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Digital Twins: A Critical Discussion on Their Potential for Supporting Policy-Making and Planning in Urban Logistics

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Abstract: Poor logistics efficiency, due to low load factors caused by high demand fragmentation, will have relevant negative consequences for cities in terms of pollution, congestion and overall city liveability. Policy-makers should equip themselves with appropriate tools to perform reliable, comprehensive and timely analyses of urban logistics scenarios, also considering upcoming (i) technological changes, (ii) business model evolutions and (iii) spatial-temporal changes these innovations will produce. This paper discusses the Digital Twin (DT) concept, illustrating the role it might play and clarifying how to properly conceive it with respect to urban freight transport policy-making and planning. The main message is that without a sound theory and knowledge with respect to the relationships linking contextual reality and choice/behaviour, it is not possible to make sense of what happens in the real world. Therefore, the joint use of behavioural and simulation models should characterise a DT within a Living Lab approach so to stimulate effective, well-informed and participated planning processes, but also to forecast both behaviour and reactions to structural changes and policy measures implementations.

Keywords: digital twins; urban freight; living lab; behavioural models; policy; planning

1. Introduction

> *All models are wrong, but some are useful. (George E. P. Box [1])*

Urban freight transport is vital for cities while being responsible of many externalities. In the last few years, we have been experiencing huge changes, which are also having impacts on the way freight is distributed. In particular, the role that both large and small e-commerce platforms are playing and the social changes taking place in society (e.g., urbanisation, aging population, income polarisation, epidemic risks) are substantial in creating a relevant demand for instant deliveries. This is also due to specific market supply strategies. Nevertheless, the phenomenon poses serious problems from an environmental sustainability perspective as well as from economic and social ones (e.g., labour, social inclusion, income distribution effects, resilience).

Poor logistic efficiency, due to lower load factors caused by higher fragmentation, will have relevant negative consequences for cities in terms of pollution and congestion. Thus, one has to *describe* and *predict* possible outcomes in a *timely* and *reliable* fashion to define and deploy appropriate intervention policies aimed at mitigating and, possibly, solving the problems these changes will cause.

Independent sources confirm the supporting motivations justifying the focus on the upcoming problems last mile deliveries will face. In fact, a while ago, McKinsey investigated last mile delivery from an industry perspective [2]. The main results pointed to the following interconnected issues: (1) high and rising customer expectations with respect to the improved service quality coupled with lower costs; (2) promising potential for automation; (3) rapid change in competition dynamics. In 2018, McKinsey published a second document suggesting that the pace of change in practice had by far exceeded expectations. Notwithstanding these considerations, the overall market potential of this segment is substantial due to the progressive digitalisation tacking place and the wide margins for improvement [3]. Models are widely used to analyse and predict the impact of possible future scenarios. However, policy-making and planning still need the support that tools, relying on sound data regarding the present situation and capable of accurately simulating the future, can produce.

This paper aims at filling this gap by discussing the Digital Twin (DT) concept as an innovative and suitable modelling tool that local planners and policy-makers might use for reducing the undesirable effects produced by last mile deliveries. It contributes to the urban freight distribution literature by adopting an exploratory and critical approach in illustrating the role DTs might play and, more importantly, clarifying how to properly conceive and use them with respect to urban freight transport policy-making and planning. This paper discusses the use of DTs in urban freight planning and brings forward a new perspective on how realism and accuracy can be shaped within a planning context that includes multiple stakeholders. As far as we know, such a perspective, in which we link central premises of the DT model with conditions for urban freight planning, has not been published before.

To this end, the paper unfolds in different sections: Section 2 describes the role played by policy-makers and the most appropriate tools they have to deal with the challenges they are facing, pointing out the relevance of DTs and how they innovate with respect to the current methods; Section 3 illustrates (i) the various definition of a DT, (ii) its structure and use in different fields and (iii) its modelling characteristics; Section 4 provides a detailed discussion on the opportunities and constraints of DT applicability to urban freight policy-making and planning; Section 5 concludes pointing to fruitful future research paths. This exploratory research is both new and needed to understand how DTs might influence and progressively change the way decisions are made in the field of urban freight transport.

2. How Can Planners and Policy-Makers Cope with Changes?

In this rapidly changing environment, city planners and policy-makers need to equip themselves with appropriate tools to perform reliable, comprehensive and timely analyses of upcoming: (a) technological change, (b) business models evolutions/innovations and (c) the spatial-temporal changes these innovations will produce.

The fundamental decision revolves around the ambition cities have with respect to managing (or at least trying to influence) this process or to simply be satisfied in accommodating it. To attempt influencing the process and pursue specific societal aims it is preferable to manage the process rather than passively second it. This can take place in different ways. One solution is to promote incremental changes linked to the adoption of new business models capable of ensuring and fostering public–private cooperation [4]. Some cities around the world (e.g., Gothenburg, London, Rome) are taking this path. They are developing logistics Living Labs, to co-produce efficient and shared solutions in disconnection with previously adopted decision-making approaches and paradigms that simply rely on the "predict and provide" approach [5]. The core of most of the logistic solutions innovative cities are looking into rests upon shared, connected and low-emission logistics concepts [6]. All this, given the complex and interactive environment within which solutions are deployed, needs to be supported by appropriate simulation instruments and planning tools.

The DT concept can be effectively used within a Living Lab approach to planning. In fact, allowing a closed data/information loop between the model and reality, DTs would be useful to achieve jointly acceptable solutions given they can provide reliable descriptions of likely scenarios illustrating now the implications that current choices might have in the future for each of the various stakeholders.

