D2.4 Synergies and benefits of Physical Internet vision to S2Z

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Deliverable information sheet

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Executive summary

Project summary

Current market dynamics in EU reveal a gap between supply - existing N1 vehicles, and demand - evolving needs of urban logistics and climate targets. In 2023, 1.2M new LCV registrations were diesel-powered, and only 108,200 battery electric. Last-mile logistics, the least efficient and most complex part of the supply chain, presents significant opportunities for improvements at vehicle and operations levels. Dynamic requirements and increasing environmental impacts require innovative solutions from the automotive industry, both from high volume OEMs and new entrants. S2Z aims to capitalize on the benefits of both vehicle platforms in the N1 segment - represented by IVECO's eDaily multipurpose platform, and Alke's ATX design-for-purpose platform - ultimately contributing to "Shifting to zero-emission logistics through right-sized, mission-focused, N1 e-LCVs".
To achieve this vision, S2Z proposes a 4-step user- and mission-centric design approach placing end-users and their needs at the core of all project activities. To this end, S2Z involves 5 logistics service providers (LSPs) & mobility operators as partners: Gruber, DHL, Diakinisis, Clem, DPD. As a result, S2Z will co-develop and shape at least 6 novel N1 concepts with enhanced and safe functionalities leading to tighter market fit, particularly in the segments of e-commerce, returns and cold deliveries.
Innovative concepts, from modular cargo bodies to vehicle control strategies with optimized tyres & brakes, as well as dual transport of people & freight, will be physically prototyped and tested in real-life operations in 6 pilot sites (Belgium, Greece, Italy, 2 in Norway, Poland).
S2Z brings a multidisciplinary consortium of 30 partners from 10 countries to cover the complete automotive and logistics value chains, complemented by policymakers to effectively ensure route to market: overcoming barriers for the adoption of S2Z e-LCVs, reducing operational costs and environmental impact in scalable urban & sub-urban operations.

Deliverable summary

Goal and objectives

Deliverable 2.4 focuses on the requirements that the Shift2Zero solutions must meet in order to enable applying synchromodality and the Physical Internet (PI). Synchromodality and the Physical Internet are quite similar concepts. Synchromodality stresses real-time flexibility to select the best transport modes according to the needs of actors, while Physical Internet envisions freight encapsulated in standardised cargo types being transported seamlessly across an interconnected open network.

The following objectives are proposed:

- **Objective 1**: Proposing guidelines and requirements for the vehicles that allow synergies with the Physical Internet vision.
- **Objective 2**: Examining how these guidelines and requirements can be feasibly integrated into the various Shift2Zero demonstrations.
- **Objective 3:** Quantifying the feasibility of these guidelines and requirements by integrating them into scenarios that will be assessed using a simulation model.

The findings from D2.4 complement the definition of user and system requirements (T2.5) and will support the technical design of Shift2Zero prototype vehicles (WP3), and the planning and implementation of the pilot demonstrations (WP6). The simulation model is linked to the simulation engine that will be developed in WP5.

Methodology

The deliverable presents two different methodologies. For the identification of the guidelines and requirements we applied a combination of literature review, a case-study review and expert consultation.

The quantification was performed via the use of an agent-based simulation model. The agents are various LSPs representing the different Shift2Zero demonstrations. The outputs are aligned with the URBANE project.

Key results

Guidelines and requirements (objective 1)

We identified six guidelines that consist of digitalisation, Internet-of-Things (IoT) technology, flexible and open LSPs, acceptance and participation of relevant stakeholders, supporting policies and the existence of a digital Physical Internet platform.

The guidelines resulted in a list of eight aggregated requirements. Firstly, there should be standardized cargo types. Next, compatible loading and unloading systems should be used. The vehicles and cargo bodies should be equipped by real-time GPS technology and Internet-of-Things sensors measuring environmental and vehicle parameters. The digital Physical Internet platform should allow interoperability and consider client requirements and current and expected traffic conditions.

Feasibility (objective 2)

To research the feasibility, we constructed five scenarios that consider the most important elements of synchromodality and the Physical Internet. They consist of (1) real-time rerouting, (2) real-time modal shift, (3) solving vehicle/sensor/cargo body breakdown, (4) reacting to sudden client requirement changes and (5) battery savings.

The feasibility is calculated from an internal cost perspective for LSPs of different sizes, and disruptions are simulated to assess the reaction of the synchromodality and Physical Internet implementation.

Impact quantification (objective 3)

Based on the results of the different scenarios calculated with the agent-based model, we can draw several conclusions. Firstly, the introduction of a Physical Internet leads to cost reductions when LSPs are encountering disruptions. The magnitude of these savings is relative to the scale of the disruptions. Synchromodality and the Physical Internet make the supply chains more robust, more cost-efficient and more sustainable.

Secondly, the Shift2Zero solutions are not more expensive and are more sustainable than business-as-usual, according to the simulations.

Thirdly, all Shift2Zero solutions are subject to the impact of a Physical Internet introduction, and this generally to a similar extent.

Fourthly, the size of the LSP plays a very important role in determining the magnitude of the impact on vehicle kilometres (vkm) travelled per parcel, as well as internal and external costs per parcel. The smaller the player, the more unfavourable the outcome. The simulation results therefore highlight the importance of horizontal collaboration between different LSPs, so that the introduction of Physical Internet does not merely further strengthen large providers but also creates a business environment in which small and emerging providers can benefit from the advantages of the system and potentially consolidate or grow their operations.

Table of contents

List of figures

List of tables

Terminology and Acronyms

B2B	*Business-to-business*
B2C	*Business-to-consumer*
BAU	*Business-as-usual*
BCR	*Brussels-Capital Region*
GPS	*Global positioning system*
IoT	*Internet-of-Things*
LSP	*Logistics service provider*
PI	*Physical Internet*
S2Z	*Shift2Zero*
SULP	*Sustainable Urban Logistics Plan*
Vkm	*Vehicle kilometres*
WP	*Work package*

1. Introduction

Within the Shift2Zero project, new vehicles are being developed for more efficient, zero-emission and sustainable last-mile delivery of goods in European cities. However, urban logistics faces several challenges. These relate to:

- Accessibility (for example congestion, one-way streets, pedestrian zones, etc.).
- Logistics costs (for example parking fees, road charges).
- Regulations (for example delivery time windows).
- Sustainability (for example low-emission zones).

The vehicles being developed must be resilient to these challenges and capable of providing a robust response to future trends and technological developments in urban logistics. One of these emerging developments, which also provides an answer to the challenges, is the rise of synchromodal transport and the Physical Internet. By anticipating changes and disruptions in the transport system in real time—through re-routing or a modal shift—synchromodal transport can contribute to a more efficient, flexible, reliable and sustainable transport system. The Physical Internet takes this a step further by proposing a global system in which information and transport flows are organised in an a-modal manner through a single system (Ambra et al., 2019). Both require technological development and hyper-connectivity between different actors in urban logistics, as well as between vehicles themselves and the decision-making system.

1.1 Objectives of the deliverable

Task 2.4 focuses specifically on the requirements that the vehicles developed within Shift2Zero must meet in order to enable synchromodality and the Physical Internet. To this end, the following research objectives are proposed:

- Proposing guidelines and requirements for the vehicles that allow synergies with the Physical Internet vision.
- Examining how these guidelines and requirements can be feasibly integrated into the various Shift2Zero demonstrations.
- Quantifying the feasibility of these guidelines and requirements by integrating them into scenarios that will be assessed using a simulation model.

More specifically, the following section discusses the definition of synchromodal transport and the Physical Internet. This is followed by an exploration of the potential applications of both concepts, from both a research and academic perspective, as well as from a practical point of view. We consider existing cases, and the extent to which they are useful for the applications being developed within Shift2Zero, so that the demonstrations and actors have a clear understanding of what they can expect.

The findings complement the definition of user and system requirements (T2.5), and will support the technical design of Shift2Zero prototype vehicles (WP3), and the planning and implementation of the pilot demonstrations (WP6). The simulation model is linked to the simulation engine that will be developed in WP5.

1.2 Structure of the deliverable

The definition of synchromodal transport and the Physical Internet comprises various elements that shape both concepts. These elements form the basis for the guidelines and requirements proposed within this task. After describing the guidelines and requirements, we discuss how both concepts can be feasibly applied to the different demonstrations within Shift2Zero.

Finally, this deliverable provides a quantification of the impact and feasibility of the guidelines and requirements by simulating different scenarios that incorporate them. First, the simulation model is described. We then address the assumptions and their implications, so that the reader is able to correctly interpret and understand the results. The results themselves are presented and explained, enabling the demonstrations and actors to form an informed expectation of what they can anticipate when implementing synchromodality and the Physical Internet.

The deliverable also includes an executive summary, lists of tables and figures, terminology and acronyms, list of references, and annexes.

2. Synchromodal transport and the Physical Internet

2.1 Definition

Synchromodal transport and the **Physical Internet** are related to one another, yet, they are different (Ambra et al., 2019).

The most commonly used definition of synchromodal transport was provided by Verweij in 2011. He defines it as follows:

"*Synchromodality presents a real-time, dynamic and optimised extension of the existing intermodal transport by including real-time re-routing to cope with disturbances and operational or customer requirements*" (Verweij, 2011).

Key terms in this definition are (1) **real-time**, (2) **dynamic**, (3) **optimised** and (4) **intermodal transport**. The latter is particularly important to emphasise. Synchromodal transport has its origins in the context of intermodal container hinterland transport. The hinterland refers to the catchment area of major seaports from which and to which containerised goods are transported. Intermodal transport therefore involves the use of different transport modes – rail, inland waterways, and road – to organise this transport without changing the cargo type (i.e. the container). By linking the real-time element to dynamic re-routing and a possible modal shift, synchromodal transport succeeds in generating efficiency gains (SteadieSeifi et al., 2014) and sustainability improvements (Alaei et al., 2024). However, containerised transport to and from ports differs greatly from urban transport, which is far more fragmented, expensive and less sustainable. Nevertheless, the concept of synchromodal transport has been extended to the urban context, as demonstrated amongst others in the study by Kin et al. (2018) on pharmaceutical goods.

In turn, the Physical Internet is defined as:

"*An open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols*" (Pan et al., 2017).

The Physical Internet (PI) is inspired by the digital internet, which we all know. Like in the digital internet, routes in the PI are treated as segments between π-nodes, similar to the routing of data between routers in the digital internet. This enables, in case of a disruption, that routes can be changed adaptively. PI was founded by Montrieul et al. (2013) as a system of components structured along:

- Π-containers: they refer to the encapsulation in the definition of Pan et al. (2017). Similar to synchromodality, PI also started with container transport. Yet, over time these π-containers were expanded to other standardized cargo types.
- Π-nodes: they are responsible for the interconnectivity, embedded and supported by interfaces and protocols.
- Π-movers: The movers are the vehicles, cranes, conveyors, trailers and wagons. The infrastructure that enables the movement of freight within or between Π-nodes.

PI builds on a full consolidation of logistics flows to pool resources and assets in connected, open and shared networks, by connecting existing company networks, resources and capacities (ALICE, 2022). PI is seen as an innovative logistics concept that has proven – in simulations – to increase the efficiency, the improved utilisation of resources and therefore consequently results in economic and sustainability gains (Kauf, 2016). It is considered as an important element to achieve the European climate goals for transport and is set forward by the European Commission and ALICE as a strategic concept with crucial development stages between 2030 and 2040 (ALICE, 2022).

As a conclusion, synchromodality stresses real-time flexibility to select the best modes according to the needs of actors (SteadieSeifi et al., 2014), while PI envisions freight encapsulated in standardised cargo types and being transported seamlessly across an interconnected open network (Pan et al., 2017). It therefore mimics the digital internet. Both have their origins in hinterland container transportation, but have evolved towards more overarching concepts with applications in the urban environment as well. The next section will elaborate on these urban applications.

2.2 Urban practices of synchromodality and the Physical Internet

For almost a decade now, the concepts of synchromodality and the Physical Internet have been applied within an urban and last-mile context (Crainec and Montreuil, 2016). From a theoretical perspective, Montreuil et al. (2018) adapted their π-nodes to the urban last mile. The π-nodes have the same functions, yet these are performed at a lower, more local level. They are defined as the next hierarchy levels in the nodal hierarchy, which translates itself into reduced volume and reduced geographical coverage of the π-nodes. This has been extended via the work of Matusiewicz (2024a).

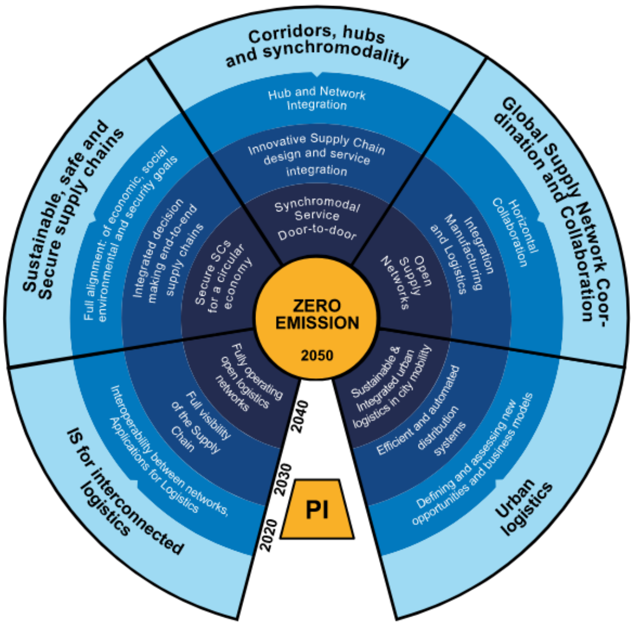


Figure 1. Physical Internet vision of ALICE (2025).

