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Digital Twins for City Logistics: Towards a Roadmap



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1 Introduction

Digital Twins are one of the key new applications of computing technology in urban management and one of the key ingredients of the smart and sustainable city paradigm. Smarter cities can significantly contribute to sustainable freight transport by curbing traffic pollution, CO_2 emissions, noise annoyance, social inequity and other externalities (Tavasszy et al. 2025). The main function of a digital twin is to support

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public and private stakeholders with the management of logistics processes inside the city, including the planning and execution of these processes, their facilitation with infrastructure and their regulation (see also Table 1). Digital twins aim to make cities more responsive, flexible and inclusive in identifying pressing problems and solutions (Tapia and Tavasszy 2024). This chapter explores the current and future approaches towards the design of digital twins for sustainable urban logistics systems.

In its simplest form, the digital twin is not more than a shadow of the system, reactive in its behaviour to data produced by the real system. In its more advanced form, it contributes to the control of system behaviour by actuating actions, responding to analysis of states, predictions of future states and prescriptive analysis to determine optimal control signals. "Smartness" then resides in the sensors that monitor the system (possibly interconnected as IoT), the digital representation of subsystems (simulation), the chained algorithms for problem interpretation, forecasting and system optimisation (opportunities for AI) and the visualisation of the system for stakeholders (VR/AR). Clearly, much technical advancement is possible to help digital twins develop from the simple implementations of today as simulation models, to advanced controllers of the urban freight transport system. In addition, urban logistics systems are complex, with many stakeholders, technologies, and processes fraught with uncertainty and volatility, and urgent problems with management of efficiency and external impacts.

Logistics management decisions can relate to many aspects (Riopel and Langevin 2005 count 48 fields of decision making) and many different stakeholders (public and private) are relevant. DTs act as decision support tools in decision cycles, which can be conveniently pictured as control loops or—in management language—Deming cycles (PDCA). We take this framing as a starting point and posit that all

Table 1 DT functions and positioning in decision types

	Decision	Measurement	Evaluation	Decision generation	Actuation
Operational	Dynamic access, traffic management	Cameras, loop detectors, GPS, trucks	Delivery satisfaction, costs, emission levels	Scenario-based algorithms in traffic management centres	Speed management, access restrictions, enforcement
Tactical	Time windows, vehicle restrictions; planning of curb use; reservations	Planning systems, capacity utilisation	(infrastructural, environmental) capacity utilisation patterns	Local policy design, implementation and enforcement teams	Local traffic and urban design plans
Strategic	Infrastructure, hub development	Land use, transport, environmental statistics	Long-term cost-effectiveness, sustainability	Political, policy departments, development actors	Land-use plans, construction and maintenance

logistics decisions, with different degrees of formality, follow such cycles. Applications of DTs for city logistics can be envisaged in strategic, tactical and operational decision cycles. Strategic decisions concern investments and heavy governance arrangements related to institutions and their governance (e.g. law). These cycles are slow and typically revolve over years. Tactical decisions are related to the reservation of asset capacity for operations, and its codification in fleet management plans, service schedules and sourcing and delivery contracts. These decisions will typically be updated on a yearly basis. Operations concern the execution of logistics services, with high-frequency decisions, measured in days or even seconds. DTs in the public policy spheres will aim to support or regulate processes at these levels (Table 1).

Clearly, the nature of and requirements for DTs will differ between these contexts. Especially in the strategic context, sophisticated simulation and optimisation models have existed since the second half of the previous century. So far, they have developed mostly as digital shadows of systems, however. Actuation happens through years-long processes of policy preparation, political decision-making and policy implementation. The different models used to support these management processes emulate and predict the behaviour of the system, using observations, which, again, move at a slow pace, typically built on public statistics. The framing of these models as digital twins (more accurately now: digital shadows) has provided a new way of looking at these models. It has opened up an innovation perspective in two new directions. Firstly, the closing of control loops (or decision-making cycles) by making the sensing and actuation activities consistent with each other. This begs the question whether the correct data are acquired to produce decisions and (ex-post) evaluate them. Secondly, it connects long and short-term cycles within the same paradigm. This opens up possibilities to use strategic data and models for tactical and operational decisions and vice versa.

This chapter reports on recent advances in digital twin development for urban logistics systems. Several recent EU projects have brought new insights about the positioning of DTs in city logistics management, the alternative trajectories that DT technology can take in this context and the possible impacts of applying DTs. While many studies and experiments have propelled our technological DT capabilities further, there has been less attention to alternative experiences with this technology in city logistics. This chapter aims to contribute by framing the DT functions in the urban logistics context, developing an innovation pathway for DTs based on this framing and positioning recent DT use cases.

