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Demand estimation adapted to hyperconnected transport systems in regional areas

Liz Araceli Cristaldo[1], Eva Petitdemange[2], Matthieu Lauras[1,2], Benoit Montreuil[2,1]
[1]Industrial Engineering Center, IMT Mines Albi – University of Toulouse, Albi, France
[2]Physical Internet Center, ISyE, Georgia Institute of Technology, Atlanta, USA
Corresponding author: liz.cristaldo_jimenez@mines-albi.fr

Abstract: *Regional transportation systems face multiple challenges, including inadequate service quality and scarce and geographically dispersed demand. The Physical Internet (PI) concept offers potential solutions to these issues, yet its focus has primarily been on urban and freight-oriented contexts, overlooking the unique challenges of regional transportation. Moreover, the limited analysis of regional transportation has resulted in a lack of detailed understanding of demand dynamics and difficulties in aligning supply capabilities with demand expectations. To address these issues, this paper proposes a methodology for analyzing regional transport demand, that embraces the PI concept by treating both freight and passenger demand within a unified framework. The methodology defines user profiles, characterizes demand in terms of volume, time, and space, and identifies the factors influencing transportation use. An experimental study using the ECOTRAIN project validates the effectiveness of this approach. This case study not only shows the applicability of the methodology but also highlights its potential to guide the development of tailored transportation solutions suited to regional areas.*

Keywords: *Hyperconnected, Physical Internet, Demand estimation, Regional, Transportation, Supply Chain management.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☐ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☒ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

Global trade expansion is putting pressure on the existing freight logistics infrastructure (Ambra et al., 2019). Modern delivery expectations, such as same-day delivery and just-in-time procurement, need smaller, more frequent shipments (Bucchiarone et al., 2021), and although innovations are increasing, they are unable to keep up with the demand (Plasch et al., 2021). Similarly, the inadequacy of traditional human mobility solutions has sparked interest in alternative transport initiatives (Bucchiarone et al., 2021). However, access to these initiatives varies significantly by location. While urban centers benefit from several passenger transport options, regional residents largely depend on personal vehicles due to limited alternatives. Yet, this dependency creates access barriers for vulnerable groups who are either not able to drive and/or own a car (Bucchiarone et al., 2021; Eckhardt et al., 2018; Hult et al., 2021; Sieber et al., 2020). Regional freight transportation also faces challenges: efficient delivery is expensive and inefficient, compounded by infrequent service and inadequate infrastructure (Bruzzone et al., 2021). Additionally, regional logistic networks suffer from organizational and spatial fragmentation, operating in silos with minimal cooperation and struggling under the weight of delivery schedules and lean inventory strategies (Sarraj et al., 2014).

At the same time, the Physical Internet (PI) concept (Montreuil, 2011) provides a novel framework to address these logistics and transportation challenges. By advocating an open system of asset sharing and consolidating flows, PI aims to enhance the integration of various transport modes, potentially improving service quality. Given the low and geographically dispersed demand in regional transport, PI's strategies of consolidation and synchronization offer promising solutions for regional transportation networks. By addressing both physical and organizational barriers, this approach aims to improve efficiency and accessibility in areas where traditional logistics and transport systems often fall short. However, the application of the PI concept has predominantly focused on urban settings and freight management, leaving regional contexts largely unexplored.

Moreover, regional transportation systems have been insufficiently analyzed, presenting several scientific challenges including a deficient understanding of detailed transport demand and difficulties in aligning supply capabilities with demand expectations. This research aims to address these challenges by providing a comprehensive understanding of both the quantitative and qualitative aspects of transport demand in regional areas. It aligns with the PI concept, treating both freight and passenger demands within a unified framework, considering them as a single customer base with common transportation needs.

The research work presented in this paper is a prerequisite for such pooling. Essential to this process is the development of methodologies capable of providing a detailed understanding of transportation dynamics, including the specifics of what is being transported, when, and how. Recognizing the unique and evolving needs of regional transport users, PI strategies must be both tailored to these specific requirements and adaptable to changing conditions. This dual need for strategies to be adapted and adaptable brings us to the following research question**: How can we accurately estimate freight and passenger transport demand in regional areas?**

To bring an answer to this question, the paper is structured as follows: Section 2 describes the theoretical background of the research. Section 3 introduces the proposed approach to characterize the regional transport demand. Section 4 describes a use case where the methodology has been applied, and finally, section 5 concludes with reflections on the findings and perspectives for future research.

