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Planning for more resilient urban transportation systems: Lessons learned from the Covid-19 pandemic

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Abstract

Grounded on public sensorization initiatives to monitor the Lisbon's mobility system as a whole, the *Integrative Learning from Urban Data and Situational Context for City Mobility Optimization* (ILU) research project was initially designed as a means of providing decision support tools for the city of Lisbon to advance towards sustainable mobility. This paper reviews a significant number of research outcomes developed in the scope of the ILU project that are aligned with such a goal. These are comprehensively analyzed through an integrated framework to identify how different theories and methods anchored in data science and transport planning were applied to the different datasets of the public transport services, converging to build principles of urban mobility resilience. Lessons learned are potentially transferrable to other European cities.

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1. Introduction

The COVID-19 pandemic revealed untapped resilience needs across worldwide public transport systems, stressing the importance of their dynamic adaptation to changes in traffic demand and safety guidelines (Anastasiadou et al., 2021; Kakderi et al., 2021). In Portugal, the Lisbon City Council (LCC) has been well active in supporting initiatives for the comprehensive monitoring of urban dynamics (Lemonde et al., 2021) so that mobility plans are fully aligned with the ongoing city changes. Among these initiatives, the ILU project unites two research institutes in Portugal, INESC-ID and LNEC, and the LCC, to bridge joint advances in Artificial Intelligence (AI), Public Transportation, and Urban Computing fields, translating them into decision support tools and city policies for more sustainable

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mobility. The ILU project is the first research and innovation effort on data science and transport planning in Portugal and aims to consolidate the diversity of data sources on city mobility stored in the Lisbon Intelligent Management Platform (PGIL) and guarantee its real-time updatability.

With the starting of the pandemic, the ILU project suffered an inevitable shift, and several novel research outcomes were developed which have addressed multimodal responses to the pandemic, including the descriptive and predictive analysis of emerging traffic patterns covering the different modes (road, railway, inland waterway, and active transport modes), dynamic route and frequency optimization of public transports, adaptive traffic signal controllers, among others. Considering the increased focus on urban transport resilience, the main objective of this work is to comprehensively review key outcomes of the ILU project, adopting the city (and transport) resilience lens and giving special attention to the research pursued during the Covid-19 pandemic period, that may lead to set new research directions The secondary objectives are: (a) to identify the main characteristics of the city resilience; and (b) the main lessons during the Covid-19 pandemic on mobility planning. As result, we provide an integrated framework to identify how the different theories and methods from this initiative are converging to build pivotal principles of urban mobility resilience.

2. Methodology

Explanatory Research Methodology was addressed to carry out the present study. Design Science Research Methodology (DSRM) steps, based on Peffers et al. (2007) and Peffers et al. (2020), were followed to position the project outcomes. The DSRM aims to leverage existing knowledge by providing new tools to advance scientific knowledge (Peffers et al., 2007). To this end, the methodologies applied in the studies were analyzed to identify the artifacts developed in each article of the ILU project. A conceptual framework was developed to structure these outcomes, identifying the applicability of the artifacts, and highlighting their contributions to advancing toward more resilient transportation systems (e.g., apps, Modelling, Origin-Destination matrices). A qualitative approach was applied, and the following steps were used to structure the study, considering the DSRM primary process iterations and process description, as follows.

- Step 1 (Problem and Motivation): identify the problems addressed within the scope of the ILU project and motivate the relevance of the proposed solutions (Section 1);
- Step 2 (Objectives and Solutions): identify the objectives of solutions proposed by each article;
- Step 3 (Design and Development): identify the main artifacts of each study in the management and planning of urban mobility in the face of COVID-19 pandemic disruption. Along this step the principles of urban mobility resilience (Reflectiveness, Robustness, Redundancy, Flexibility, Resourcefulness, Inclusiveness, Integrated), defined by Polis, and Rupprecht Consult (2021) in order to improve the sustainability of the urban mobility system, were identified and included in the analysis.
- Step 4 (Demonstration): demonstrate the use of artifacts produced in step 3;
- Step 5 (Evaluation): evaluate how well the artifacts support the solution of the problem;
- Step 6: (Communication): publications related to the studies developed based on the main contributions of the ILU project. Only published articles and articles of conference proceedings were considered for this analysis.