Within the scope of the complete and multi-dimensional framing of DTs, this chapter takes a narrow approach in two respects. Firstly, our focus lies on the representation capabilities of DTs in the context of city logistics, in contrast to the sensing and control capabilities. Such a DT is often called a digital shadow of the physical system. The main difference with a fully bi-directional DT is that the sensing and actuation of the system are not fully automated. Secondly, we limit ourselves to strategic decisions related to policies of public institutions, specifically supporting infrastructure and the permanent regulation of its use. Broader discussions of DTs for short-cyclic urban management, the bi-directional, control-focused

DTs and their respective positioning along the lines of Table 1 can be found elsewhere in the literature (Nag et al. 2025; Le et al. 2024; Tavasszy and Quak 2023; Batty 2018).

It is worthwhile to note that the scientific literature on digital twins for city logistics is still nascent. Recent work which addresses the use of DTs for urban freight policy purposes can be found in (Tavasszy et al. 2025; Belfadel et al. 2023; Marcucci et al. 2020; Abouelrous et al. 2023; Tapia and Tavasszy 2024; Jeong et al. 2022; Nag et al. 2025; Grotto et al. 2024; Taniguchi et al. 2024; de Bok et al. 2024). In this chapter, we contribute by presenting results from European projects that have focused on two very different architectures: a centralised, single-form DT which is used in similar way for different cities and cases (de Bok et al. 2024; Gürcan et al. 2025) and a federated approach with a library of DTs, where model components are chosen to be applied depending on the policy question (Belfadel et al. 2023). The second, even though experimental, is interesting as it shows the direction for the evolution of DTs according to a generic maturity model (Tapia and Tavasszy 2024), from sectoral to multi-sectoral DTs. This model shows that sectoral city DTs can be seen as systems-of-systems.

The next section provides an overview of these approaches. Section 2 provides examples of applications. Section 3 reiterates main learnings from the projects and concludes the chapter.

2 Digital Twins for City Logistics: Three Cases

2.1 Alternative Architectures

Here, we introduce the approaches for urban DTs as implemented in recent EU projects. A general architecture for the DT/PT duplet is shown here, based on (Belfadel et al. 2023). The physical world communicates with the DT by feeding it with relevant data obtained from measurements and sensors (lower arrow) and recording recommendations for policy and decision making (upper arrow). Note that the storage system includes the model library, which can also be reduced to an extreme case of a single model. The existence of such a library with the resulting degrees of freedom marks the difference between a centralised and a distributed architecture. In the centralised case, one model will be prescribed for all cases as the simulation engine for the DT. In the distributed case, a whole library of models can be used, and the model management system has the additional task of configuring the specific model system required to answer a question. In other words, parts of the system thought to be less relevant will be switched off in the DT. This approach has the advantage of efficiency and flexibility, but may also reduce the transparency of the applications and their validity, if pragmatic choices are made in the selection of models (Fig. 1).

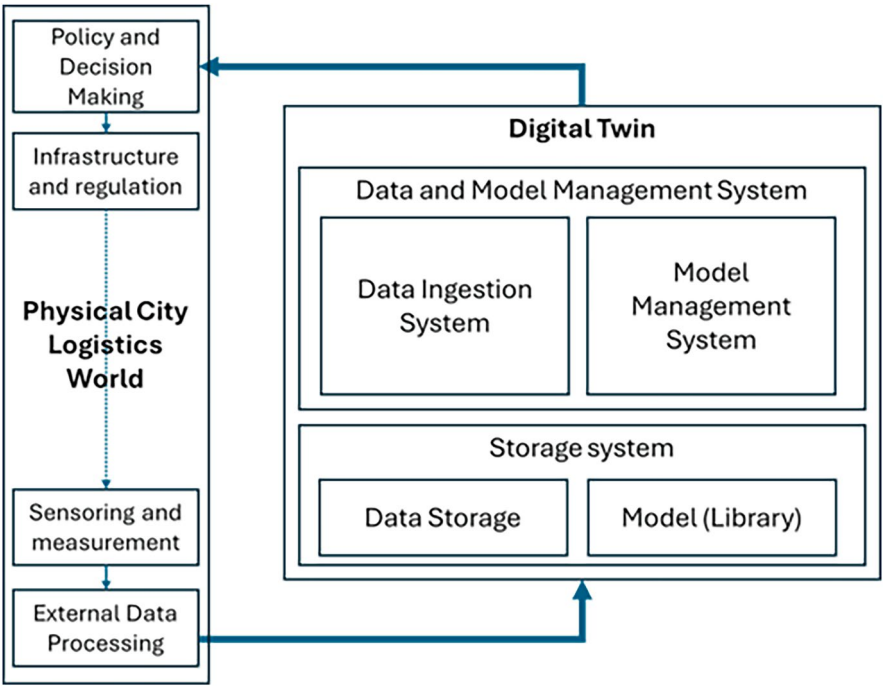


Fig. 1 Basic architecture of DT in relation to the physical world (Adapted from (Belfadel et al. 2023))

