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The smaller, the better? Nano-hubs for cycle logistics as an urban-friendly alternative to micro-hubs

Je kleiner, desto besser? Nano-Depots als stadtverträgliche Alternative zu Mikro-Depots in der Radlogistik

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Especially for last-mile delivery in dense urban areas, cargo-bikes have become a sustainable alternative to overcome motorized delivery vehicles' traffic and environmental disadvantages. However, as their capacity and range are lower compared to conventional delivery vehicles, there is a need for additional cargo-bike transshipment hubs near the respective delivery areas. While some parcel service providers show that they are successfully testing different concepts such as micro-hubs, several barriers prevent the implementation beyond pilot status. Hence, our work aimed to overcome these barriers by introducing nano-hubs as an urban-friendly alternative to micro-hubs. In particular, we proposed a modular design concept that enables the customization of transshipment hubs considering urban planning restrictions and logistical processes. Further, we aimed to prove that the nano-hub approach also has economic advantages compared to previous cycle logistics processes. For this, we first developed nano-hub-modules on a conceptual level following the methodological approach for product development according to VDI 2221. We then implemented a simulation model to compare different (cycle) logistics processes with regard to their sustainability and operational effort. The findings of our work are twofold. First, based on the proposed modular system design, we offer suggestions for further development and elaboration of infrastructure elements for cycle logistics. Second, by applying our approach as a case study to the city of Magdeburg, Germany, we could show that existing cycle logistics processes have ecological and economic advantages over motorized delivery traffic. In addition, we proved that these benefits could be further increased by implementing the nano-hub concept.

[Keywords: Cycle logistics, Micro-hubs, Nano-Hubs, Cargo-bikes, Urban logistics, Last mile]

Vor allem in urbanen Gebieten stellt der Einsatz von Lastenrädern für die Sendungszustellung auf der letzten Meile einen vielversprechenden Ansatz dar, um die verkehrlichen und ökologischen Nachteile konventioneller Lieferfahrzeuge zu adressieren. Da Lastenräder jedoch geringere Ladevolumina und Reichweiten aufweisen, entsteht ein Bedarf an zusätzlichen Umschlagsknoten in unmittelbarer Nähe der jeweiligen Zustellgebiete. Entsprechende Konzepte wie Mikro-Depots werden bereits von einzelnen Paket-Dienstleistern erprobt, können sich jedoch aufgrund diverser Herausforderungen nicht über den Pilotstatus hinaus etablieren. Im Rahmen der Arbeit werden daher Nano-Depots als stadtverträgliche Alternative zu Mikro-Depots vorgestellt. Speziell wird ein Infrastrukturkonzept für Lastenräder entwickelt, welches sich durch eine modulare Bauweise an verschiedene städtebauliche Einschränkungen und logistische Abläufe anpassen lässt. Darüber hinaus wird gezeigt, dass der Nano-Depot-Ansatz auch wirtschaftliche Vorteile gegenüber bestehenden Radlogistik-Prozessen aufweist. Auf Basis des methodischen Vorgehens zur Produktentwicklung nach VDI 2221 werden dafür zunächst einzelne Nano-Depot-Module auf konzeptioneller Ebene erarbeitet. Anschließend findet die Implementierung eines Simulationsmodells zum Vergleich der Nachhaltigkeit und Wirtschaftlichkeit verschiedener (Rad-)Logistikprozesse statt. Auf Grundlage des entwickelten Modulbaukastens bietet die Arbeit Anregungen für die weitere Entwicklung und Ausarbeitung von Radlogistikanlagen. Durch die Anwendung des entwickelten Simulationstools im Rahmen einer Fallstudie lässt sich darüber hinaus zeigen, dass herkömmliche Radlogistikprozesse sowohl ökologische als auch ökonomische Vorteile gegenüber dem motorisierten Lieferverkehr aufweisen, wobei sich letztere durch die Umsetzung des neuartigen Nano-Depot-Konzepts weiter ausweiten lassen.

