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A simulation study of the impacts of micro-hub scenarios for city logistics in Rotterdam

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ABSTRACT

Micro-hubs are considered to be a potential solution to increase the consolidation of inner-city deliveries: in the City of Rotterdam it is a potential measure to increase the logistic efficiency in and around the planned zero-emission zone in the city center. When designing the configuration of micro-hubs in an urban setting multiple aspects should be considered, such as their location, the type of vehicles to operate them, and the business model to be adopted for their operation. And although the topic is much studied it remains difficult to predict how different micro-hub configurations affect the transportation system in terms of transport movements, number of travelled kilometers, etc. This paper describes the use of the Tactical Freight Simulator (TFS) to investigate the impact of micro-hubs on the transportation system in case they would be implemented at a wider scale across the city center, and make a comparison with the current state of last-mile delivery. The case study explores three different design aspects: location, type of vehicles (delivery robots, cargo bike, LEV), and the business model (individual/full collaboration). Results show that the largest reduction of vehicle kilometers can be achieved in the scenarios with full collaboration between the CEPs.

1. Introduction

In the Netherlands, from 2025 on a zero-emission zone (ZEZ) policy for logistics will be implemented in the center of large cities like Rotterdam (Rotterdam, 2019). This policy necessitates a shift to green vehicles that is undeniably a significant step towards decreasing the CO2 footprint which has become a national and global focal point. The aftermath of this policy, following the entrance prohibition of diesel (ICE) vehicles into the ZEZ, is the confinement of Business to Customer (B2C) last-mile delivery of goods, which constitutes a large part of the logistic streams that run in an urban environment. In parallel to that, there is increasing competition for urban space which drives logistics facilities outside of city centers to peripheral locations (Dablanc et al., 2014), taking its toll on the kilometers the service providers have to travel. To deal with the constrained B2C last-mile delivery streams, and operate as efficiently as possible in and around the introduced ZEZ, micro-hubs are introduced as a possible solution as they can increase the consolidation of inner-city deliveries (Aljohani & Thompson, 2016; Onstein, Bharadwaj, Tavasszy, van Damme and el Makhloufi, 2021).

As per the definition of the Urban Freight Lab (2020) micro-hubs are "logistics facilities inside the urban area boundaries where goods are bundled, which serve a limited number of destinations within a bounded spatial range, and allow a mode shift to low (or zero) emission vehicles or soft transportation modes (e.g., walking) for last yard deliveries". Micro-hubs generally generate a two-stage delivery process, as depicted in Fig. 1. In the first stage, defined as 'last mile delivery' and referred to as tour type 1, the consolidated goods are delivered with high-capacity vehicles such as trucks from depots located outside the city to the micro-hubs. This is followed by the second stage, defined as 'last yard delivery' and referred to as tour type 2, where goods are deconsolidated and delivered with zero-emission vehicles to customers (Anderluh et al., 2020). This delivery process, combined with the ZEZ policy which imposes the deployment of green vehicles only, can lead towards more efficient, organized, and greener last mile deliveries.

When designing the configuration of micro-hubs in an urban setting multiple aspects should be considered, such as their location, the type of

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vehicles to operate them, and the business model to be adopted for their operation. Micro-hubs should be placed in strategic positions in the city to ensure their easy access by trucks, as well as close to areas that present large parcel demands to ensure their sustainable operations in the long run and be able to exploit them in the best possible way. Different types of zero-emission vehicles can operate the micro-hubs that vary in speed, capacity, operating costs, operational range, accessibility (car-lanes, cycle-lanes, pedestrian areas), etc. which can affect the number and locations of micro-hubs. Concerning the business model, micro-hubs can be operated by a single CEP (courier express parcel service), or multiple CEPs following a shared logistics or white-label business model. The latter can be further segregated into a hybrid or full-collaboration model. Obviously, all business models have benefits and drawbacks, depending on the point of view, but it is important to note that the shared logistics model can lead to more efficient urban land use which constitutes one of the most pressing issues in modern urban land management.

One of the major barriers to the implementation of urban consolidation centers or micro hubs is the extent to which the various participants (carriers, receivers and local authorities) are willing and able to meet the financial costs of the UCC in return for the benefits that they receive (Allen et al., 2012). From this perspective it is important for urban freight policies to have an accurate prediction of potential benefits of micro hubs, and the best strategy to optimize these benefits.

Although the use of Micro-hubs is a well-studied topic in city logistics, it is yet not completely clear how different micro-hub configurations affect the transportation system in terms of transport movements, number of travelled kilometers, etc. The objective of this use case is to use the Tactical Freight Simulator (TFS) to investigate the impact of micro-hubs on the transportation system in case they would be implemented at a wider scale across the city center and make a comparison with the current state of last-mile delivery. Currently, the last-mile delivery process is usually performed with vans that visit the customers directly from the depot and is referred to henceforth as tour type 0 (see Fig. 1.B). Except for the fact that the majority of vans still run on a diesel engine, which makes them incompatible with the ZEZ policy, they also contribute greatly to the number of vehicle movements in a city.

The three micro-hub design aspects mentioned previously (location, type of vehicle, and type of business model) will be the main pillars in designing distinctive micro-hub configurations (scenarios) to be simulated in the TFS. Input for the simulator will be based on the Rosie demonstration in the HARMONY project, retrieved from the literature, as well as other recent Living Labs in Rotterdam (van Duin et al., 2022).

2. Literature review

Micro-consolidation initiatives go by a variety of definitions that nevertheless agree and portray similar characteristics. As per Kim and Bhatt (2019) delivery micro-hubs are a form of an urban consolidation center point with a smaller physical footprint located between a major suburban warehouse and a final delivery destination to allow for a shift in last mile deliveries typically with more clean vehicles. A delivery micro-hub can be a building or mobile structure and may be operated by one or more businesses in parallel. In a similar manner, Verlinde, Macharis, & Witlox (2012) referred to micro-consolidation centers as "alternative" additional transshipment points that downscale the scope of the consolidation initiative further than an Urban Consolidation Center (UCC). The Urban Freight Lab (2020) has defined micro-hubs as a special case of UCCs with closer proximity to the delivery point and serving a smaller range of service area. They continue saying that it is a logistics facility where goods are bundled inside the urban area boundaries and that it allows a shift to low-emission vehicles or soft transportation vehicles. In this research the definition of the Urban Freight Lab will be followed as it covers all the expected aspects.

The analysis of Janjevic and Ndiaye (2014) allowed them to define six common typologies for micro-consolidation initiatives. The first typology concerns vehicle reception points in the city where a zone is set up for carriers to load and unload the goods destined for the neighboring receivers. No suburban depot (SD) is used for this typology while for the five rest typologies it is a prerequisite. The second and third typology, namely, goods reception points and logistics parcel lockers, follow a similar principle: the couriers deliver to a communal delivery point at which the goods are bundled, and thereafter transported to the urban reception points. The goods reception points act as stores with employees while the automatic logistic box offers the customer the possibility to pick up his packages at any time of the day. The fourth typology, a micro-consolidation center, adopts a similar scheme to the classical urban consolidation center but in opposition, it is set up in closer proximity to the delivery area with more limited spatial range. The fifth typology consists of a transshipment point used for transferring goods to lighter and more adapted vehicles while the last identified typology consists of a mobile logistical facility that is used to perform the consolidated transport of goods towards the urban area.