Recent EU projects that have contributed to DTs for city logistics are HARMONY, LEAD and URBANE. One of the objectives of these projects was to create models for DTs. In LEAD, the emphasis was on a library which could allow many existing models to be used, which led to the distributed approach. In HARMONY and URBANE, a centralised approach was chosen due to the innovative nature of the models, which were developed within the project. HARMONY created the Tactical Freight Simulator, an agent-based simulation system for urban logistics (de Bok et al. 2021a). The model development for URBANE focused on the joint application of ABMs for social-network-driven learning behaviour and urban freight simulation, respectively HUMAT (Jager et al. 2025) and MASS-GT (de Bok et al. 2025a). Our focus in this chapter is on the URBANE model. In addition to these EU project results, we provide a third example of a unique DT development in The Netherlands, where a freight simulation system was integrated into a full-fledged urban digital twin toolbox, to strengthen its capabilities for transport analyses.

Here, we describe in more detail the following three DTs: the URBANE development of coupled models together forming a DT to be applied for various cities, the LEAD project that created a DT with a whole library of models, and the broader city DT toolbox which included MASS-GT.

2.2 *URBANE: A Marriage Between Agent-Based Models*

2.2.1 Method

In URBANE (Franklin et al. 2025), the MASS-GT model has been further developed by integrating components of consumer decision-making behaviour using the model HUMAT, which simulates decisions of individuals who are part of a social network and allows the learning process from decisions to propagate through the social network (Tapia et al. 2023). One of the living labs of the project was situated in the city of Helsinki, Finland. The overall ambition of this Living Lab is to achieve carbon neutrality by implementing the Carbon-Neutral 2035 Action Plan. The Helsinki LL proposed testing the concept of micro hubs in the city, specifically focusing on innovative LMD options such as robot deliveries using autonomous delivery vehicles (ADVs), cargo bikes and teleoperation. The LL included multiple piloting locations. To explore the acceptability of ADVs, the integrated modelling framework given here is calibrated and used for such a use case (Gürcan et al. 2024) (Fig. 2).

In this use case, while the HUMAT modules simulate consumer choices between the ADV service and home delivery options over time, MASS-GT is used to generate household demand and a vehicle routing model (VRP) in the calibrated modelling framework. This collaboration between the two models can be extended to encompass the full range of capabilities of MASS-GT and include simulation of logistics decisions. Conceptually, this architecture allows a simulation of social and logistics networks to inform decision makers. As agent-based simulations can be relatively easily connected to practice, this approach allows us to connect to data

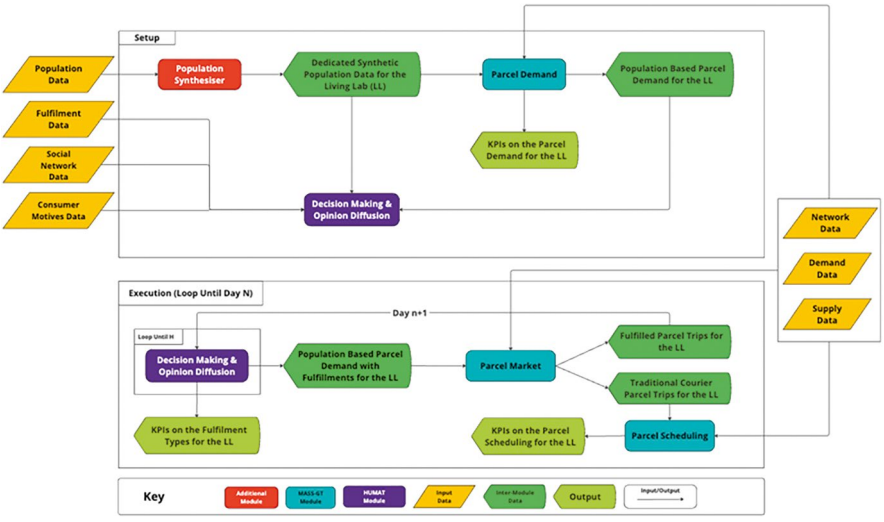


Fig. 2 Integrated modelling framework in URBANE

sources which monitor daily delivery operations, as well as to advise or steer management decisions related to daily operations. In URBANE, these applications and extensions have been out of scope.

2.2.2 Application

Simulations with the URBANE ABM were carried out by implementing what-if scenarios in a digital twin of Helsinki. The Parcel Demand module of MASS-GT estimated the demand based on various socio-demographic characteristics and the household structure of the population. Demand data provided by an LSP company were used to populate the system. The Parcel Demand module generated 220 parcels for the study area. Next, detailed simulations with HUMAT were conducted to show the service and queuing times under different parameters (Fig. 3).

Figure 4 shows the performance of an ADV over 31 days by comparing the number of parcels to deliver and parcels delivered under various capacity and customer arrival rates.