2 Background and challenges of regional transportation

This section reviews the literature on current methodologies used in demand forecasting for transportation systems, focusing on models that integrate both freight and passenger flows.

Traditional demand forecasting methodologies like the Auto-Regressive Integrated Moving Average (ARIMA) have been widely used due to their capability to handle time series data. However, these models often fail to capture the complex spatial and temporal relationships among various transportation modes. More advanced techniques such as Recurrent Neural Networks (RNN), Convolutional Neural Networks (CNN), and Graph Convolutional Networks (GCN) have emerged to better address these relationships. Despite their advancements, these models predominantly focus on single-mode predictions and struggle to integrate multi-modal data effectively, highlighting the need for a unified approach that can accommodate the spatial-temporal intricacies and facilitate knowledge sharing across different prediction tasks (Ke et al., 2021).

Most existing research on transport demand modeling concentrates on urban environments, benefiting from the availability of extensive passenger and freight data. This focus leaves a notable deficiency in models suitable for regional contexts, where data is often scarce or imbalanced. Recent studies like those by (Liao et al., 2022) and (Toque et al., 2017) advocate for the integration of geographical information and the use of diverse data sources to improve prediction accuracy in these less-documented areas.

Transport demand models typically focus on either passenger or freight flows. This separation leads to inefficiencies, especially in environments where interactions between both flows are significant. The predominant models adjust demand predictions based on price or service level, risking biased estimations by ignoring the competitive effects of different transport modes (Tsekeris & Tsekeris, 2011). This highlights the need for models that are specifically designed to handle both freight and passenger data within a single framework.

There is a significant gap in the literature regarding demand forecasting within intermodal, multimodal, or synchromodal transport systems, particularly in hyperconnected environments. This gap originates from the limited detailed demand descriptions and the scarcity of studies focused on these complex networks. The current methodologies often fall short in accurately characterizing and forecasting demand in regional transport systems that require coordination between different modes.

This paper addresses these gaps by proposing a methodology designed specifically for regional contexts. It incorporates spatial and temporal elements to define more accurately the characteristics of regional transport demand, given the inadequacy of existing models to simultaneously address the demand for freight and passengers in regional transport.

3 Methodological framework for analysis

This chapter introduces a structured methodology designed to analyze the demand in regional transport systems. This methodology treats passenger and freight transport as a unified entity, thereby facilitating the application of the PI concept across both domains without distinguishing between flows. As illustrated in Figure 1, the methodology involves three sequential steps, each addressing a key question.

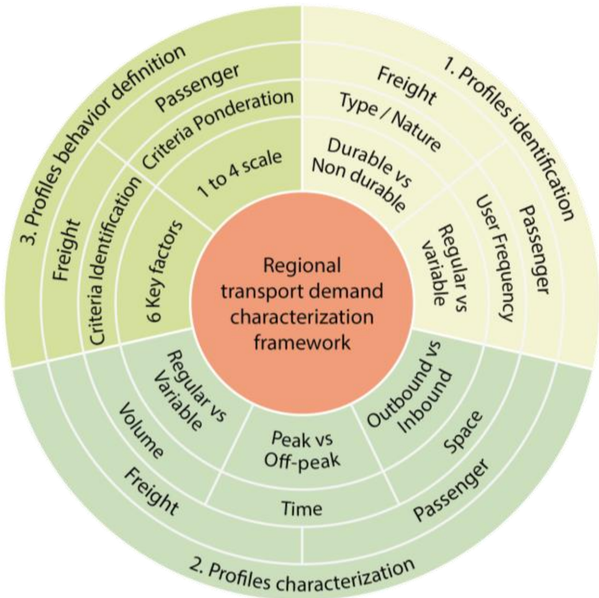

Figure 1: Regional transport demand characterization framework.