[Schlüsselwörter: Radlogistik, Mikro-Depots, Nano-Depots, Lastenräder, Urbane Logistik, Letzte Meile]

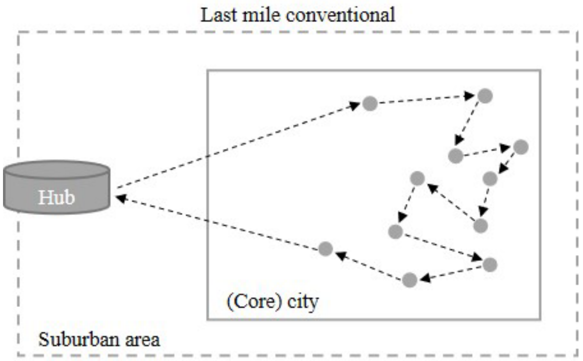
1 INTRODUCTION

The expanding freight traffic in the courier, express and parcel services (CEP) sector is increasingly posing major challenges to urban agglomerations [1]. The main driver for this development is the dynamic growth of e-commerce [2], as it causes a change in consumer behavior towards an on-demand economy [3], [4], and continuous growth in the volume of shipments in the CEP market [5]. In addition, a demographic change is altering the urban population structure. As a result, both the urban population [6] and the number of single-person households [7] are increasing. The interactions between these developments are leading to a change in the goods distribution process for the last mile. Thus, deliveries no longer occur only punctually in sub-areas designated for this purpose by urban planning but extend over the entire city area [7]–[9]. This creates a number of conflicts, particularly for areas near the city center with a high population and building density and a varied mixture of residential and commercial utilization.

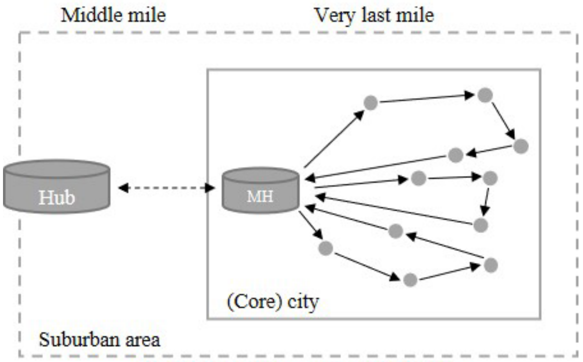
One of the challenges involves the reduction of traffic space, which compromises both traffic flow and safety [10], as well as the efficiency of delivery processes [11]. In addition, the emission of air pollutants (greenhouse gases, nitrogen oxide, fine dust) and noise causes negative environmental impacts and reduced quality of stay [12], [13]. While the use of low-emission vehicles (battery, fuel cell) already addresses environmental issues, infrastructural conflicts remain due to the constant vehicle size [10], [14]. Hence, in order to decongest urban infrastructure and meet the wide-ranging requirements of delivery processes in terms of efficiency and sustainability, CEP service providers are forced to test new delivery concepts and vehicles [15]. According to Wittowsky et al. [2], along with the implementation of additional delivery and loading areas and the establishment of an extensive network of pick-up points, the utilization of cargo-bikes for parcel delivery is an up-and-coming option.

Cargo-bikes offer numerous advantages for last mile delivery as they drive with zero local emissions, defuse traffic conflicts and feature low acquisition and operating costs [16]. However, major disadvantages are that cargo-bikes only provide 15 % to 20 % of the capacity of a conventional delivery vehicle and maximum tour lengths of 20 km [17]. In a monomodal system (one vehicle type as sole means of transport, Figure 1a), the use of cargo bikes is therefore impractical from either a logistical or an economic perspective. One solution to overcome these limitations is to establish a multimodal logistics system by dividing the last mile into a middle mile and a very last mile, as well as setting up additional cargo-bike transshipment hubs such as micro-hubs near the target delivery area [16]. Within those multimodal systems, conventional delivery vehicles realize the inflow from a hub (warehouse, transshipment terminal, etc.) to the micro-hub for fine distribution of goods to the recipient with cargo-bikes.

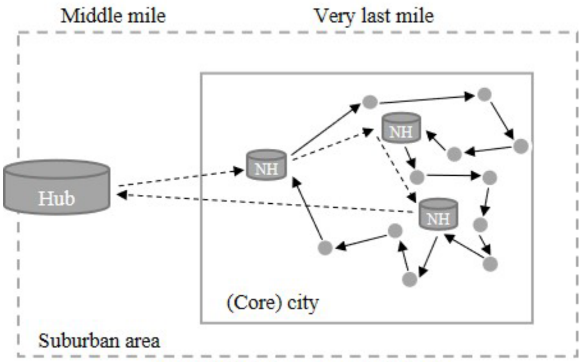
The transshipment of parcels can be generally realized by using two different procedures. Within the currently prevailing operating concept, the transshipment of parcels is done manually, i.e. pre-picked parcels are fine-sorted at a micro-hub according to the delivery tour and loaded manually into the vehicle. Due to the load volume of cargo-bikes and the location of the micro-hub, it is usual that parcel deliverers return to the micro-hub several times a day to restock shipments (Figure 1b).