The arrival rates of customers show that higher ADV capacities (30 and 300 parcels) do not significantly improve the delivery rate. The main reason for this outcome is the time window constraint (i.e. the period within which the ADV must visit a location, e.g. between 11:30 and 12:45) and the capacity constraint of the ADV. The analysis shows that increasing ADV capacity alone does not ensure higher delivery efficiency, especially under higher demand scenarios. Increasing the width of the time windows as well as the ADV's waiting time at each delivery



Fig. 3 Demand setting in the Helsinki LL

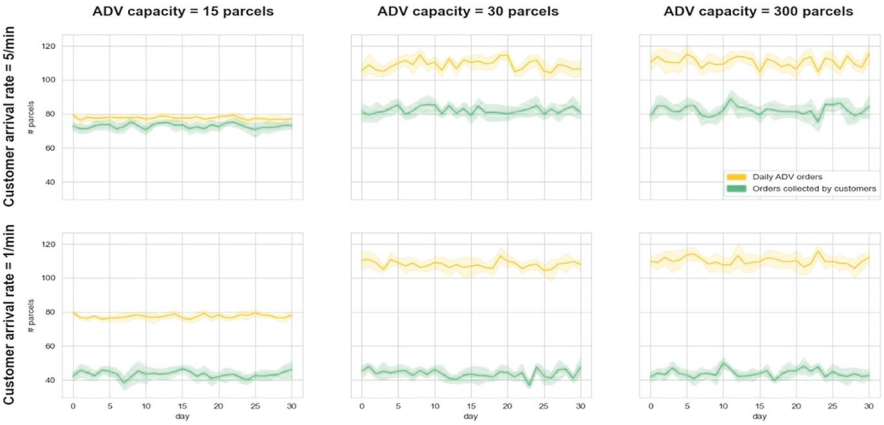


Fig. 4 Average parcels delivered by ADV



Fig. 5 Average waiting time and queue length with ADV delivery

location will improve the delivery rate. This, however, will result in an increase in the ADV's total operating time. For a given delivery scenario, the locations' time windows and waiting times should be optimised such that a high delivery rate is achieved while ensuring that the ADV is capable of operating for the required length of time. Figure 5 shows the average waiting time and average queue length over a 31-day period of ADV delivery.

As expected, when the customer arrivals are higher (5 customers per minute), the average waiting time and average queue length become higher since there are more customers picking up their parcels from the ADV, creating higher waiting times and a longer queue.

2.2.3 Discussion

Together, the DT-like implementation of the two models analysed the deployment of autonomous vehicles for direct parcel deliveries to consumers. The simulation suggests that while increasing the capacity of ADVs can reduce the number of trips, this benefit is most effective when coupled with optimised delivery schedules. The environmental impact of ADVs is also significant, with the potential for substantial reductions in CO_2 emissions in regions where renewable energy sources are prevalent. However, in areas dependent on fossil fuels, the environmental benefits are less pronounced. By integrating social networks into the simulation of delivery services, the model captures how consumer preferences can be influenced by peer influence.

2.3 LEAD Project: A Model Library-Driven DT

2.3.1 Method

The approach of the LEAD project to develop DTs was to establish a set of Living Labs with the objective of obtaining different use cases in detail that could be combined in a single platform. This way, the DT could develop a deep understanding of the public authorities' and private sector requirements. The multiplicity of use cases and models needed to approach them requires a flexible modelling framework, besides having the flexibility to adopt further use cases. This was done by developing a model library (ML) that is model and ontology agnostic. This means that the ML can include different model types, with different assumptions, timescales, coding languages and frameworks in a flexible and modular way. The communication between models is done by a set of connectors (similar to APIs) that make the relevant data transformations to make the outputs of a model compatible with another one. By being ontology agnostic, the ML allows the easy inclusion of new models that may use different terminologies or conceptual frameworks, provided they generate the relevant connections with existing models.

The main disadvantage of this decentralised approach compared with a centralised approach is that there is not an internal consistency guarantee, relying on the users to be sure that they deploy the set of models that do not have conflicting assumptions. This makes the approach more reliant on either already developed use cases, or an expert user that is able to understand the strengths and limitations of each model from the ML. The Meta Model (M2) of the ML helps users select models and assists developers in creating them. The M2 organises and categorises the models according to their aggregation and temporal scope, and by their type of model. In the M2, the connectors are mapped by the relationships between different models.

The temporal scales used in the M2 are strategic, where long-term models are included, such as population synthesis and echelon models; tactical, where medium-term (such as a week or a full day) models are included, such as tour formation; and

operational, where short-term models such as routing are included. The level of aggregation dimension can be either zonal aggregation or a lower-level disaggregated parcel and shipment level. These two dimensions are related to the types of logistical decisions as described in Table 1. The M2 also distinguishes different types of models, such as optimisation models, demand models, ABMs, network models and impact assessment models. More details on the ML structure and the LEAD DT can be found in (Belfadel et al. 2023). Figure 6 shows the M2 of the LEAD library.

2.3.2 Applications

A large number of use cases were applied in the LEAD project, all supported by the LEAD DT.