It is important to underline that planning is a function that recursively interlinks with piloting, deployment and evaluation. This remark is fundamental and suggests/clarifies how a Living Lab approach can integrate with a cutting-edge method such as DT when planning for urban freight transport. A Living Lab approach to urban freight (please see CITYLAB—City Logistics in Living Laboratories project, http://www.citylab-project.eu/) is the most up-to-date planning strategy inherently relying on data-driven models [7]. A reliable model for planning should not only be capable of mimicking real-life experiments, so to reproduce past events, but also be able to predict the future, assuming different scenarios have different probabilities of actually materialising. Besides, models typically used for freight transport simulations relate to different levels of decisions, i.e., strategic, tactical and operational [8] and it is difficult to combine all the levels in a comprehensive model. Some recent attempts go in this direction, by using multi-scale multi-agent models [9,10]. Under this respect, disaggregated modelling techniques, like agent-based models, have been progressively used in the last years. This allows for not only illustrating to the stakeholders involved in the planning process the implications that present policy choices might have in the future, but also for making them aware of their active role within the overall urban freight system [11]. This, in turn, provides stakeholders with reliable information concerning the future implications of present decisions that are valuable in either confirming or modifying their current choices. This approach, however, is not fully dynamic since it does not foresee continuous updating based on a closed model-reality loop. One can bridge this gap by adopting a DT approach. While this innovation is very promising and worth investigations in the field of last mile logistics, the paper also clarifies how to properly conceive DTs for policy-making and planning and discusses some caveats one should have clearly in mind when using them. This, we believe, constitutes a relevant value added to the current status of knowledge while also representing a valuable contribution to policy-making and planning. Under this respect, while DTs have been explored with respect to freight transport problems [12,13], their potential for policy-making and planning has not been explored so far.

3. Digital Twins: Definition, Description, and Use

This section discusses the definition of the DT concept, given that so far there is not a commonly accepted one. It also provides a succinct history and evolution of DTs followed by a discussion of their structure and functions. Finally, it quickly touches upon the current use of DTs in different sectors and the link with model building. The section aims at contextualising and clarifying the use of DTs at the current stage.

3.1. Definition

One should clarify from the outset that there is not a unanimous consensus with respect to the definition of what exactly a DT is. An early notion of this concept dates back to the early 1960s when NASA used basic twinning ideas for space programming. In fact, NASA created physically duplicated systems at ground level to match the systems in space and used them to assess and simulate conditions on board Apollo 13. The original definition was then put forward by Grieves [14] in a presentation hosted by the Challenge Advisory (https://www.challenge.org/), focusing on technology innovation centred around the development of an innovative product lifecycle management approach. DT is described as a digital informational construct where a physical system is represented as a separate digital entity but linked to the physical system in question. The presentation already comprised all the basic elements characterising a DT and these include: (1) real space, (2) virtual space and (3) the spreading of data/information flow between real and virtual space.

Since its early use, different authors have defined DT differently. Glaessgen and Stargel [15] offer a comprehensive definition. In particular, they state that a "digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin". Boschert and Rosen [16] define a DT as a description of a component/product/system that evolves with the real system. Alam and El Saddik [17] (p. 2051) state that a DT is "an exact cyber copy of a physical system that truly represents all of its functionalities". Grieves and Vickers [18] state that the digital representation of reality should include *all information* concerning the system asset that could be potentially retrieved by inspecting the real world. The integration of the information flow between the physical and digital element is so relevant in the definition that different integration levels produce different subcategories. According to Kritzinger et al. [19], there is a:

(1) *digital model* when the physical object does not use any automated data exchange between the physical object/system and the digital one;
(2) *digital shadow* when there is a one-way data flow between the state of an existing physical object/system and the digital one whereas a change in the state of the physically object/system leads to a change in the digital one;
(3) *digital twin* when the data flow is bi-directional between the two items and the objects are fully integrated.

In the last case, the digital object might also have a controlling function with respect to the physical one and, furthermore, a change in the state of the physical object leads to a change in the state of the digital one and vice versa. This is a fundamental feature when one assumes using a DT in policy-making and planning for urban freight transport. This circularity aspect connecting reality and virtuality poses daunting causality questions discussed in Section 4.

3.2. Structure and Use

The DT architecture typically includes sensors, measurement technologies and machine learning. Taking a computational perspective, DTs need both data and information fusion techniques capable of transforming raw sensory data into high-level understanding and insights [20]. The primary function a DT addresses is descriptive in nature. In fact, it allows accurate operational descriptions of the assets considered through physics-based models and data-driven analytics [21]. The DT can mirror the activities of its corresponding physical twin, thus providing early warning, anomaly detection and, under specific circumstances, prediction and optimisation. The Internet of Things smart gateway and edge computing devices system provide real-time data acquisition while pre-processed online sensory data are fused to feed the DT model.

Different sectors use/apply DTs [22]. Among the prominent ones, one can recall:

(1) *Machine Building*: use a DT where a virtual copy of a physical machine is created and simultaneously developed to simulate and test different solutions/configurations;
(2) *Manufacturing and Maintenance*: analyse system performance via time series data and real-time data comparisons so to detect possible maintenance needs and avoid breakdowns;
(3) *Performance Optimisation*: determine the optimum set of parameters and actions that maximise some key performance indicators, while providing long-term planning on the assumption that the underlying relations are stable;
(4) *Healthcare*: describe and visualise a hospital system to test safe environment implications when altering system performance;
(5) *Customer Experience*: test alternative environments to study customer buying attitude, preferences, satisfaction and loyalty;
(6) *Smart Cities*: describe, capture and simulate policy (both real and potential) implications of alternative solutions for optimising them with respect to a given objective or set of them.

The multiple sectors where DTs have been applied, from 1 to 6, differ in terms of progressive system complexity (from low to high) and stability (from high to low) of the relationships linking causes and effects that the DT is trying to iteratively model.

In fact, one issue, which is particularly pertinent to the use of DT for simulating urban freight distribution in a planning context, relates to *data types* and *stakeholder preferences*. Richter et al. [23] critically discuss and illustrate data-related challenges and a possible solution to the problem with respect to the issues urban areas are currently facing due to the challenges urbanisation, passenger transport, logistics, maintenance of complex traffic and supply infrastructure are posing when considering the limited space and resources available. In fact, different stakeholders including, among others, governmental actors, road operators, fleet managers, car manufacturers and private companies in general are interested in using detailed, precise and up-to-date data. Many stakeholders are concerned in testing new intelligent transportation systems, connected/automated vehicles and innovative intervention policies in realistic and complex urban simulation environments. Assuming just one of the motivations for using the data, one can easily realise that there are several issues to deal with when aiming for a shared vision on data acquisition, standardisation and use. In particular, different stakeholders have different views on several data-related uses. In particular, when assuming a limited number of data sets are available for DT input, one has to consider some critical aspects. Among these, the most relevant are:

1. number of possible data sources to use;
2. link/ease of access to different data sources;
3. data quality and the frequency of data updates;
4. data sovereignty;
5. data base extension/integration;
6. data import/export capabilities;
7. data business cases formulation/characterisation;
8. third-party data access issues;
9. third parties' data use;
10. third parties' data quality and simultaneous availability.