ALICE identifies PI in the vision for the future of logistics and as the enabler to achieve zero emission freight transport in Europe. The Physical Internet represents a far-reaching transition for the freight transportation sector. This transition is ongoing. Urban logistics forms one of the thematic groups with a dedicated PI pathway. Currently, the aim is to define and assess opportunities and business models, to evolve towards efficient and automated distribution systems by 2035. A fully integrated and sustainable PI system for urban logistics is foreseen by 2040 by ALICE (2025).

ALICE promotes its Physical Internet (PI) vision through various European projects related to urban logistics and the last mile. Among these, the URBANE project aligns most closely with the objectives of T2.4 of S2Z. URBANE stands for *Upscaling Innovative Green Urban Logistics Solutions through Multi-Actor Collaboration and PI-Inspired Last-Mile Deliveries*. The project tests novel, resilient, sustainable and effective last-mile solutions. The Physical Internet constitutes a key cornerstone of the URBANE project. In Deliverable 1.1 (URBANE, 2023), the URBANE consortium describes the Physical Internet and its applications for urban logistics and the last mile. This work provides an ideal foundation for the S2Z partners and other actors wishing to engage with the PI concept. Although the deliverable offers an in-depth discussion of the building blocks of urban PI, its needs and potential applications, it does not provide concrete guidance for the technical and practical implementation of a PI system. For this, attention turns to the so-called Lighthouse Living Lab in Bologna.

In the Italian city, URBANE supports the rollout of a Sustainable Urban Logistics Plan (SULP) and the associated innovative delivery methods. The Physical Internet plays an important role in this context, as the living lab in Bologna introduces a new approach based on collaboration between competitors. This business model aligns with the principles of the Physical Internet. Initial findings indicate that it is not easy to persuade companies outside the URBANE consortium to participate in the PI system. This is a concern that several PI pilot projects have already encountered (URBANE, 2024).

While the final results of the living lab in Bologna are still pending, research within and outside the URBANE project using simulation models already provides insight into the potential effects of the Physical Internet in urban logistics. Zheng et al. (2019) found that the results of running different scenarios with an agent-based simulation model indicate that the PI system outperforms traditional logistics in terms of time and cost. Also Kin et al. (2019) came to the conclusion that supplying urban nanostores via a PI system leads to significant reductions in total vehicle kilometres and lead times. The amount however, highly depends on the location of the distribution center. PI also offers opportunities for other innovative delivery solutions, like supporting crowd logistics (Di Febbraro et al., 2018).

While the potential opportunities and benefits are being quantified, big steps still need to be developed to realize an European PI system by 2040. IKIGAI is a promising project that just started in the summer of 2025, with the aim to accelerate the realisation of the Physical Internet. Five pilots, of which one focussing on urban hubs, will address the barriers for scalability. Next, a PI norm will be developed to provide actors with a set of standard and universal operating procedures. Lastly, it facilitates the engagement of stakeholders and the development of a shared governance structure (IKIGAI, 2025).

3. Preconditions and requirements

3.1 Preconditions

The integration of synchromodal transport and the Physical Internet with the logistics solutions developed within Shift2Zero requires a number of preconditions. Preconditions are understood as the prior conditions that must be met before the requirements for implementing the concepts within the S2Z solutions can be applied.

As a first precondition, the logistics sector needs to undergo **digitalisation** so that parameters can be monitored, communicated and optimised (Bekrar et al., 2021). To this end, vehicles, cargo types, actors and sensors must be able to interconnect in line with the **Internet of Things** concept (Tran-Dang and Kim, 2021). This approach enables a dynamic system in which the logistics solution can respond rapidly to changes such as disturbances, breakdowns, congestion or weather conditions.

Secondly, the logistics sector needs to become more **flexible and open**. At present, it is difficult to collect and share data within the sector due to the costs associated with data collection and the fear of disclosing commercially sensitive information (Pfoser et al., 2016). Both synchromodality and the Physical Internet are based on an a-modal transport system, meaning that the choice of transport mode is not predetermined or fixed in advance. However, an a-modal system requires a willingness to share data on available capacity and services. Both concepts assume horizontal collaboration among logistics service providers (LSPs) (Pan et al., 2019; Tavasszy et al., 2017). Such willingness is currently very limited (Ceulemans et al., 2024; Sun et al., 2024). Several studies and projects aim to increase this willingness, for example, by developing new routing algorithms that do not require data sharing (Sun et al., 2026) and through the use of blockchain technologies (Hribernik et al., 2020).

The above precondition describes the logistics sector. However, the concepts of synchromodality and the Physical Internet extend beyond the logistics sector alone. Shippers, receivers, infrastructure managers, governments and technology providers are also indispensable for the successful adoption and operation of these concepts. For many of these actors (40–50%), both concepts are still relatively unknown (Alaei et al., 2024; Matusiewicz, 2024b). Raising awareness is the first step, but the real precondition is **acceptance of and participation in both concepts by all actors**.

Such participation is essential, as uncertainty about the profitability and reliability of innovations is not the only factor hindering change in the sector. In several European countries, policy measures are still in place that are designed to support and thus perpetuate the current mode of operation in the logistics sector. **Supportive policies** for the introduction of synchromodal transport and the implementation of the Physical Internet - such as the internalisation of external transport costs - constitute a precondition for both concepts if they are to be implemented within the coming decade (ALICE, 2022). Reducing or **removing legal and regulatory barriers** is also a key element of such supportive policy (URBANE, 2023). The precise form that this supportive policy should take falls outside the scope of this deliverable but will be examined in WP5 of the S2Z project.

The final precondition is that the concepts require a **platform** within which decisions can be made, essential data and processes can be shared, agreements can be established and validated, and actors can communicate. The initial idea for such a platform was based on a centralised control tower. Current approaches are evolving towards decentralised platform networks. In recent years, several platforms have been developed that operate at the level of individual LSPs or involve only a limited number of actors. However, a fully-fledged platform does not yet exist, and such a platform constitutes a precondition for both concepts.

3.2 Requirements

To enable synchromodality and the Physical Internet connectivity of the S2Z vehicles, those vehicles will need to comply with different requirements. These requirements are listed below and are the results of a process that entailed a literature review, a case-study review and expert consultation.

A first requirement is the **use of standardized cargo types** (e.g. containers, pallets) that can be easily transferred between vehicles and modes. Both synchromodality and the Physical Internet are founded, according to their definitions, on the idea of a standardised cargo type. In the case of synchromodality, this is because such standardisation is a prerequisite for enabling a modal shift. In the case of the Physical Internet, as originally conceived by Montreuil et al. in 2010, there is also a literal reference to standardised containers (π-containers) or cargo types of varying sizes. The idea of standardisation serves not only to facilitate a modal shift, but also to improve the efficiency of operations throughout the supply chain. The current interpretation of the Physical Internet and synchromodality - particularly outside the context of intermodal hinterland transport - places less emphasis on the container as a standardised unit (ALICE, 2022). Nevertheless, some form of standardised cargo type remains necessary and forms the basis for the (future) implementation of both concepts within S2Z. The demonstration of the *Swapbox* fits perfectly within this context. It constitutes a standardised cargo type tailored to urban distribution and to the associated challenges and requirements. Other standardised cargo types are also possible, provided they allow for an efficient, easy and safe modal shift and delivery. Based on literature, best practices, discussion with Paxster and alignment with S2Z tasks 21, 2.2 and 2.3, we distilled more specific requirements, which consist of:

- The standardised cargo type must enable easy and efficient handling across all logistics operations (filling the cargo unit, loading it onto the vehicle, transporting the cargo unit, and unloading the goods).
- The standardised cargo type must be safe for its users and for bystanders.
- The standardised cargo type must protect the goods against damage and theft.
- The standardised cargo type must be able to accommodate the specific requirements associated with the goods, such as temperature control or vulnerability to damage.

The second requirement is closely related to the previous one, as vehicles must be equipped with **compatible loading and unloading systems** in order to enable such efficient, easy and safe modal shift and delivery. This requirement applies at the vehicle level but is also linked to logistics processes and operations in warehouses and during delivery. It requires that all vehicles be mutually compatible, ideally without the need for additional equipment to enable a modal shift within the city. Once again, *Swapbox* provides an example of how this requirement can be fulfilled. This requirement translates into two specific sub-requirements. Each of these sub-requirements are proposed based on literature, best practices, discussion with relevant consortium partners and the are aligned with S2Z tasks 21, 2.2 and 2.3.

- Vehicles must be compatible with the standardised cargo type in order to avoid transporting empty space.
- Vehicles must allow for efficient, safe and easy loading and unloading.

Figure 2. Illustration of a standardized cargo type, the Swapbox (Paxster, 2025).

To meet the real-time preconditions, a **tracking system** is required that monitors the position of the vehicle over time and space and reports it to the PI system – regardless of whether this system is centralised or decentralised. Many GPS-based applications for this purpose are already available on the market. These are widely deployed, even as services offered directly to consumers. Ideally, however, the tracking system should also enable the driver to be informed of emerging disturbances and of the desired response to them.

- Vehicles must be equipped with a GPS system that measures the vehicle's location in real time and transmits it in real time to the PI system.
- Vehicles must be equipped with a system that keeps track, in real time, of which deliveries have been completed, whether any deliveries have been missed, and transmits both in real time to the PI system.

This leads to the next requirement, namely that a **digital platform** must be provided that is **interoperable so as to enable real-time coordination across vehicles and carriers**. The digital platform forms part of the PI as envisaged by Montreuil et al. (2010). The digital platform is accompanied by agreements on **norms, standards and protocols**, as well as by a **governance structure** that provides actors with trust. Several projects are currently underway, including IKIGAI, which focuses on these elements.

- A digital PI platform must exist that is capable of organising logistics operations.
- A digital PI platform must exist that allows the various actors to subscribe to and that they can trust.
- The digital platform must have a governance structure that is trusted by the various actors.
- The digital platform must be built upon shared norms, standards and protocols

With such a digital platform in place, **Internet of Things (IoT) technology is required to enable communication between the driver, the various sensors and trackers of the vehicle, and the PI system**. Without this communication, it is impossible to detect disturbances and to respond to them. Communication provides the PI system with real-time information on delivery status, temperature, load factor and battery status. Consequently, these elements (**temperature in the different sections of the cargo body, load factor, route status and battery status**) must be measured. The system can use this information to optimise operations in real time, to predict potential shortages or emerging failures, and to anticipate and respond to them. The driver must be integrated into the communication system so that he or she can act accordingly.

- Vehicles must be equipped with Internet of Things technology that measures the relevant parameters in real time.
- Cargo units must be equipped with Internet of Things technology that measures the relevant parameters in real time.
- Sensors must communicate information and data in real time to the PI system and the relevant actors.

In addition to the requirements for sensors monitoring the vehicle and its cargo, environmental parameters are also important, as they influence the temperature in the cargo area and the driver’s cab. They also affect, for example, battery performance and driving behaviour. In order to maximise optimisation and to be able to predict, anticipate and respond to potential disturbances and failures from the PI system, sensors are therefore required that **monitor temperature, weather conditions and precipitation** and report this in real time to the PI system.

- Vehicles must be equipped with sensors that monitor outside temperature and precipitation.

Delivery routes are subject to the traffic conditions in which they operate, which can fluctuate significantly. Traffic density and the number of traffic interactions can vary considerably across time and space. In addition, there are predictable and unpredictable traffic disruptions, for example due to roadworks or accidents. All of these have a major impact on delivery efficiency, transport costs, and societal and environmental costs. The **integration of current and predicted traffic conditions** – as already provided by various service providers – into routing and real-time decision-making within the PI system is therefore a requirement for S2Z.

- Integration of current and anticipated traffic conditions into the PI system.
- Integration of current and anticipated traffic conditions into the dynamic route display in the vehicle.

Finally, there are client requirements. Clients may, for example, impose time windows within which deliveries must take place. These are highly determinative for routing and the decision options available to the PI system. Today, client requirements are typically taken into account during initial planning and routing; however, once adjustments are required due to changing circumstances, the driver is often not informed of these requirements. As a result, they are frequently the first constraints to be lost in the decision-making process, despite being essential from a commercial perspective. It is therefore important that **client requirements** are generally known to all relevant actors and are taken into account throughout the various decisions and any real-time adjustments that must be made within the PI system.

- Listing of client requirements per route, per vehicle and within the overall PI system.
- Accessibility to the client requirements for all relevant actors

The requirements can be appointed to the level of the vehicle, the fleet, the system or a combination of them. The table below provides the overview these levels and the related categories for each of the requirements.

Table 1. List of requirements.

Requirement	Level	Category
Standardized cargo type	Vehicle	Flexibility of cargo space
Compatible (un)loading system	Vehicle/fleet	Flexibility of cargo space
GPS real-time	Vehicle/fleet/system	Driver interaction & feedback
Interoperable digital platforms	System	Driver interaction & feedback
Internet-of-Things	Vehicle/fleet/system	Driver interaction & feedback
Environment- and vehicle parameters	Vehicle/fleet/system	Driver interaction & feedback
Traffic conditions	Vehicle/fleet/system	Driver interaction & feedback
Client requirements	Vehicle/system	Compatibility user, purpose & system

The requirements are identical and necessary for all demonstrations. Their impact, however, will differ depending on the demonstration. For instance, temperature monitoring will be more important in the Multi-Temperature Cargo demonstration than in non-refrigerated transport. While the impact of the requirements varies, there is currently insufficient knowledge regarding their effects on operational performance and sustainability. In order to quantify the impact of these requirements for the demonstrations within S2Z and for future developments beyond the project, a simulation model is therefore used. The following section describes this research.