The main elements of the research process based on DSRM and the methodological steps followed are illustrated in Fig. 1.

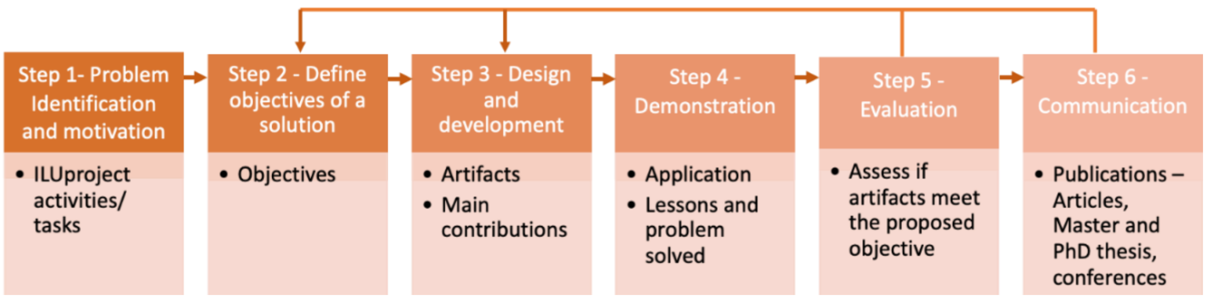

Fig. 1. Central Elements and DSRM and the research steps developed (based on Peffers et al., 2007).

To conclude, and brief analysis of the lessons learned is presented in Section 3.1, and a framework of the knowledge contribution for urban mobility planning in the scope of ILU project is presented in Section 3.2. Section 4 presents the conclusions and final remarks.

3. Integrated analysis of the ILU project outcomes

The efficient management of urban mobility is one of the great challenges in most European capital cities. In contexts of disruptive changes and uncertainties, it becomes even more challenging as it generates constant changes in scenarios, mainly motivated by changes in user behavior (Neves et al., 2020; Aparício et al., 2021a). These changes often lead to non-linear responses, especially in public transport usage patterns, which directly affect operation and supply. In this context, current sensorization technologies, including integrative AFC systems, mobile devices, and stationary privacy-preserving sensors along the city, may help in the real-time monitoring process, which also allows for greater flexibility in decision-making to solve specific problems with greater agility, considering the resilience needs of the transport network and urban traffic.

Several research activities and published outcomes were developed within the scope of the ILU project and are analyzed in the present paper. These aimed to identify the usage profile of public transport in Lisbon, the main characteristics of the network and user profile behavior, including multimodal origin-destination citizen flows (Cerqueira et al., 2021b; Silva et al., 2022), actionable mobility patterns (Neves et al., 2020, 2021; Lemonde et al., 2021), the impact of diverse sources of situational context on urban traffic dynamics (Cerqueira et al., 2021a; Sardinha et al., 2021; Silva et al., 2021; Leite et al., 2020), as well as significant vulnerabilities of the public transport network (Aparicio et al., 2021b; Tiam-Lee et al., 2021; Cerqueira et al., 2021b). Also, city traffic data were analyzed to generate a traffic profile that may help policymakers and managers make decisions to improve city mobility (Varela et al., 2021; Silva et al., 2022; Rico et al., 2021).