a) Monomodal logistics system



b) Cycle logistics – micro-hub (MH)



c) Cycle logistics – nano-hub (NH)

Figure 1. Monomodal vs multimodal logistics systems

In addition to manual transshipment, cargo-bike swap bodies are discussed, and several cargo-bike manufacturers

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provide first technical solutions. Within this operating concept, parcels are already loaded into swap bodies in a hub according to the delivery sequence. The swap bodies are then transported to the respective delivery areas and loaded onto a cargo-bike as a closed unit. Concerning transshipment points, cargo-bike swap bodies are advantageous as they can be temporally stored within the delivery area with moderate space requirements. This allows the placement of several very small transshipment hubs, namely nano-hubs, in the delivery area and thus eliminates the need to return to a central micro-hub multiple times (Figure 1c). Further, regardless of the type of transshipment hub, cargo-bike swap bodies can significantly reduce the effort for manual sorting and loading at the transshipment hub [18].

Many pilot projects indicate that urban cycle logistics concepts can be successfully implemented (e.g., [19]). However, the lack of specific knowledge about the diversity of functions and special features of cycle logistics and related transshipment hubs, extensive urban planning regulations, and the limitation in generalized planning knowledge prevents the establishment and scaling of cycle logistics systems beyond pilot status [18]. Therefore, this paper contributes to overcoming this knowledge gap by introducing a toolbox for planning and implementing infrastructure elements within cycle logistics systems. In particular, we propose nano-hubs as a modular infrastructure design concept for implementing cargo-bike transshipment hubs with regard to extensive urban planning restrictions and different cycle logistics process types. Further, we validate the ecological and economic viability of the nano-hub approach in comparison to existing (bicycle) logistics processes using a simulation-based case study for the city of Magdeburg, Germany. Our results show that using cargo-bike for parcel delivery can significantly improve last-mile logistics in terms of sustainability and economic efficiency. In addition, we show that implementing nano-hubs can reduce the operational costs of cycle logistics processes compared to the conventional micro-hub approach and thus provide a valuable contribution to the large-scale implementation of cycle logistics.

The remainder of this paper is organized as follows. In section 2, we describe the development of nano-hubs as modular cargo-bike transshipment hub. In addition, we give application examples for the implementation of nano-hub modules on repurposed parking areas. Subsequently, in section 3 we describe the experimental design for comparing different logistics processes as well as the implementation and application as a case study. In section 0, we present our modelling results. In section 5, we finally discuss our findings, summarize our work, and highlight future research initiatives.

2 NANO-HUBS AS MODULAR CARGO-BIKE TRANSSHIPMENT HUBS

2.1 SYSTEMATIC DESIGN PROCESS

The methodological approach for developing the nano-hub system design comprises a three-step process. First, we conducted an extensive analysis of the CEP market with regard to existing best practices on alternative delivery concepts and urban planning strategies to reduce motorized (delivery) traffic (Table 1). Considering the first and second main phases of product development according to VDI 2221 Blatt 1 [20], we developed principle solutions for the modular infrastructure concept in the second stage (conceptual design). For this purpose, we first determined requirements for nano-hubs from the previously identified best practices as part of a lessons learned analysis.

Table 1. Best Practices

No.	Project title	Summary
1	City2Share	4 semi-stationary singular micro-hubs (swap bodies) in the city center of Munich [19], [21], [22]
2	KoMoDo	Stationary cooperative micro-hubs in the city center of Berlin [3], [10]
3	Nachhaltige Stadtlogistik Nürnberg	Implementation of stationary micro-hubs in vacant properties in the city center of Nuremberg [23]–[25]
4	SMILE	4 semi-stationary singular micro-hubs (swap bodies) in the city center of Hamburg [26], [27]
7	Mini-Hollands	Reduction of motorized traffic to promote pedestrian and bicycle traffic and increase the quality of stay in residential areas in London [28]–[30]
8	Plan Velo	Repurposing existing motor vehicle infrastructure in favor of walking and cycling in Paris [10], [31], [32]
9	Superblocks	Reduction of motorized traffic to promote pedestrian and bicycle traffic and increase the quality of stay in residential areas in Barcelona [33]–[35]