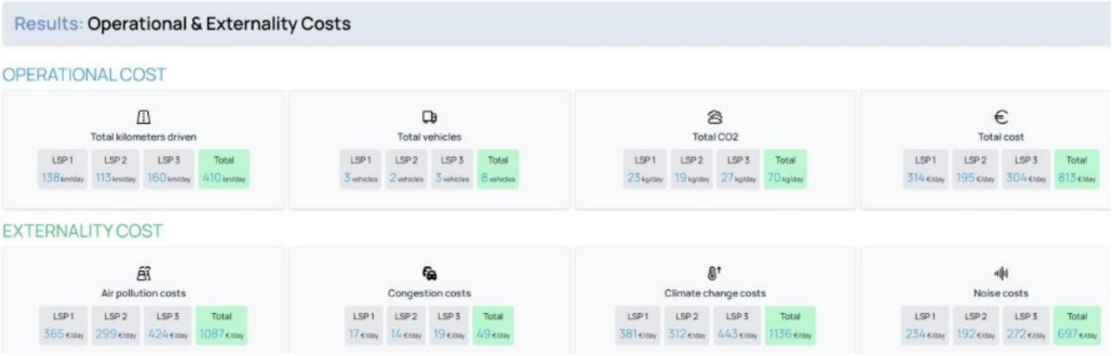
4. Feasibility- and impact assessment

4.1 Introduction

The requirements are expected to have an impact on the demonstrations and on further upscaling in the future (Kauf, 2016; SteadieSeifi et al., 2014). Their impact, however, will vary, and these differences have so far not been sufficiently quantified. The following section describes this quantification by means of a simulation model, applied to the different demonstrations. This will enable the various actors to be better prepared for the implementation of synchromodality and the Physical Internet.

The impact analysis is divided into three components, each addressing key aspects for the actors. First, **transport performance** is considered, which in this impact analysis is expressed in *vehicle-kilometres travelled*, the *number of vehicle-kilometres per parcel*, and the *average load factor*. The second component concerns **internal transport costs per parcel**, which include fixed vehicle costs, time-dependent costs (for example, driver wages), and distance-dependent costs (for example, energy consumption), as well as a penalty in cases where planned deliveries are not executed. Internal costs are presented relative to the business-as-usual scenario, as the simulations are based on hypothetical values rather than on the results of the demonstrations, which will take place later in the project. Finally, the societal and environmental impact is assessed. This is expressed in **transport-related external costs per parcel**. External costs are the monetary expression of externalities, defined as impacts that affect the well-being of those outside a market transaction. The following externalities are taken into account: *congestion, air pollution, climate change, accidents, infrastructure damage, noise nuisance,* and *upstream and downstream processes*. These are the most significant externalities for freight transport.

The requirements are expected to have an impact on the demonstrations and on further upscaling in the future (Kauf, 2016; SteadieSeifi et al., 2014). However, their impact will differ, and these differences have so far not been sufficiently quantified. The following section describes this quantification by means of a simulation model, applied to the various demonstrations. This will enable the different stakeholders to be better prepared for the implementation of synchromodality and the Physical Internet.



Results: Operational & Externality Costs

OPERATIONAL COST

Total kilometers driven

LSP 1	LSP 2	LSP 3	Total
138 km/day	113 km/day	160 km/day	410 km/day

Total vehicles

LSP 1	LSP 2	LSP 3	Total
3 vehicles	2 vehicles	3 vehicles	8 vehicles

Total CO2

LSP 1	LSP 2	LSP 3	Total
23 kg/day	19 kg/day	27 kg/day	70 kg/day

Total cost

LSP 1	LSP 2	LSP 3	Total
314 €/day	195 €/day	304 €/day	813 €/day

EXTERNALITY COST

Air pollution costs

LSP 1	LSP 2	LSP 3	Total
365 €/day	299 €/day	424 €/day	1087 €/day

Congestion costs

LSP 1	LSP 2	LSP 3	Total
17 €/day	14 €/day	19 €/day	49 €/day

Climate change costs

LSP 1	LSP 2	LSP 3	Total
381 €/day	312 €/day	443 €/day	1136 €/day

Noise costs

LSP 1	LSP 2	LSP 3	Total
234 €/day	192 €/day	272 €/day	697 €/day

Figure 3. Illustration of the Impact Assessment Radar outputs from the URBANE project (URBANE, 2024).

The impact analyses are aligned with the outputs of the *Impact Assessment Radar* developed within the URBANE project. External costs related to infrastructure damage, accidents, and upstream and downstream processes are added to the analyses. Operational costs are adjusted only minimally. For example, CO_2 emissions are not included, as the use of electric vehicles is assumed, and these have no tailpipe emissions. The number of deployed vehicles is replaced by the number of vehicle-kilometres per delivery.

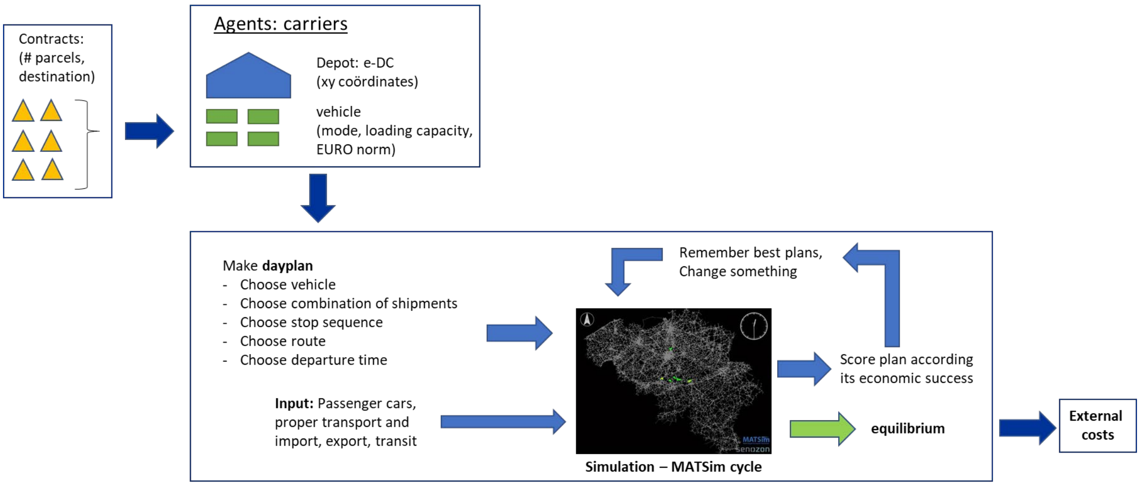
4.2 Methodology

4.2.1 Model description

To quantify the feasibility and impact of the requirements, an agent-based simulation model is used. Agent-based simulation models are considered the current state-of-the-art in transport modelling. They are capable of predicting and simulating transport movements and behaviour at a very detailed level. This is possible because they are built from the perspective of individual agents that are assigned specific characteristics. Agents are often actors within the transport system - such as individuals, logistics service providers, shippers, etc. - but more fluid definitions of agents also exist, which may, for example, include transport infrastructure or equipment such as vehicles or cargo units (Ambra et al., 2019). The advantage of this approach is that specific attributes and behaviours can be linked to these agents. In addition, many agent-based simulation models adopt an activity-based approach, in which transport movements are the result of a sequence of interconnected activities. In this respect, they differ from other modelling methods that do not use causal relationships between individual transport movements.

For this project, the open-source software MATSim is used (Horni et al., 2016). Although the software was originally developed - like most transport modelling methods - for passenger transport and is still predominantly applied in that domain, there is also a substantial branch focusing on freight transport. This work builds on the Freight Extension (Schröder et al., 2014). In this extension, carriers are modelled as agents. They operate a vehicle fleet and a depot from which they attempt to serve a daily transport demand.

MATSim simulates a single day, during which the agents - in this case, the carriers - construct a daily plan per depot to meet the transport demand. The plan consists of decisions regarding which vehicle from the fleet is used, when the vehicle departs from the depot, which consignments are loaded onto the vehicle, the stop sequence in the case of multiple consignments, and route choice. This plan is then simulated on a transport network and evaluated in terms of its performance. A time-dependent and vehicle-dependent cost-minimisation algorithm calculates the optimal route. The success of a plan is determined by its economic outcome - comprising fixed costs and time - and distance-related costs - combined with a penalty for deliveries that could not be executed (on time). The optimisation process therefore focuses on cost minimisation and is influenced by underlying factors such as load factor, congestion and the ability to meet delivery time windows. The model also accounts for passenger car traffic during peak hours in order to represent congestion. After execution, the performance score of the plan is calculated, and a new plan is generated in which previous decisions are adjusted. Through an iterative process, plans are simulated, scored and modified. The best-performing plans are retained, and the system gradually evolves towards a user nearoptimum over successive iterations. At that point, the iterative process is terminated and the best-scoring plan for each agent is extracted and linked to transport performance indicators (such as vehicle-kilometres travelled) and sustainability impacts (expressed in emissions and external costs). Figure 4 illustrates the structure of the model.



Based on MATSim Freight extension (Schröder et al., 2012)

Figure 4. Model structure.

The model uses three inputs. The first input is the transport network. For this purpose, the road network based on *OpenStreetMap* data for the Brussels Metropolitan Region is used. This area includes the administrative boundaries of the city as well as the surrounding municipalities, where logistics depots are often located from which the city is supplied. For the simulations, a real-world network and network load are used in order to ensure that the results correspond as closely as possible to reality. Brussels was selected because it offers a variety of transport network characteristics, including, among others, a circulation plan for the city centre and a pedestrian zone.

The second input is the transport demand per carrier or agent. Transport demand is expressed in parcel volume, or the number of parcels per day. For the transport demand per operator, a real dataset of 833,449 parcels with Belgian business-to-business and business-to-consumer destinations at postcode level is used. Based on data from the BIPT (2025), this dataset was extrapolated to the total annual volume and subsequently converted to a daily volume. From this, the volume for the Brussels-Capital Region was extracted. The volume per postcode is shown in Figure 5 below. This dataset is considered representative in terms of spatial distribution. On a daily basis, 87,029 parcels are delivered in the Brussels-Capital Region.

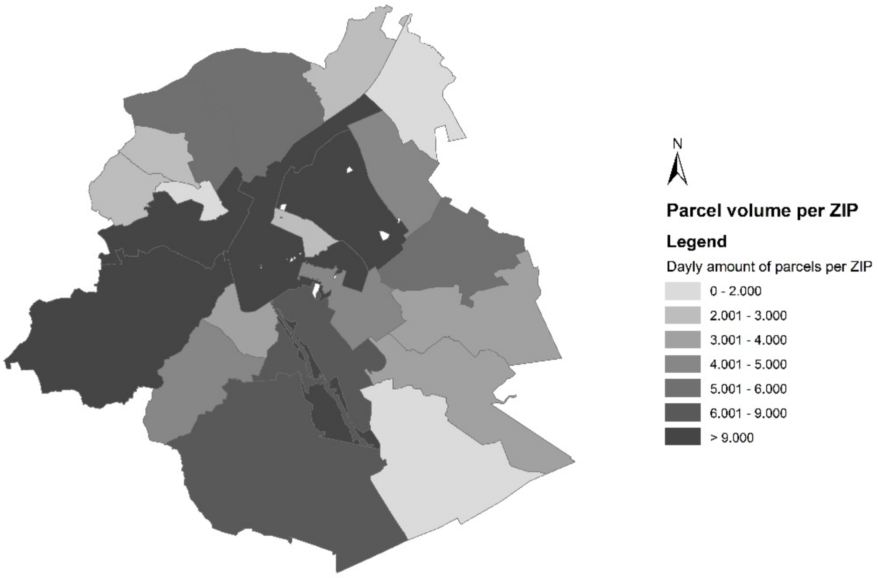


Figure 5. Transport demand for the Brussels-Capital Region (in daily amount of parcels / ZIP).

Finally, the model uses a third input, namely the carriers as agents. The data for the carriers consists of:

1. The locations of their depots.
2. The composition of their vehicle fleets, which also includes underlying information on vehicle size, cost, and other vehicle characteristics.

In order to quantify the research objectives, the different demonstrations must be represented within the agents. Therefore, each demonstration and the business-as-usual scenario (BAU) are represented by three agents (see Table 2), each with its own vehicle fleet and depot. The business-as-usual agents use diesel vans. They represent the pre-S2Z activities. In the multi-temperature cargo (Multi_temp) demonstration, goods requiring different temperature regimes are transported together, which requires multi-zone cooled vehicles. This agent is the first S2Z type of agent. All S2Z agents are using electric vehicles. The third group of agents comprises those using electric vehicles equipped with holistic energy management systems (Energy_man). The energy management allows to reduce energy use thanks to technical improvement in recuperation, or a similar monitoring function in a smart version. A fourth demonstration focuses on thermal comfort and safe ergonomics (Thermal_com), which requires energy from the battery for the thermal comfort. In addition, there are agents that use the Swapbox system, which facilitates loading, unloading and the modal shift. Finally, there is the Geofencing demonstration. These agents have no specific vehicle characteristics that affect the simulations. Consequently, these agents can be considered as the standard S2Z vehicle. The Dynamic Space demonstration cannot be included as a differentiating factor at the agent level due to the structure of the model.

Table 2. List of agents.