The presence of emerging changes in urban traffic was observed given the safety norms changing, emerging work habits, and new transport mode preferences triggered by the pandemic (Aparício et al., 2021a). To account for ongoing urban mobility changes, principles from incremental data mining and online learning, including those brought by Nallaperuma et al. (2019), the developed works in ILU further place them to guarantee the ability to learn from continuously arriving traffic records. An additional relevant direction in pandemic contexts is the early discovery of emerging mobility patterns. As an example, Neves et al. (2020) introduced principles for the timely discovery of emerging traffic dynamics (See Table 1, Step 2 and Step 3), generally corresponding to new traffic flows or road/station/vehicle (de)congestions, creating the possibility to anticipate potential mobility bottlenecks, critical knowledge for tactical and strategic mobility planning.

What can be noticed in the analysis of the articles is that technological advances are present in several areas and have different facets. Initiatives for city sensorization are highlighted as increasingly important due to the delineated mobility changes since the start of the COVID-19 pandemic (Lemonde et al., 2021). Essential sources of traffic data include road traffic data from stationary sensors and mobile GPS devices (Neves et al., 2021), pedestrian traffic data from privacy-compliant sensor technologies, public passenger data from AFC systems (Cerqueira et al., 2021a), and shared micro-mobility data from mobile app logs (Dias et al., 2021). In this context, emerging secure technologies associated with Internet of Things (IoT) solutions and remote sensing via privacy-aware satellite vision are gaining momentum (Allam & Jones, 2021).

Each step of the analysis defined in the methodology (Section 2) are summarized in Table 1. It is possible to identify the main artifacts of each study (Step 2), its contributions by design and development (Step 3), demonstrations and its application to public transport, mainly using sub-sets of data from the Lisbon City Council (Step 4). The majority of these artifacts were already integrated into the Lisbon Intelligent Management Platform (PGIL) (Step 5). They are currently in use in a real environment, which allows for a greater scale of analysis and evaluation of the proposed solutions.

Finally, the resilience principles were identified for each article being an important contribution to the objective of this article, defined in Section 1.

Table 1. Summary of the ILU articles analyzed

ILU Project					
Author (Step 6)	**Objectives of a solution (Step 2)**	**Design and development (Step 3)**	**Demonstration (Step 4)**	**Evaluation (Step 5)**	**Resilience principle**
Aparicio, et al., 2021a	Modeling and assessment of the topological vulnerabilities of multimodal transport networks.	Principles on how to model multimodal transport systems and quantitatively evaluate their robustness.	Case study on the network topological vulnerabilities of 14 carriers operating in the Lisbon's metropolitan area are.	Under integration in Lisbon Intelligent Management Platform (PGIL)	Inclusiveness Integration Robustness Redundancy
Aparicio, et al., 2021b	Development of approaches and visuals to capture changing urban mobility dynamics in multimodal transport systems from user trip records.	Methods to model and visualize changes and disruptive patterns in urban traffic dynamics.	Case study comprehensively measuring the impacts of COVID-19 on public transport demand (e.g., considerably lower impact in low-income areas, imbalanced demand distribution towards peripheries).	Functional prototype at CML	Integrated
Cerqueira et al., 2021a	Consolidated analysis of multiple sources of situational context in urban traffic models with both descriptive and predictive ends.	Descriptive and predictive modeling principles to capture the impact produced by heterogeneous sources of situational context like planned events, road interdictions, traffic generation/attraction poles and calendrical context in different modes of transport.	Case study in the city of Lisbon, considering bus, subway and cycling modes of urban traffic (by smart cards validation and georeferenced time series data).	Under integration in PGIL	Integrated Flexibility
Cerqueira et al., 2021b	Extending inference approaches of dynamic Origin-Destination (OD) matrices to model trip and transfer status from individual multimodal trip record data.	OD inference and visualization tools for the efficient identification of network vulnerabilities pertaining to time and distance spent on transfers and trips.	Case Study - decomposition of traffic flows in accordance with calendrical rules and user profiles in the city of Lisbon.	Functional prototype at CARRIS	Redundancy Flexibility Resourcefulness
Dias et al., 2021	Prospective assessment of effects that can be achieved in urban mobility through the proper implementation of shared e-scooter systems.	Principles for multimodal micro-mobility.	(a) Case study - shared e-scooters became a great asset in many cities worldwide promoting social distancing during pandemic; (b) Stimulate not use private cars to replace public transport rides for short-distance trips.	City of Braga, Portugal	Inclusiveness
Lemonde et al., 2020	Urban traffic data consolidation and computation of actionable spatiotemporal indices of multimodality against available situational context.	Principles for the consolidation and efficient retrieval of heterogeneous traffic data sources, and the context-sensitive analysis of multimodality indices	Case study for context-aware multimodal mobility in the city of Lisbon	Under integration in PGIL	Resourcefulness Integrated
Neves et al., 2021	Linear-time method to discover emerging patterns from heterogeneous spatiotemporal data (including mobile	Visualization tool (E2PAT) to support the analysis and guide the navigation	Guided case study on how E2PAT can be used at the Lisbon city Council to support urban mobility reforms.	Under integration in PGIL	Resourcefulness