During the requirements engineering process, in addition to the high diversity of requirements related to different cycle logistics process types, it was shown that the large-scale implementation of freight containers for road transport (swap bodies) as semi-stationary micro-hub is not suitable. This is mainly due to the lack of visual integration into the overall streetscape (Table 1 – 1,4). Further, for urban districts offering a high potential for cycle logistics, a lack of space for implementing micro-hubs and associated delivery and loading areas for conventional trucks became evident. Approaches toward the cooperative deployment of transshipment hubs address this problem but result in additional requirements for implementation and locally higher demand for space (Table 1 – 2). Another option is to create stationary transshipment hubs in vacant buildings. However, suitable properties are often unavailable in sufficient numbers or are associated with high rental costs (Table 1 – 3). The best practices further revealed that residents are affected by the lack of space in addition to logistics. Within this context, they have also shown that despite all the negative consequences, limited public space has been prioritized for motorized traffic for many years. To address this issue, larger cities are increasingly adopting different strategies to reduce motorized traffic whilst promoting pedestrian and bicycle traffic. In this regard, the rededication of streets or parking spaces into areas for sustainable local mobility or leisure activities has proven particularly effective (Table 1 – 7,8,9). For developing the nano-hub modules, we adopted the dimension of standard parking spaces according to RASt 06 [36] to allow urban-friendly integration into existing infrastructure by rededicating parking spaces or using small (left-over) public spaces.

Due to the limited information available on the specific expectations of different CEP stakeholders, we further evaluated the identified requirements with the help of experts from the CEP sector and representatives from the administration. Therefore, we evaluated the results of several expert workshops conducted as part of a study to determine the infrastructure needs for cargo bikes in Hamburg [37].

We then defined the main functions and associated sub-functions within a functional structure based on the resulting requirements. As a next step, we developed the product structure, which describes the hierarchical composition of the overall system from the individual components or modules, including their physical relationships. Within the product architecture, we afterwards specified which modules fulfill the particular sub-functions. To enable simple configuration of different product variants and function-oriented solution finding for the individual modules, this involved assigning each (sub)function to exactly one module (see [38]). Based on the product architecture, we applied Zwicky's methodology for systematic combination [39] to generate principle solutions for the individual modules and their assembly in the overall system. Finally, we selected promising solution variants for further development using a weighted point evaluation [40].

The resulting solution concepts were elaborated in the third stage (design phase). Following the third main phase of product development according to VDI 2221 Blatt 1 [20], we developed the component structure on a conceptual level and determined the shape, dimensioning and material of relevant parts and modules. The design stages and results of the presented product development process are described in [41] (master thesis) in detail.

2.2 APPLICATION

The modular infrastructure concept is designed for broad application and hence adaptable to different types of urban districts. The demand for individual modules can be determined based on population, business, and shipment data. A potential configuration of a nano-hub for cargo-bike swap bodies is illustrated as a 3D CAD model in Figure 2. The proposed concept enables the secured storage of four swap bodies. Three parking spaces (in-line) are required to implement of the nano-hub and an associated loading zone. The applicability to different neighborhoods and cycle logistics processes is illustrated by means of a module catalog in Table 5 (Appendix). The size or amount, color and exterior design of the modules can be adapted to the urban environment in the neighborhood or its corporate design. Further, to increase residents' acceptance towards the rededication of parking areas as well as to increase the efficiency of (cycle) logistical processes, different additional modules which also offer added value for residents are listed in Table 6 (Appendix).

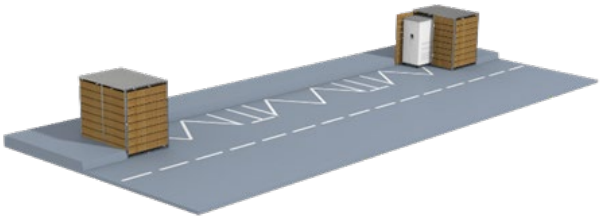

Figure 2. Nano-hub for cargo-bike swap bodies

3 EXPERIMENTAL DESIGN AND IMPLEMENTATION

3.1 GENERAL FRAMEWORK

In addition to urban planning advantages, the nano-hub concept can increase the efficiency of last mile parcel delivery compared to existing (cycle) logistics concepts. To evaluate this, we used a simulation-based case study to examine and compare different logistics concepts in terms of sustainability and profitability. In particular, we compared the delivery of parcels with conventional diesel-powered vans and cargo bikes (micro-hub and nano-hub). The model only covers the mere delivery of parcels. Returns and pick-ups as well as time windows are not included.