Agent	Fleet size	Vehicle type	Daily parcel volume
1. BAU_niche	unlimited	Diesel van	870
2. BAU_regular	unlimited	Diesel van	8 703
3. BAU_large	unlimited	Diesel van	26 109
4. Multi_temp_niche	unlimited	Cooled electric vehicle	870
5. Multi_temp _regular	unlimited	Cooled electric vehicle	8 703
6. Multi_temp _large	unlimited	Cooled electric vehicle	26 109
7. Energy_man_niche	unlimited	Electric management vehicle	870
8. Energy_man_regular	unlimited	Electric management vehicle	8 703
9. Energy_man_large	unlimited	Electric management vehicle	26 109
10. Thermal_com_niche	unlimited	Electric thermal vehicle	870
11. Thermal_com_regular	unlimited	Electric thermal vehicle	8 703
12. Thermal_com_large	unlimited	Electric thermal vehicle	26 109
13. Swapbox_niche	unlimited	Electric vehicle	870
14. Swapbox_regular	unlimited	Electric vehicle	8 703
15. Swapbox_large	unlimited	Electric vehicle	26 109
16. Geofencing_niche	unlimited	Electric vehicle	870
17. Geofencing_regular	unlimited	Electric vehicle	8 703
18. Geofencing_large	unlimited	Electric vehicle	26 109

All agents have an unlimited fleet size. This means that, in the simulations, the number of vehicles is not a limiting factor for the execution of deliveries. This allows the impact of the requirements to be quantified without being influenced by fleet size. In WP5 of S2Z, scenarios that explicitly address fleet size and upscaling are simulated. All agents operate a single depot that is responsible for deliveries within the Brussels-Capital Region. This depot is located in the northern fringe of the city, which is a representative location, as the depots of the major parcel operators are also situated there in reality. The table below presents the vehicle characteristics. As the demonstrations are not yet operational, the data used are based on sector figures that were collected and validated by VUB in previous projects. These figures were also aligned with the values used in Task T2.3 of S2Z. The figures for the demonstrations may differ from those used in the model. However, the objective is to quantify the relative impact of the requirements, rather than their absolute values.

Table 3. Vehicle types.

Vehicle types	Capacity (# parcels)	Maximum speed (km/h)	Purchase cost (€)	Energy consumption
Diesel van	90	90	35 000	8l / 100km
Electric vehicle	70	70	30 000	20kWh /100km
Multi-zone cooled electric vehicle	70	70	45 000	27kWh /100km*
Electric management vehicle	70	70	32 000	20kWh /100km
Thermal comfort vehicle	70	70	32 000	20kWh /100km
Cargo bike	40	30	10 000	1kWh /100km

*S2Z vehicles can use a eutectic cooling system- meaning they won't draw energy from the battery.

4.2.2 Assumptions

Every model is a simplified representation of a part of reality. In order to capture the complexity of this reality, models need to make assumptions. Knowledge of these assumptions is essential to understand and correctly interpret the results. The following paragraphs elaborate on the assumptions underlying the results presented in this deliverable.

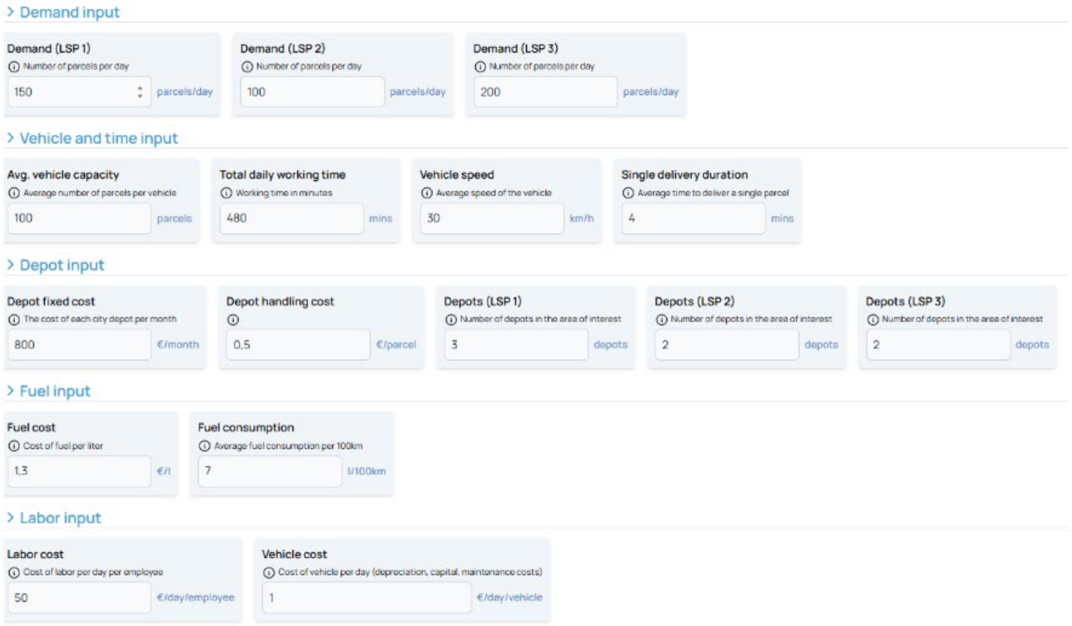
An abstraction is made from deliveries to manned and unmanned collection points. Collection points allow logistics service providers to reduce the number of drops and thus operate more efficiently. They also lead to fewer failed deliveries. The downside is that they can generate additional passenger trips, with associated impacts on traffic and the environment. Integrating different types of delivery locations could therefore significantly influence the results for the reasons outlined above, as demonstrated by previous research. Consequently, taking the research objective into account, **only private address deliveries** (B2C and B2B) are considered. A delivery – starting from stopping the vehicle to restarting the vehicle to continue the round – takes 1 minute and 6 seconds. This value is based on measurements of parcel deliveries in an urban environment.

No account is taken of failed deliveries and returns. Failed deliveries have an impact on logistics, but this impact exceeds the time horizon of a single day, which forms the basis of the simulation model used. As a result, the impact of failed deliveries cannot be captured by the model. Returns are highly dependent on the type of good. They also have a significant impact on the environment and the e-commerce sector. However, in the simulations, we only consider the receipt of parcels from the consumer perspective, not the sending of parcels.

Synchromodality and the Physical Internet are based on a transport system that is a-modal, where it is irrelevant to the sender and receiver of goods who ultimately organises the transport. As a result, in such a system, in the event of a disruption, goods transported by one logistics service provider (LSP) could be transferred to a vehicle of another LSP because they are part of the same system. In practice, this form of the Physical Internet is difficult to realise in the short term. Consequently, developments in this field are moving towards a decentralised Physical Internet system, in which LSPs participate voluntarily, thereby strengthening the system and creating benefits from which they themselves can profit. In such a decentralised network, however, LSPs maintain bilateral relationships with other actors and participants in the Physical Internet system, making transfers between vehicles of different LSPs unlikely. For this reason, such **transhipments between different logistics service providers are excluded** from the model. An additional advantage of this choice is that the analyses allow the impacts to be assessed at the level of an individual agent (LSP). This is currently the most useful level at which to convince stakeholders of the value of synchromodality and the Physical Internet.

The urban or rural environment in which transport operations take place has a significant impact on last-mile costs and their associated impacts. Several elements play a role in this. This is because the environment influences traffic conditions. In an urban environment, for example, there is a higher number of intersections, a greater presence of different road users, and a higher number of traffic interactions than in a rural environment. All of these factors are inherently linked to speed and safety. In addition, it can be assumed that so-called receptor density - the density of people affected - is higher in urban environments than in rural ones. This affects air pollution and noise nuisance, as the monetary cost depends on the number of people affected by air pollutants and noise emissions. In these analyses, scenarios are developed for the Brussels Metropolitan Region, which can be considered an exclusively urban area.

The final assumption is that deliveries take place between 8 a.m. and 9 p.m. A delivery takes 1 minute and 6 seconds, and a delivery shift lasts 480 minutes. These assumptions correspond to the inputs of the *Impact Assessment Radar* developed within the URBANE project (URBANE, 2024). The previously described transport demand per agent/LSP, as well as vehicle and staff costs, are also included among the inputs of the *Impact Assessment Radar*.



Demand input

Demand (LSP 1)
Number of parcels per day
150 parcels/day

Demand (LSP 2)
Number of parcels per day
100 parcels/day

Demand (LSP 3)
Number of parcels per day
200 parcels/day

Vehicle and time input

Avg. vehicle capacity
Average number of parcels per vehicle
100 parcels

Total daily working time
Working time in minutes
480 mins

Vehicle speed
Average speed of the vehicle
30 km/h

Single delivery duration
Average time to deliver a single parcel
4 mins

Depot input

Depot fixed cost
The cost of each city depot per month
800 €/month

Depot handling cost
0,5 €/parcel

Depots (LSP 1)
Number of depots in the area of interest
3 depots

Depots (LSP 2)
Number of depots in the area of interest
2 depots

Depots (LSP 3)
Number of depots in the area of interest
2 depots

Fuel input

Fuel cost
Cost of fuel per liter
1,3 €/l

Fuel consumption
Average fuel consumption per 100km
7 l/100km

Labor input

Labor cost
Cost of labor per day per employee
50 €/day/employee

Vehicle cost
Cost of vehicle per day (depreciation, capital, maintenance costs)
1 €/day/vehicle

Figure 6. Illustration of the Impact Assessment Radar inputs from the URBANE project (URBANE, 2024).

4.3 Scenarios

The model is used to simulate and compare different scenarios. In this context, the relative differences in the results are of primary importance. The scenarios are based on the analyses conducted for the requirements, as described in Section 3.2 of this deliverable. The most relevant requirements were retained and linked to the capabilities and limitations of the simulation model. For example, it is not relevant to simulate a scenario that cannot be included as a variable in the model, such as location analyses for collection points. The scenarios were presented at the S2Z consortium meeting in Bergen (Norway), where feedback was collected and incorporated. Additional bilateral discussions between VUB and experts from within and outside the S2Z consortium further refined and ultimately validated the scenarios. The scenarios are independent of the analyses to be carried out in WP5 and aim to investigate policy measures and upscaling, supported by data derived from the demonstrations.

Disruptions are introduced into the transport network in order to assess how the scenarios respond. On a daily basis, 10 randomly selected road segments are completely closed for the entire day. An additional 20 randomly selected road segments are disrupted for 1 hour, for example, to simulate accidents. The disruptions are applied to all scenarios, with no differences in the selected road segments or time windows between scenarios. In addition to these disruptions, a dynamic network load of passenger cars is applied to the network during peak periods. This is necessary because the number of vehicles operated by the agents is not sufficiently high to generate congestion, while congestion constitutes a significant component of urban traffic.

Furthermore, client requirements are incorporated into the simulations. Ten per cent of consumers are assigned a 2-hour time window within which the delivery must take place. If this requirement is not met during the simulations, a penalty is applied to the economic score.

The scenarios for T2.4 are described below.

1. Pre-S2Z

The first scenario represents the situation prior to the introduction of synchromodality and the Physical Internet (PI). This scenario serves as the baseline for comparison with the other scenarios, as changes in costs and other potential advantages or disadvantages can only be assessed relative to the current system, in which synchromodality and PI are not applied.

2. Real-time rerouting

This scenario focuses on quantifying the effect of real-time rerouting. Vehicles are able to respond to disruptions by adjusting their routes and/or delivery sequences during execution.

3. Real-time modal shift

Similar to the previous scenario, agents can respond to disruptions in real-time by executing a modal shift. In this scenario, two vehicle types are added to the agents' initial fleet to enable this: cargo bikes and diesel vans. The characteristics of these vehicles can be found in Table 3.

4. Vehicle/cargo body issue

During delivery rounds, unexpected issues may arise. A vehicle may break down, be involved in an accident, a sensor may fail, etc. Systems already exist to detect or predict such failures early, in order to avoid stopping a delivery round in progress. However, in this scenario, it is assumed that such a stoppage is unavoidable and must be managed by the PI system and the involved agent. Possible interventions include: (1) transferring the goods to other operational vehicles of the agent, (2) dispatching a replacement vehicle to which the goods are transferred, and (3) sending a repair service to make the vehicle operational again within one hour. Each solution has an equal probability (1/3), and two vehicles are assumed to be affected. The model's iterative process ensures that the most efficient solution is selected.

5. Changing client requirements

In the fifth scenario, client requirements are adjusted, such that 5% of customers—or half of those with time windows—are assigned a delivery window of 1 hour instead of 2 hours.

6. Battery/energy savings

Thanks to the real-time monitoring of the battery, the assumption is that 10% of energy consumption during delivery can be saved. This scenario incorporates this energy saving during the operations.

4.4 Results

4.4.1 Scenario 1 – Pre-Shift2Zero

The total number of kilometres travelled depends on the transport demand per agent. Niche agents with a daily volume of 870 parcels travel approximately 800 kilometres per day (788 km ⬄ 831 km). Regular agents, with a 10% market share, are responsible for 3,600 kilometres per day (3,527 km ⬄ 3,707 km). Finally, the market leader travels between 7,808 and 8,723 kilometres per day. However, it is more relevant to consider vehicle kilometres per parcel. Here, significant differences can be observed between niche agents on one hand and regular and large agents on the other. Once a sufficiently high drop density is reached, delivery rounds can be organised efficiently. The figure below shows the vehicle kilometres travelled per parcel for the different agents. Note that travel kilometres between the distribution centre and the delivery area are included. Business-as-usual agents have a slightly shorter distance, which is caused by the higher capacity of their diesel vehicles that reduces the number of trips required.