	and static traffic sensors), together with a score to measure pattern actionability.	throughout the outputted emerging pattern.			
Neves et al., 2020	Structured view on why, when, and how to apply biclustering for mining traffic patterns from geolocalized speed data and inductive loop counters.	Modeling – principled adaptation of biclustering to find non-trivial, yet relevant and statistically significant road patterns.	Case study in the city of Lisbon - recurrent road traffic patterns (combining speed limits, vehicle passage frequencies) with spatiotemporal footprint	Functional prototype	Reflectiveness
Rico et al., 2021	Road map to apply recent developments and applications of graph neural networks, a new family of deep learning models, to road traffic forecasting.				Reflectiveness
Sacoor et al., 2021	Assessment of public transport service quality.	Balanced Scorecard model for the main bus public transport company in the city of Lisbon focused on urban sustainability goals	Case study applied at CARRIS bus public transport company	Expert evaluation at CARRIS Innovation Department	Inclusiveness
Sardinha et al., 2021	New principles to incorporate both historical and prospective sources of spatial, meteorological, situational, and calendrical context in predictors of urban traffic demand.	Recurrent neural processing principles and architectures senstive to available historical and prospective context data.	Case study targeting Lisbon's public bike-sharing system (GIRA)	Under integration in PGIL	Integrated Flexibility
Silva et al., 2022	End-to-end system to redesign a (multimodal) transport network using OD demand inferred from smartcard validations by combining multi- and single-objective optimization stances.	Modeling/optimization system to dynamically improve passenger-related objectives, including travel time and transfers per trip, while reducing operator costs and	Case study comprising smartcard validations of METRO and CARRIS, major public transport companies in the city of Lisbon	CARRIS and METRO (public transport companies)	Reflectiveness Robustness
Tiam-Lee et al., 2021	Robust approach to estimate individual passenger route choices from smart card records in complex rail transit systems, sensitive to uncertainties and delays in vehicle scheduling and walking times.	Methodology to estimate passenger route choices based only on automated fare collection data, not requiring train timetable information or prior route choice models, further ensuring robustness to unforeseen events like malfunctions and delays	Case study - Lisbon METRO rail transit system	Functional prototype	Resourcefulness
Varela et al., 2021	Methodology for the development of adaptive traffic signal controllers using Reinforcement Learning (RL), from simulation setup to experimental design, from problem formulation to evaluation.	Modelling/simulation/optimization of adaptive RL-based controllers to improve traffic congestion and strengthen coordination between adjacent intersections.	Two real-world scenarios in the Lisbon metropolitan area.	Functional prototype	Reflectiveness Resourcefulness

3.1. Lessons learned

The pandemic showed that the value of static studies is of limited relevance as their findings quickly become obsolete. Instead, multimodal traffic data analysis should be fully automated and updatable once more recent data becomes available (Lemonde et al., 2021; Cerqueira et al., 2021b; Neves et al, 2020). In this context, there is the need to guarantee that the ongoing mobility changes are reflected in the computational models, as well as the real-time ability to learn from continuously arriving traffic data observation and detect emerging traffic patterns.