3.1. Profiles identification

In this initial phase, the focus is on identifying the potential users of the regional transport systems by establishing clear criteria for segmenting these users. This process addresses the fundamental question: *Which are the user profiles of the regional transport systems?* and is essential for accommodating their diverse transportation needs within a unified operational framework.

Passenger profiling

Users are categorized based on their transport system usage frequency (Kieu et al., 2015). The first group includes frequent commuters who make up most of the daily transportation flows. Their number (volume), travel patterns (points of origin and destination), and schedules are regular. The second group use the services less frequently than the first group, leading to a variable number of users (volume), travel patterns (points of origin and destination), and schedules.

Freight profiling

Freight is categorized based on the type of goods being transported, which affects their transport requirements. The methodology for developing freight profiles was inspired by the goods segmentation outlined by the ASCM (Pittman & Atwater, 2022), which separates goods into durable and non-durable segments. Durable goods are those expected to provide service for more than three years, such as trucks and furniture. Within durable goods, a further distinction is made between consumer goods (e.g., refrigerators) and industrial goods (e.g., forklifts). On the other hand, nondurable goods are those with a service life of less than three years, including perishable and semidurable goods.

3.2. Profiles characterization

Transport demand reflects the need for movement of both people and goods, irrespective of the extent to which these needs are met, and is quantified in terms of number of people, volume, or tons per unit of time and space (Rodrigue, 2020). This definition supports the second step of the methodology, which seeks to analyze the interactions between the different user profiles and the transport systems. The analysis involves a multidimensional characterization, examining volume, timing, and spatial factors, covering both passenger and freight transportation within a single framework. The guiding question here is: *What are the usage patterns of these profiles within the regional transport systems?*

The volume analysis distinguishes between the number of passengers, determined by user frequency, or the number of items moved, expressed in tons (Rodrigue, 2020). Then, the temporal dimension analysis begins by classifying vehicle types as heavy (freight) or light (passenger) and then gathers traffic data on each category. By examining patterns of travel, it distinguishes between peak and off-peak hours, calculating the proportion of traffic for each type during these times. Finally, the spatial analysis concentrates on identifying the most frequented points of origin and destination, considering the layout of residential, commercial, and industrial areas providing to gain insights into movements patterns, as outlined by (Rodrigue, 2020). This differentiation is crucial for understanding the dynamics of both passenger and freight movements. The analysis evaluates cities based on whether they primarily expel or attract passengers. For freight, the focus is on distinguishing between in-shop (retail) movements and domicile (consumer delivery) operations.

3.3. Behaviors definition

Building upon the identified profiles and their usage characteristics, the final step analyses the underlying factors influencing the users' choice of transport. It seeks to reveal the criteria that guide users' preferences and decisions, answering: *What motivates the usage behaviors of customers in the regional transport systems?*

Studies by (Grison et al., 2016) and (Zhu et al., 2017) underline the factors influencing public transport users' choices and satisfaction, pointing out the importance of context in transportation decisions. These studies suggest that user experiences and preferences vary significantly across different situations, suggesting the need for a flexible approach to study user preferences that recognizes these changing influences. (Beirão & Sarsfield Cabral, 2007) further contribute by focusing on the critical aspects of service quality, convenience, and the psychological basis of mode choice, underlining the need for models that adapt to situational contexts and the interplay among factors affecting transportation mode choices.

Building on these observations, this step involves two tasks: initially, identify the factors that influence travel behavior and mode choice among different users, derived from a preliminary literature review. Subsequently, evaluate how these users prioritize such criteria in their mode of transport selection. This involves cross-referencing the list of factors with real-world data to confirm if the theoretical assumptions from literature match actual transportation behaviors.

a. Factors identification

Several studies highlight the significance of transport quality from the passenger's perspective, focusing on factors such as in-vehicle time, comfort, safety, and pricing (Alkharabsheh et al., 2019), along with service quality attributes like reliability and responsiveness (Awasthi et al., 2011). They suggest using both qualitative and quantitative methods to enhance customer satisfaction. (Grison et al., 2017) suggest that comfort often prevails over the availability of transport options, especially for longer journeys, where both practical and emotional considerations influence passenger choices. (Tyrinopoulos & Antoniou, 2014) affirm that service frequency, travel conditions, and punctuality significantly impact satisfaction. Finally, trends in transport preferences are moving towards sustainability and multimodal solutions to improve efficiency and reduce environmental effects (Jonuschat et al., 2015).