These considerations, while extensive, are probably not exhaustive. When actually implementing a city DT, other relevant and detailed concerns might arise simply when considering data related issues.

Data creation is fundamental for DTs. The Smart Cities approach, promoting and supporting urban mobility, has helped increasing connectivity and generating an unprecedented amount of data [24]. Big Data are not only big in terms of volume, velocity and variety, as Chen et al. [25] and Kitchin and McArdle [26] suggest, but they request dealing with noise accumulation, spurious correlation, measurement errors, and incidental endogeneity that, in turn, might affect data reliability and timely availability [27].

One should clearly keep in mind that all these efforts are performed to improve urban governance, in general, and, in our case, urban freight distribution, in particular. The widespread urban digitalisation in most developed cities ignited a process of change that has modified how they operate and how they are governed [28,29]. In particular, newer socio-technical governance methods and practices—that new technologies and data availability made possible—can, at least in principle, produce more sustainable, efficient and citizen-centred decisions. In other words, data allow for mobilising knowledge and supporting planning processes, procedures and participated decisions [24]. These considerations seem particularly pertinent when planning at a strategic level for the transportation sector in a city, in general, and for its freight component, in particular. This is due to the: (1) complexity of the system; (2) heterogeneity among the stakeholders; (3) degree of interconnection and correlation among the choices made.

3.3. Model Building

Batty [30] underlines that since its origin, the DT concept has widened and loosened somewhat. In fact, researchers now use it for different digital simulation models/purposes running alongside real-time processes, social and economic systems, as well as physical systems, blurring the distinction between any real system and any computer model of that system. A DT seems to refer to any system mimicking the operation of another as a model that, de facto, constitutes a simplification and abstraction of the structure/processes defining the system to which it is paralleled/compared. Models are, by their nature, simplifications of reality [31]. They should never aim at fully replicating the original system in the same detail as they, in that case, would be useless and cease to be a model. A model never perfectly mirrors a given system. This automatically makes it intrinsically different from the original system. Should, in fact, the model be a complete mirror image, which is exactly what a DT definition assumes when taken verbatim, then one might argue that a perfect "virtual" DT could not be distinguished from the "real" system itself. Thus, should this be the case, a full-blown DT would not differ from the system. In this case, one could question the use one could actually make of it to learn about the system by exploring, simulating and testing new configurations.

Before discussing the role DT can play in urban freight policy planning and implementation, it is useful to critically discuss some basic yet important methodological issues linked to model building in economics. A quotation reported in Meersman and Van de Vorde [32] clarifies the limits and caveats that a self-conscious modeller should always bear in mind when attempting to model a complex system that is undergoing rapid structural changes that, in turn, might have relevant implications for both the modelling process itself as well as for the reliability of the results produced. Boland [33] (p.144) underlines that, in this type of situations, "the key issue is unknown unknowns, specifically unanticipated shifts in the underlying process that were not pre-modelled". While we believe these considerations are always pertinent when dealing with models, we consider them *essential* when dealing with urban freight transport distribution policies.

Building models, assuming an underlying economic theory, always brings along some methodological decisions on the part of the model builder. Given the relevance these choices have on the result, it is much better to state them openly and clearly from the outset. Furthermore, the decisions taken will also depend on the intended purpose the model builder wants the model to serve. While there are few generally accepted principles in model building, economic model testability has always been a concern for most model builders [34]. Models are, by their nature, artificial. A main criterion to evaluate a given model is adequacy, which is how well it serves the purpose the model builder is pursuing. Two are the main purposes one can trail when building a model: (1) to produce an abstract representation of the underlying logic of the theory one intends to model (pure model); (2) a simplified representation of a general theory considered appropriate to solve or apply to a given or specific real world situation. One can develop the latter both to explain/describe a given phenomenon/problem and to develop a policy recommendation to tackle/solve the problem. While the distinction is, in principle, useful, one, following Samuelson, should also remember that "most sciences make a legitimate distinction between their applied and pure aspects, even though the borders are fuzzy" (Samuelson in [34]).

The rationale of model construction rests on testing various theories and comparing them on the base of the possible error with respect to known data. The objective the researcher pursues is to use the policy implications of the model, which minimise the error, given the data at hand. He or she assumes the model is true when applying it. The truth status is typically determined by the econometric estimation of the parameters. The parameters values one has logically deducted from the posited model, in turn, are obtained on the assumption of the model being true that is by considering that all the statements put together in the model generate a jointly true compound statement. This is a critical issue when using DTs for policy-making. A detailed discussion is provided in the next section.

4. Digital Twins for Urban Freight Policy-Making and Planning

Meersman and Van de Vorde [32] underline that transport policy after WWII primarily revolved around stimulating mobility to foster economic growth. This influenced the type of modelling approach researchers developed. The models in this period focused on estimating and forecasting transport demand with a great attention paid to passenger and much less to freight. The same authors suggest that the in the period 1970–2000, when the increase in transport demand kept rising due to the progressive extension of supply chains linked to a steadfast globalisation process, the modelling focus veered towards a short-term planning. In this case the aim was promoting both productivity and efficiency growth within the transportation system. The overall economic situation was such that a steady and growing interest developed in freight transport modelling, planning and management of logistics chains. The intensive use of transportation services to achieve economies of scale in production, the interest in sourcing intermediate goods from remote areas where comparatively lower salaries warranted lower labour costs, the importance of reaching far away markets at relatively low transport prices have spurred policy-makers' attention towards the negative external costs transport is producing. The geographical focus of this latter issue revolves around cities given these are the loci where end consumers are located and where most of the products flow into. In fact, freight transport produces approximately 30% of greenhouse gases (GHG) emissions due to the increase in road freight transport representing around 90% of all city incoming freight movements. Independently of the substantial improvements in technology (e.g., improved Euro-standards for cars), curbing freight transport-related GHG emissions in cities is simply not taking place (see Figure 1).

