Antifragile Cities – Decision Support Tools to Support the Implementation of the Climate-neutral and Smart Cities

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***Abstract*—Urban systems and cities are complex ecosystems continuously challenged by a wide range of environmental, health, social and economic stressors. This paper will identify an ensemble of models, methods, tools, and a framework that gives a geographically and operationally diverse set of data and information to cities, when they need it, and the intelligence to anticipate potential stressors and inform decision-making, to help them learn and capitalize on emergent situations and implement new mobility measures. The paper will present an innovative framework that: a) Recognizes when an event may disrupt the existing urban equilibrium; b) Manages the short-term effects of the mobility disruption to maintain safety, innovation, and city operations; c) Examines and simulates potential scenarios for future growth while adhering to the EU sustainability and CO2 reduction targets; d) Proposes an optimal new path forward that optimizes the improvements in the urban mobility landscape, while ensuring public acceptance and rapid adoption. The implementation of the methodology will result in improved urban space utilization, elevated quality of life, and enhanced sustainability and resilience in long-term urban development plans. This research acknowledges the necessity for robust decision support tools in realizing Climate-neutral and Smart Cities, making the AntifragiCity Framework an essential instrument in urban resilience management.**

Keywords— Mobility and transportation, antifragile, homeostasis, black swans, decision-support systems

I. INTRODUCTION

Crises can have long-lasting and sometimes irreversible effects with local and/or global impacts. Most importantly, cities transitioning out of these crises struggle to recover their state of equilibrium, exacerbated by a sense and perception of uncertainty. This paper introduces the AntifragiCity Framework, a strategy that not only aims for resilience but goes a step further to seek enhancement from adversity, by treating cities as adaptive systems rather than static entities. However, they also note that the infinite variety of future threats cannot be adequately predicted and measured [1]. In recognition of measures, Gallotti et al. emphasized that attributes relating "to health and wellbeing of communities to urban structure and function, from traffic congestion to distinct types of pollution, can be better understood considering a city as a multiscale and multilayer complex system. The solution is to Rethink Cities that involve citizens in codesigning the city where widespread adoption of good practices leading to emergent effects with collective benefits, which can be directly measured" [2]. In the midst of this uncertainty, cities face a mobility reorganization – Electric Vehicles (EV) and their relevant infrastructure, teleworking growth, and a massive energy crisis are all contributing factors. Challenges of Urban Mobility (UM), such as the growing motorization in our cities has led to an increase in traffic congestion, noise, carbon emissions and concerns about road safety, resulting in social, environmental, and economic consequences. Black swans ("A black swan is a highly improbable event with three principal characteristics: It is unpredictable; it carries a massive impact; and, after the fact, we concoct an explanation that makes it appear less random, and more predictable, than it was" [3]) has disrupted the operational hypotheses and status quo (business as usual scenarios) for resilience thinking. This paper's core concept Antifragility is beyond resilience as the "resilient resists shocks and stays the same; however, the antifragile gets better" [4]. Drawing from this concept, the AntifragiCity Framework seeks to fortify cities by giving them the tools they need to anticipate potential stressors, learn from emergent situations, and implement new mobility measures that are not only environmentally sustainable, but also promote social equity and economic viability. The paper will create an ensemble of models, methods, tools, and a framework that gives cities the data and information they need, when they need it, as well as the intelligence to anticipate potential stressors, and inform decision-making, to help them learn and capitalize on emergent situations and implement new mobility measures. In section 2 objectives and ambitions are fully discussed.

II. DESIGNING INCLUSIVE, SAFE, AFFORDABLE, AND SUSTAINABLE URBAN MOBILITY OF USE

Within this article, we discuss the AntifragiCity framework, a strategy that uses antifragile principles to mitigate the impacts of mobility disruption, ensure safety, foster innovation, and improve urban mobility landscapes over time. AntifragiCity's overall aim is to pave the way to a new UM governance approach that enables cities to understand their business-as-usual modus-operandi (defined hereafter as their state of equilibrium) and to monitor (near) real-time continuous stressors and deviations from this state, assess potential implications through a simulation and prediction capability, inform adapted decision making to mitigate their consequences, while continuously enhancing their overall sustainability and resilience.