We defined the district of Stadtfeld-Ost (Magdeburg, Germany) as our study area. This is a densely populated mixed-use district with a high residential share and a narrow street network with many one-way streets. Especially at peak times, the district suffers from traffic congestion further aggravated by motorized delivery traffic. Hence, there is a need for the implementation of traffic-friendly and sustainable logistics concepts within this district.

3.2 EXPERIMENTAL DESIGN

The data for the evaluation of daily delivery tours was derived from shipment data of a local CEP service provider in Magdeburg. They contain the addresses and amounts of all delivered parcels in Stadtfeld-Ost in 2021. From this set of customer locations, we first retrieved GPS-coordinates from OpenStreetMap using the R-package *tidygeocoder* [42]. We then created randomized delivery tours containing 500 parcels each. This number is based on findings from Assmann et al. [43], which state that a district like Stadtfeld-Ost has a demand of ~ 4500 parcels per day. Hence, the sample size of 500 accounts for a market share of approximately 11 %, which is a realistic assumption for a local CEP provider.

For the case study, we defined a total of three scenarios. The first scenario represents the parcel delivery with diesel-powered vans (light-duty vehicles, LDV). The starting and ending point for a delivery tour is an urban hub on the outskirts of the city. A single van is assumed to transport 70 parcels per tour on average. In the second scenario, parcels are delivered by cargo-bikes with a micro-hub in the city center serving as starting and ending point of each delivery tour. Cargo-bikes are assumed to have a capacity of 40 parcels. The feeder traffic is handled by diesel-powered trucks (heavy-duty vehicles, HDV). In the third scenario, parcels are also delivered by cargo-bikes. However, the starting and ending points are a total of ten nano-hubs, which are distributed throughout the entire delivery area. We selected the micro-hub and urban-hub locations based on the facilities of a local CEP service provider. To determine the number and locations of nano-hubs, we adopted the methodology for location planning of mobile parcel stations according to Rolf et al. [44].

After defining the hub locations, we implemented a routing algorithm that determines the optimal route between the hub(s) and each delivery point. The algorithm aims to deliver packages at the lowest possible cost using distance as the cost metric. Since the number of parcels exceeds the capacity of a single van or cargo-bike, the computation of several tours was necessary. Operations research considers this a capacitated vehicle routing problem (CVRP). To solve the CVRP, we used a local search algorithm that, based on an initial solution, iteratively searches for better solutions. The initial solution was determined by using a simple greedy nearest neighbor algorithm which selects the next stop based on the lowest costs until the vehicle's maximum capacity is reached. The basis for this is a cost matrix that includes the distance between individual delivery points. To reduce the computational effort for the distance calculating, we considered Haversine distance instead of existing road networks and multiplied it with a factor of 1.3. This has proven to be a sound approximation of actual distances travelled within urban areas.

3.3 IMPLEMENTATION

We used Python for the implementation of our algorithm. In particular, for the optimization of the CVRP, we used the solver of the Google OR-Tools library. This is a specialized solver for vehicle routing problems based on constraint programming and large neighborhood search with routing-specific neighborhoods [45]. To visualize the results, we implemented an interactive web interface using the Folium library [46]. Figure 3 shows an example for the visualization for the simulation of a delivery tour using the nano-hub concept. The coloring of nodes and edges marks the tours, where several tours can be covered by one vehicle. Each tour starts and ends at a nano-hub. The distance a vehicle has to cover between different hubs for starting a new tour is not shown, although it is considered in the calculation of the total distance.