In this study we will focus on the fourth typology, which will be referred to as micro-hubs. Micro-hubs are generally based on a two-stage delivery process, the first of which comprises of the consolidated delivery of goods from the depots, in the outskirts of the city, to the respective micro-hubs, followed by the second stage of last mile delivery

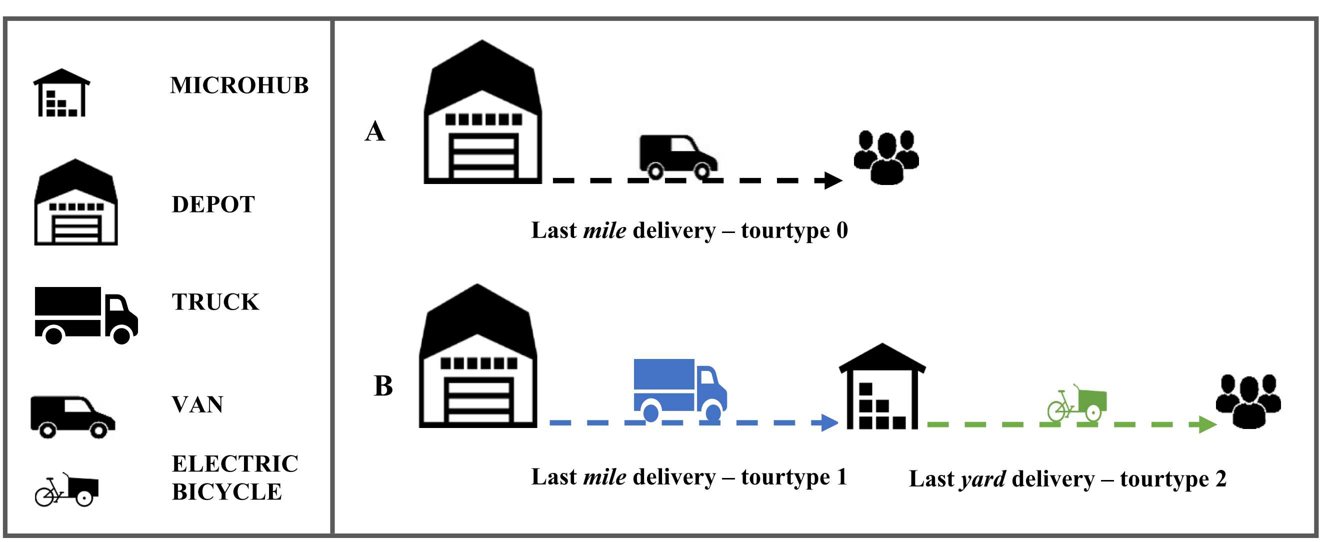

Fig. 1. Last-mile and last-yard delivery process.

to customers (Anderluh et al., 2020). This allows logistics companies with deliveries scheduled in the urban area to avoid entering the congested area, in an attempt to increase efficiency, while reducing the total travelled kilometers and greenhouse gas emissions produced by delivery vans.

Micro-hubs can be used as a transshipment facility to transfer parcels from larger vehicles to smaller greener vehicles but also as an overnight storage and charging point for these vehicles. Micro-hubs are also an important component 'proximity logistics': the development of logistics facilities in high-demand areas, which are essentially urban, dense and mixed-use (Buldeo Rai et al., 2022).

There is a variety of operational models of how businesses may integrate micro-hubs into their logistics and supply chain operations. Limited availability of public space and high urban property prices make shared logistics solutions highly attractive (Russo et al., 2021). The key consideration is whether a micro-hub will be implemented under a multi-carrier consolidation effort or if it will be solely used by one carrier. Kim et al. (2021) demonstrate the potential of the physical internet concept on the urban logistics system, which is currently fragmented, into seamless asset sharing to overcome economic efficiency, service capability and environmental requirements. Cleophas, Cottrill, Ehmke, & Tierney (2019) point out that physical internet achieves the combination of vertical and horizontal collaborations. In vertical collaboration transport is organized among vehicles and service operators, as for example between different legs of the supply chain, whereas in horizontal collaboration multiple providers work together sharing infrastructure and orders.

While Hribernik, Zero, Kummer, & Herold (2020) agree with the benefits of horizontal collaboration between CEP couriers, they in contrast state that trust and inter-organizational data exchange are considerable barriers to the introduction of this type of collaboration. Therefore, if no state-of-the-art technology is used to overcome these barriers, couriers will most likely opt to operate independently. However, horizontal collaboration and shared logistic services remains an important design component in the implementation of micro-hubs.

Several key elements can influence the potential success of micro-hubs operations. The Urban Freight Lab (2020) and Kim and Bhatt (2019) agree stating that there are four significant factors that can influence the design, size, scale, and viability of urban logistic spaces. To begin with, the population density of a delivery district is of utter importance to justify the need for change in the urban freight system as well as to keep micro-hubs sustainable and efficient during their operation. In continuance to that, location is another important aspect to consider as the facility should serve areas in the city where delivery activities are difficult due to limited accessibility, traffic conditions etc. The third important factor involves the necessity of a multi-sectoral collaboration in which it is crucial to have strong cooperation and trust among partners along with a shared mindset to improve city's economy and environment. Support from public authorities regarding funding and subsidization of urban logistic spaces as well as scientific support through research is fundamental in the planning phase to achieve a working, self-sustaining facility. Finally, public policy support for low-emission goods movements must be enabled. Some examples for this are: designated low emission zones for restricting access to polluting vehicles, policies supporting the use of green vehicles, regulation for delivery in urban centers etc.

3. Micro hub scenario

The use case focuses on the parcel logistics streams taking place in the Rotterdam city center. This area is ideal to examine the concept of micro-hubs as a delivery station (Buldeo Rai et al., 2022) for local parcel demand due to its limited vehicle accessibility. Its high pedestrianization currently acts as a hindrance to delivery operations with larger vehicles. The city center area which will be explicitly served by the micro-hubs is henceforth referred to as Micro-hubs catchment area (MCA) and is depicted with orange color in Fig. 2. The MCA lies inside the ZEZ of the city (see the combined orange and green area in Fig. 2), which explains the need for a separate name. For this use case, it is assumed that the micro-hubs are operated by the CEPs currently operating in the investigated area, while the number of parcels each CEP will handle is calculated according to their local current Business-to-Customer (B2C) market shares.