A. Objectives and ambition

The overarching aim of this potential decision support tool translates into the following 4 objectives formulated alongside the framework as shown in Figure 1.

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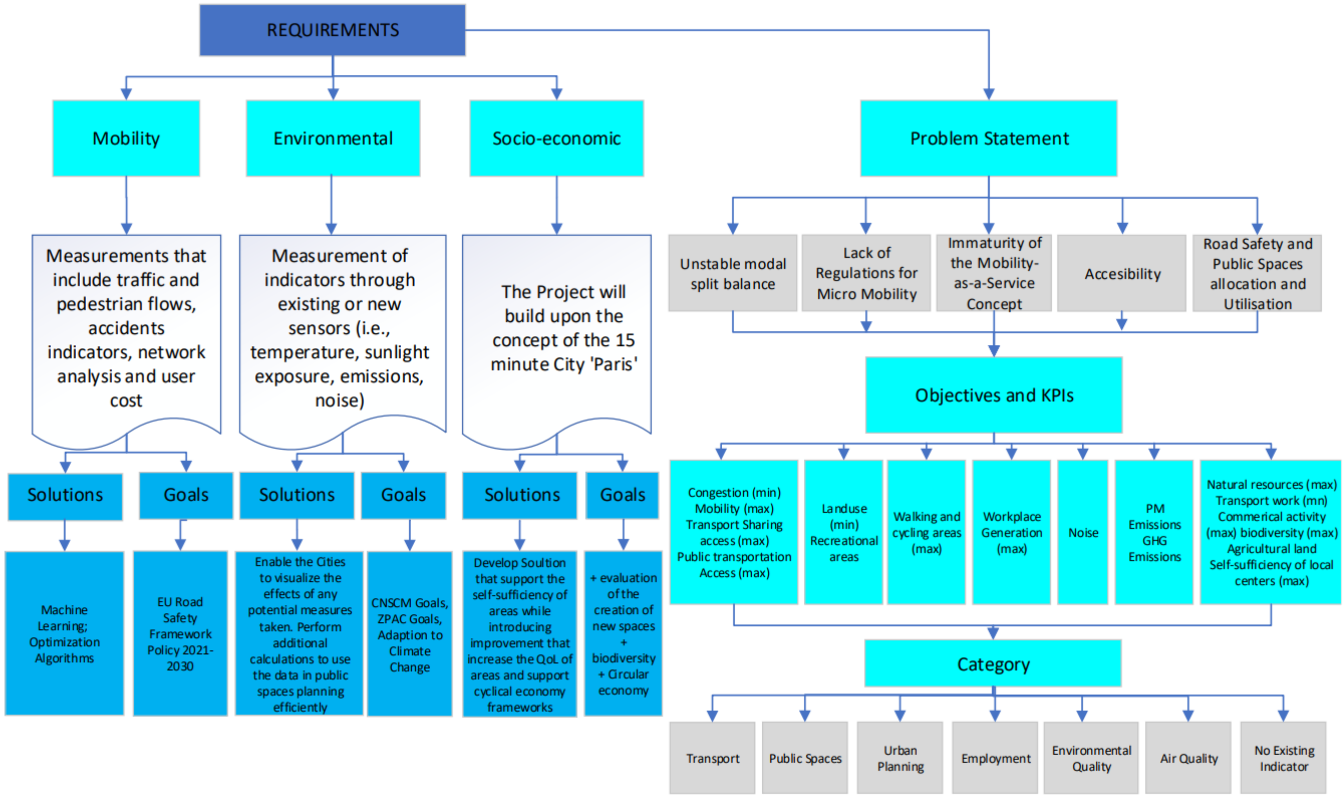

Figure 1. AntifragiCity Conceptual Framework.

OBJ1: Specify, assemble, and deliver a simulation, prediction, and decision-making environment, namely Simulator for Urban Mobility Antifragility (SUMA), Platform as a Service (PaaS), dedicated to UM management, while factoring in wider environmental, social, and urban planning considerations. The main goals of the Platform are to model the urban environment, the flow of different modes of transport, users' behavior, and incorporate them to tackle the UM problems.