Paradigmatic examples of descriptive analytics emerging in pandemic years include the computational inference of dynamic multimodal origin-destination matrices from AFC data for detecting bottlenecks to multimodal mobility (e.g., waiting times, commutes, walking distances within and outside commutes) (Cerqueira et al., 2021b), as well as the discovery of actionable traffic patterns, including frequent, periodic, emerging and anomalous patterns (Neves et al., 2020). Another essential need of an intelligent traffic system are computational solutions for bus route adaptation, and schedule redesign to ensure efficient transit systems that quickly adapt to the dynamic changes in demand of the passengers (Silva et al., 2022; Varela et al., 2021; Tiam-Lee et al., 2021).

Finally, the growth in the use of shared mobility modes, such as bikes and e-scooters, has also been propelled by technological advances (Bubicz et al., 2022; Dias et al., 2021; Sardinha et al., 2021; Neves et al., 2021), including lower-cost supplies and smartphone applications with easy monitoring and payment facilities. In fact, the acceleration of digitalization activities is pervasive across many services related to urban mobility, especially diminishing the need for low interpersonal contact and supporting the situational awareness of the citizens.

3.2. Knowledge contribution for urban mobility planning

The proposed framework structures advances and the main artifacts developed along the ILU project in the AI and transportation fields in four major axes: (a) Foundational works descriptive, (b) predictive, and (c) prescriptive context-aware traffic data analytics.

Along the descriptive axis, three major dimensions are considered: the robustness of the multimodal transportation system as a whole; the context-sensitive discovery of emerging traffic patterns (e.g., road congestion, public transport bottlenecks, bike-sharing needs); and the multimodal inference of dynamic origin-destination matrices. The practical application of actionable principles from temporal pattern discovery (Neves et al., 2020), integrative mining of heterogeneous data sources (Lemonde et al., 2021), alighting stop inference (Cerqueira et al., 2022), subspace clustering (Neves et al., 2021), network science (Aparício et al., 2021b), and multivariate statistics (Cerqueira et al., 2021b; Tiam-Lee et al., 2021) were covered along this first axis. At the predictive axis, advances in neural processing have been pursued to assist short- and long-term traffic forecasting (Sardinha et al., 2021; Rico et al., 2020). Finally, at the prescriptive axis, principles from optimization, reinforcement learning, micro-simulation, and multi-agent systems have been considered to aid urban mobility's tactic and strategic planning. Paradigmatic examples of intelligent transport systems developed in ILU range from adaptive traffic signal controllers sensitive to mode-specific traffic status (Varela et al., 2021) and dynamic optimizers of public transportation from real-time demand (Silva et al., 2022) in the presence of background context (e.g., large-scale events and other externalities).

The gathered results emphasize the importance of integrating urban mobility data in different contexts to improve urban mobility plans. The interrelationship between the different studies points to the interconnections and impact of different transport modes on mobility patterns, quality of public transport service provision, traffic flow, and commuting times, as well as the role of the existing transport intermodality along each origin and destination of users. These are essential outputs that point out the robustness of the multimodal transportation system in Lisbon and the resilience capacity given the sudden changes in conditions, such as the Covid-19 pandemic.

Practical applications of the artifact like OD modeling (Cerqueira et al., 2021b; Cerqueira et al., 2022) and traffic forecasting (Rico et al., 2021) are helping decision-makers to improve the quality of urban mobility in Lisbon.

Figure 2 shows the scope of the studies (by artifacts developed) and their real-world applicability in the city of Lisbon in the context of the ILU project, contributing to a more sustainable urban planning.