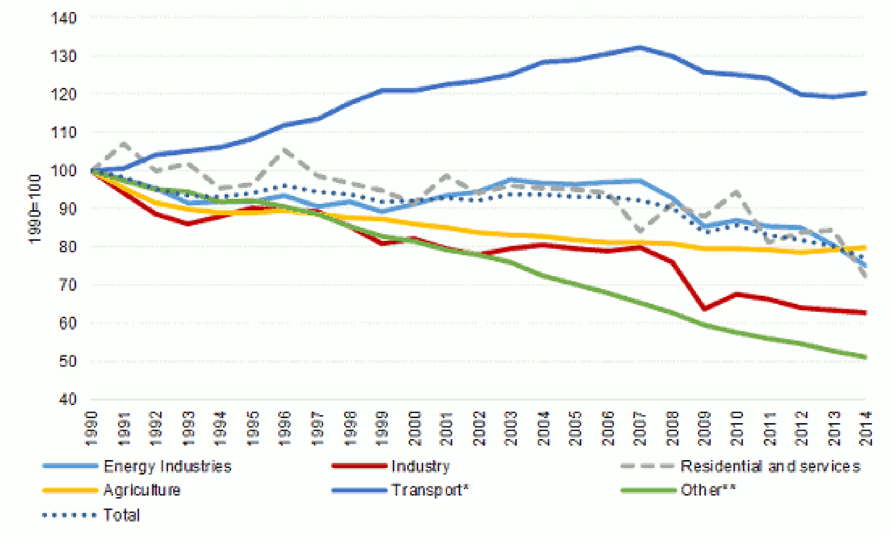

Figure 1. Greenhouse gas (GHG) emissions by sectors. (Note: * Transport includes international aviation but excludes international maritime; ** Other include fugitive emissions from fuels, waste management and indirect CO2 emissions). Source: EEA [35].

The outlook seems unfavourable given the likely negative effects growing e-commerce-related deliveries will have. The technological changes and the strong attention towards global warming and GHG emissions may call for predictions of effects that may follow from more radical changes in technology and policy. These are likely to be far stronger than the more conventional incremental changes that most current freight models are designed for. The main motivations for a more scenario-oriented type of modelling approach are primarily due to the limited ability to include larger structural, organisational and behavioural change issues in the current freight models. The complexity of urban networks combined with prospective needs for policy changes raise important challenges connected to the handling of uncertainty, heterogeneity, correlation among agents' preferences, substantial time lags elapsing form the time when a decision is taken/a policy implemented and the measurement/comparison of the effects/results provoked, et cetera. The implications that time lags and uncertainty have in measuring behaviour change substantially depend on the amount of time stakeholders need to understand the implications the policy enacted might have and the time needed to detect the implicit behaviour changes that they need to implement. This process might have, in turn, implications on stakeholders' preferences for the policy under discussion and, in a participatory planning process, ultimately, modify their choices. The specific modelling approach in this context is fundamental. In fact, it could provide all the stakeholders involved in the planning process a timely, reliable and, possibly, correct forecast of the consequences, a given policy under discussion, might have in the future. The mere availability of such information might have strong implications with respect to their position and preferences expressed during the participatory planning process. Structural changes and uncertainty should be deeply embedded in the modelling process developed [36]. Urban freight modelling has substantially evolved from a non-structural, aggregated engineering approach [37]. Changes in empirical methods and higher data availability at shipment level have allowed for more detailed, disaggregated and behavioural intuitions [38,39]. The overarching needs for e.g., GHG emission reductions is likely to affect the transport sector severely. Rapid and/or radical changes in the transport sector may give rise to such profound changes as to make the existing modelling approach hardly usable and less reliable. One can no longer realistically assume a stable context thus the traditional mechanistic model approach is unserviceable. One needs to evaluate possible alternatives capable of adequately deal with current challenges that include heterogeneity, correlation both in preferences and in the decision-making process/architecture.

All this said, one important question emerges: what are the practical implications when using DTs for urban freight policy-making and planning?

Firstly, one would have to abandon the idea that a DT it is a "perfect twin" of reality. Provocatively one could argue that a **DT is a *heterozygotes* rather than a *homozygotes* twin of reality.** One could hence argue that a DT is de facto a conventional model that abstracts in a limited number of variables and processes from reality, but still abstracts. This distinction between a DT model and reality is what finally allows using a DT for policy-making and planning when employing it in a human-based context. DT models thus should be incomplete mirrors or twins of reality if they are going to be of any use in making sense of the world. We should conceive the DT as a metaphor expressing the desire of modellers to build models that are progressively closer to reality. Tomko and Winter [40] suggest a more realistic and appropriate characterisation of a DT as a *cyber–physical–social system* with sensing, agency and immune system properties. Following Tomko and Winter [40], one can qualify these characterising properties as follows: (1) *sensing*—the modelling approach is capable of sensing the environment and update its counterpart accordingly; (2) *agency*—the model can change (both the physical and digital) the environment on the base of instructions deriving from the counterpart; (3) *immune system*—the resilient model can moderate the system attempts to preserve its operational state. One can assimilate a *cyber–physical–social system* to an organism with a brain where the digital counterpart interacts with reality via sensors, actuators and communication lines thus enabling agency. In this functional exemplification, the digital representation can interact with the real system thus enabling the realistic simulation of alternative physical systems.

Secondly, one has to be particularly careful when using DT modelling approach for policy-making and planning purposes since one cannot realistically assume a stable long-term relationship between exogenous and endogenous variables. Zheng et al. [41] define a DT as "an integrated system that can simulate, monitor, calculate, regulate, and control the system status and process". While this might well be easily understood and accepted when involving a physical production process, where the relation between causes and effects can reasonably be considered stable, the same cannot realistically be assumed when the policies implemented are specifically targeted at changing stakeholders' behaviour. For urban logistics planning purposes, these seemingly intrinsically unrealistic assumptions about DTs properties in our case will: (1) determine the robustness of the results the modelling approach can produce; (2) depend on the scope and breadth of the policy implemented; (3) hinge on the rapidity of its deployment; (4) be subject to the interconnections the policy has along the supply chain; (5) be contingent on the number/power of stakeholders it aims to influence. In fact, the relationship between causes and effects in urban freight is not a mere physical law as those governing gravity or electromagnetism, but is rather based on stakeholders' preferences and utilities which, is reasonable to assume, are much less stable and predictable. Thus, having only raw data available, without knowing the underlying motivations that generated those observable data, is not of great use if one intends to control the process. This is especially so when dealing with a given policy deployed with the specific aim of changing the underlying relationship between causes and effects. In other words, whereas **one can safely use DTs for short-term predictions, when one can assume a stable relationship between causes and effects, the same does not apply when using DTs for planning and long-term decisions** such as those characterising Sustainable Urban Mobility

Plans. Furthermore, even in a short-term scenario, one should test rather than assume stability in the explained behavioural relations.