The case study explores three different design aspects: location of the micro-hubs, type of vehicles (delivery robots, cargo bike, LEV), and the business model (individual/full collaboration). The scenarios are elaborated in five steps:

1. Identification of candidate micro-hub locations
2. Determination of the zero-emission vehicles' specifications
3. Description of the business models
4. Development of the scenarios to be simulated in the TFS
5. Selection of the key performance indicators

3.1. Identification of candidate micro-hub locations

The selection of possible micro-hub locations was inspired by the transferability framework of established micro-consolidation initiatives developed by Janjevic and Ndiaye (2014) and is followed in this use case to identify candidate micro-hub locations in the Rotterdam city center. The indicators to select new locations include: (1) demand, (2) area accessibility, (3) access restriction and (4) loading/unloading infrastructure.

The Urban Freight Lab (2020) and Kim and Bhatt (2019) underline that demand is of great importance to justify the need for change in the urban freight system, as well as to keep micro-hubs sustainable and efficient during their operation. To this end, the indicators associated with zonal demand are the number of business units, the number of household units and the generated number of parcels. As micro-hubs should be placed in locations where demand is the highest, for each of the three indicators the zones with the ten highest values were identified and saved as separate layers. For accessibility a condition was applied that micro-hubs should be located in areas nearby high-level hierarchy roads and roads with high urban speeds. In QGIS two different layers were created with selections of links to the road network that met either of the two criteria. For each layer, a buffer of 100 m was applied to trace suitable locations for the micro-hubs placement. The overlap of the two buffered layers revealed the most accessible areas for the micro-hubs placement. The access restrictions attribute corresponds to the ZEZ policy, therefore it was followed to set the boundaries of the study area. Due to the unavailability of loading/unloading infrastructure data, it was decided that large public parking garages in the city that could accommodate micro-hubs operations could be used instead. The parking places and garages were traced through Google maps, and were subsequently drawn in a separate layer in QGIS. Fig. 3 combining the indicators (left) and the selection of potential location in (right).

3.2. Determination of the zero-emission vehicles' specifications

The zero-emission vehicle types considered for this use case are autonomous robot, electric bicycle, and light electric vehicle (LEV), some examples of which are presented in Fig. 4. These vehicles differ greatly in range, speed, and capacity which allows us to investigate which is most beneficial for the operation of micro-hubs. For the TFS only one type of parcel is considered, meaning it has no specified weight or size. To compensate for this simplification, the capacity of each vehicle was deduced from other studies.

Manufacturers generally provide both the average and maximum values of the speed of the vehicles they produce. To approximate urban traffic conditions in the TFS, only the average values of range and speed were considered. For the vehicles where this information was

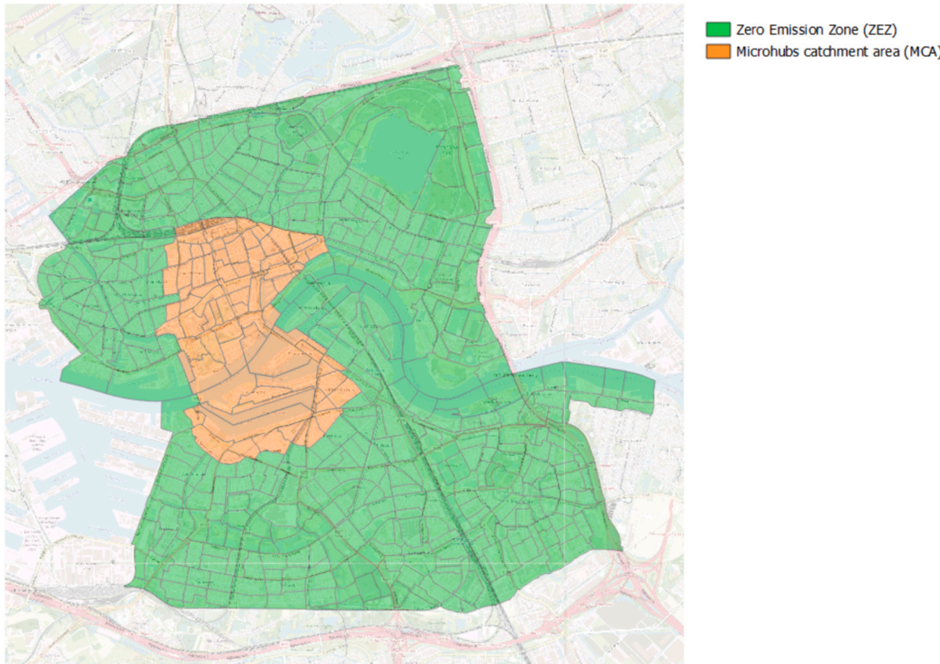

Fig. 2. Geographical boundaries of the study area.

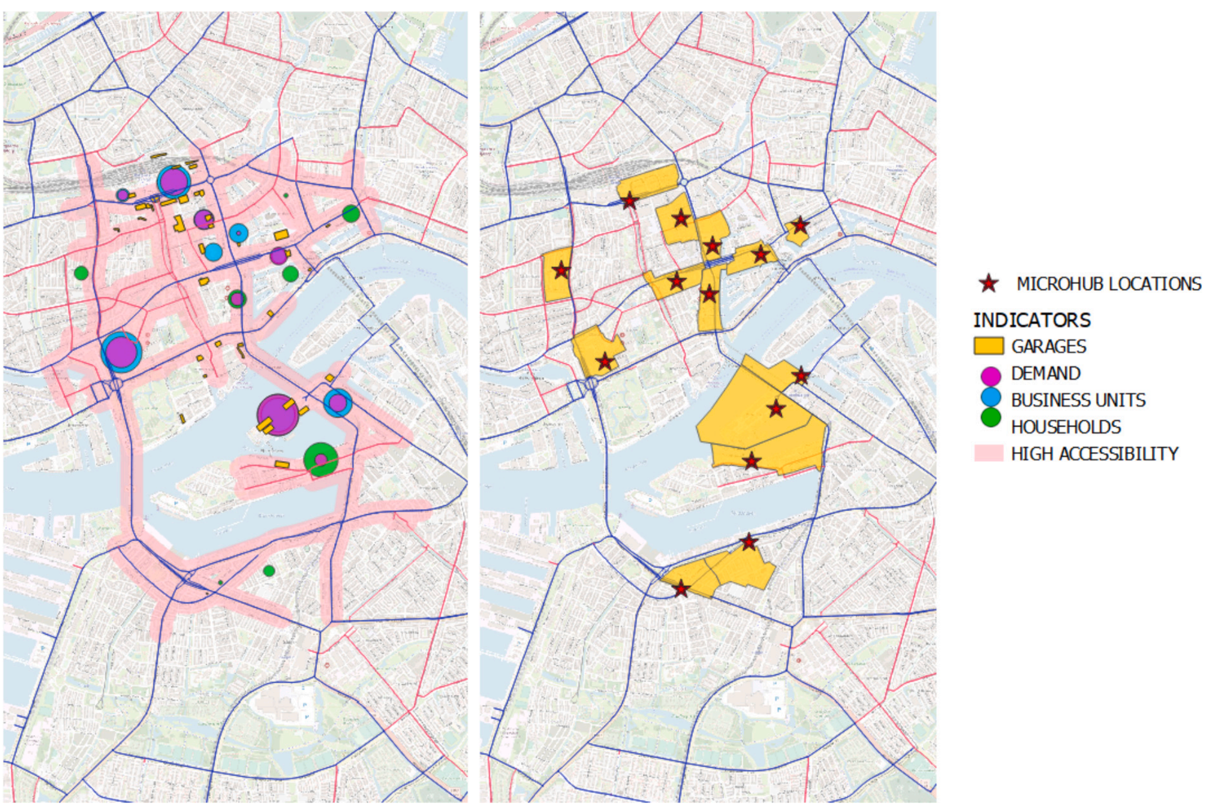

Fig. 3. Combined QGIS layers (left), candidate micro-hub locations (right).

unavailable, the corresponding maximum values were multiplied by a factor of 0.7. This factor indicates that 30 % of the time in transit the vehicles are stopped due to congestion, waiting at traffic lights, pedestrian crossings etc. Table 1 summarizes the resulting values of average speed and maximum capacity of each vehicle that was considered in the simulation.