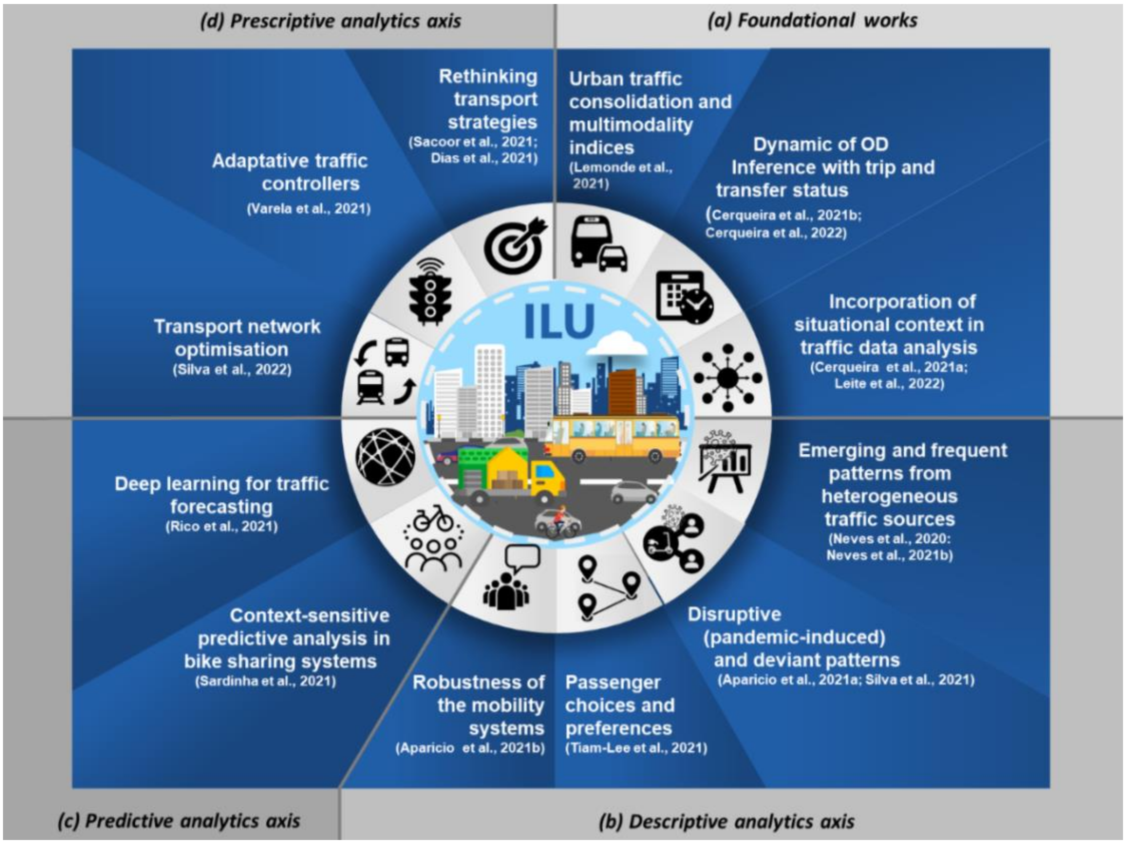

Fig. 2. Landscape of scientific contributions in ILU studies according to four major axes

4. Conclusion

The contributions placed by the ILU project highlight the relevance of dynamic, cross-modal, and context-aware diagnostics, prognostics, and recommendations in urban mobility planning, leveraging the resilience of transport facilities to both gradual and disruptive traffic changes. It further motivates the role of Big Data to support more transparent and sustainable mobility planning decisions, promote coordination among public transport operators, and dynamically align transport supply with the emerging urban traffic dynamics.

Although the principles of resilience were identified in the published works reviewed in Section 3, further research can identify which principles are more sensitive to disruptive periods and address them in future studies.

Furthermore, the results show that these applied studies are used by local operators and can help decision-makers to adopt measures that are in line with the concepts of smart cities and yet, corroborate with the principles of resilience for Sustainable Urban Mobility (POLIS, and Rupprecht Consult, 2021). The integration of different data sets also opens up opportunities for intelligent transport systems that promote sustainability, aiming to improve the well-being of all users of public spaces.

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