From the perspective of freight carriers, the priority shifts to efficiency and logistical effectiveness. (Palšaitis & Ponomariovas, 2012) underline the need for high quality transport services, emphasizing reliability, punctuality, and cost as critical. This perspective is echoed by (Ľoch & Dolinayová, 2015), who identify price and delivery time as the primary criteria for selecting freight services.

Synthesizing the criteria influencing transportation choices, from both passenger and freight domains, as shown in Table 1, six key factors have been identified across the literature.

Table 1: Transportation choices criteria for freight and passengers.

<table>
<tr><th>Factor</th><th>Description for passengers</th><th>Description for freight carriers</th></tr>
<tr><td>Price</td><td colspan="2">It is the negotiated monetary cost of moving a passenger or a unit of freight between a specific origin and destination (Rodrigue, 2020).</td></tr>
<tr><td>Transport time</td><td colspan="2">Concerns the real duration of transport (Rodrigue, 2020). Includes waiting time and in-vehicle time if some.</td></tr>
<tr><td>Environmental impact</td><td colspan="2">Is defined as the measure of carbon emissions from a person, organization, building, or operation (Pittman & Atwater, 2022), and is evaluated based on the carbon footprint produced during the transport of passengers and/or goods.</td></tr>
<tr><td>Timetable compliance. (Reliability)</td><td colspan="2">Signifies the adherence to published timetables, offering a measurable expectation of service reliability through the percentage probability of on-time arrival and/or departure (Pittman & Atwater, 2022).</td></tr>
<tr><td>Comfort</td><td>Assessed through physical and emotional well-being during travel. Physically, it can be quantified by the availability of seats, comparing</td><td>Refers to the conditions under which goods are transported, including material handling and preservation of</td></tr>
</table>

	the time spent seated versus standing (Beirão & Sarsfield Cabral, 2007; Grison et al., 2017).	cargo’s integrity (Pittman & Atwater, 2022).
Safety	Measured by the maximum speed at which the vehicle can react to emergencies, stop safely in response to obstacles or signals, and navigate through curves and other structural elements without causing danger to passengers (Wu et al., 2011).	Security concerns have been directed in two areas: worker safety and theft (Rodrigue, 2020). It refers to measures and practices to safeguard freight during transport.

b. Factors prioritization

To evaluate how each criterion influences user choices, a significance score was assigned to each criterion: 1 (indicating 'Low' importance), 2 (indicating 'Medium' importance), 3 (indicating 'High' importance), and 4 (indicating 'Very High' importance).

4 Application case

The French ECOTRAIN project, aimed at rehabilitating old railway lines and integrating them with other modes of transportation, provides an ideal environment for testing and improving the proposed regional transport demand characterization methodology. This initiative is particularly focused on introducing autonomous regional railway shuttles for both freight and passenger transportation. This section focuses on implementing the framework previously described through a case study involving six cities from the Occitanie region in France: Carcassonne, Castelnaudary, Narbonne, Castres, Béziers, and Revel. These cities were selected for their demographic diversity, population size, existing transport infrastructures, and the potential for integrating new transport services (as part of the ECOTRAIN project), which collectively provide a basis for applying and validating the proposed methodology. Such criteria ensure they mirror the complexities of regional transportation and underscore the project's goal to connect less accessible regions.

4.1. Profiles identification

Passenger profiling

The first category, which comprises regular users, is divided into students and workers who rely on public transport for their daily commutes. The second category includes variable users, notably the elderly, who consistently use the transport system, and tourists, who depend on public transportation (PT) during their visits. Further refinement within these groups took specific characteristics into account: Students were classified by age, while workers and the elderly were differentiated by their socio-professional categories. Tourists, however, are treated as a homogeneous group due to their shared characteristics and expectations of the PT system.

This analysis will primarily focus on the regular users—students and workers. By concentrating on these groups, the study intends to address the core of daily transportation demand, offering solutions for those who most frequently rely on the system.