Thirdly, DTs can play a fundamental role when adopting a Living Lab approach in order to assist policy-making and planning. In fact, a Living Lab is usually organised around four basic and useful principles: (1) practical "real life" setting with implementation in the field; (2) multiple stakeholders; (3) co-creation of innovative solutions and end-user involvement; (4) iterative learning and development. All this is in line with the underlying logic of a DT approach. In fact, the basic idea behind a Living Lab approach is the recursive involvement of the stakeholders in the co-creation process which is also at the base of the DT functioning where the "real" and "digital" reality iteratively interact. Furthermore, the development of a DT would allow an "on-the-fly" check of the correspondence between the functions that are assumed to govern agents' behaviour (estimated utility functions based on stated preference data) and those that actually drive their behaviour (real-life data collection after the policy is implemented). This would be useful for the recurrent planning process for two reasons. The first, and most obvious, is the development of a dynamic model of reality. The second has to do with the joint use of a DT and Living Lab approach to deeply involve all the interested stakeholders in the planning process. This could benefit also from the use of virtual reality tools to illustrate the future implications of current choices. **DTs might help clarifying to the stakeholders participating in the planning process the likely implications a given choice taken *now* might have with respect to the whole system in the *future* thus potentially altering their *current* preferences and choices**. In fact, being capable of realistically predicting the potential implications of a given policy, in a participatory policy-planning context centred on a Living Lab approach, is valuable, especially when operating within a complex system characterised by difficult-to-predict emerging phenomena. However, it is important to underline the high data updating frequency characterizing a DT model and compare this with a regular model, which typically needs a much lower data update frequency. This distinction is crucial to allow enough time for the DT to acquire some inputs from the real system so to provide the former with some diagnostic function thanks to latency. These considerations clarify the role DTs can play in increasing awareness, shortening understating lag time and modifying perceptions of not-yet-implemented policies.

The fourth point, linked to the third one, relates to the contribution of DTs to improved impact visualization and realism to aid urban freight transport planning and decision-making. **DTs can be used to visualise complex and perhaps abstract causes and effect relationships**, e.g., to what extent urban design principles from theory (cityscapes, building design, transport systems etc.) applied on the urban case in question are met by the proposed plan or project through a visual comparison. Another example could be the location of a micro-hub in the middle of a residential area, where a DT through visualization could enhance the understanding of the changes in the number of in-/outbound cargo movements, with what type of vehicles, and how the hub in various physical shapes could actually look like. One could also simulate and visualise how other structures like a new shopping mall will affect its surroundings and the various flows. On a more macro-oriented level, a DT could also help to visualise flows and impacts of changes in the urban freight network, based on some underlying model(s). Visualisation tools, such as DTs, provide a way of transferring the complex ideas underpinning design and planning into more intuitive thus accessible visual forms. One can use DTs to foster and possibly shape a common understanding of problems and solutions [42]. Visualisations have also been criticised, when presented in a way that aims to persuade the public of a projects value or steer the public towards a specific direction [43,44]. For this reason, it is important that plans and visualisation tools are accurate and realistic when presenting scenarios while should always adopt a multiple stakeholder perspective [42,45]. DTs represent a valid and useful complement to the currently used paper-based drawings, sketches and maps [46–4748].

To summarise, today, data exist in such an unprecedented dimensionality and granularity, in most of the research contexts we are working in, even if for complex systems such as urban freight, we often do not have the quality nor the quantity of the data we would like to have. We live in a progressively more complex world in which the behaviour of different stakeholders aggregates to produce novel and unexpected phenomena. Nevertheless, **it is not possible to *make sense* of what**

happens in the real world without a sound theory and knowledge with respect to the relationships linking contextual reality and choice/behaviour that one might call deep causality. Data are an instrument not a goal, and they do not speak for themselves. One should simply acknowledge what was clearly stated by the Nobel Prize winner political-economist Elinor Ostrom [49] (p. 430) when she said: “It is not possible yet to point to a single theory of human behaviour that has been successfully formulated and tested in a variety of settings”. In other words, a model of human behaviour should in principle be capable of describing and predicting how people cooperate, vote, start protests, get married, divorce, chose to wear a fashionable pair of trousers, invest in stocks or even become addicted to alcohol or drugs. To account both for coherence and allow for variety, one can either consider people acting as rule-based or rational actors. Rules can be, of course, fixed or adaptive since a rational actor would adapt his/her rule-based decision-making process on the evidence produced by his/her choice given the rule adopted to take it. This distinction, while clear in principle, can become totally blurred in practice. One should simply acknowledge that the modelling approach adopted much depends both on the context as well as on the goals pursued.

Figure 2 summarises the DT concept applied to urban freight transport policy-making and planning. A good DT model of the urban freight transport ecosystem is fundamentally based on real-time data, which can also stem from a Living Lab approach with the co-creation and implementation of policies, but it also strongly relies on stakeholder preferences and their dynamic choices and behaviours. These are in turns intertwined with the Living Lab approach, which accounts for stakeholder involvement in the planning process, and on behavioural models capable of predicting the impact of different scenarios on stakeholder behaviours and choices. Only by looking at the overall picture it will be possible to use the DT approach as a suitable support-tool for policy-making and planning in urban freight transport. Practical implications of the approach proposed refer to the: (1) greater robustness of the predictions; (2) higher reliability in defining the most appropriate intervention policies and (3) more effectiveness of the solutions identified.