OBJ2: Create an event ontology, including a taxonomy, to characterize (near) real-time endemic and acute events and their associated risks in an urban and wider regional landscape. The ontology will provide context to sensory data and social media information acquired across urban areas, and will serve as a basis to simulate, predict, and inform decision-making.

OBJ3: Develop a (near) real-time response capability to sense deviations from the urban equilibrium state and propose mitigation measures to counter potential risks, using the concept of mobility triage to enhance resilience.

OBJ4: Deploy the proposed AntifragiCity models, methods, and tools (i.e., SUMA) across selected unsafe areas and assess their progress beyond the current business-as-usual modus-operandi, using adapted Key Performance Indicators (KPIs).

Table 1 explains the various techniques that will be applied to each objective and its evaluation defined through measurement. "Measurement supports realistic planning, provides insight into actual performance, and facilitates assessment of suitable actions" [5].

TABLE I. METHODS & MEASUREMENTS

OBJ	*Methods*	*Measurement*
OBJ 1: SUMP	Devise innovative, reliable, and efficient solutions for the movement of people by taking different user profiles and their behavior into account; Deploying the models, methods, and tools, developed as part of SUMA across the demonstration projects	Develop decision-making mechanism with dynamic risk-based prediction incorporating cutting-edge forecasting models continuously augmented with real data
OBJ 2: Ontology	Corroborate and make sense of sensory and social media data and information real-time, using a combination of machine learning and natural language processing algorithms; Rely on the AntifragiCity ontology that elaborates on potential risks based on historical information and state-of-the-art literature.	Develop forecasting models that leverage sensory and social media data and information; Develop forecasting risk models that leverage sensory and social media data and information.
OBJ3: Real-time senses	Improve road infrastructure safety by redesigning the hierarchy of road system based on the need of speed limit. Appropriate measurement of data of traffic volumes and modes that are important	Re-assess and re-design road infrastructure system. Share of micro-mobility vehicle parking in dedicated parking areas (e.g. micro-mobility-hubs).
OBJ4: Models	The methods used for the environmental assessment are based on the performance approach (versus means approach) to	In situ sensors, to "reduce air pollutant emissions" and "decrease noise hindrance". • Dynamic Life Cycle Assessment

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OBJ	***Methods***	***Measurement***
	cover the goals of the climate change mitigation and adaptation, the biodiversity preservation, and no net land take. Thus, the environmental performance of implemented solutions (e.g., increase the green area and bike lines, better communication, etc.), will be assessed	(DLCA) method, to "Reduce greenhouse gas emissions". • Biotope Area Ratio/Factor (BAR/BAF) method to "reduce impacts on global biodiversity & enhance local/in-situ biodiversity" and "Optimise the urban area/land use: contribute to the no net land take goal".

B. The scope and requirements

AntifragiCity Framework adopts a socio-technical approach where citizens, including transport users and commuters, are active, as opposed to passive, agents in the UM landscape. Citizens can share and provide feedback about their mobility experience, which is then factored into the decision-making process.

This feedback includes qualitative (social media) as well as quantitative data that will be integrated with the urban sensory data streams to provide a holistic and accurate account of the transport situation to maximize co-benefits across the mobility value chain. Furthermore, AntifragiCity's resilience approach is nature-inspired, with a focus on homeostasis ("Subjective Wellbeing (SWB) Homeostasis theory asserts that each individual has a set-point for their SWB, which is a genetically determined individual difference" [6]), but also incorporates antifragile and allostatic attributes for a more dynamic response to change. Lessons learnt during the period of imposition and lifting of Covid related restrictions, as well as other stressors and disruptions experienced by participating cities, will be analyzed and key lessons shared and factored into the decision support tool approach.