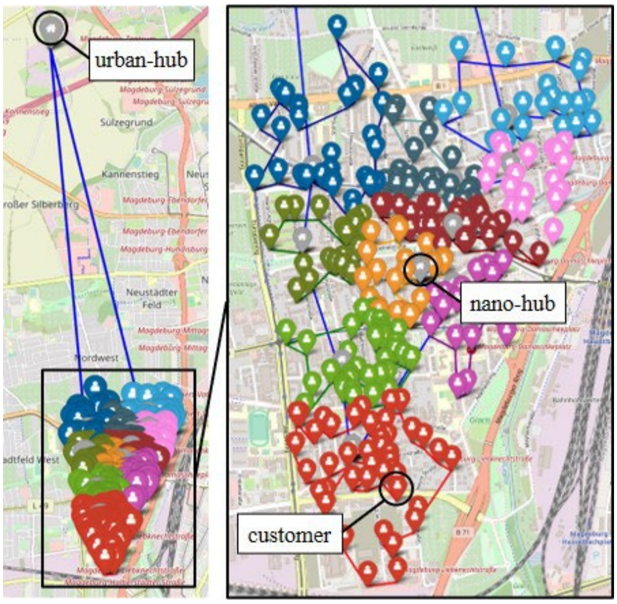

Figure 3. Visualization of a delivery tour with the nano-hub concept

3.4 PROFITABILITY ANALYSIS

To obtain representative results, we ran the algorithm for ten randomized delivery tours (random states) for each of the three scenarios. As an output, the model provided the distances each vehicle had to cover while delivering the parcels. The average distances are shown in Table 2. In addition, the simulation model estimated an average number of 282 stops per delivery tour. Based on these values, we calculated operational and environmental costs in order to compare the individual scenarios in terms of their viability and sustainability.

Table 2. Average vehicle distance for each scenario

Scenario	**Distance [km]**		
	Total	**LDV/ HDV**	**Cargo-bike**
(1) LDV	130.6	130.6	0
(2) Micro-hub	76.9	18	58.9
(3) Nano-hub	56	19	37

The operating costs comprise wage and vehicle cost (leasing and energy). The wage costs result from the duration of a delivery tour and the required personnel. For the LDV and cargo-bike personnel, we assumed a maximum working time of eight hours plus a 30-minute break (full-time) or 4 hours (part-time) per employee. For HDV, we calculated the personnel costs only for the started working hours, assuming that they also supply other parts of the city. We applied personnel costs of 25 Euro per hour. This value results from the German minimum wage, employer share, downtime, and indirect costs. The tour duration was determined from the deployed vehicles' average speed and stopping time. The average speed of cargo bikes and average stop durations of cargo bikes and LDV are based on the findings of Assmann et al. [43]. The average speeds for LDV and HDV are calculated from the average speed on major roads in 10 large German cities at rush hour [47]. The stopping time of HDV is equal to that of cargo bikes for delivery with nano-hubs and 30 minutes for delivery with micro-hubs. This is based on the experience of the local CEP service provider. Further, for LDV and cargo-bikes, we extrapolated the respective monthly leasing costs to a whole day, assuming six working days per week. As with personnel costs, for HDV we have only considered started working hours for the calculation. The leasing costs are also based on the experience of the local CEP service provider. Finally, the energy costs result from the covered distance, energy consumption per kilometer, and energy source costs. The latter are based on current costs for diesel and electricity (as of August 2022) in Germany.

In order to estimate environmental costs, we used cost rates for the emission of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM10). They are provided by the German Environment Agency [48]. For CO_2, we used a cost rate of 684 Euro per emitted ton. For NO_x and PM10, we used a cost rate of 15,800 and 30,000 Euro per emitted ton, respectively. In this context, we assumed that cargo bikes do not emit nitrogen oxides or particulate matter, but emit CO_2 to a small extent due to the electric driving assistance. The latter is based on the current German electricity mix, which includes electricity from fossil sources. The emission rates for LDV and HDV were taken from the Handbook Emission Factors for Road Transport (HBEFA 4). In particular, we used emission factors of a Euro 6 7.5-12-ton truck and a N-III Euro 6d light-duty vehicle as they are likely to represent the current fleet mix. The assumed input values for the individual calculations are quantified in Table 3.