- Madrid: Study the impact of implementing an Urban Consolidation Centre in a parking lot at the entrance of the limited traffic zone. The LL consisted of the city transport authority, a logistic service provider, a shipper, a vehicle routing service provider and academic partners.
- The Hague: Study the impact of connecting different logistical networks and enhancing collaboration across logistical service providers. The LL consisted of

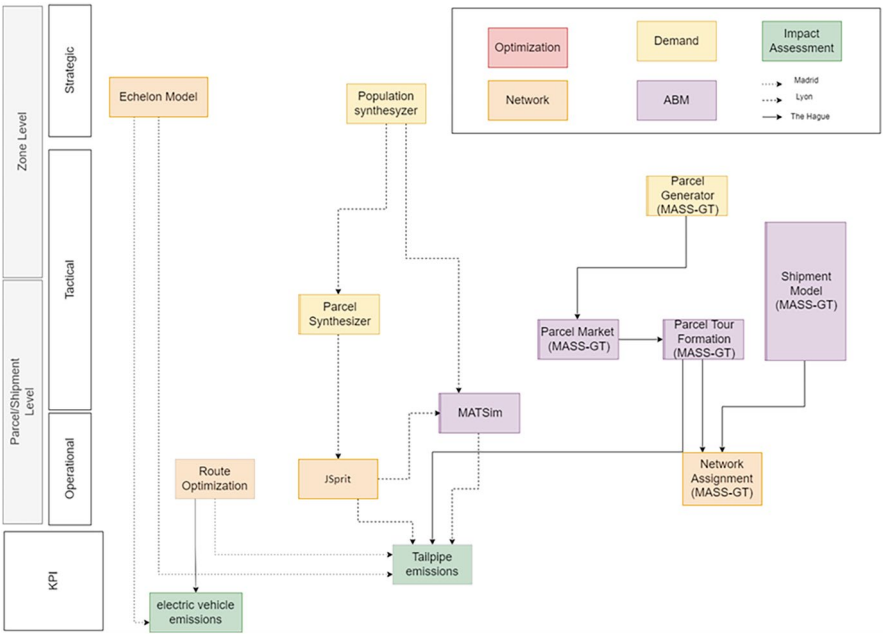


Fig. 6 Meta-model of the DT model library in the LEAD project (Abouelrous et al. 2023)

the city authorities, a digital infrastructure company, parcel locker companies, a crowdshipping company and academic partners.
- Lyon: Study the impact of cargo bikes and autonomous last-mile distribution vehicles in the city centre. The LL consisted of city authorities, a technology provider, a carrier and academic partners.
- Oslo: Study the impact of implementing crowdshipping for last-mile delivery. The LL consisted of a crowdshipping company, public authorities and academic partners.
- Budapest: Study the impact of the location of Urban Consolidation Centres outside the city centre. The LL consisted of the city authorities, a shipper and academic partners.
- Porto: Optimise delivery routes for electric delivery vans, considering grid restrictions and characteristics. The LL consisted of a technology provider, a shipper, a carrier and academic partners.

Here, we provide some illustrative outcomes of the living lab in The Hague, The Netherlands. Here, the LEAD DT has been used to test the effect of crowdshipping in the urban environment. The main question asked in this simulation is the effect of pricing on the total emissions and congestion. The KPIs obtained are GHG emissions by car and vans, total distance travelled by cars and vans and the expected revenue by the crowdshipping company. The first set of simulations changed the remuneration given to crowdshipping carriers, assuming a flat rate. From all the simulations we registered the crowdshipping platform remuneration and selected the one with the maximum (7 euros) for a more in-depth analysis. In this case, it is assumed that the platform would set the prices that maximise its own revenue. Next, flows were simulated for all the parcels in The Hague. It can be seen in Fig. 7 how these parcels are fulfilled across the multiple carriers and, in the case of crowdshipping, which mode they take. Since crowdshipping is only available for Local-to-Local flows (i.e. flows that start and end in the area), they are restricted to these flows that represent around 4% of the total demand. From these, it can be seen that circa two-thirds of the crowdshipping is done by car.

2.3.3 Discussion

The DT approach has also been proven as an interesting element throughout the LL activities. Some of the KPIs were not possible to measure in the physical implementation, since the pilots were done in an open system (i.e. not in a controlled environment). By using data collected from the pilots and the DT approaches, the DT was able to simulate large-scale implementations. Through the DT, the possible effects of crowdshipping were measured and signalled a warning regarding the potential detrimental effects it can have if it attracts car travellers (Cebeci et al. 2024; Tapia et al. 2023). This procedure can become a key in the future, when public authorities are able to simulate the effects of a new logistic innovation and be aware of the