Freight profiling

Freight was further subdivided based on the categorization of economic activities related to the type of goods being transported: durable and non-durable. Durable goods were further divided into construction, industrial, and consumer goods. Meanwhile, non-durable goods comprised agricultural and livestock products.

4.2. Profiles characterization

Volume

For the passenger volume analysis, INSEE data was used to assess each city's population, which was then classified by profile. Similarly, the freight volume analysis involved estimating the volume for each freight category (in Tons) throughout the cities under study. Figure 2, shown below, illustrates these calculations.

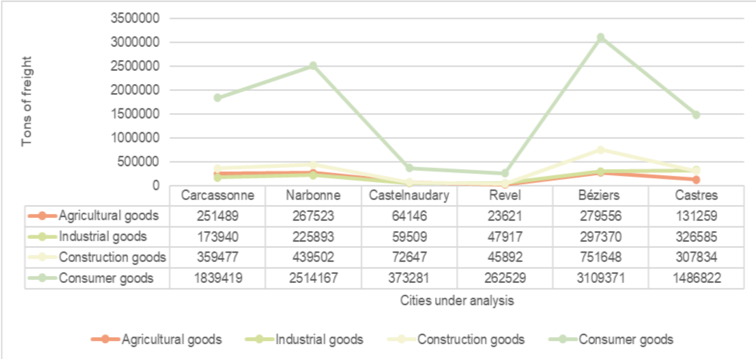

Figure 2: Profiles characterization – Volume dimension – Freight.

Time

The freight and passenger proportions of traffic are used to determine the respective contributions of freight and passenger vehicles to the overall traffic volume. Below, Figure 3 shows these traffic patterns over a 24-hour period, with freight and passenger traffic displayed separately.

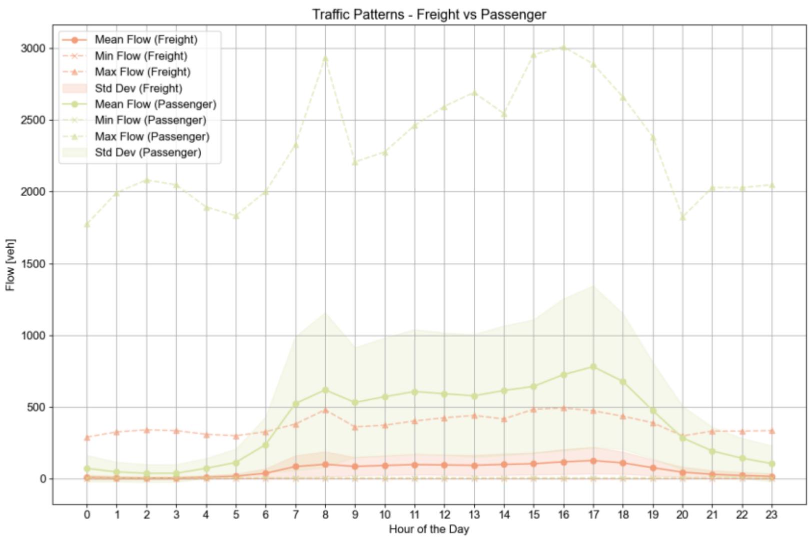

Figure 3: Profiles characterization - Time dimension - Passenger and Freight.

Space

Data from the French National Institute of Statistics and Economic Studies (INSEE) shed light on commuting patterns related to work and education between the cities being studied. Additionally, information on the locations of major employment hubs and educational institutions helps explain why certain cities attract more workers and students than others. Similarly, the freight movement analysis uses the SIRENE database (French System for the Identification of the Directory of Enterprises.), also managed by INSEE. It records legal entities and their branches throughout France and examines the principal activities of these establishments, categorizing them based on their roles in importing (bringing finished products into the city) or exporting (dispatching finished products out of the city).

Figures 4 and 5, shown below, illustrate the movement of students and workers between the cities under analysis. The origins and destinations are color-coded: green indicates cities from which more passengers depart, and red denotes cities that receive more passengers.