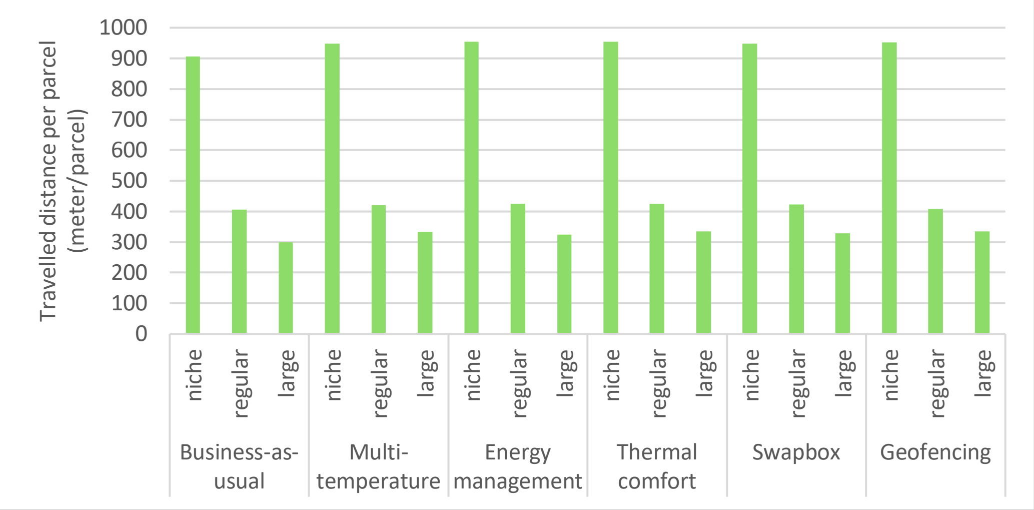


Figure 7. Travelled vehicle-kilometres per parcel per agent for scenario 1.

The average parcel volume carried per round also differs significantly between niche agents and the other agents. For niche agents, less volume is carried per round because the distance between individual deliveries is greater and delays due to urban traffic conditions play a relatively larger role. For the other agents, the average parcel volume per delivery round more closely matches the maximum vehicle capacity. This effect is even more pronounced for the S2Z agents, as the vehicles they use have lower capacities.

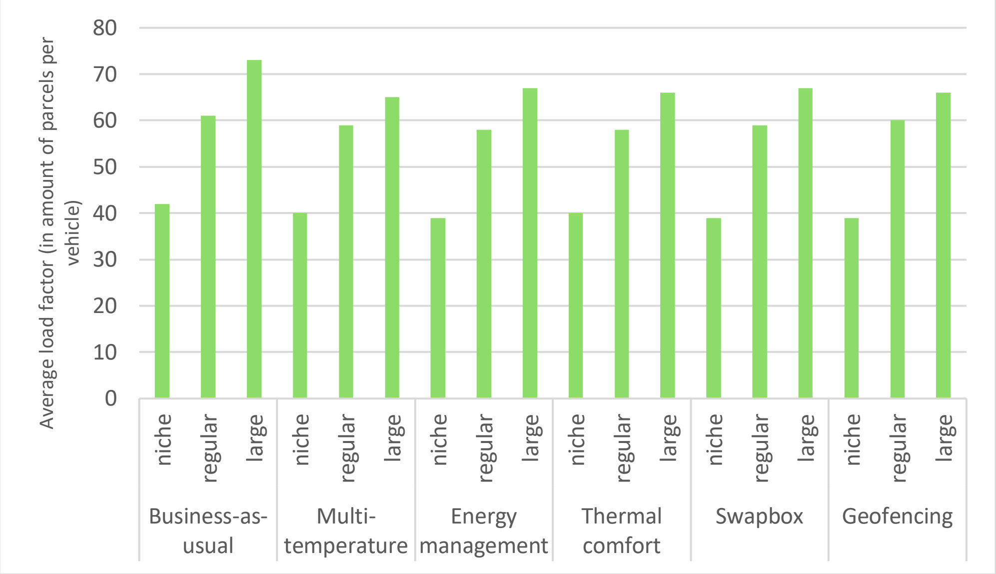


Figure 8. Average load factor per agent for scenario 1.

The combination of distance travelled per parcel and the vehicles used impacts internal transport costs per parcel. It is clear that the greater the volume, and thus drop density, the lower the internal transport cost per parcel will be. Costs range between €4 and €5 per parcel for niche agents, while large agents vary between €3.4 and €3.6 per parcel.

Vehicles with their own refrigeration are significantly more expensive per parcel due to their higher purchase cost and greater energy consumption during operations. For the other agents, internal costs are very similar when considered by agent type (niche, regular, large). S2Z vehicles are assumed to be slightly cheaper to purchase, but in this scenario, their delivery rounds are somewhat less efficient, resulting in a slightly higher number of vehicle kilometres per parcel.

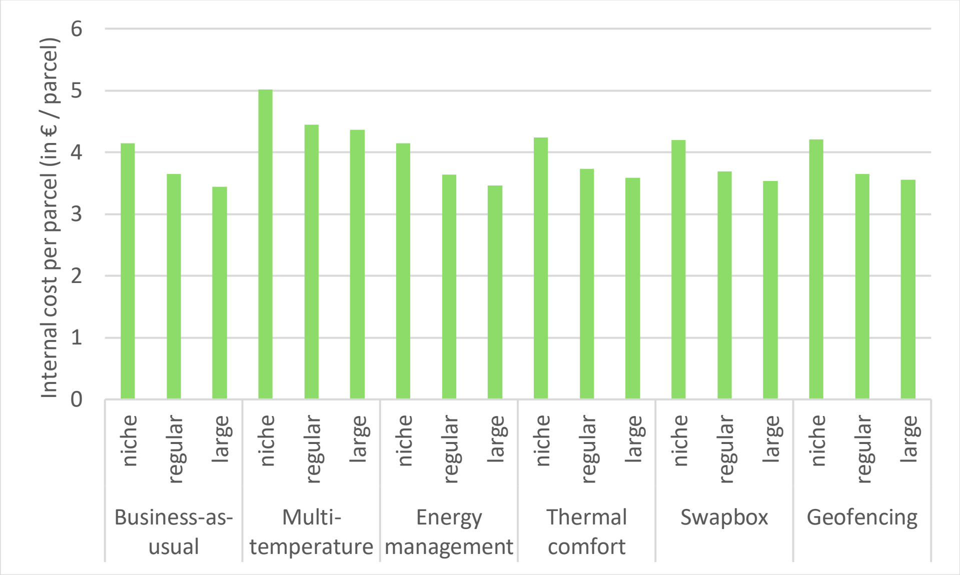


Figure 9. Internal cost per parcel per agent for scenario 1.

External costs per parcel follow a similar pattern. The smaller the volume and drop density, the higher the external cost per parcel. In addition, S2Z agents are significantly more sustainable than the business-as-usual agents. The latter use diesel vehicles, whereas S2Z agents only use electrically powered vehicles. Electric vehicles produce no tailpipe emissions and therefore have no external cost for climate change or air pollution associated to tailpipe emissions. Emissions related to electricity production and distribution are accounted for in upstream and downstream processes. However, these represent the smallest externality in terms of magnitude. Emission for the production of the vehicle are considered out-of-scope.

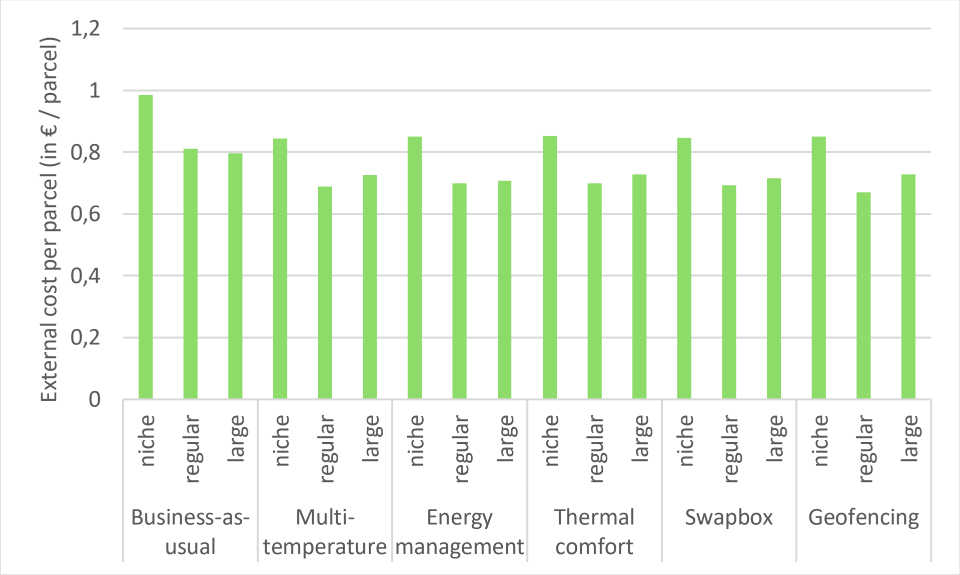


Figure 10. External cost per parcel per agent for scenario 1.

4.4.2 Scenario 2 – Real-time rerouting

As the scenarios are based on input values obtained through expert consultation involving project partners Bax, Certh and Paxster, rather than from the demonstrations themselves (which are yet to take place), the results are presented not in absolute terms but relative to the pre-Shift2Zero situation. Absolute results for the different scenarios can be found in Annex 1.

This scenario, in which agents are able to respond to disruptions in real-time via rerouting, results in a reduction in vehicle kilometres travelled per parcel compared with the pre-Shift2Zero situation. In the latter, agents are also confronted with disruptions, but their responses are less optimised. Since even the shortest disruption lasts at least one hour, agents will not simply wait it out; all will choose an alternative route.

Reductions in vehicle kilometres per parcel range between 2% and 4%, depending on the extent to which delivery rounds are affected by the disruption location. That explains also the difference between the types of agents. In some cases the Regular agent is most affected, like the Thermal Comfort agents, while in others, like the Multi-temperature, the Regular agent has the smallest impact.

It is evident that the magnitude of the reduction also depends on the number of disruptions. This number is kept relatively limited in the simulations because the model already accounts for congestion. The disruption location will also strongly influence the impact. Major city access roads, key traffic junctions, and the access routes around LSP distribution centres are particularly vulnerable.

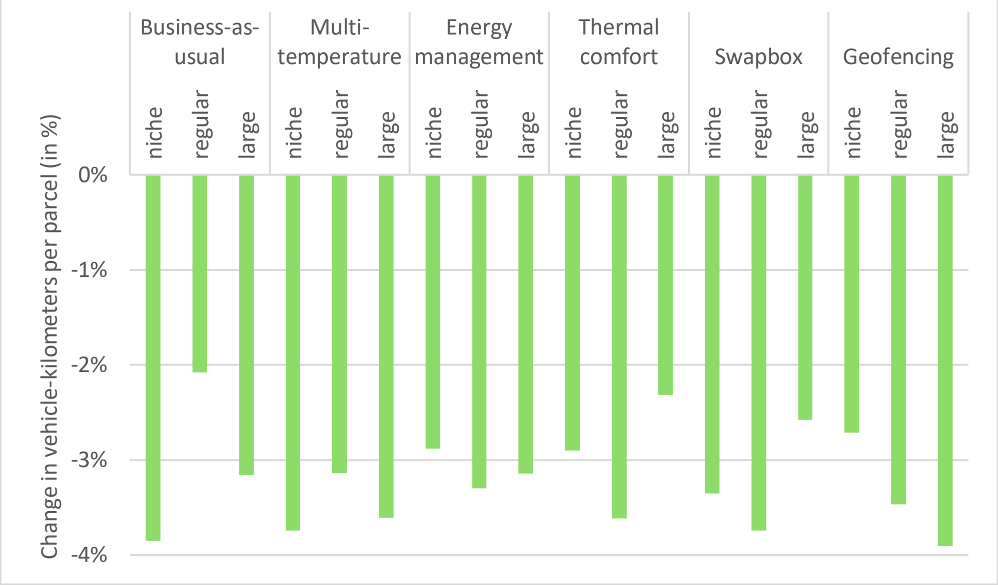


Figure 11. Change in vehicle-kilometres per parcel per agent for scenario 2 compared to scenario 1 (in %).

A reduction in vehicle kilometres per parcel also results in a reduction in internal transport costs per parcel. Unsurprisingly, these reductions follow the same pattern at the agent level as those observed for vehicle kilometres, as presented in Figure 11. The reductions are, however, more limited in magnitude, ranging between 0.6% and 1.2%. This is because distance-dependent costs represent only one component of total transport costs. From this, we can infer that the introduction of a PI system that allows real-time rerouting will enable all agents—both large and small—to reduce their vehicle kilometres travelled and achieve the associated cost savings.

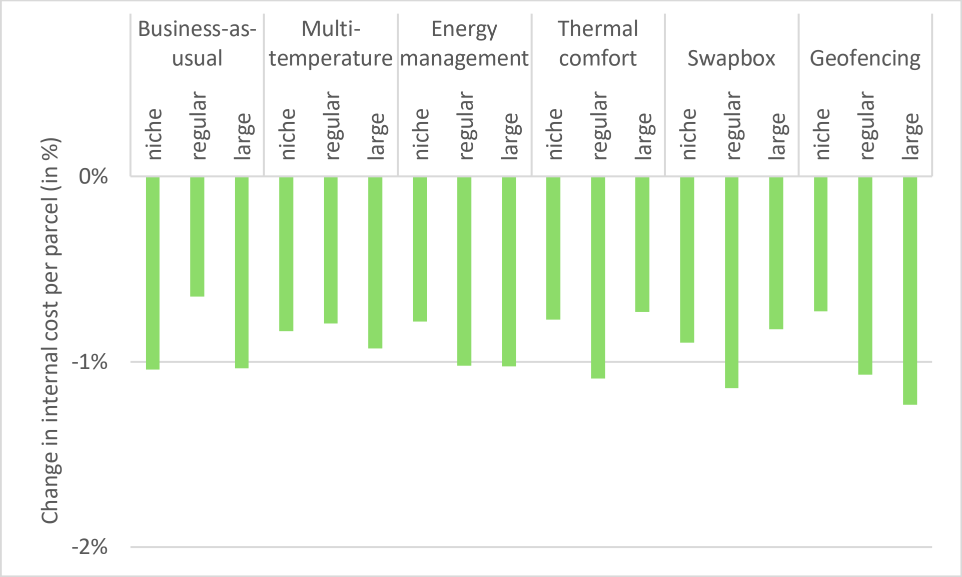


Figure 12. Change in internal cost per parcel per agent for scenario 2 compared to scenario 1 (in %).