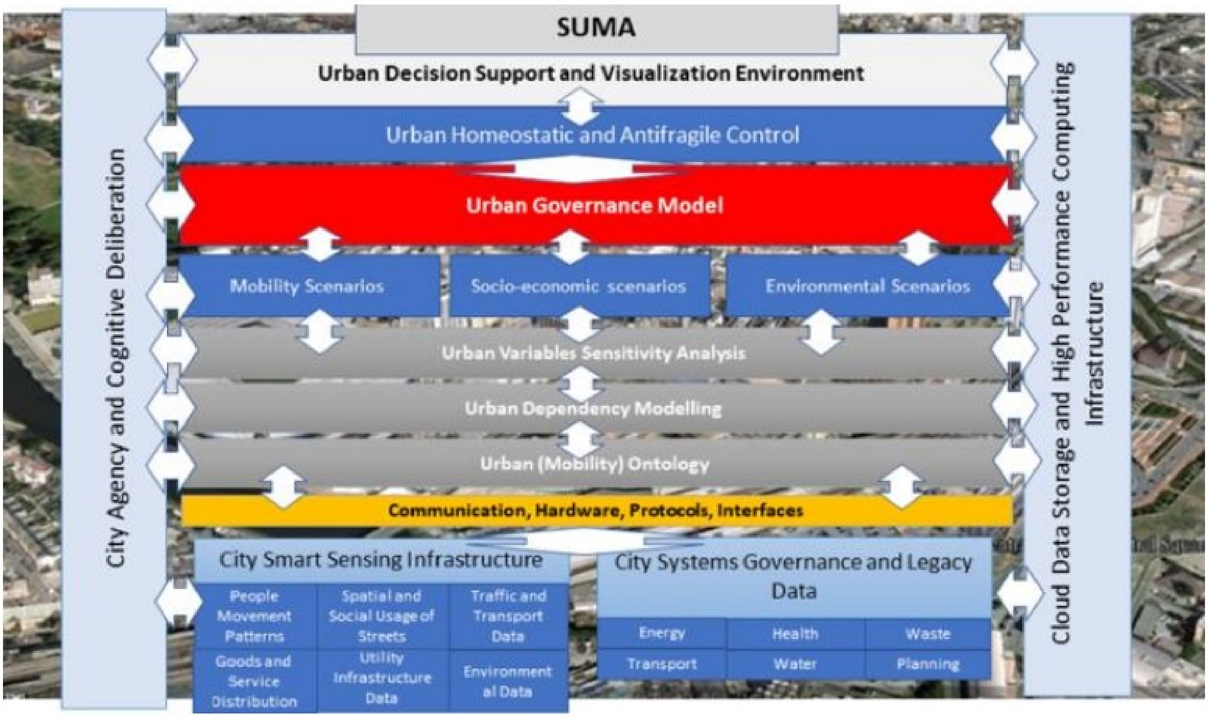

Figure 2. AntifragiCity Conceptual Framework

III. CONCEPT AND METHODOLOGY

AntifragiCity's vision recognizes that urban environments consist of multiple layers of complex and dynamic data from various systems and user groups. When captured, analyzed, and interpreted correctly in a timely manner, this data can significantly enhance the city's monitoring system, enabling real-time responses that present various opportunities. This approach allows for optimal management of city pressures, leading to improved immediate outcomes for citizens and helping update long-term sustainable development and resilience management plans.

A. Six-stage nature-inspired approach

The methodology approach to Antifragility resilience will involve a six-stage nature-inspired approach exploiting the concept of homeostasis, augmented with antifragile and allostatic attributes. Antifragility describes a system, which under stress or deviation from the normal, improves its overall state. Allostasis extends the antifragility of our urban systems when the city is under continuous stressors.

The first stage involves citizen engagement with a view of preparing the local population to the step changes that will be brought to the city via the planned demonstration project. Through the process itself, citizen participation can be used instrumentally to identify critical risk issues on developing and integrating infrastructural developments. The AntifragiCity Framework proposes participatory methods to be applied to explore public understanding, expertise, values, and preferences in respect of city systems integration and the underpinning governance models.

The second stage concentrates on developing an urban systems integration approach, which involves semantic conceptualization of urban systems. An integrated semantic representation of built, infrastructure, and mobility facilities across the 10+1 selected urban areas (including energy, transport, water, land use, IT, and health) is proposed to be developed, which will enable holistic system reasoning and analytics in a way that makes possible cross-sectoral evaluation of changes / perturbations to city networks (including design, configuration, pricing, management, and governance). The resulting urban ontological referential can be used as a basis for reasoning on a city network interdependencies between infrastructure variables ranging from traffic flow intensity to public health indicators.