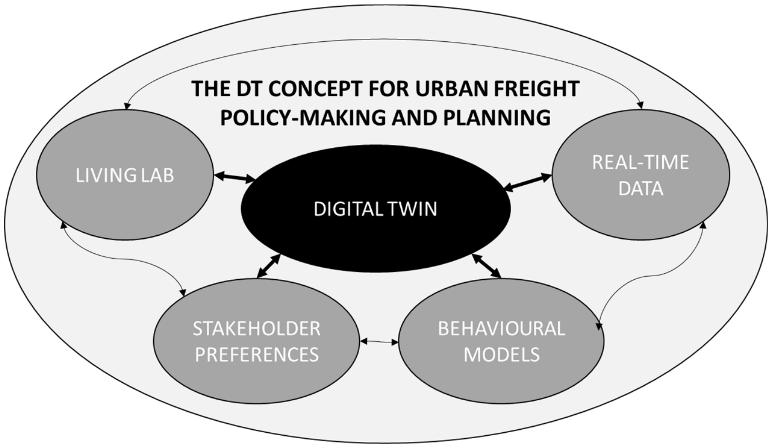

Figure 2. The Digital Twin (DT) concept for urban freight policy-making and planning. Source: own elaboration.

5. Conclusion and Future Research

This paper discusses theoretically grounded issues that one should explicitly consider when using a DT-based modelling approach within a planning-intense context given the implications that might derive from its adoption. In particular, we considered the urban freight transport planning and policy-making environment, which has some peculiarities that make it different from other (transport) planning contexts. Under this respect, a general lack of knowledge and data, heterogeneity of stakeholders and need of policy packaging to address different objectives are main aspects to consider when dealing with this important, yet sometimes overlooked, component of city planning [50].

Three main conclusions can be derived from the analysis presented.

I. A DT system cannot be fully representative of the reality of urban freight transport. This is due to the often cited and widely recognised deep complexity of an urban freight distribution system, on one side, the lack of readily available data to continuously feed the model on the other and, most importantly, the instability of the relationships describing agents' behaviour. In fact, DTs are using data recursively from reality as inputs for the model, which are, in turn, used to forecast policy's impact on reality assuming a stable underlying behavioural relationship between causes and effects. This approach, though reasonable in developing a product or predicting necessary maintenance, cannot be simply assumed as realistic and valid when the purpose of the intervention is exactly modifying how stakeholders react to "reality". This seems even more problematic when jointly considering heterogeneity, non-linearity and correlation among stakeholders' utility functions, which one needs to consider in an urban freight context when trying to provide realistic explanations of behaviours. The use of DTs has to undergo a scrupulous scrutiny in terms of internal validity and appropriateness for policy-making, since one cannot exclude that by choosing appropriate starting values and taking specific behavioural assumptions/relationships one can, in principle, substantially steer and manoeuvre the decision-making process. Furthermore, one should use this methodological approach with caution especially for long-term predictions when the stability assumption of the behavioural relationships between exogenous and endogenous variables is even less defensible.

II. DTs can play a very important role in supporting experimentation/piloting in urban logistics planning and policy-making, in general, and for its on-demand component, in particular. Using DTs to inform stakeholders about the future implications of a given policy in order to structure and reinforce their information set could allow for a more informed decision process. This is particularly important in a participatory planning environment. The recognition lag of the consequences, in fact, largely depends on the capability of the modelling approach to promote stakeholders' awareness on the implications the about-to-be-implemented policy might have on them. This is extremely relevant since, in this complex and articulated system, stakeholders' primary reactions might have non-negligible impacts on secondary reactions. This might well support participatory planning processes as well as affecting the final equilibrium conditions and preferences.

Paradoxically, the intrinsically daunting characteristics of an urban freight distribution system are exactly those that make it appropriate to use in a joint DT and Living Lab approach assuming the modeller and the decision-makers are well aware of the operating characteristics and limitations the specific context poses on the planning procedures adopted. If correctly conceived and deployed this process should be capable of producing knowledge and reliable simulations of the impacts potential policy deployment might have on the system itself.

III. Behavioural and simulation models are the two elements to use jointly when modelling urban freight transport. Whereas the former proceed from stakeholders' random utility functions to calculate the most probable choice behaviour, the latter dynamically replicate reality. In fact, this is not only useful to stimulate an effective, well-informed and participated planning process but also to forecast both behaviour and reactions to structural changes and policy measures implementations. This is reinforced when considering the public-private urban context this phenomenon is taking place. This approach is also beneficial when adopting a Physical Internet perspective to urban freight distribution, which represents one of the most innovative and forward-looking vision to ensure an increase in efficiency coupled with the achievement of an environmental economic and social sustainability goal. The European Technology Platform ALICE (Alliance for Logistics Innovation through Collaboration in Europe, http://www.etp-logistics.eu/) acknowledges the need for an all-encompassing strategy on logistics, supply chain planning and control in which shippers and logistics service providers cooperate aiming for efficient operations. This perspective allows for both virtuous competitions and relevant cooperation.

The focus of future urban freight modelling research will revolve around: (1) microeconomic explanations of stakeholders' choices; (2) structural policy impact assessment/evaluation; (3) real time data modelling integration. When considering the three main urban freight modelling pillars one should always have clear in mind that the pace of technological innovation (i.e., digitalisation and automation) is deeply and rapidly transforming the logistic industry with logistic chains responding to new opportunities by developing digital services and new business models that imply profound reorganisations and new labour structures. Stakeholders' preferences might undergo swift and deep changes in the future. One of the main changes revolves around business "servitization" that is now attracting substantial research interests as the special issue on "Product-service innovation systems: Opening-up servitization-based innovation to the manufacturing industry" in the Journal "International Journal of Operations & Production Management" testifies (see also Tukker [51]).

Furthermore, the convergence process in an opinion dynamic modelling framework will be recursive in nature, especially considering the manifestation of possible peer effects influencing the planning process [52]. There can be some advantages when using statistical science-based surrogate modelling with preference-based assessment procedures to recursively build, update and validate predictive models as it has been demonstrated in the case of manufacturing design preferences [53]. It is, in fact, appropriate to investigate, as research in neurosciences has made clear, how preferences emerge, why they might change and how they can be influenced.

An illuminating article by Tavasszy [54] discusses the effects of logistic innovations on freight systems. The paper argues that qualitative understanding of logistic innovations is a prerequisite to develop quantitative analysis and correct transport policy predictions. The article convincingly discusses three fundamental tenets that should characterise a modelling approach capable of dealing under these circumstances. In particular, it argues that there is a need for model improvements with respect to: (1) structural elements of the system that is modelled; (2) functional relations among those elements; (3) dynamic properties. Innovation, modelling, policy planning and implementation are not only intertwined, but one should also treat them jointly so to avoid inconsistent/unreliable modelling/forecasting outputs.