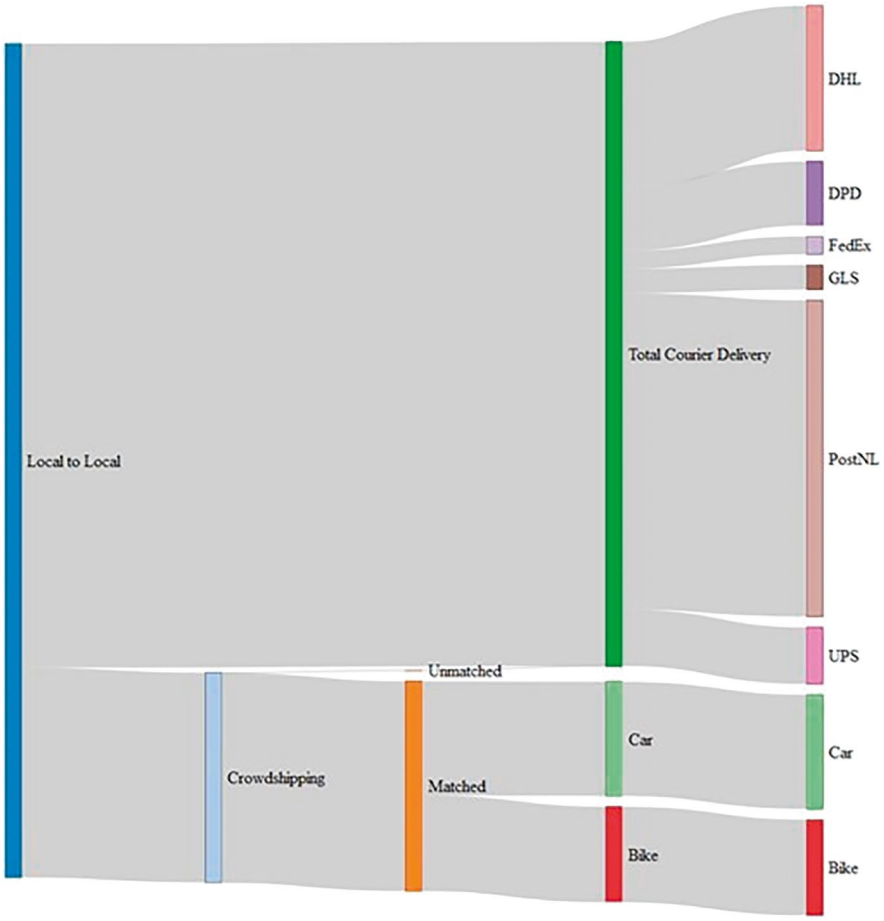


Fig. 7 Parcel fulfilment in LEAD LL

potential impacts before they happen and be able to avoid possible negative externalities.

2.4 MASS-GT Integration into DT Toolbox

Finally, we present an example of how the MASS-GT simulation model was integrated into an existing digital twinning framework for Amsterdam (Winkelmann et al. 2025). It shows how an agent-based simulator can be added as a module to describe the city's logistic activities. In a test application, it is shown how the simulator capabilities of MASS-GT are used for strategic policy application, in this case, the introduction of a ZE zone.

2.4.1 Method

The method integrates the MASS-GT city logistic simulator into an existing DT toolbox. The starting point is the TNO Digital Twin, an extensive digital twinning framework that focuses on scenario-based analysis in the mobility domain (Lohman et al. 2023). The tool consists of several models, which simulate a variety of travel modes including cars, freight, bicycles and public transportation. These travel modes are assigned to a transport network using an assignment model. For the Amsterdam case study, the Verkeersmodel Amsterdam traffic model, VMA 4.5, is integrated into the DT to predict the mobility demand (Gemeente Amsterdam 2024). Motorised traffic is assigned using a (multi-user class) volume averaging (car) or an all-or-nothing (freight) assignment algorithm. The Digital Twin can be used in an interactive fashion to adjust urban characteristics, to allow users (e.g. city authorities or municipalities) to actively simulate a variety of policy scenarios. Example cases include the impact of road closures (city-wide), speed reduction, population growth or increased parking prices. All simulated scenarios can be evaluated using a variety of indicators. Moreover, a number of models exist to compute air quality, emissions and noise pollution, but also further indicators related to mobility (e.g. vehicle kilometres, modal split), health or accessibility.

MASS-GT was integrated into the toolbox as an additional module to evaluate the city's logistic developments. MASS-GT is an agent-based model for urban freight transportation (de Bok et al. 2025b). The model utilises a commodity-based approach to distinguish between the number of agents in the freight transportation system and models their behaviour according to their respective sector. This agent-based approach is integrated with commodity data and synthesised firm locations to simulate representative freight transportation patterns through logistics choice models. The demand is simulated at the shipment level to accurately reflect the decision-making process within eight logistics segments: food (general cargo), miscellaneous (general cargo), temperature controlled, parcels and express, facility logistics, waste logistics, construction logistics and dangerous goods. Furthermore, shipments originate from supply nodes and are transported to consumers, either directly or via one or more logistics nodes, such as distribution centres or trans-shipment terminals. MASS-GT makes various decisions regarding vehicle type, distribution channel and shipment size. Once all shipments are generated, they are organised into tours and assigned to specific times of day. Additionally, a parcel module operates in parallel, generating similar choices for parcel-specific traffic while considering unique specifications of parcel logistics. Similarly, an additional service demand module generates the tours for construction and service vans.

