis on the capacity expansion of critical nodes (for example, those in the top 20% of the power-law distribution), since their operational capacity plays a strategic role in maintaining desired service levels for customers.

Not all LSPs are equally capable of delivering greater degrees of flexibility. Asset-based carriers (2PLs) and most traditional 3PLs usually have pre-established modal, contractual, or geographic coverage and cannot provide flexibility beyond what they offer in their operational coverage. Non-asset-based 3PLs, and in particular 4PL-type orchestrators, which have greater planning authority and coordination across multiple carriers and transport modes, are better positioned to offer network-level transportation flexibility. This difference explains why network-level flexibility is a realistic and cost-effective goal for LSPs, whereas complete flexibility is too expensive for many providers.

An essential factor for LSP managers is the cost of providing different levels of flexibility (Gerwin, 1993). Fig. 8 provides a conceptual framework for how varying levels of transportation flexibility could affect LSPs' expenses and revenues. The expected cost of providing different flexibility levels increases from arc/node/mix to full flexibility. While providing network-level flexibility may cost more than arc/node/mix levels, it is significantly lower than providing a fully flexible transportation network, in which all nodes and arcs remain flexible at all times, which would entail high investment and maintenance costs. It indicates the importance of the network structure in enabling efficient provision of network-level flexibility, for example, by maintaining sufficient residual capacity on critical nodes/arcs in a scale-free network. From a revenue-generation perspective, while network-level and full-level flexibilities also generate the same revenue, other flexibility levels may not generate revenue because they cannot offer flexible transportation services. As a result, the profitability of network-level flexibility is expected to be higher than that of other flexibility levels.

Although having more than one flexible walk, i.e., multiple feasible itineraries, does not raise the level of flexibility beyond network-level flexibility, it can provide cost advantages by allowing LSPs to choose lower-cost itineraries among available options. These benefits are mainly available to LSPs with a network-wide presence and decision-making authority. Although fully flexible networks can lower the average fulfillment costs per request, their long-run cost structure can be expensive, limiting their economic appeal.

LSPs can differentiate their transportation service packages by grading flexibility based on their capability to accommodate different numbers of customer change requests. When network-level flexibility is developed as an internal capability, transportation services can be distinguished by their flexibility grade, defined as the proportion of change requests satisfied. The flexibility grade of a transportation service can be measured as follows:

Transportation service flexibility grade (FG) = The number of successful change fulfilments/The total number of change requests by the shipper firm.

For example, when LSP's network can accommodate 75% of change requests, it can be considered high-grade flexibility. Therefore, FG > 75%, FG > 50%, and FG > 25% could be regarded as high-grade, Medium-grade, and Low-grade service flexibility, respectively.

Transportation network flexibility can also be improved through governance and coordination mechanisms. LSPs can utilize parallel arcs and modes more effectively once shippers delegate routing and mode-choice decisions to them, based on the foundations of synchromodal transportation systems (Tavasszy et al., 2010; Khakdaman et al., 2020; Acero et al., 2022; Alaei et al., 2024). This authority transfer provides more freedom for LSPs to plan their transportation operations, offering higher flexibility in the transportation network's arcs and lower overall average costs (Khakdaman et al., 2020). The transfer of such authority is best suited to non-asset-based 3PLs and 4PL orchestrators, as these entities have network-wide planning capabilities and can utilize residual capacity more effectively.

Flexible nodes, such as cross-docking terminals and warehouses, are central to enabling aggregation, deconsolidation, and rerouting of flows under changing shipment requirements. Network-structurally, collaboration among LSPs can be an effective way to expand the pool of available nodes and arcs without necessarily expanding the physical infrastructure, and hence increasing the number of possible origin–destination itineraries. Horizontal collaboration between LSPs on the same tier (for example, 3PL–3PL collaboration) enables partners to share logistics infrastructure, such as regional distribution centers or cross-docking terminals, and provides another way to effectively create additional alternative paths and decrease the risk of network disconnection by the failure or saturation of a single node (Sheffi, 2012; Ballot et al., 2021).

Vertical collaboration among supply chain tiers, for example, between shippers, LSPs, and carriers, allows the distribution of routing and mode-selection authorities to logistics providers. These arrangements can dynamically redistribute transportation flows across parallel arcs or modes connecting the same origin–destination itineraries, making it more likely that at least one unutilized itinerary remains available when capacity constraints tighten (Tavasszy et al., 2010; Acero et al., 2022).