The average speeds of each examined zero-emission mode were used to calculate their respective skim time matrices. A skim time matrix is a matrix that provides the time impedance between zones, and is used in the simulator to calculate the duration of tours. Even though these modes use the same network for their operations (bicycle and pedestrian lane), taking their average speeds into consideration for this purpose is important due to their relatively small capacities. The skim time matrices of the diesel vehicles (van and truck) are the same, as they are

Fig. 4. The green vehicles considered for last yard delivery in the scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Specifications of the selected green vehicles.

Modes	Av. speed (km/h)	Capacity (nr parcels)
Autonomous robot	4.5	5
Electric bicycle	17.5	13
Light electric van (LEV)	18	180
Truck	Av. road network speeds	1800
Van	Av. road network speeds	180

both constructed based on the average speeds on each link of the road network on which they operate. The average road network speeds were retrieved by the MRDH model operated by the Rotterdam Municipality.

3.3. Description of the business models

As previously mentioned in section 3.1.2, the objective of this use case is to compare various micro-hubs configurations with the current state of last-mile delivery. The top diagram in Fig. 5 illustrates how the current last-mile delivery is taking place in the MCA between different CEPs. It can be seen that the parcels are delivered directly from the depots of each CEP to their respective customers with vans. As the tours are not coordinated, this results in relatively many vehicle kilometers travelled by delivery vans inside the MCA.

The middle and below diagrams illustrate in a respective manner the Individual CEP and full-collaboration (and hybrid) business models. In both of these business models, the consolidated flows of goods towards the micro-hubs are served by trucks, while every other zone outside the MCA is explicitly served by vans. Trucks have a higher capacity than vans, which can lead to a lower number of vehicle kilometers as a lower number of delivery tours is required. The last-yard delivery in the MCA is performed by green vehicles for both business models. If the business model is individual CEP, then each CEP has its own assigned micro-hubs and is the responsible company for performing the last leg of the delivery. If the business model is full-collaboration then each CEP has the advantage of using any of the micro-hubs located in the area, and a neutral company is responsible for the last-yard delivery. If the business model is hybrid, some micro-hubs are operated independently by their assigned CEPs while the rest are shared among the rest of the CEPs.

3.4. Scenario development

A multitude of scenarios of distinctive micro-hub configurations was designed to investigate how micro-hubs can affect the transportation system, which is presented in Table 2. Three key aspects were considered, the business model adopted for their operation, the number of micro-hubs, and the type of green vehicles used for the last-yard delivery.

The fourteen (14) micro-hub locations that were identified represent the most complete set of micro-hub locations. Given the scarcity of available urban space and competing activities, from the perspective of the city planners the number of locations should be minimized. For this reason we have chosen to reduce the number of micro-hubs in the collaborative business models. The selection is based on logical assumptions. Thus, scenarios 1,2, and 3 examine the Individual CEP business model using the full set of micro-hubs. Scenarios 4,5 and 6 examine the hybrid business model combining single- and multi-carrier operations using a practical subset of eight 8 micro-hubs, while scenarios 7,8 and 9 use the same subset to examine the full-collaboration setup. It must be noted that the subset of 8 micro-hub locations selected for the second and third scenarios represent the zones with the highest parcel demand among the whole set of 14 micro-hub locations.

Every business model is examined in combination with every green vehicle to better understand the impact of each design component. It is assumed that autonomous robot operations are complemented by electric cargo bicycles as they are expected to not be able to operate independently in such a large area due to capacity, speed, and range limitations. This solution restricts the operation of autonomous robots into a 500 m radius around the micro-hubs and allocates the orders outside of this radius to be delivered by electric cargo bicycles. Overall, nine (9) configurations were developed and compared with the reference scenario which represents the current state of the last-mile delivery.

The current local shares of the CEPs and the parcel demand per zone were taken into account in deciding the number of micro-hubs to be allocated to each CEP. For the "Individual CEP" model, the CEPs with market shares of less than 5 % were assigned only one micro-hub each (GLS, UPS, DPD, FedEx), while the rest of the 14 micro-hubs were assigned to the rest CEPs according to their relative shares, that is 6 micro-hubs to PostNL and 4 micro-hubs to DHL.

For the "Hybrid" scenario, 2 of the 8 micro-hubs were decided to be shared among the CEPs with market shares of less than 5 %, while the remaining 6 micro-hubs were to be assigned to the rest of the CEPs in a similar manner to the first scenario, resulting in 4 micro-hubs assigned to PostNL and 2 micro-hubs assigned to DHL. For the "Full-collaboration" model every micro-hub of the selected 8 is shared among every CEP.

The candidate micro-hub locations were identified in Fig. 3. Micro-hub locations are allocated to CEPs in an arbitrary but systematic way, using their market shares, their depot locations, and the parcel demand per zone. More precisely, the assignment process started from the CEPs with the largest market shares which were then assigned the micro-hub locations with the largest parcel demand. The CEPs with market shares of less than 5 % were consequentially assigned the micro-hub locations with the lowest parcel demand, but the location of their depot was taken into consideration to place them in the most efficient location possible. The resulting micro-hub configurations for all three models are presented in Fig. 6.