2.4.2 Application

The integrated DT toolbox is applied in a case study to analyse the impacts of a planned zero-emission zone (ZEZ) for city logistics traffic in Amsterdam, the Netherlands. The case study analyses scenarios with two different potential sizes for

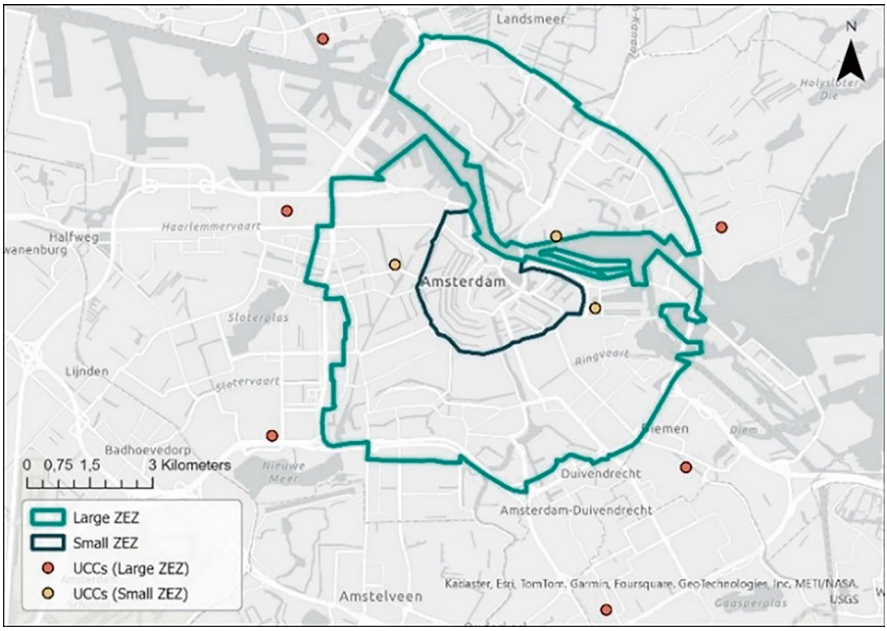


Fig. 8 Small and large zero-emission zone (ZEZ) scenarios and their respective UCCs

the ZEZ (see Fig. 8). The smaller example follows the S100 orbital road, and the larger example follows the A10 highway. In both examples, the (ring) road itself (i.e. S100 and A10) is not considered to be part of the ZEZ. The MASS-GT module simulates the behavioural impacts: existing transports with conventional vehicles are either replaced by zero-emission vehicles (electric trucks or vans) or they are redirected to urban consolidation centres (UCC) on the edge of the zero-emission zone, and the last-mile is organised from these UCCs using zero-emission vehicles. Due to the scope of the research, it is assumed that all last-mile transportation from the UCC is done by electric light commercial vehicles (ELCV). The behavioural parameters are based on previous empirical studies (City of Rotterdam 2019; de Bok et al. 2021b).

The objective of the case study is to analyse the spatial distribution of impacts. Outputs confirmed that in the scenarios analysed, the neighbourhoods of lower socio-economic status bear the largest part of negative effects, while higher income neighbourhoods, often located closer to city centres and therefore ZEZs, experience an increase in air quality (see Fig. 9). One example of this is the neighbourhood of Slotermeer, located in the west of Amsterdam, close to the middle UCC in the large ZEZ scenario. The average income in Slotermeer is €26.350 (CBS 2023) and from the relative NO_2 chart in Fig. 6, a large increase in emissions can be seen throughout the neighbourhood. In contrast, the neighbourhood of Jordan, located on the western side of the city centre of Amsterdam, has a population with an average income of €45.500 (Antosz et al. 2019) and is shown to experience a large decrease in

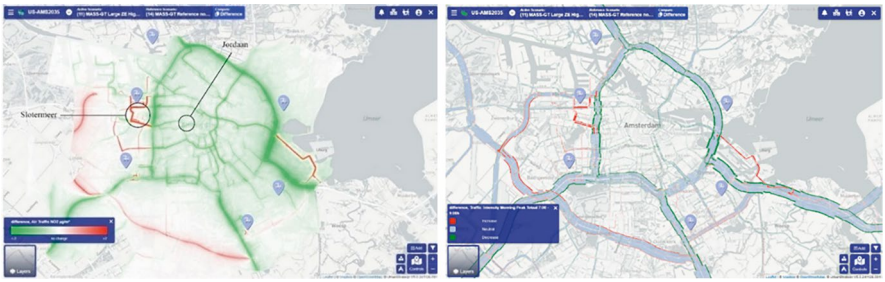


Fig. 9 Difference in total traffic intensity for the large ZEZ scenario (left; green = reduction, red = increase) and difference in NO_2 emissions (right; green = reduction, red = increase)

overall NO_2 emissions. This warrants attention, since the placement of a UCC will determine the location of these negative externalities, potentially causing emissions to be shifted to lower socio-economic neighbourhoods.