Finally, external costs also follow the same reduction pattern, although they exhibit a direct proportional relationship with vehicle kilometres travelled per parcel. We can therefore conclude that the introduction of a PI system allowing real-time rerouting will make the transport system more sustainable than the current one. Transport will thus not only be more robust and flexible, but also more efficient and environmentally sustainable.

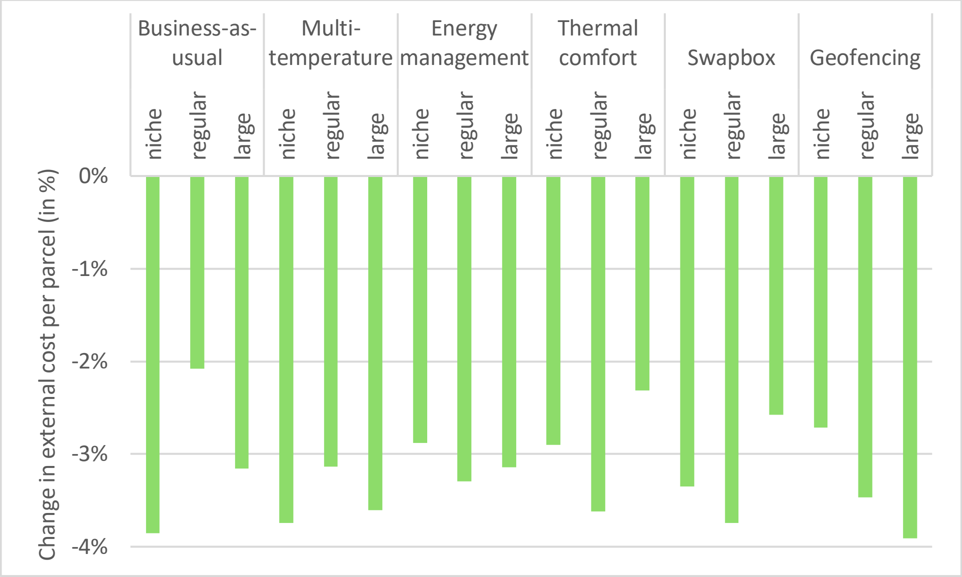


Figure 13. Change in external cost per parcel per agent for scenario 2 compared to scenario 1 (in %).

4.4.3 Scenario 3 – Real-time modal shift

Scenario 3 considers a real-time modal shift towards diesel vans or cargo bikes in response to disruptions. Agents don't react on disruptions by changing the routing. It results in longer distribution times when a modal shift occurs. In the simulation, we observe that agents rarely adopt such a response. On the one hand, this can likely be partly explained by the relatively limited number of disruptions, although these are long enough in duration to justify a potential modal shift. On the other hand, we believe that the additional complexity, effort, and cost associated with a modal shift are the main reasons agents seldom choose this option. In practice, a modal shift is already difficult to implement, even when it is policy-driven.

Niche agents never undertake a modal shift and therefore produce the same results as in Scenario 1. For the other agents, a limited real-time modal shift is observed, which immediately results in a relatively large increase in vehicle kilometres per parcel (+1% to +4.5%). This increase occurs because the modal shift involves moving from S2Z vehicles to cargo bikes, which also need to travel access distances and must operate differently due to their more limited load capacity.

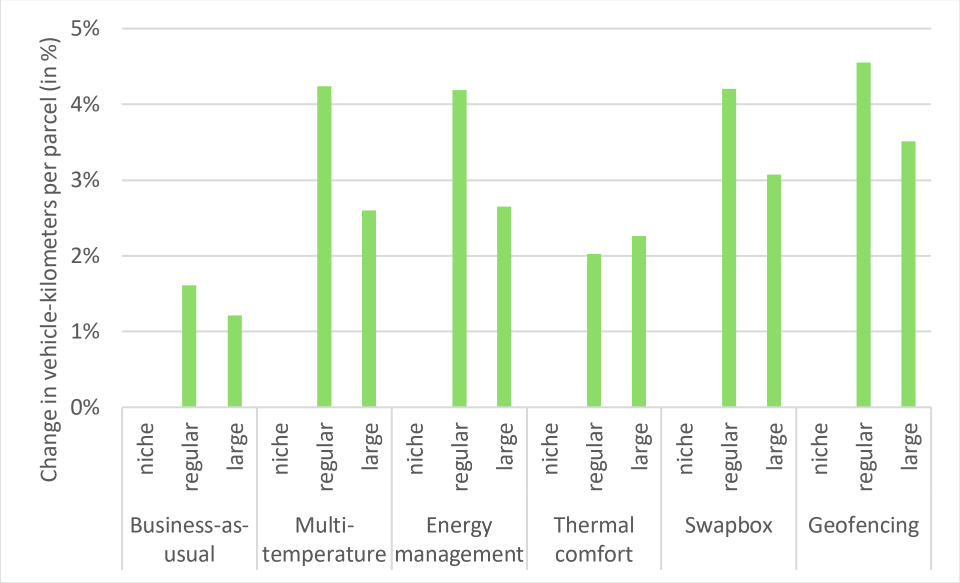


Figure 14. Change in vehicle-kilometres per parcel per agent for scenario 3 compared to scenario 1 (in %).

The additional vehicle kilometres per parcel also translate into higher internal transport costs for the agents. Transferring the goods from an S2Z vehicle to cargo bikes furthermore entails additional costs. Together, these factors outweigh the lower purchase and operating costs of cargo bikes compared with S2Z vehicles—particularly in the local completion of disrupted delivery rounds. It should also be noted that the increase in internal costs is lowest for the Swapbox agents. This is achieved because the Swapbox significantly reduces transhipment costs between the two vehicle types.

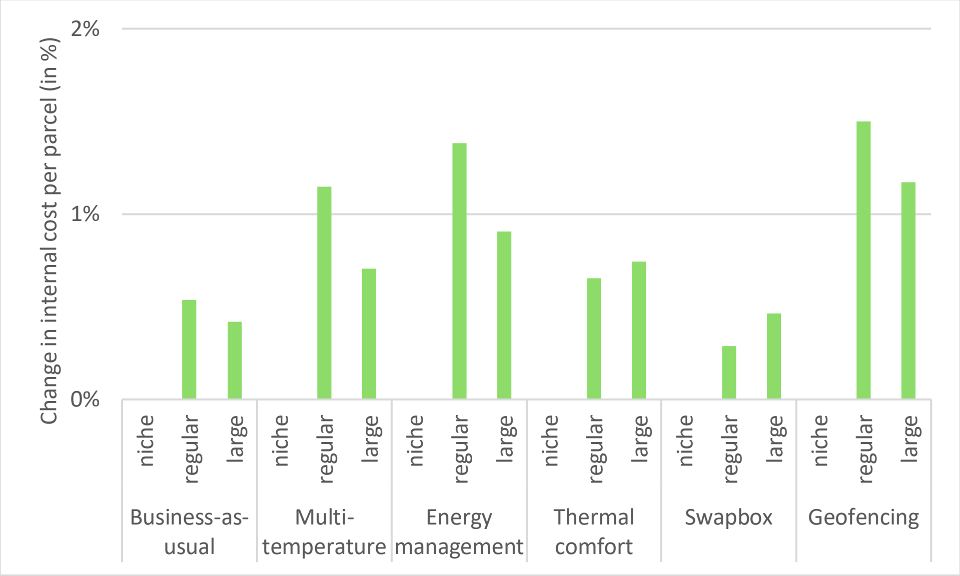


Figure 15. Change in internal cost per parcel per agent for scenario 3 compared to scenario 1 (in %).

While internal transport costs increase, external transport costs decrease in this scenario compared with Scenario 1. The reductions are relatively substantial, despite the limited modal shift. This is because, in those limited cases, cargo bikes are used, which are not only emission-free but also have significantly lower external costs related to accidents, infrastructure damage, noise nuisance, and congestion.

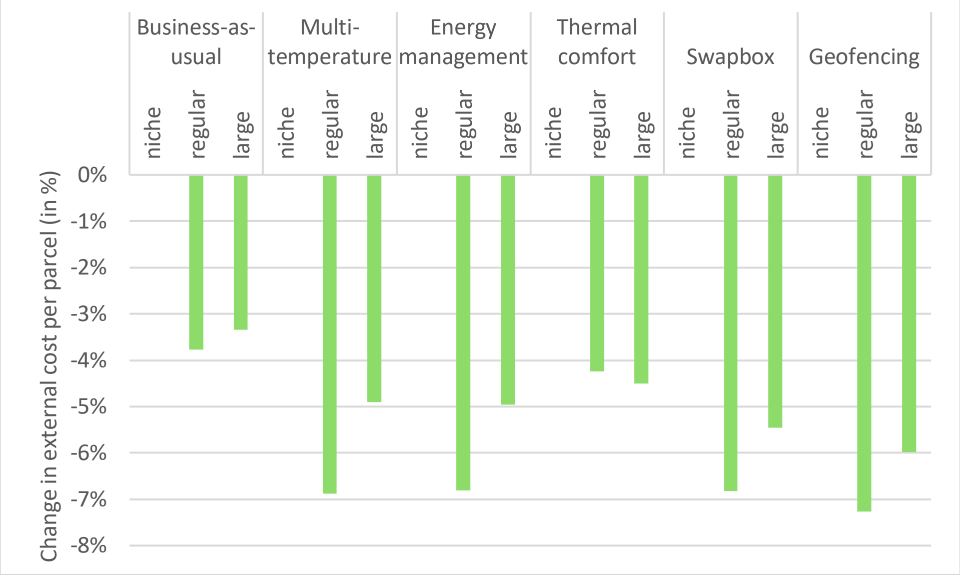


Figure 16. Change in external cost per parcel per agent for scenario 3 compared to scenario 1 (in %).

Although the simulations indicate that a real-time modal shift in response to prolonged disruptions is unlikely, two conclusions can nevertheless be drawn from the model results. First, from both an economic and a sustainability perspective, it appears desirable to consider cargo bikes as a logistics solution for a very local last mile. In addition, a planned modal shift—such as through mobile micro-hubs or larger vehicles supplying local fixed micro-hubs—represents a potentially attractive solution. From these micro-hubs, cargo bike deliveries can then be organised. This type of organisation has already proven successful in practice.

4.4.4 Scenario 4 – Vehicle/cargo body issue

In Scenario 4, two vehicles per agent become completely unusable and must be repaired or replaced. The impact of losing two vehicles is naturally greatest for agents with a limited vehicle fleet, namely the niche agents. They experience an increase of almost 10% in vehicle kilometres travelled per parcel compared with Scenario 1 in which no breakdowns are simulated. This increase is ten times greater than for the regular agents and twenty times greater than for the large agents.

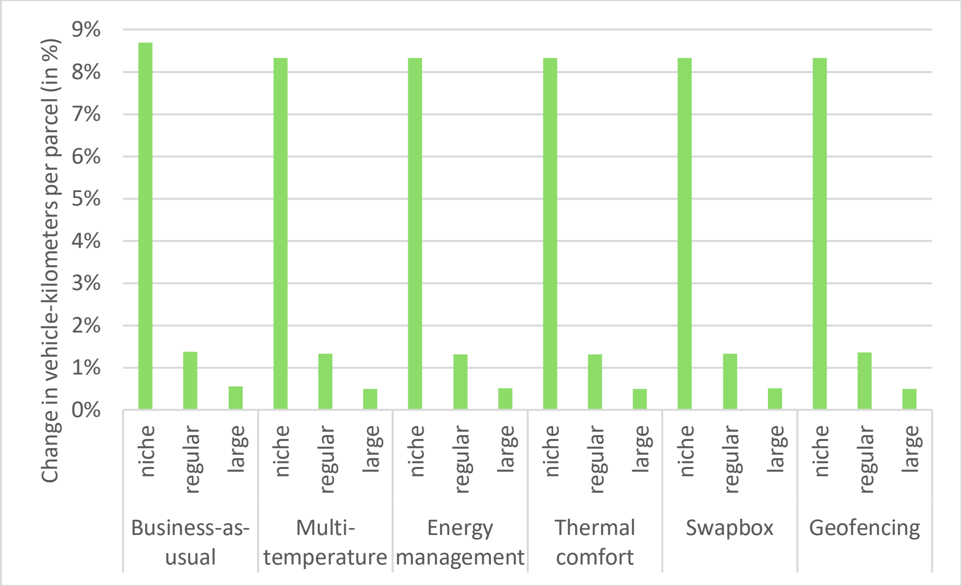


Figure 17. Change in vehicle-kilometres per parcel per agent for scenario 4 compared to scenario 1 (in %).

The additional kilometres travelled also translate into an increase in internal transport costs. However, since distance-dependent costs represent only one component of total costs, the increase is more limited in magnitude (+2.5% for the niche agents). Note that the purchase cost of replacement vehicles, or of the vehicle used to bring the repair service to the site, was not accounted for in the simulations. Consequently, the actual increase in costs is likely to be higher in practice.