In this respect, we suggest working more, both theoretically as well as empirically, with DTs in urban freight planning and policy-making since the two elements are not only conceptually linked but are also needed to foster improvements. Providing an application of the proposed approach to a real case will show its practical feasibility and usefulness, as well as the improvements, compared to alternative approaches. At the same time, one should properly address dynamics and uncertainty in models and data, while also clearly stating both the limitations and the possible intrinsic shortcomings of the approach used.

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References

1. Box, G.E., Draper, N.R. Empirical Model-Building and Response Surfaces. John Wiley & Sons: Hoboken,NJ, USA, 1987, p. 424.
2. Joerss, M.; Schröder, J.; Neuhaus, F.; Klink, C.; Mann, F. *Parcel Delivery: The Future of Last Mile*; McKinsey & Company: New York, NY, USA, 2016.
3. De Smet, A.; Lurie, M.; St George, A. *Leading Agile Transformation: The New Capabilities Leaders Need to Build 21st-Century Organizations*; McKinsey & Company: New York, NY, USA, 2018.
4. Brettmo, A.; Browne, M. Business Improvement Districts as important influencers for changing to sustainable urban freight. *Cities* **2020**, *97*, 102558, doi:10.1016/j.cities.2019.102558.

5. Gatta, V.; Marcucci, E.; Le Pira, M. Smart urban freight planning process: Integrating desk, living lab and modelling approaches in decision-making. *Eur. Transp. Res. Rev.* **2017**, *9*, 32, doi:10.1007/s12544-017-0245-9.
6. Allen, J.; Bektaş, T.; Cherrett, T.; Friday, A.; McLeod, F.; Piecyk, M.; Piotrowska; M; Austwick, M.Z. Enabling a freight traffic controller for collaborative multidrop urban logistics: Practical and theoretical challenges. *Transp. Res. Rec.* **2017**, *2609*, 77–84.
7. Nesterova, N.; Quak, H. A City Logistics Living Lab: A Methodological Approach. *Transp. Res. Procedia* **2016**, *16*, 403–417, doi:10.1016/j.trpro.2016.11.038.
8. Tavasszy, L.; de Jong, G. *Modelling Freight Transport.*; Elsevier BV: Amsterdam, The Netherlands, 2014.
9. De Bok, M.; Tavasszy, L.; Thoen, S. Application of an empirical multi-agent model for urban goods transport to analyze impacts of zero emission zones in The Netherlands. *Transp. Policy* **2020**, in press, doi:10.1016/j.tranpol.2020.07.010.
10. Sakai, T.; Alho, A.R.; Bhavathrathan, B.; Chiara, G.D.; Gopalakrishnan, R.; Jing, P.; Hyodo, T.; Cheah, L.; Ben-Akiva, M. SimMobility Freight: An agent-based urban freight simulator for evaluating logistics solutions. *Transp. Res. Part. E Logist. Transp. Rev.* **2020**, *141*, 102017, doi:10.1016/j.tre.2020.102017.
11. Marcucci, E.; Le Pira, M.; Gatta, V.; Inturri, G.; Ignaccolo, M.; Pluchino, A. Simulating participatory urban freight transport policy-making: Accounting for heterogeneous stakeholders' preferences and interaction effects. *Transp. Res. Part. E Logist. Transp. Rev.* **2017**, *103*, 69–86, doi:10.1016/j.tre.2017.04.006.
12. Pedersen, T.A.; Glomsrud, J.A.; Ruud, E.-L.; Simonsen, A.; Sandrib, J.; Eriksen, B.-O.H. Towards simulation-based verification of autonomous navigation systems. *Saf. Sci.* **2020**, *129*, 104799, doi:10.1016/j.ssci.2020.104799.
13. Carvalho, A.; Melo, P.; Oliveira, M.A.; Barros, R. The 4-corner model as a synchromodal and digital twin enabler in the transportation sector. In Proceedings of the 2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Cardiff, UK, 15–17 June, 2020; pp. 1–8.
14. Grieves, M. Conceptual ideal for PLM. Available online: https://www.researchgate.net/publication/307509727_Origins_of_the_Digital_Twin_Concept (accessed on 14 December 2020).
15. Glaessgen, E.; Stargel, D. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference20th AIAA/ASME/AHS Adaptive Structures Conference14th AIAA, Honolulu, Hawaii, 23–26 April 2012, 2012; p. 1818.
16. Boschert, S.; Rosen, R. Digital twin—The simulation aspect. In *Mechatronic Futures*; Springer, Cham, Switzerland, 2016; pp. 59–74.
17. Alam, K.M.; El Saddik, A. C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems. *IEEE Access* **2017**, *5*, 2050–2062, doi:10.1109/access.2017.2657006.
18. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems*; Springer: Berlin, Germany, 2017; pp. 85–113.
19. Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J.; Sihn, W. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine* **2018**, *51*, 1016–1022, doi:10.1016/j.ifacol.2018.08.474.
20. Liu, Z.; Meyendorf, N.; Mrad, N. The role of data fusion in predictive maintenance using digital twin. *AIP Conf. Proc.* **2018**, *1949*, 020023, doi:10.1063/1.5031520.
21. Schmidt, M.D. *Delivering a Digital Twin. ANSYS Advantage XI:43–45*; Ansys: Canonsburg, PA, USA, 2017.
22. Rasheed, A.; San, O.; Kvamsdal, T. Digital Twin: Values, Challenges and Enablers from a Modeling Perspective. *IEEE Access* **2020**, *8*, 21980–22012, doi:10.1109/access.2020.2970143.
23. Richter, A.; Löwner, M.O.; Ebendt, R.; Scholz, M. Towards an integrated urban development considering novel intelligent transportation systems: Urban Development Considering Novel Transport. *Technol. Forecast. Soc. Chang.* **2020**, *155*, 119970.
24. Allam, Z.; Dhunny, Z.A. On big data, artificial intelligence and smart cities. *Cities* **2019**, *89*, 80–91, doi:10.1016/j.cities.2019.01.032.
25. Chen, H.; Chiang, R.H.L.; Storey, V.C. Business Intelligence and Analytics: From Big Data to Big Impact. *MIS Q.* **2012**, *36*, 1165, doi:10.2307/41703503.
26. Kitchin, R.; McArdle, G. What makes Big Data, Big Data? Exploring the ontological characteristics of 26 datasets. *Big Data Soc.* **2016**, *3*, 2053951716631130, doi:10.1177/2053951716631130.
27. Fan, J.; Han, F.; Liu, H. Challenges of Big Data analysis. *Natl. Sci. Rev.* **2014**, *1*, 293–314, doi:10.1093/nsr/nwt032.