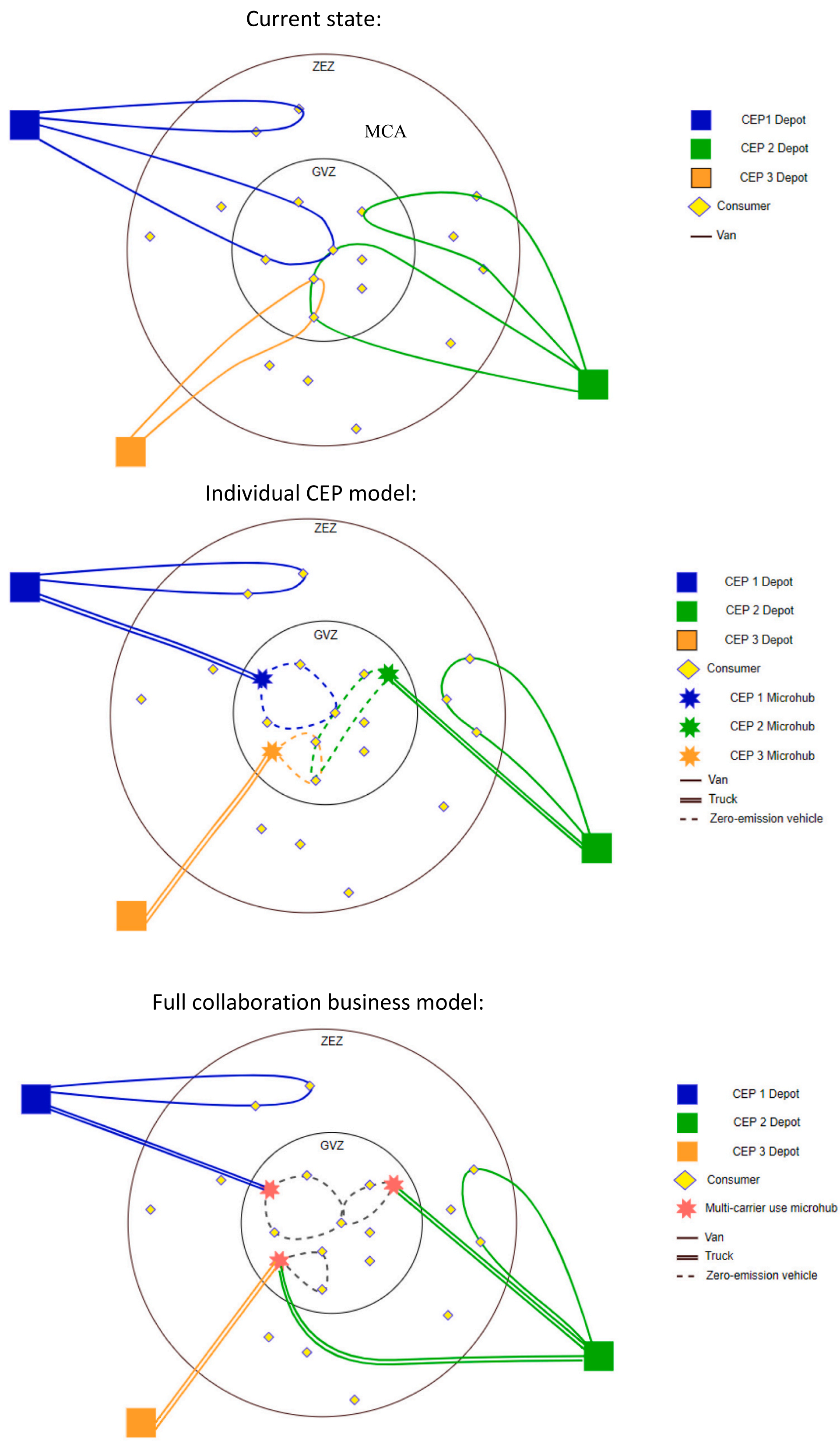

Fig. 5. Different business models for micro hub operations.

Table 2
Scenarios simulated in the TFS.

Scenario	Business model	Nr. micro-hubs	Mode	Mode Abb.
0	Reference		Van	
1	Individual CEP model	14	Autonomous robot + Electric bicycle	AR
2			Electric bicycle	EB
3			Light Electric vehicle	LEV
4	Hybrid model	6 + 2	Autonomous robot + Electric bicycle	AR
5			Electric bicycle	EB
6			Light Electric vehicle	LEV
7	Full collaboration model	8	Autonomous robot + Electric bicycle	AR
8			Electric bicycle	EB
9			Light Electric vehicle	LEV

3.5. Methodology: HARMONY tactical freight simulator

The scenarios are explored with the Tactical Freight Simulator, a multi-agent urban freight transport demand model developed in HARMONY to simulate the decision-making of freight agents on the level of individual firms and individual freight shipments (de Bok et al., 2021). It allows policymakers to quantify the effects of future scenarios on the freight transport system. For the simulation of the micro-hub scenarios, the following modules and main assumptions were used in the applications:

- *Skim Module:* to calculate the time and distance skim matrices
- *Parcel Demand Module:* to generate the demand of parcels per CEP in the study area
  - o Only one generalized type of parcel is assumed with no specified weight or size to reduce the model complexity
  - o For home-delivery a success rate of 75 % of first-deliveries is assumed based on general market statistics
- *Parcel Scheduling Module:* to construct the tour matrices of all parcel deliveries
- *Traffic Assignment Module*: to calculate vehicle trajectories on the road network for each delivery tour and calculate relevant KPIs such as vehicle kilometers and emissions

Fig. 7 shows the network usage for the delivery of parcels in the case study. In the reference case all deliveries are made with conventional delivery vans.

4. Results

The impacts from the 9 micro-hub scenarios are evaluated using a variety of indicators. The following key performance indicators (KPIs) were calculated to evaluate the scenarios: number of tours per vehicle, total number of kilometers travelled inside/outside of the ZEZ per vehicle, average tour distance per vehicle and total number of kilometers travelled by empty vehicles.

4.1. Number of tours

Table 3 gives an overview of the number of tours per vehicle type for the 9 scenarios. The types of vehicles used vary between scenarios. In the reference scenario in total 44 tours are made by delivery vans: see also Fig. 7. As can be seen 8 or 9 consolidated truck tours are used for the consolidated delivery of all the parcels from the different depots to the micro-hubs. It is also apparent that the number of last-yard deliveries from the micro-hubs will lead to many tours, obviously the result of the smaller capacity of the cargo bikes (EB) and autonomous robots (AR).

Every CEP has multiple depots spread around the region which can act as the supply chains' origins. Multiple depots from the same CEP can serve the same study area as they are assigned to micro-hubs based on their proximity. At the same time, every selected depot is responsible for its last-mile delivery, meaning that a truck does not visit other selected depots to collect parcels before arriving at the assigned micro-hubs. This indicates that, regardless of the number of parcels that need to be transported, a minimum of one tour is guaranteed per selected depot. It can be understood then that the higher the number of micro-hubs per CEP, the higher the possibility that a larger number of different depots is selected, which indirectly translates to a larger number of truck tours, for example in the individual CEP and full-collaboration models (see Table 3). In contrast, a lower number of micro-hubs per CEP, as in the hybrid model, can lead to a higher consolidation potential of parcels which can sequentially affect the final number of constructed tours.

A closer look at Table 3 also shows a significant high number of AR vehicles in the full-collaboration model. It should be reminded that these vehicles only operate in a 500 m radius around each micro-hub. In case of a full collaboration model, all parcels are delivered to the micro-hub closest to the final destination. In effect this leads to a much higher delivery density of parcels around the micro-hub. This enables a much higher usage of AR. At the same time, the AR usage for the individual

Fig. 6. Micro hub configuration in the individual CEP (left), hybrid model (middle) and full collaboration scenario (right).