2.4.3 Discussion

This study exemplifies how simulation models are developing into dynamic toolboxes, evolving incrementally from digital shadow to a digital twin. This study shows how an agent-based simulator for urban freight traffic (MASS-GT) is integrated into a digital twin framework (TNO Digital Twin), which brings together existing policy support tools for traffic analysis, emission modelling and urban environmental impact assessment. Such a framework allows the assessment of impacts across different aspects with high spatial granularity. The use case shows how diverse the spatial distribution of these impacts may be.

Another aspect of the modular structure of a DT toolbox is that the data formats and interfaces between modules are automated, which allows more efficient updates with new observed data compared to conventional (freight) transport models, e.g. once every 4 years. We consider the presented Digital Twinning toolbox as a logical step from a digital shadow towards a digital twin.

3 Concluding Remarks

Together, the cases from the different EU and non-EU projects suggest a clear evolutionary line for DTs for urban freight, which has materialised so far. Individual models that provide answers to policy questions evolve further into coupled models, which fulfil complementary roles and together are larger than their sum. Finally, libraries of models can create flexible digital twins, which boost the applicability of the DT for a multitude of cases. DTs that already contain such a library can continue to absorb models to elevate their capabilities. This is only the start of a larger change,

however. DTs will evolve further into the future, stepping beyond their current function of digital shadows of systems and becoming more instrumental for urban freight decision-making and management. As next steps, DTs for city logistics will focus on the following:

- Explicit connections to city sensors and databases—this can build on digitalised connected assets in IoT-like structures, and on aggregation processes for data that help to monitor longer-term, stable developments.
- Explicit connections to actuators in the system, be it policy processes, investment planning processes or operational management systems. Today, the impact of DTs is still indirect, largely without automation or pre-programmed connections to decisions.
- Once these connections are in place, DTs will allow faster and automated decision-making for long-cycled and short-cycled decisions by closing the control loop and installing (partial or full) autonomous decision-making and management.

The DTs presented here are a prerequisite for the above-mentioned development. It seems likely that the above-mentioned evolution of closing the control loop will occur domain by domain, or sector by sector, as also in the physical world control across domains and sectors is still an important challenge. Therefore, we position these projects as cornerstones for a roadmap which contains different lines of development that, when converged, will eventually lead to cross-domain, city-level DTs with full control capabilities (Fig. 10).

We argue that such an evolution is necessary for targeted progress, as it sets a clear agenda for R&D and valorisation of technology. This should help to drive the next steps forward in applied computing technology and decision-making processes, ultimately allowing convergence towards fully functional digital twins for city logistics.

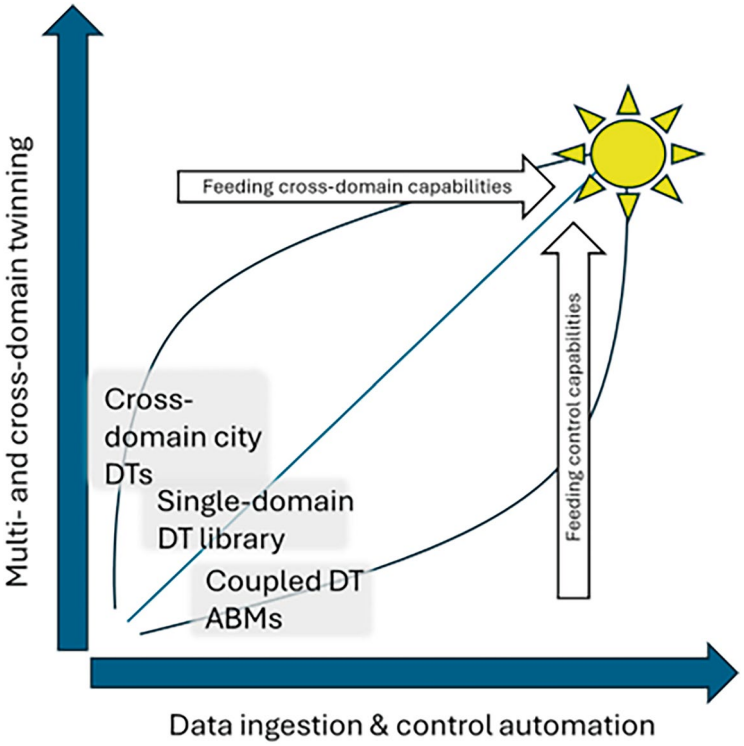


Fig. 10 DT roadmap with cases as cornerstones

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