The third Stage involves the understanding and mapping of Technical, Commercial, Geospatial and Regulatory Interdependencies within each participating city. The decision support tool proposes to identify existing urban system analytical models unravelling governing variables and parameters where the analysis of system-specific flow network data models, can be done by using existing GIS techniques to determine each of the main 'flow' sectors: transport, and water. A conceptual framework for identifying governing risks of city system interdependencies will be developed with a view of promoting system adaptability and resilience.

The fourth stage will involve building a holistic and dynamic urban analytical modelling environment that incorporates the above understanding of inter-systems variable interdependencies and uses indicators to: (a) organize technical, socioeconomic, and environmental data to understand real-time urban system dynamics and interrelated impacts, and (b), aid in risk and impact assessment and city holistic informed decision making. The predictive models will be developed with a high degree of plasticity, allowing exploration of the influence of a broad range of socio-technical variables on system performance – e.g., the impact of different governance styles (markets, hierarchies, and networks) norms, and regulations.

The fifth stage will involve exploiting the semantic, dependency, and predictive models developed in the previous stages to deliver managed city systems with a decision-making capability that factors in decision criticality, implications, stakeholder, and citizen views, as well as security, confidentiality, and data sensitivity issues. A multi-layered architecture is proposed that delivers integrated city systems with a view of achieving adaptability and resilience. One of the innovative aspects of the framework is the reliance on the concept of agency (*cognitive and collaborative agents*) to provide an abstraction capability and interface to hardware and software components. The semantic layers 'machinery': City Ontology, dependency modelling and sensitivity analysis play a central role in interpreting actively requested low level data about the city integrated systems environment. Machine Learning (ML) approach and related functionality/service will be implemented whenever it is needed to handle the problem of missing data and produce predictive model control algorithms. The upper layer (SUMA PaaS) represents the user front-end that exploits all the above modules using adapted visualization metaphors to enable decision makers monitor and manage the performance of their city systems.

The sixth stage will be to explore the potential of different business models to promote efficient integrated UM and wider infrastructure systems, and develop tools for monitoring and evaluation by understanding the mechanisms, which enable mobile, domestic and community capital to be allocated to integrated infrastructure projects in an economically and environmentally efficient manner, and to consider effects of scale economies in gaining finance packages; developing a taxonomy of potential project ownership and control models for integrated infrastructure and outline their strengths and weaknesses in terms of impact on social, economic and environmental variables; understanding how transitions might occur from existing forms of project ownership and control to those, which permit greater levels of local resilience and local determinism in the process; and to develop understanding on how city systems can be developed and how processes will be adopted, which will optimize understanding of the trade-offs between economies of scale, financial cost, social equity and environmental impact.

B. The AntifragiCity Urban demonstration activities

The AntifragiCity demonstrations should aim to support cities in achieving the goals of the Climate Neutral and Smart Cities Mission [7] through the development of an innovative working environment in which mobility solutions are developed based on a user-designed approach and are monitored and improved by the input of a sensor-supported monitoring system and citizen participation scheme. The methodology of the demonstrations follows the approach below:

- **User-centered design plan:** includes the user research and analysis of each demonstration, and the development of a detail plan to ensure greater value of the demonstration for its end-users, the citizens.
- **Living lab design:** This task contemplates 3 steps. First, the co-creation of the living lab design together with the end-users, second, the testing prototypes in SUMA and the users-testing, and third, the detailed design of the living labs, including the technical, legal, operational, and communication requirements of each living lab, together with the city specific KPIs to monitor the performance of the demonstration.
- **Preparation for the demonstration and monitoring system:** This task includes the implementation of the operational, legal, commercial/communication and citizen engagement activities identified by the cities' Living Labs design and user-centered design plan. In addition, it will include the setting up of the monitoring system, based on Internet of Things (IoT) technologies, for each Living Lab, to ensure baseline measurement and a Smart project monitoring.
- **Demonstrations:** User-centric innovations are implemented, and demonstrations will be conducted in each lead city. Physical and digital campaigns will be conducted to raise awareness of the innovations among citizens. Co-creation activities shall be conducted to receive feedback from citizens and stakeholders. Quantitative and qualitative data from citizens/users, stakeholders, network, and operations are collected through surveys and sensor devices as part of the monitoring process.
- **Assessment of the demonstrations:** The data collected in the monitoring system along with other data collected in the previous steps are used to assess the multidimensional impact of the implemented concepts. Comparisons can be made between the baseline and the implementation phase to assess changes in travel behavior, user satisfaction, modal shares, risk factors mitigation, emissions, noise, resilience, etc. Based on the lessons learned in the evaluation phase, a decision shall be made regarding the continuation of the living lab as is or the initiation of a new experimental cycle of co-