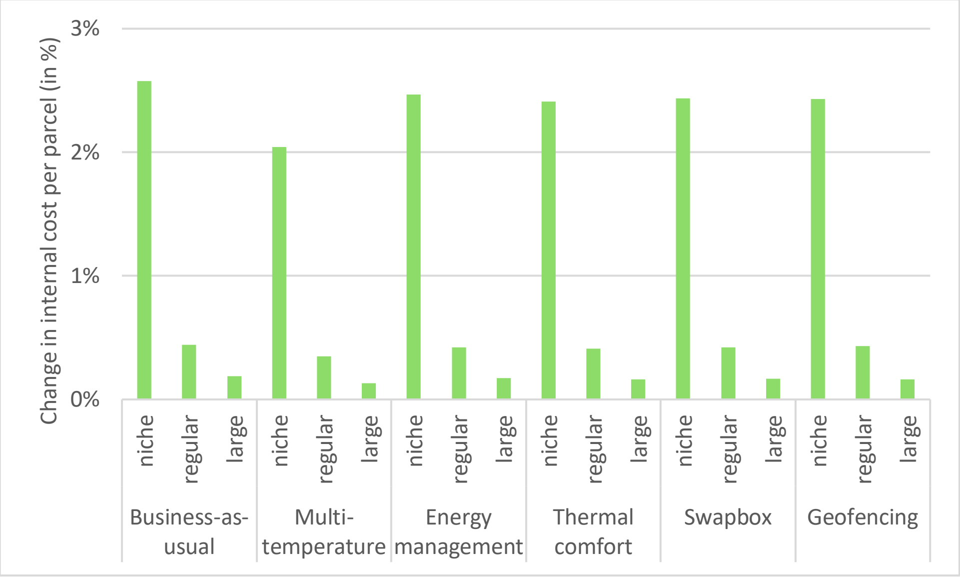


Figure 18. Change in internal cost per parcel per agent for scenario 4 compared to scenario 1 (in %).

External costs per parcel also increase in this scenario compared with Scenario 1, and to the same order of magnitude as the increase in vehicle kilometres travelled per parcel.

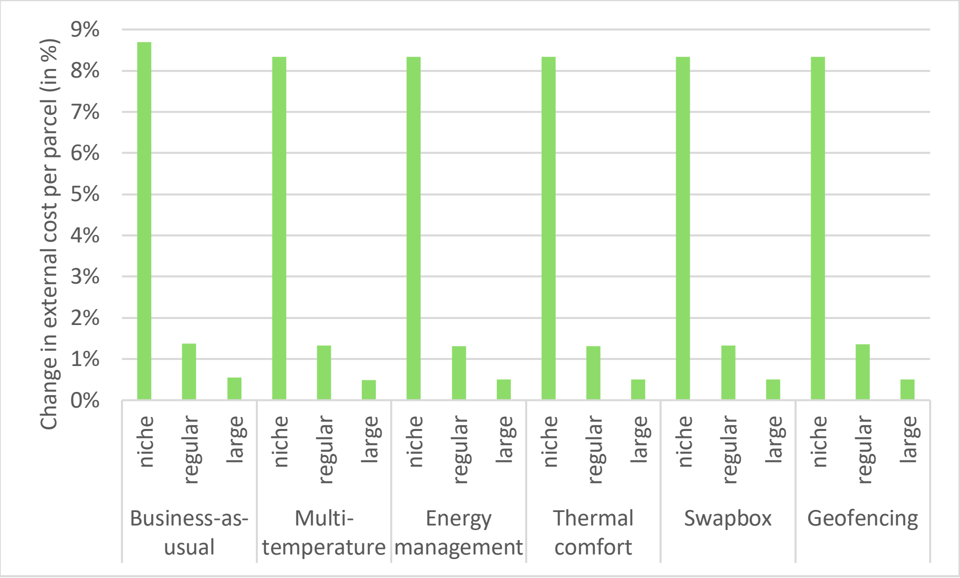


Figure 19. Change in external cost per parcel per agent for scenario 4 compared to scenario 1 (in %).

Although this undoubtedly has an economic and sustainability impact, its relative magnitude appears to remain manageable for agents with a substantial vehicle fleet. This is because two vehicles represent a smaller share of the total fleet. Moreover, such agents often have operating vehicles in close proximity that can help absorb the disrupted delivery round. This provides an additional argument for moving towards a PI system in which different logistics service providers (LSPs) engage in horizontal collaboration.

4.4.5 Scenario 5 – Changing client requirements

Scenario 5 examines how the PI system is able to respond to real-time changes in client requirements in the form of delivery time windows. We observe that this leads to additional vehicle kilometres travelled per parcel, with increases of around 0.6% for regular and large agents and up to 2,5% for niche agents. Differences between agent types are due to the random selection of clients whose requirements change. Owing to their location, some clients have a greater impact on planning than others, a phenomenon that is most pronounced for the niche agents.

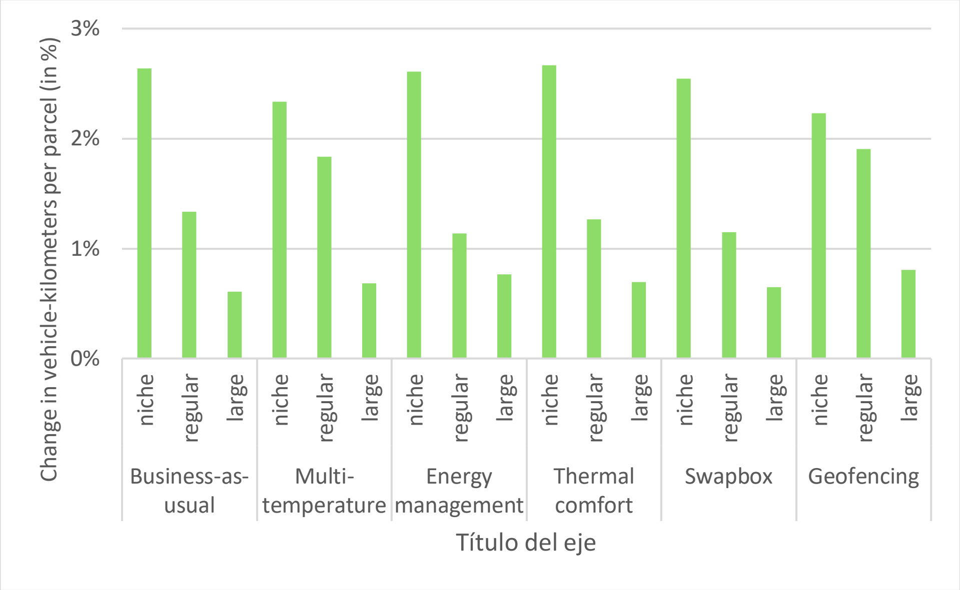


Figure 20. Change in vehicle-kilometres per parcel per agent for scenario 5 compared to scenario 1 (in %).

The additional kilometres driven once again translate into rising internal transport costs per parcel. These increases are also of a smaller magnitude here (0.2% to 1%), but the difference is smaller than in the earlier scenarios. This is because, in this scenario, not only distance-related costs are primarily affected, but time-related costs as well.

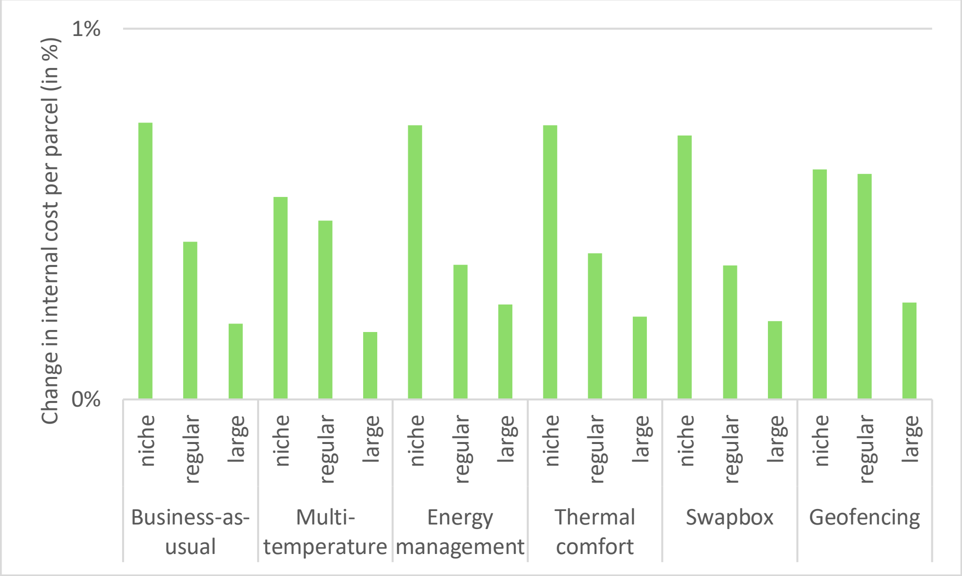


Figure 21. Change in internal cost per parcel per agent for scenario 5 compared to scenario 1 (in %).

The external costs per parcel increase in Scenario 5 compared to Scenario 1, again in line with the same order of magnitude as the increase in kilometres driven per parcel shown in Figure 20.

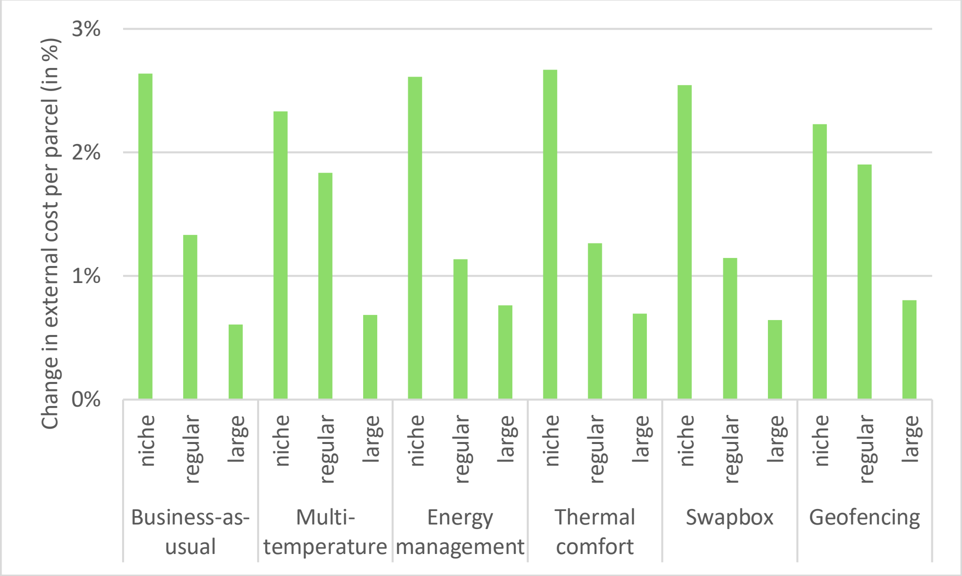


Figure 22. Change in external cost per parcel per agent for scenario 5 compared to scenario 1 (in %).

Changing client requirements inevitably lead to more kilometres driven and the associated internal and external costs. However, the main difference is again noticeable between smaller market players (niche) and the larger ones (regular and large). Real-time changing client requirements are best accommodated by an extensive PI network, in which horizontal collaboration forms a key component.

4.4.6 Scenario 6 – Battery/energy savings

In the final scenario, the assumption is made that 10% of battery consumption can be saved by properly monitoring all vehicle and load parameters through the PI system. This has no impact on the vehicle kilometres driven per parcel. The impact of this scenario is also very limited in terms of external costs per parcel. This is because neither the kilometres driven nor the transport mode and propulsion are changed. Only the upstream and downstream processes are affected, but this represents a small externality in relative terms. As a result, we see a reduction of 0.08% in external costs for all agent types except the business-as-usual agents operating diesel vehicles. The integration of the energy saving functionality can be associated with increased driving range, which we however did not include in the vehicle characteristics and simulations.

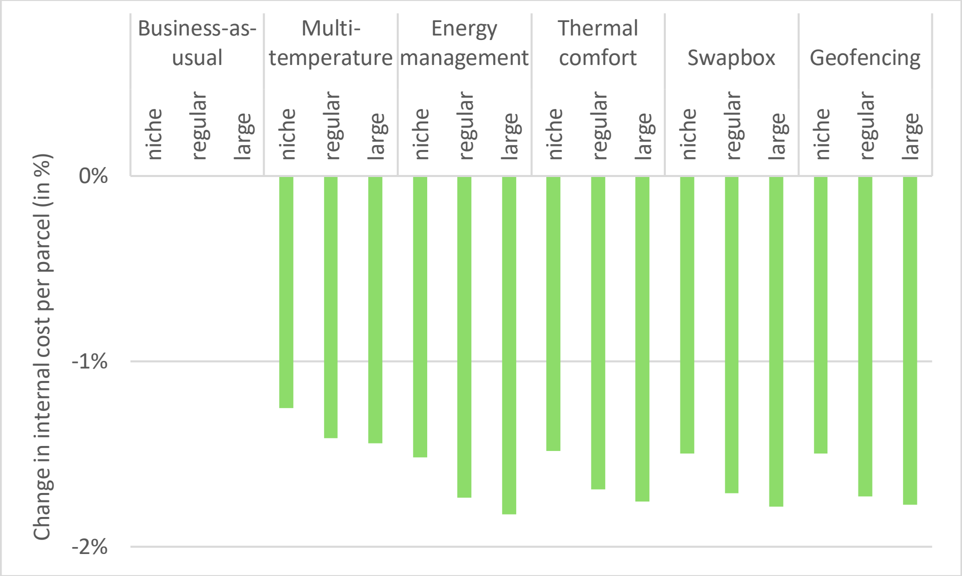


Figure 23. Change in internal cost per parcel per agent for scenario 6 compared to scenario 1 (in %).