Diagonal collaboration happens when orchestrating providers – usually non-asset-based 3PLs or 4PLs – coordinate a variety of carriers, terminals, and transport modes across service layers. In synchromodal and Physical Internet systems, network nodes and arcs across operators interoperate using standardized interfaces and shared infrastructure, enabling functional integration of the network structure across operators and, thus, facilitating expanded connectivity and resiliency of the network structure (Montreuil, 2011; Ballot et al., 2021; Matusiewicz et al., 2024).

In these collaborations, the resulting structural impact is typically the expansion and recombination of viable network elements, which enhance the probability of sustaining at least one feasible residual itinerary between source and sink during capacity degradation, a notion of network-level transportation flexibility adopted in the research.

5.2. Implications for research

One of the key implications of this study is the need to reconceptualize transportation flexibility research by treating the network level as the unit of analysis rather than generalizing system-wide flexibility from the characteristics of individual network nodes, arcs, or facilities. A majority of the available literature focuses on local responsiveness and then generalizes such results to network-level outcomes, which risks ecological and atomistic fallacies when conclusions are transferred across analytical levels. Recent research on transportation network resilience and recovery has shown that system-level performance is highly dependent on network structure rather than on the performance of individual components. Future studies should thus clearly differentiate between network-level transportation flexibility and arc- and node-level flexibility, and justify the level of analysis at which flexibility theorizing and measurement are performed. Network-level flexibility, defined as the existence of at least one feasible origin–destination itinerary subject to capacity and time constraints, should be considered a distinct structural property, in line with network science perspectives on emergent system behavior (Borgatti and Li, 2009).

The research also has implications for empirical research design and measurement in transportation and logistics. The empirical literature often uses static network statistics (such as density, degree, connectivity, or centralization) as proxies for flexibility, robustness, or adaptability (for example, Lin and Ban, 2013; Zanin et al., 2018). Nevertheless, current empirical studies of freight and intermodal networks indicate that these metrics fail to provide an adequate understanding of how networks can adapt to change in the face of congestion, disruption, or demand spikes (Salvo et al., 2025; Goodarzi et al., 2024). Future empirical studies need to adopt feasibility-based and stress-testing approaches that explicitly assess the existence of alternative origin–destination itineraries in the presence of stochastic capacity degradation. Notably, empirical designs should draw a clear distinction between structural feasibility (the existence of feasible itineraries) and operational performance (the efficiency of using them), because conflating these dimensions undermines causal inferences about the impact of network structure.

The results also suggest that network design, optimization, and modeling studies consider network-level flexibility as an explicit analytical objective rather than a by-product of reserve capacity or redundancy. The classic models in transportation network design typically focus on cost-effectiveness or service performance under nominal conditions without necessarily considering whether the resulting structures would admit viable alternatives when capacity is degraded (Farahani et al., 2013). Innovations in stochastic optimization and resilience modeling indicate that incorporating feasibility under uncertainty as a design criterion can produce more structurally adaptable networks with no excessive cost increases (Goodarzi et al., 2024). Further studies can incorporate network flexibility measures (the likelihood of having at least one viable origin–destination itinerary under stochastic time- and volume-capacity degradation) into network design, assignment, and multi-commodity flow models. These formulations would enable the systematic investigation of trade-offs among efficiency, robustness, and flexibility, and could result in a shift of interest from uniform capacity expansion to the strategic placement of capacity within the network.

Lastly, this paper provides a foundation for bridging transportation network flexibility studies with related streams on resilience, synchromodality, and the Physical Internet. Although this literature focuses on adaptability and dynamic reconfiguration, recent reviews indicate that it often fails to distinguish between structural enablers and operational control mechanisms (Alaei et al., 2024; Ballot et al., 2021). Network-level transportation flexibility provides a formal way to assess the structural conditions required to support resilience strategies or synchromodal decision-making before attempting operational switching. Future studies can thus apply network flexibility metrics as a structural benchmark to evaluate synchromodal systems and Physical Internet architectures, especially under disruption scenarios or capacity tensions. The clear separation of structural feasibility from operational implementation in future studies can enhance theoretical consistency and empirical rigor in transportation, logistics, and supply chain research.