creation (*agile approach to innovation*) to explore new ideas. Additionally, the evaluation will include a cross-cities impact evaluation and a transferability assessment.

C. Potential barriers and obstacles

Table 2 presents identified barriers and mitigation measures to secure AntifragiCity's impacts.

TABLE II. POTENTIAL BARRIERS & OBSTACLES

Barriers / Obstacles	*Proposed mitigation measures*
Dispersed regulatory framework and the need for cross-modal and cross-sectoral interoperability and commonly accepted standards	It is widely acceptable that there are important discrepancies in the regulatory framework governing, either at Member State, regional or even local level coupled with the need for cross-modal and cross-sectoral interoperability and the use of commonly accepted regulations and standards. They comprise of an innovation challenge that may affect the adoption of AntifragiCity's models at European-wide up-take framework. The requirement is to analyze these implications to adopt an approach that utilizes collective methods and tools that ensures the participation of all related stakeholders from an early stage to highlight and adequately discuss the respective implications from the design phase.
Implementation dependent of political decisions	AntifragiCity's proposed approach will involve stakeholders from different disciplines, from the design stage to the implementation stage. In particular, the participation of city authorities in the consortium, which have the political mindset to implement the proposed actions, that will ensure the successful implementation of the Decision support tool actions at pilot level.
Conservative mindset and lack of confidence in innovative solutions from the demand / consumer side	The decision support tool user-centric approach is designed to gather and analyze user intelligence, together with its co-creation approach that directly involves users as key stakeholders, ensures high user acceptance rates and is expected to confront any symptom of conservative mindset and lack of confidence in the proposed innovative solutions and services.
Capital intensiveness of innovation, reinforced by problems of financing	The innovative business models and services that will be co-created and proposed by the decision support tool will take into account *capital investment needs vs. potential funding sources*. Those will be further accompanied by a preliminary estimation of service implementation *costs vs. potential inflows for the value chain as a whol*e. The approach aims to ensure that the suggested innovative business models and services will constitute a financially viable and sustainable option for the targeted stakeholders, pre-describing and assessing potential financing sources at either public or private sector.

D. Assessing existing software to be incorporated into SUMA

The current technique aims to exploit existing technology and software developed in previous European research projects to structure the multimodal functionality of the Simulator for UM Antifragility (SUMA), in line with the proposed architecture. The combination of existing software will result in saving valuable resources from redeveloping already existing technology. The outcome of this assessment will be a cohesive analysis of the different available software that will be incorporated into the SUMA.

IV. BEYOND STATE-OF-THE-ART

The AntifragiCity Framework will progress current state-of-the-art in the following areas:

a) resilient urban areas,

b) land use and urban planning,

c) urban semantic models for mobility management,

d) reference architectures for mobility management, and

e) smart city platforms for UM.

A. Resilient urban areas

Resilient Urban Areas: Resilience is generally defined as the capacity of a system to withstand an external disturbance and **proactively recover towards a new stable state** [8] AntifragiCity decision support tool will progress state-of-the-art in the field of urban resilience by exploiting the nature-inspired concept of biomimicry, as exemplified by the natural phenomenon of homeostasis, representing the natural tendency towards maintaining a relatively stable equilibrium between the constituents of a complex system, as maintained by physiological processes, while acquiring an increased resilience. Such a concept will implement homeostatic interventions to bring deviation back to the setpoints and if such events create permanent issues in the city, an allostatic state will then be initiated.