Table 3. Parameters for cost calculation

Variable	**Unit**	**Vehicle**		
		Cargo-bike	**LDV**	**HDV**
Average speed	km/h	15	22	22
Stop duration	min	3.6	7.2	Nano-hub: 3.6 Micro-hub: 30
Leasing costs	€/month	300	500	2000
Diesel consumption	l/100 km	-	10	20
Diesel costs	€/l	-	1.927	1.927
Electricity consumption	kWh/100 km	2.5	-	-
Electricity costs	€/kWh	0.371	-	-
CO_2 emission	g/km	14	258.1	601.5
NO_x emission	g/km	0	0.06	0.6
PM10 emission	g/km	0	0.04	0.26

4 MODELLING RESULTS

The average costs for each scenario are presented in Table 4. In general, our model demonstrates the economic and ecological advantages of cargo bikes for last-mile parcel delivery. In particular, for our application, the conventional cargo-bike approach (cargo-bike and micro-hub) enables operational cost savings of around 38.6 %. This is mainly due to the lower leasing and energy costs as well as decreased tour length and duration. Further, in terms of sustainability, there is a reduction in environmental costs of almost 65 %. On the one hand, this is due to a significant reduction in emissions of CO_2. Further, compared to LDV, cargo-bikes hardly emit air pollutants such as nitrogen oxide or particulate matter. Especially traffic-related particulate matter emissions have an increasing impact on the health of residents in densely populated urban areas, as they are emitted close to the ground and are thus more strongly inhaled [48]. The commercial use of cargo-bikes therefore not only contributes to climate protection but also has a positive effect on residents' health and quality of stay.

Table 4. Average costs for each scenario

Scenario	**Costs [€]**		
	Environmental	**Operational**	**Total**
(1) LDV	23.35	1219.31	1242.66
(2) Micro-hub	8.28	748.68	756.96
(3) Nano-hub	8.50	658.86	667.36

While comparing both cargo-bike scenarios, the modelling results indicate that the micro-hub concept has slightly lower environmental costs. This is due to the nano-hub concept involving more trips with an HDV to supply the individual nano-hub locations. However, the results further indicate that the utilization of nano-hubs results in lower operating costs, as tour length and duration are further decreased. This is of particular interest for both small and medium-sized as well as larger CEP service providers as handling and scaling of prevailing processes in a cost and time efficient way is impossible for last mile delivery [3]. Thus, although nano-hubs have a slightly lower positive impact on the environment than micro-hubs, due to significantly lower operational costs they can contribute to the establishment of cycle logistics processes in urban areas.

5 DISCUSSION AND FUTURE RESEARCH

Within this paper, we introduced nano-hubs for cycle logistics as an urban-friendly and profitable alternative to micro-hubs. In particular, we contribute to existing research as we conducted a systematic design process for developing a modular nano-hub system design that enables the customization of small cargo-bike transshipment hubs regarding urban planning restrictions and logistical processes. As a result, we illustrated the applicability of nano-hubs and additional modules to different neighborhoods and cycle logistics processes by means of a module catalog. Further, to prove the economic and ecological viability of nano-hubs, we applied a simulation-based case study to compare the nano-hub concept with existing (cycle) logistics processes.

As our results show, using cargo bikes can improve the cost-efficiency and sustainability of last-mile parcel delivery. In addition, cargo bikes also contribute to improving residents' health and quality of stay. However, despite the many positive effects, a lessons-learned analysis and discussions with experts from the CEP sector also revealed that the large-scale implementation of existing bicycle logistics concepts is currently failing due to a lack of available space and the optical integration of micro-hubs. These problems can be overcome with the help of the modular nano-hub approach, as the individual hubs require significantly less space and can thus be integrated more easily into the public (street). In addition, we demonstrated that the process costs can be significantly reduced compared to the micro-hub concept. This is particularly relevant for CEP service providers as last mile delivery is considered not cost-effective. Overall, nano-hubs therefore contribute to further establishing cycle logistics processes in urban areas and thus reduce delivery-related drawbacks to the environment, traffic, and quality of stay.

While providing a novel concept for cargo-bike transshipment hubs, our study also raises the need for additional research. One limitation of our work is that our findings on the exact scale of cost savings relate to a specific delivery area, which was investigated as part of a case study. The results can be generalized to a certain extent and give insights into the economic and ecological potential of different cycle logistics processes. However, to further improve our methodology and precisely quantify the cost savings on a generalized scale, it is necessary to investigate other delivery areas and logistics processes in future work. The latter include, for example, electric LDV, mobile packing stations or autonomous cargo-bikes.

While developing the infrastructure elements, as they are conceptual designs, we did not consider the production and assembly of the individual modules and associated production costs in detail. In addition, we neglected building and traffic regulations. Concerning the technical implementation, it is therefore necessary to transfer the designs into a market-ready product in future work.