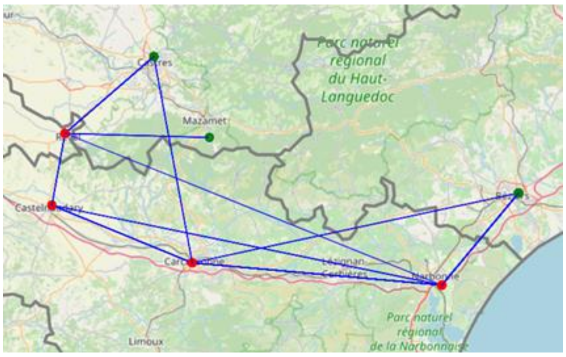

Figure 4: School mobilities of individuals (2019).

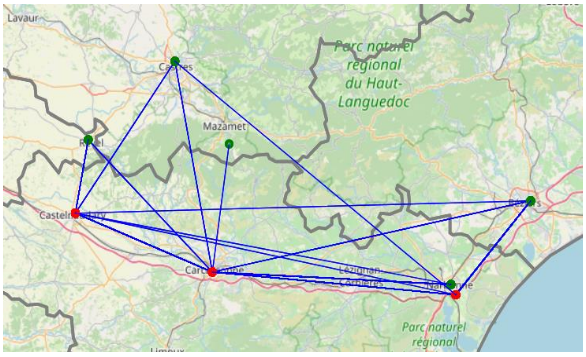

Figure 5: Professional mobility of individuals (2019).

4.3. Behaviors definition

The resulting analysis contrasts the considerations of both passengers and freight carriers, illustrating how each group prioritizes different aspects of transportation services.

Among passengers, Primary Level Students place a high value on safety above other considerations, while Secondary Level Students also prioritize environmental sustainability and timetable reliability, though less so on safety. Tertiary Level Students and Farmers show a keen sensitivity to price and time, with a special focus on trip time for the former. Individuals in Intermediate Professions and Employees/Workers express concerns over budget and time sensitivity, alongside a strong expectation for safety and reliability. Senior Intellectual Professionals, Craftsmen, Traders, and Business Leaders maintain a balanced attention across all criteria, notably valuing trip time and sustainability.

In the freight domain, the priorities shift towards operational efficiency and environmental responsibility. Construction Products and Consumer Goods profiles underscore a critical focus on all evaluated criteria, with a significant emphasis on optimal handling conditions and safety. The Industrial Products profile mirrors this critical concern but with an additional focus on sustainability and achieving carbon neutrality. Agricultural/Livestock Products, like their freight counterparts, prioritize trip time and optimal handling conditions.

Across all profiles, there is a consistent demand for reliability, comfort, and safety, with variations in priority given to price sensitivity, environmental impact, and trip time. The emphasis on sustainability and environmental concerns is more pronounced in certain passenger segments (e.g., Secondary Level Students, Senior Intellectual Professionals) and in the freight segment dealing with industrial products.

5 Conclusion and perspectives

This study develops a proposal to support the necessary demand estimation in the context of hyperconnected transportation in regional areas. Specifically, the ECOTRAIN project serves as a practical application of this analysis. This approach involves identifying user profiles and delineating their attributes in terms of volume, time, and space. It identifies price, transport time, environmental impact, schedule compliance, comfort, and safety as the main factors influencing user decisions. Additionally, the significance of these factors is quantitatively evaluated across different user profiles in selecting transportation options through a weighted matrix.

Limitations of the current methodology include potential biases in data, the impact of external factors such as economic fluctuations, and the scalability of the proposed solutions. Further discussion is needed on methodologies to address regions with sparse data availability, along with adding guidelines for scaling and adapting the methodology to different regional characteristics and technological advancements. This involves developing flexible frameworks that can be tailored to various regional contexts and integrating technologies to improve data collection and analysis. Additionally, a deeper evaluation into the roles of different stakeholders in the regional transportation ecosystem is necessary, particularly in terms of identifying their responsibilities in implementing and sustaining hyperconnected regional transport systems.

Future research will focus on practical applications to improve demand estimations for regional transportation networks. The next steps involve using the collected data alongside identified demand drivers to develop a simulation-based demand generator. This tool will incorporate scenario analysis to predict user responses to changes in transportation options. Key tasks at this stage include overcoming barriers to precise data access, selecting a demand forecasting model that accurately reflects actual demand patterns in regional contexts, and aligning supply capabilities with fluctuating demand.

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