B. Land use & urban morphology

Research shows that efficient planning of land use contributes significantly to resilience when dealing with urban development [9]. AntifragiCity will develop holistic approach to model the urban dynamics from a social (human-driven) perspective factoring in a wide range of variables. This model will assist local authorities in their planning process as well as their quest to transition towards inclusive, sustainable, and resilient (including from a gentrification perspective) urban areas. AntifragiCity will also provide services that incorporate the vulnerable road users dimension into infrastructure planning, including aspects of safety and security, accessibility, digital and smart tools for enforcing speed limits and vehicle access, design and operation or services and public spaces, including mobility hubs, public transport, and shared mobility.

C. Urban semantic models for mobility management

Semantic web technologies such as OWL ontologies introduce a common taxonomy to a specific domain and explicit real world concepts' interrelationships, which can ultimately help tackle data heterogeneity and facilitate information discovery [10]. Several ontologies in connection with urban sustainability assessment will be analyzed from literature (i.e., building structure, water quality or personal health information) [11]. For example, the Transport Disruption ontology that describes travel and transport related events, assessing their disruptive impact on mobility at the urban level [12]. These ontologies are examples of the efforts made in semantic development for urban sustainability or sustainability subdomain representation. However, none of these ontologies abstract the high-level concepts required by AntifragiCity, as the existing models provide a fragmented view of the whole domain. AntifragiCity will progress current state-of-the-art in UM modelling by developing an UM Ontology that factors in all aspects that underpin the Urban metabolism, thus providing a holistic approach for managing mobility.

D. *Reference architectures for UM management*

AntifragiCity will focus on aligning the existing discipline-oriented models to form a reliable and comprehensive multi-disciplinary reference model that will be used and progressed / enriched on a continuous basis. The decision support tool will extend the IoT stack architecture to include a semantic referential, in the form of an UM reference model, that extends City information models, such as City Geography Markup Language (CityGML), while factoring in security (including data governance) considerations. The decision support tool reference architecture will factor in social constructs to promote a participative approach considering the complete value chain, with a focus on UM. It will include an inference layer that is grounded in the semantic description of UM. This form of intelligence will be distributed, i.e., available on the cloud as well as on the edge, to address network latency and security issues.

E. *Smart City Platforms for UM*

The decision support tool will comply with OASC (Open & Agile Smart Cities), and promote interoperability between various urban artefacts, including mobility, through dedicated APIs to access data, and context information. It will also provide the capability to develop a semantic contextualization of data feeds originating from connected objects found in cities, in the form of model constructs aligned with the proposed UM semantic reference model. These extensions will be reusable across platforms. Furthermore, the decision support tool will integrate the principles of agency to deliver an agent-based platform, with an application for mobility and related areas. Finally, it will also develop security approaches that adopt the principle of least privilege while factoring in existing standards, such as ISO 19650-5 as well as a model-based governance approach taking into account the complexity of the urban metabolism.

V. CONCLUSION

This paper focused on a framework orientated on designing inclusive, safe, affordable, and sustainable UM. The proposed conceptual framework ‘AntifragiCity’ is based on the theory of antifragile whereby the city will resist short-term effects of mobility disruption, maintain safety, innovation and optimize improvements. Four specific objectives (SUMP, Ontology, Real-time Senses, and Models) have been identified with recommended techniques and measurements. The framework’s adaptive process of maintaining resilience relating to Homeostasis theory through subjective well-being has been integrated into the methodology. The methodology has been presented in 6 phases that will support positive outcomes for citizens such as better use of urban spaces and increase quality of life, while updating the city’s long term sustainable development and resilience management plans. A methodology for urban demonstrations was highlighted featuring recommended goals from the Climate Neutral and Smart Cities Mission. In acknowledgement to novel framework the paper addresses five beyond state-of-the-art requirements; a) Resilient urban areas – implementation of homeostatic interventions; b) Land use & urban morphology - develop holistic approach to model the urban dynamics; c) Urban semantic models for mobility management - progress current state-of-the-art in UM modelling by developing an UM Ontology; d) Reference architectures for UM management - a reference architecture that will factor in the complete value chain, with a focus on UM; e) Smart City Platforms for UM – it will comply OASC, and promote interoperability between various urban artefacts. In the opinion of the authors the development framework for ‘Antifragile Cities - Decision Support Tools’ is an essential tool to Support the Implementation of the Climate-neutral and Smart Cities.

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