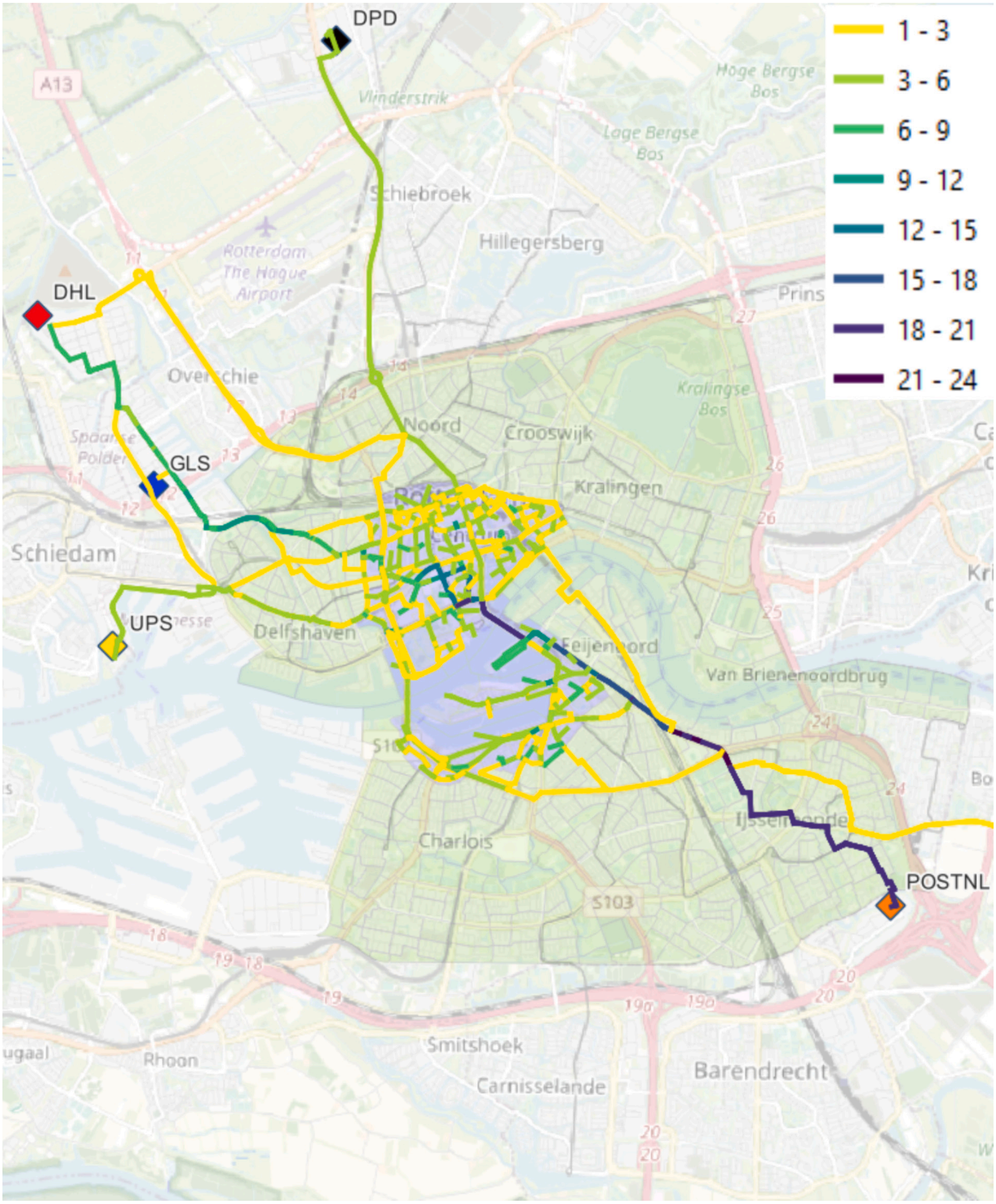

Fig. 7. Reference scenario –road network usage by delivery vans.

CEP model is higher than for the hybrid business model even though no facility sharing takes place: this is explained by the fact that the number of considered micro-hubs is almost double. A higher number of micro-hubs indicates that they occupy more urban space, and in this case, CEPs like PostNL or DHL are assigned the majority of micro-hubs (10 out of 14) as they are the largest market shareholders. This factor in combination with the above reasoning of micro-hubs attracting more local demand, explains the increased AR usage. Nevertheless, this mode's usage for the individual CEP model is almost half of that in the full-collaboration model due to the decreased degrees of freedom.

It is straightforward that the higher the AR usage is, the lower the electric bicycle (EB) usage becomes when they operate simultaneously. For this reason, when the main mode is AR, the full-collaboration model presents the least number of EB tours, but simultaneously the largest number of zero-emission vehicle movements. In contrast, the hybrid model presents the largest number of EB tours but at the same time the lowest total number of green vehicle movements.

As regards the number of tours per EB when the main mode is EB, all

Table 3
Number of tours per vehicle.

Scenario	Business model	Mode Abb.	TRUCK	VAN	AR	EB	LEV
0	Reference scenario	VAN	–	44	–	–	–
1	Individual CEP model	AR	9	–	176	494	–
2		EB	9	–	–	559	–
3		LEV	9	–	–	–	47
4	Hybrid model	AR	8	–	120	511	–
5		EB	8	–	–	556	–
6		LEV	8	–	–	–	44
7	Full-collaboration model	AR	9	–	324	430	–
8		EB	9	–	–	556	–
9		LEV	9	–	–	–	44

the models seem to perform similarly. Only the Individual CEP model constructs three additional routes (59 in total) for this mode which may be attributed to the fact that the bicycles carry only parcels from the CEP they are assigned to. Therefore, parcels assigned to the same destination but originating from different CEPs cannot be transported by the same bicycle, as could be witnessed partially in the hybrid model and to its full extent in the full-collaboration model. This indicates that the micro-consolidation potential for the last-yard delivery is lost, hence requiring the construction of additional routes. The fact that the biggest shareholders are assigned to the majority of the micro-hubs in the Individual CEP model, meaning they have a large proportion of the clients and sequentially carry the majority of the parcels, compensates for the loss of the micro-consolidation potential.

The scenarios based on last-yard delivery using LEV, shows a similar number of constructed tours compared to the reference scenario and across the scenarios. Since this number of tours is much lower compared to the electric bicycle scenarios, this may provide considerable operational advantages. However, compared to electric bikes or delivery robots, light electric vehicles need urban space for parking for deliveries. The 44 to 47 delivery tours from the scenarios will have larger impact on parking pressure at street level. These impacts could not be localized as address density were not available at street level.