For the internal costs per parcel, we do see reductions of between 1.2% and 1.8%, with the reductions being slightly more pronounced for the larger market players. For the multi-temperature agents, the savings are smaller because a portion of the electricity they use is for cooling, and this electricity is not affected by the PI system in this scenario.

4.4.7 Overall comparison

When reviewing the results of the scenarios, several recurring patterns can be identified. First, the introduction of a Physical Internet (PI) system for the S2Z demonstrations leads to cost reductions in dealing with disruptions. The magnitude of these savings is relatively small in the analyses, but it is proportional to the scale of the disruptions. PI makes the supply chain more robust in a cost-efficient and sustainable manner. Addressing disruptions through a modal shift, however, appears to be unlikely. Nevertheless, it is worthwhile to consider modal shift and the use of supporting (micro-)hubs in the initial delivery network design.

A second conclusion is that the S2Z demonstrations are not more expensive and are more sustainable than business-as-usual. The impact of introducing PI as measured across the scenarios does not differ between business-as-usual agents and S2Z agents. Where significant differences do occur, they can be attributed to the random impact of disruption locations or changing client requirements. The demonstrations themselves do, however, have a relative impact when compared to one another. For instance, Swapbox promotes a modal shift, while multi-temperature delivery strongly affects costs.

In scenarios that inherently have a negative impact on vehicle kilometres travelled, internal costs and external costs - namely vehicle breakdowns and changing client requirements - the introduction of PI results in a reduced negative impact.

Across all scenarios, however, the size of the market player plays a very important role in determining the magnitude of the impact on vehicle kilometres travelled per parcel, as well as internal and external costs per parcel. The smaller the player, the more unfavourable the outcome. The simulation results, therefore highlight the importance of the scale of the PI network in achieving economies of scale and high drop density. Horizontal collaboration between different logistics service providers (LSPs) appears to be crucial in this respect, so that the introduction of PI does not merely further strengthen large market players but also creates a business environment in which small and emerging players can benefit from the advantages of the system and potentially consolidate or grow their operations.

5. Conclusion

Deliverable 2.4 focuses on the requirements that the Shift2Zero solutions must meet in order to enable to apply synchromodality and the Physical Internet. Synchromodality and the Physical Internet are both innovations that promise to reduce logistics costs, improve sustainability and support the transition towards zero-emission freight transportation. Synchromodality stresses real-time flexibility to select the best transport modes according to the needs of actors, while Physical Internet envisions freight encapsulated in standardised cargo types and being transported seamlessly across an interconnected open network. It mimics the digital internet.

The Physical Internet is still in a development stage. Currently, the aim is to define and assess opportunities and business models, to evolve towards efficient and automated distribution systems in urban logistics by 2035. The URBANE project is working on these business models and aligns most closely with the objectives of T2.4 of S2Z. Deliverable 1.1 of URBANE forms a good basis for the description of the Physical Internet and its applications for urban logistics and the last mile.

This S2Z deliverable has three objectives:

- **Objective 1**: Proposing guidelines and requirements for the vehicles that allow synergies with the Physical Internet vision.
- **Objective 2**: Examining how these guidelines and requirements can be feasibly integrated into the various Shift2Zero demonstrations.
- **Objective 3**: Quantifying the feasibility of these guidelines and requirements by integrating them into scenarios that will be assessed using a simulation model.

We followed two different methodological approaches. For the identification of the guidelines and requirements and defining feasibility, we applied a combination of literature review, a case-study review and expert consultation. The quantification was performed via the use of an agent-based simulation model. The agents are various logistics service providers representing the different Shift2Zero demonstrations. The inputs and outputs are aligned with the *Impact Assessment Radar*, developed within URBANE.

The research resulted in different takeaways for the S2Z consortium partners and the different stakeholders outside of the consortium.

Guidelines and requirements (objective 1)

We identified six guidelines that consist of digitalisation (1), Internet-of-Things technology (2), flexible and open logistics service providers (2), acceptance and participation of relevant stakeholders (3), supporting policies (4) and the existence of a digital Physical Internet platform (5).

The guidelines resulted in a list of eight aggregated requirements. Firstly, there should be standardized cargo types (1). Next compatible loading and unloading systems (2) should be used. The vehicles and cargo bodies should be equipped by real-time GPS technology (3) and Internet-of-Things sensors (4) measuring environmental and vehicle parameters (5) and communicate them with the PI system and its actors. The digital Physical Internet platform (6) should allow interoperability and consider client requirements (7) and current and expected traffic conditions (8).

Feasibility (objective 2)

To research the feasibility, we constructed five scenarios that consider the most important elements of synchromodality and the Physical Internet. They consist of real-time rerouting (1), real-time modal shift (2), solving vehicle/sensor/cargo body breakdown (3), reacting to sudden client requirement changes (4) and battery savings (5).

The feasibility is calculated from an internal cost perspective for logistics service providers of different sizes, and disruptions are simulated to assess the reaction of the synchromodality and Physical Internet implementation.

Impact quantification (objective 3)

Based on the results of the different scenarios calculated with the agent-based model, we can draw several conclusions. Firstly, the introduction of a Physical Internet leads to cost reductions when logistics service providers are encountering disruptions. The magnitude of these savings is relative to the scale of the disruptions. Synchromodality and the Physical Internet make the supply chains more robust, more cost-efficient and more sustainable.

Secondly, the Shift2Zero solutions are not more expensive and are more sustainable than business-as-usual, according to the simulations.

Thirdly, all Shift2Zero solutions are subject to the impact of a Physical Internet introduction, and this generally to a similar extent.

Fourthly, the size of the logistics service provider plays a very important role in determining the magnitude of the impact on vehicle kilometres travelled per parcel, as well as internal and external costs per parcel. The smaller the player, the more unfavourable the outcome. The simulation results, therefore highlight the importance of horizontal collaboration between different logistics service providers, so that the introduction of Physical Internet does not merely further strengthen large providers, but also creates a business environment in which small and emerging providers can benefit from the advantages of the system and potentially consolidate or grow their operations.

As a conclusion, D2.4 findings will feed the technical design of Shift2Zero prototype vehicles (WP3), the planning and implementation of the pilot demonstrations (WP6), and the simulation engine to be developed in WP5.

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7. Annex

7.1 Agent-based simulation results (Annex 1)

Scenario 1 – Pre-Shift2Zero

Agent	Agent size	Total daily vehicle-kilometers	Vehicle-kilometers per parcel	Average load factor	Internal cost per parcel	External cost per parcel
Business-as-usual	Niche	788	0,91	42	4,15	0,99
	Regular	3528	0,41	61	3,65	0,81
	Large	7808	0,30	73	3,44	0,80
Multi Temperature	Niche	824	0,95	40	5,02	0,84
	Regular	3654	0,42	59	4,45	0,69
	Large	8695	0,33	65	4,37	0,73
Energy management	Niche	831	0,95	39	4,15	0,85
	Regular	3707	0,43	58	3,64	0,70
	Large	8463	0,32	67	3,46	0,71
Thermal comfort	Niche	831	0,96	40	4,24	0,85
	Regular	3705	0,43	58	3,73	0,70
	Large	8724	0,33	66	3,59	0,73
Swapbox	Niche	825	0,95	39	4,20	0,85
	Regular	3672	0,42	59	3,69	0,69
	Large	8572	0,33	67	3,54	0,72
Geofencing	Niche	829	0,95	39	4,21	0,85
	Regular	3557	0,41	60	3,65	0,67
	Large	8720	0,33	66	3,56	0,73

Scenario 2 – Real-time rerouting

Agent	Agent size	Total daily vehicle-kilometers	Vehicle-kilometers per parcel	Average load factor	Internal cost per parcel	External cost per parcel
Business-as-usual	Niche	759	0,87	42	4,11	0,95
	Regular	3456	0,40	61	3,62	0,79
	Large	7569	0,29	73	3,40	0,77
Multi Temperature	Niche	794	0,91	40	4,98	0,81
	Regular	3543	0,41	59	4,41	0,67
	Large	8393	0,32	65	4,33	0,70
Energy management	Niche	807	0,93	39	4,11	0,83
	Regular	3588	0,41	58	3,60	0,68
	Large	8205	0,31	67	3,43	0,69
Thermal comfort	Niche	808	0,93	40	4,21	0,83
	Regular	3576	0,41	58	3,69	0,67
	Large	8527	0,33	66	3,56	0,71
Swapbox	Niche	798	0,92	39	4,16	0,82
	Regular	3539	0,41	59	3,65	0,67
	Large	8357	0,32	67	3,51	0,70
Geofencing	Niche	807	0,93	39	4,18	0,83
	Regular	3438	0,40	60	3,61	0,65
	Large	8392	0,32	66	3,52	0,70

Scenario 3 – Real-time modal shift

Agent	Agent size	Total daily vehicle-kilometers	Vehicle-kilometers per parcel	Average load factor	Internal cost per parcel	External cost per parcel
Business-as-usual	Niche	788	0,91	42	4,15	0,99
	Regular	3586	0,41	61	3,67	0,78
	Large	7904	0,30	73	3,45	0,77
Multi Temperature	Niche	824	0,95	40	5,02	0,84
	Regular	3816	0,44	59	4,50	0,64
	Large	8927	0,34	65	4,40	0,69
Energy management	Niche	831	0,95	39	4,15	0,85
	Regular	3868	0,44	58	3,69	0,65
	Large	8693	0,33	67	3,49	0,67
Thermal comfort	Niche	831	0,96	40	4,24	0,85
	Regular	3782	0,43	58	3,75	0,67
	Large	8925	0,34	66	3,62	0,70
Swapbox	Niche	825	0,95	39	4,20	0,85
	Regular	3833	0,44	59	3,70	0,65
	Large	8844	0,34	67	3,56	0,68
Geofencing	Niche	829	0,95	39	4,21	0,85
	Regular	3727	0,43	60	3,71	0,63
	Large	9037	0,35	66	3,60	0,69

Scenario 4 – Vehicle/cargo body issue

Agent	Agent size	Total daily vehicle-kilometers	Vehicle-kilometers per parcel	Average load factor	Internal cost per parcel	External cost per parcel
Business-as-usual	Niche	863	0,99	42	4,26	1,08
	Regular	3577	0,41	61	3,66	0,82
	Large	7852	0,30	73	3,44	0,80
Multi Temperature	Niche	899	1,03	40	5,12	0,92
	Regular	3704	0,43	59	4,47	0,70
	Large	8739	0,33	65	4,37	0,73
Energy management	Niche	906	1,04	39	4,25	0,93
	Regular	3756	0,43	58	3,65	0,71
	Large	8506	0,33	67	3,47	0,71
Thermal comfort	Niche	906	1,04	40	4,34	0,93
	Regular	3754	0,43	58	3,74	0,71
	Large	8768	0,34	66	3,60	0,73
Swapbox	Niche	900	1,03	39	4,30	0,92
	Regular	3722	0,43	59	3,70	0,70
	Large	8616	0,33	67	3,54	0,72
Geofencing	Niche	905	1,04	39	4,31	0,93
	Regular	3606	0,41	60	3,67	0,68
	Large	8764	0,34	66	3,56	0,73

Scenario 5 – Changing client requirements

Agent	Agent size	Total daily vehicle-kilometers	Vehicle-kilometers per parcel	Average load factor	Internal cost per parcel	External cost per parcel
Business-as-usual	Niche	809	0,93	42	4,18	1,01
	Regular	3575	0,41	61	3,66	0,82
	Large	7856	0,30	73	3,44	0,80
Multi Temperature	Niche	844	0,97	40	5,05	0,87
	Regular	3722	0,43	59	4,47	0,70
	Large	8755	0,34	65	4,37	0,73
Energy management	Niche	853	0,98	39	4,18	0,87
	Regular	3749	0,43	58	3,65	0,71
	Large	8528	0,33	67	3,47	0,71
Thermal comfort	Niche	854	0,98	40	4,27	0,88
	Regular	3752	0,43	58	3,74	0,71
	Large	8785	0,34	66	3,60	0,73
Swapbox	Niche	846	0,97	39	4,23	0,87
	Regular	3714	0,43	59	3,70	0,70
	Large	8628	0,33	67	3,55	0,72
Geofencing	Niche	848	0,97	39	4,23	0,87
	Regular	3626	0,42	60	3,67	0,68
	Large	8791	0,34	66	3,57	0,73

Scenario 6 – Battery/energy savings

Agent	Agent size	Total daily vehicle-kilometers	Vehicle-kilometers per parcel	Average load factor	Internal cost per parcel	External cost per parcel
Business-as-usual	Niche	788	0,91	42	4,15	0,99
	Regular	3528	0,41	61	3,65	0,81
	Large	7808	0,30	73	3,44	0,80
Multi Temperature	Niche	824	0,95	40	4,96	0,84
	Regular	3654	0,42	59	4,39	0,69
	Large	8695	0,33	65	4,30	0,73
Energy management	Niche	831	0,95	39	4,08	0,85
	Regular	3707	0,43	58	3,57	0,70
	Large	8463	0,32	67	3,40	0,71
Thermal comfort	Niche	831	0,96	40	4,18	0,85
	Regular	3705	0,43	58	3,67	0,70
	Large	8724	0,33	66	3,53	0,73
Swapbox	Niche	825	0,95	39	4,14	0,85
	Regular	3672	0,42	59	3,63	0,69
	Large	8572	0,33	67	3,48	0,72
Geofencing	Niche	829	0,95	39	4,14	0,85
	Regular	3557	0,41	60	3,59	0,67
	Large	8720	0,33	66	3,50	0,73