28. Kernaghan, K. The Post-Bureaucratic Organization and Public Service Values1. *Int. Rev. Adm. Sci.* **2000**, *66*, 91–104, doi:10.1177/0020852300661008.
29. Willis, K.S.; Aurigi, A. *Digital and Smart Cities*; Informa UK Limited: London, UK, 2017.
30. Batty, M. Digital twins. *Environ. Plan. B Urban Anal. City Sci.* **2018**, *45*, 817–820.
31. Korzybski, A. *Supplement III. A Non-Aristotelian System and its Necessity for Rigour in Mathematics and Physics*; International Non-Aristotelian Library: Lakeville, MN, USA, 1931.
32. Meersman, H.; Van De Voorde, E. Freight transport models: Ready to support transport policy of the future? *Transp. Policy* **2019**, *83*, 97–101, doi:10.1016/j.tranpol.2019.01.014.
33. Boland, L.A. *Model. Building in Economics*; Cambridge University Press (CUP): Cambridge, UK, 2014; Volume 9781107032941.
34. Boland, L.A. *The Methodology of Economic Model Building (Routledge Revivals): Methodology after Samuelson*; Routledge: Abingdon, UK, 2014.
35. European Commission. A European Strategy for low-emission mobility. At: https://ec.europa.eu/clima/policies/transport_en (accessed on 14 December 2020).
36. Lyons, G.; Davidson, C. Guidance for transport planning and policymaking in the face of an uncertain future. *Transp. Res. Part. A: Policy Pr.* **2016**, *88*, 104–116, doi:10.1016/j.tra.2016.03.012.
37. D'Este, G. Urban Freight Movement Modeling. In *Handbook of Transport Geography and Spatial Systems*; Emerald: Bingley, UK, 2007; pp. 633–647.
38. Ben-Akiva, M. E., Meersman, H., & Van de Voorde, E. (Eds.). Freight Transport Modelling. Emerald: Bingley, UK
39. Marcucci, E. Logistics Managers' Stated Preferences for Freight Service Attributes: A Comparative Research Method Analysis. In *Freight Transport Modelling*; Emerald: Bingley, UK, 2013; pp. 251–280.
40. Tomko, M.; Winter, S. Beyond digital twins–A commentary. *Environ. Plan. B Urban Anal. City Sci.* **2019**, *46*, 395–399.
41. Zheng, Y.; Yang, S.; Cheng, H. An application framework of digital twin and its case study. *J. Ambient. Intell. Humaniz. Comput.* **2018**, *10*, 1141–1153, doi:10.1007/s12652-018-0911-3.
42. Hansson, L. Visual representation in urban transport planning—Where has all the cars gone? *Transp. Res. Part A Policy Pract.* **2020**, *133*, 1–11.
43. Downes, M.; Lange, E. What you see is not always what you get: A qualitative, comparative analysis of ex ante visualizations with ex post photography of landscape and architectural projects. *Landsc. Urban. Plan.* **2015**, *142*, 136–146, doi:10.1016/j.landurbplan.2014.06.002.
44. Sheppard, S.R. Guidance for crystal ball gazers: Developing a code of ethics for landscape visualization. *Landsc. Urban. Plan.* **2001**, *54*, 183–199, doi:10.1016/s0169-2046(01)00135-9.
45. Hopkins, L.D.; Knaap, G.-J. Autonomous planning: Using plans as signals. *Plan. Theory* **2016**, *17*, 274–295, doi:10.1177/1473095216669868.
46. Daniel, T.C.; Meitner, M.M. Representational Validity of Landscape Visualizations: The Effects of Graphical Realism on Perceived Scenic Beauty of Forest Vistas. *J. Environ. Psychol.* **2001**, *21*, 61–72, doi:10.1006/jevp.2000.0182.
47. Wu, H.; He, Z.; Gong, J. A virtual globe-based 3D visualization and interactive framework for public participation in urban planning processes. *Comput. Environ. Urban. Syst.* **2010**, *34*, 291–298, doi:10.1016/j.compenvurbsys.2009.12.001.
48. Stevens, D.; Dragicevic, S.; Rothley, K. iCity: A GIS-CA modelling tool for urban planning and decision making. *Environ. Model. Softw.* **2007**, *22*, 761–773, doi:10.1016/j.envsoft.2006.02.004.
49. Ostrom, E. *Beyond Markets and States: Polycentric Governance of Complex Economic Systems. Am. Econ. Rev.* **2010**, *100*, 641–672, doi: 10.1257/aer.100.3.641 .
50. Le Pira, M.; Marcucci, E.; Gatta, V.; Inturri, G.; Ignaccolo, M.; Pluchino, A. Integrating discrete choice models and agent-based models for ex-ante evaluation of stakeholder policy acceptability in urban freight transport. *Res. Transp. Econ.* **2017**, *64*, 13–25, doi:10.1016/j.retrec.2017.08.002.
51. Tukker, A. Eight types of product-service system: Eight ways to sustainability? Experiences from SusProNet. *Bus. Strat. Environ.* **2004**, *13*, 246–260, doi:10.1002/bse.414.
52. Narayan, V.; Rao, V.R.; Saunders, C. How Peer Influence Affects Attribute Preferences: A Bayesian Updating Mechanism. *Mark. Sci.* **2011**, *30*, 368–384, doi:10.1287/mksc.1100.0618.

53. Krishnamurty, S.; Wilmes, G. Preference-Based Updating of Kriging Surrogate Models. In Proceedings of the 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference; American Institute of Aeronautics and Astronautics (AIAA), Albany, NY, USA, 30 August–1 September 2004; p. 4484.
54. Tavasszy, L. Predicting the effects of logistics innovations on freight systems: Directions for research. *Transp. Policy* **2020**, *86*, A1–A6, doi:10.1016/j.tranpol.2019.11.004.