4.2. Vehicle kilometers

Table 4 shows for every examined scenario the total number of kilometers travelled in and out of the ZEZ per vehicle type. It shows clearly that the total vehicle kilometers of movements with vans inside the ZEZ reduce considerably in the micro-hub scenarios. This is very important if we consider the fact that those movements are currently performed with diesel vehicles mainly. To be more specific, the total number of kilometers travelled in the ZEZ with vans for the reference scenario is 776, while the corresponding number of kilometers travelled with a truck in the worst performing model, which is the full-collaboration model, is around 140. If we compare the scenarios where the LEV is used as the last-yard mode, as it is equivalent to the van in terms of capacity, we can still see that the total travelled kilometers in the ZEZ are reduced. More specifically, the combined total number of kilometers of trucks and LEVs in scenario 3, which is the Individual CEP model with LEV as last yard vehicle, is $333 + 83 = 416$ km, which is still almost half of the reference scenario. This is a reduction of 53 %, which is very comparable to a real-world case study in London where parcel delivery consolidation centers led to a reduction in total distance travelled of 52 % (Clarke & Leonardi, 2017).

As previously observed, 9 truck tours are constructed for both the individual CEP model and the full-collaboration model, with only a small difference in vehicle kilometers. Nevertheless, it is clear that the road network usage for each of these models is very different when we compare their activity in and out of the ZEZ. The full-collaboration model makes more use of the road network inside of the ZEZ zone (see Fig. 8), which can be explained by the fact that the trucks have to travel to all 8 micro-hubs to deliver their assigned parcels. It is interesting to point out that for this model, the trucks visit the closest micro-hub to their origin depot first, thus decreasing the number of kilometers travelled outside of the ZEZ. In contrast, the individual CEP model makes more use of the network outside of the ZEZ zone (see Fig. 8) as the trucks must visit first only one of their closest *assigned* CEP micro-hubs, therefore they lack the flexibility of the full-collaboration model.

The hybrid model exhibits characteristics of the Individual CEP model but proves that the number of micro-hubs can be of trivial importance in the travelled kilometers inside or outside the ZEZ. From Table 4 it can be seen on one hand, that they hybrid model leads to almost the same number of truck kilometers outside of the ZEZ as the individual CEP model, even though the latter has 6 additional micro-hubs. On the other hand, even though they hybrid model has the same number of micro-hubs as the full-collaboration model, it can be seen that it leads to almost half of the number of kilometers travelled inside the ZEZ. In comparison to the Individual CEP model, it leads to just 13 lesser kilometers which again indicates that the number of micro-hubs is not an important factor.

In regards to the EB that complement the AR operations (in scenarios 1, 4 and 7), it is interesting to notice that for the full-collaboration model 430 tours are constructed, in comparison to the 494 of the Individual CEP model, which result in a total of 894 km which is almost half of the corresponding kilometers travelled in the Individual CEP model. This of course is affected by the increased usage of the AR (almost 90 additional AR kilometers), but it nevertheless proves that micro-consolidation even

Table 4
Total vehicle kilometers travelled inside and outside of the ZEZ per vehicle type.

Scenario		0	1	2	3	4	5	6	7	8	9
Business model		REF	Individual CEP model			Hybrid model			Full-collaboration model		
Mode		VAN	AR	EB	LEV	AR	EB	LEV	AR	EB	LEV
	Total	–	284.8	284.8	284.8	270.3	270.3	270.3	278.9	278.9	278.9
TRUCK	**Inside ZEZ**	–	82.9	82.9	82.9	69.7	69.7	69.7	139.4	139.4	139.4
	Outside ZEZ	–	201.9	201.9	201.9	200.6	200.6	200.6	139.5	139.5	139.5
	Total KM	958.4	–	–	–	–	–	–	–	–	–
VAN	**Inside ZEZ**	776	–	–	–	–	–	–	–	–	–
	Outside ZEZ	182.4	–	–	–	–	–	–	–	–	–
	Total KM	–	94.1	–	–	59.6	–	–	155.9	–	–
AR	**Inside ZEZ**	–	94.1	–	–	59.6	–	–	155.9	–	–
	Outside ZEZ	–	–	–	–	–	–	–	–	–	–
	Total KM	–	1623.2	1663.1	–	1664.5	1689.6	–	893.4	953.4	–
EB	**Inside ZEZ**	–	1623.2	1663.1	–	1664.5	1689.6	–	893.4	953.4	–
	Outside ZEZ	–	–	–	–	–	–	–	–	–	–
	Total KM	–	–	–	333	–	–	218.5	–	–	101.3
LEV	**Inside ZEZ**	–	–	–	333	–	–	218.5	–	–	101.3
	Outside ZEZ	–	–	–	–	–	–	–	–	–	–