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APPENDIX

Table 5. Module catalogue for nano-hubs

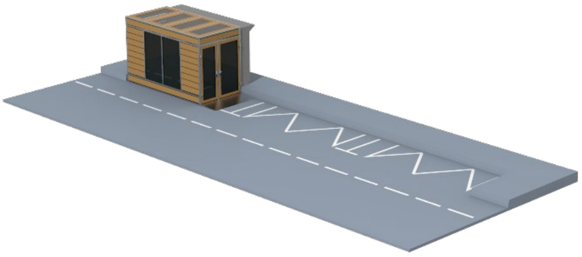
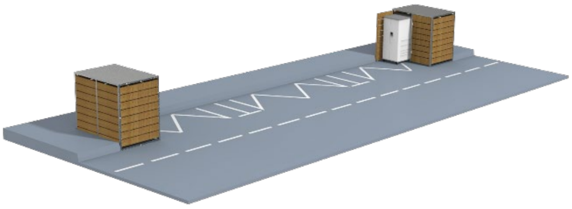
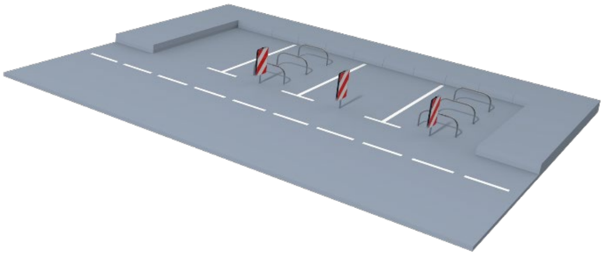
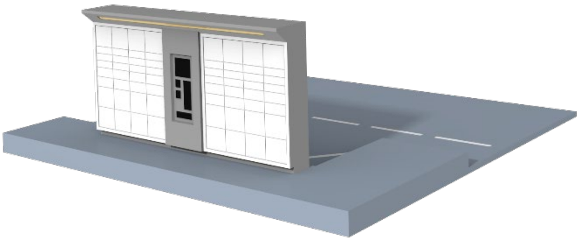
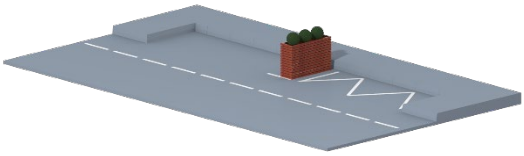
[1]	**Multi-use nano-hub**		
	Application:	Logistics	
	Location:	Quarter periphery, near main roads	
	Space requirement:	2-3 parking spaces (in-line)	
	Capacity	1 cargo-bike and 3 cargo-bike swap bodies or 6 swap bodies	
	Description:	Combination with loading area required, suitable for both manual process and cargo-bike swap bodies as well as (night-time) parking of commercial cargo-bikes possible	
[2]	**Swap-body nano-hub**		
	Application:	Logistics	
	Location:	Quarter periphery, near main roads	
	Space requirement:	Depending on the number of hubs, 1-3 parking spaces (in-line)	
	Capacity	2 cargo-bike swap bodies each	
	Description:	Combination with loading area required, suitable for cargo-bike swap bodies, very low visual impact	

Table 6. Module catalog for additional modules

[1]	**Cargo-bike parking facility**		
	Application:	Private use	
	Location:	Residential areas, decentralized	
	Space requirement:	1 parking space (parallel) for up to 3 cargo-bikes, additional parking space for maneuvering (depending on accessibility)	
	Description:	Theft-proof parking of private cargo bikes (various models and sizes), low locking bars prevent misuse through parking of conventional bicycles	

[2]	**Pick-up point**		
	Application:	Logistics, Private use	
	Location:	Quarter periphery, near main roads, POIs, Public transport nodes	
	Space requirement:	Depending on the size of the parcel box	
	Description:	White-label, combination with other modules possible, peripheral location reduces delivery traffic in the quarter	
[3]	**Battery swapping station**		
	Application:	Logistics, Private use	
	Location:	Near nano-hubs, bike parking facilities or pick-up points as well as main roads	
	Space requirement:	Approx. 1 m² plus parking space for (cargo-)bike	
	Description:	Battery swapping for commercial and/or private (cargo-)bikes, only few easily accessible locations are sufficient	
[4]	**Cargo-bike loading area**		
	Application:	Logistics	
	Location:	Near POIs, on shopping streets	
	Space requirement:	1 parking space (in-line)	
	Description:	Relevant to avoid obstruction of visibility of shop windows and obstruction of pedestrian and bicycle traffic	