6. Conclusions, limitations, and future research directions

This research advances the existing literature by characterizing transportation network flexibility as a structural, network-level capability rather than an operational performance outcome. This study draws on graph theory and complex adaptive systems theory to formally define the concept of transportation network flexibility by distinguishing between the flexibility of arcs/nodes and the flexibility at the network level, thereby clarifying the appropriate unit and level of analysis for flexibility research. Present definitions in the transportation flexibility literature fail to explicitly differentiate operational service-level flexibility from structural network-level flexibility, which could lead to flexibility challenges being considered mostly at the node or arc level and to limited or unreliable inferences about network-level impacts. The proposed definition and conceptualization enable logistics service providers (LSPs) to interpret transportation network flexibility as a “little yet adequate” level of structural flexibility to support effective strategic, tactical, and operational decisions, without incurring excess costs of having fully flexible network designs.

Beyond conceptual clarification, this study investigates the critical role of transportation network structure in achieving network-level flexibility by identifying and comparing the flexibility of seven canonical transportation network topologies under controlled conditions that isolate structural effects. The results show that network structures with power-law degree distributions, such as scale-free networks, exhibit substantially higher transportation network flexibility than alternative topologies. These findings highlight network structure as a key driver of flexibility, complementing common operational practices that seek to enhance flexibility via allocating extra capacity to nodes or arcs.

Finally, this study develops a transportation network flexibility index and compares it with commonly used network topological metrics. Methodologically, the study advances existing methods by proposing a probabilistic, residual-network-based index of flexibility that captures joint volume and time capacity and reveals the shortcomings of conventional topological measures in evaluating network-level flexibility. The proposed flexibility index is a principled approach for assessing the role of network structure in supporting or limiting flexibility, by shifting the assessment of flexibility from static structural descriptors to a probabilistic evaluation of feasible origin–destination itineraries under volume and time capacity uncertainties.

Multiple academic and professional communities can apply the contributions of this study. For graph theory and network science researchers, the study shows that topological descriptors are inadequate for assessing flexibility-related capabilities and proposes a probabilistic, feasibility-based approach that captures emergent behavior at the network level under capacity constraints. For scholars of logistics and supply chain management, the research highlights the distinction between operational transportation service flexibility and structural transportation network flexibility, and offers a formal framework for studying how network structure shapes an LSP's capability to support changes demanded by shippers. For practitioners and policymakers in transportation network design and resilience, the study suggests network structure as a strategic design lever and provides a method to evaluate flexibility beyond incremental capacity additions at specific nodes or connections.

Assumptions made for this study introduce limitations and suggest directions for future research. First, the analysis assumes uniform probabilities of arc and node deactivation in the residual network, implying equal likelihood that all network elements retain sufficient capacity to satisfy a customer request. While this assumption isolates structural effects, it may not be realistic in real-world networks, where the importance of nodes and arcs varies with their operational characteristics. Future studies can relax this assumption by incorporating heterogeneous or correlated deactivation probabilities to investigate the interactive effect of structural flexibility and uneven capacity distributions.

Second, the analysis does not account for heterogeneous arc/node resource magnitudes, including volume and time capacity. Even though such an assumption allows theory-based, controlled comparisons across network structures, future research can examine how heterogeneous resource allocations affect the probability of having feasible origin–destination itineraries in the face of uncertainty.

Third, the transportation network topologies in this study are stylized and size-controlled, which limits direct generalizability. By fixing the number of nodes across network structures, the analysis actually isolates topological influences instead of measuring scale-dependent phenomena. Although this design choice provides a meaningful structural comparison, future studies can expand the analysis to include larger, empirically based networks to investigate the joint influences of scale and topology on transportation network flexibility.

Finally, although transportation flexibility is an emerging research area, the concepts and measurements of network flexibility remain underexplored. This calls for further analytical and empirical research revealing the role and impact of transportation network flexibility on the overall flexibility and responsiveness of the supply chain network. Future work could incorporate multimodal transportation networks to investigate the potential for finding more itineraries, particularly during network disruptions. Spatial metrics, such as straightness centrality (Lin and Ban, 2013), can be applied to real-world spatial transportation networks to investigate the impact of spatial variables on network flexibility. The concept of a flexible transportation network could be integrated into analytical and operational research studies of classic flow problems, including assignment, transportation, multi-commodity flow, and minimum-cost flow models (Flow Network, 2019). Empirical research can also apply the transportation service flexibility grades introduced in this study to assess the willingness of shipper supply chains to utilize flexible transportation services.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgment

No funding was received to support this study.

Data availability

No data was used for the research described in the article.

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