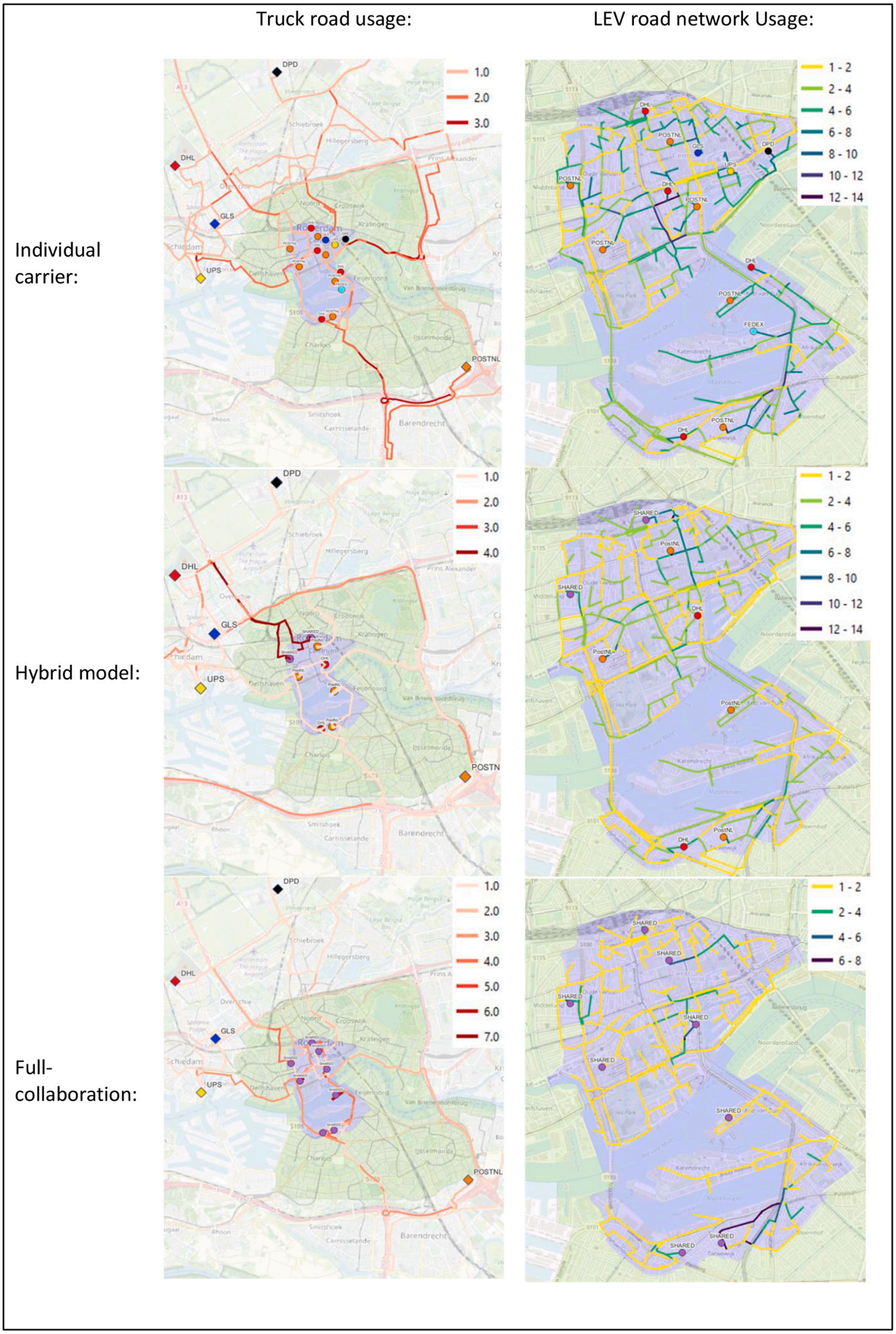

Fig. 8. Network usage in the scenarios.

in such a small scale can still lead to significant gains.

Combining Table 3 and Table 4 shows that the total kilometers travelled with the AR are relative to the number of tours performed for each by almost a factor of 2, a fact which can also be supported by Table 5 as the average tour distance with an AR fluctuates at around 0.5 km for every examined scenario. This can be explained as they only deliver parcels which fall into a 500 m radius around each micro-hub. The hybrid model seems to lead to the least total travelled kilometers for this mode, but also to the least kilometers when it travels completely empty (see Table 6).

The full-collaboration model seems to be the most beneficial in terms of least total travelled kilometers and least total travelled kilometers

Table 5
Average tour distance per vehicle.

Scenario	Business model	Mode Abb.	TRUCK	VAN	AR	EB	LEV
0	Reference scenario	VAN	–	21.78	–	–	–
1		AR	31.64	–	0.53	3.29	–
2	Individual CEP model	EB	31.64	–	–	2.98	–
3		LEV	31.64	–	–	–	7.09
4		AR	33.78	–	0.50	3.26	–
5	Hybrid model	EB	33.78	–	–	3.04	–
6		LEV	33.78	–	–	–	4.97
7		AR	30.98	–	0.48	2.08	–
8	Full-collaboration model	EB	30.98	–	–	1.71	–
9		LEV	30.98	–	–	–	2.30

Table 6
Total number of kilometers travelled with empty vehicles.

Scenario	Business model	Mode Abb.	TRUCK	VAN	AR	EB	LEV
0	Reference scenario	VAN	–	366.8	–	–	–
1	Individual CEP model	AR	134.9	–	24.2	730.3	–
2		EB	134.9	–	–	744.0	–
3		LEV	134.9	–	–	–	63.2
4	Hybrid model	AR	134.6	–	7.9	792.8	–
5		EB	134.6	–	–	799.1	–
6		LEV	134.6	–	–	–	60.7
7	Full-collaboration model	AR	99.8	–	19.8	416.6	–
8		EB	99.8	–	–	425.0	–
9		LEV	99.8	–	–	–	35.2

when vehicle is empty as observed for both the EB and LEV operations. Operating with the LEVs under this business model, proves to be the most optimal scenario as also the least number of vehicle tours is constructed, with most of them starting under full capacity. Looking at Fig. 8, it is obvious that the frequencies of use of the roads by the LEVs are much smaller in the full collaboration model compared to the individual CEP and hybrid models. Table 4 proves this as the number of kilometers travelled by the LEVs for the Individual CEP is almost double the kilometers travelled for the hybrid model, and almost triple the kilometers travelled for the full-collaboration model. This explains why the average tour distance for the LEVs presents a similar pattern under each examined model (see Table 5).

5. Conclusions and recommendations

The presented case study explores the impacts of nine scenarios for a large-scale micro-hub implementation in the city of Rotterdam with the objective to determine the effectiveness in reducing vehicle kilometers with conventional delivery vans. Three different design aspects of micro-hub implementation were considered: location, type of vehicles (delivery robots, cargo bike, LEV), and the business model (individual/full collaboration).

The largest reduction of vehicle kilometers can be achieved in the scenarios with full-collaboration between the CEPs. Therefore, shared white label operation of micro-hubs proves to be most beneficial in order to reach higher logistic efficiency from the network perspective. This is an important insight for urban planners that are responsible for the allocation of urban space to competing usage types: urban space is scarce, and shared use of micro-hubs not only reduces the claim on scarce urban space (reduced number of micro-hubs) it also increases the efficiency of the usage of logistic vehicles in terms of vehicle kilometers. Another impact, not measured here, could be a higher efficiency of the space occupied for loading and unloading of vehicles: consolidated deliveries lead to fewer delivery vehicles. Urban planners can use regulation and concessions to steer the operation of micro-hubs into a shared logistics concept.

New automated technologies such as delivery robots are considered to be a good solution to make urban deliveries more efficient, but the operational range and capacity of the vehicles are important restrictions to the large-scale deployment for urban deliveries. The limited operational range was dealt with by using electric cargo bikes as complementary vehicles for last-yard delivery. However, the autonomous robot scenarios predict more than 1500 daily delivery tours. This implies a considerable fleet of autonomous robots needed for operation: the exact number depends on battery capacity and number of tours that can be operated per delivery robot.

Light electric vehicles have a higher capacity and on average fewer tours from the micro-hubs; this is considered an operational advantage. The hybrid and full-collaboration models show better vehicle utilization than the individual carrier model. The full collaboration model with light electric vehicles leads to the fewest vehicle kilometers in and outside the study area. Collaborative models can also benefit the introduction of autonomous delivery robots with generally a small operating range: simulations show that full collaboration leads to higher delivery densities around the delivery hubs and thus bigger potential for efficient operation.

To evaluate the impacts of a large-scale implementation of micro-hubs the method of simulation was used to make an a-priori impact assessment on number of tours and vehicle kilometers. Other impacts, such as the use of urban space for logistic facilities and loading/unloading of vehicles, are not included in this study but the simulation results could be used as input to quantify these impacts. The simulation results are highly dependent on the scenario assumptions. In this case a limited number of scenarios were evaluated, varying with three different solutions for the last-yard delivery. In future studies, also other innovative solutions for last-mile or last-yard deliveries can be evaluated such as crowdshipping services (Buldeo Rai et al., 2017) or other forms of hyperconnected logistic services.

CRediT authorship contribution statement

Michiel de Bok: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Sofia Giasoumi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Lori Tavasszy:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Sebastiaan**

Thoen: Writing – review & editing, Software, Methodology. **Ali Nadi:** Writing – original draft, Methodology. **Jos Streng:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. Any interpretation or opinion expressed in this paper are those of the authors and do not necessarily reflect the view of the European Commission (H2020 funding), Delft University of Technology, Significance or the City of Rotterdam.

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