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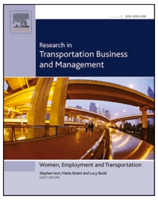

Economic and logistical performance of refrigerated electric and hydrogen light commercial vehicles. A total cost of ownership and hybrid simulation perspective

Romeo Danielis [a,b], Arsalan Muhammad Khan Niazi [a], Mariangela Scorrano [a,b,*], Manuela Masutti [a,c]

[a] Department of Economics, Business, Mathematics and Statistics, University of Trieste, 34127 Trieste, Italy
[b] Interdepartmental Center "Giacomo Ciamician" for Energy, Environment, Transport, University of Trieste, 34127 Trieste, Italy
[c] Area Science Park, 34149 Trieste, Italy

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ABSTRACT

The paper investigates whether refrigerated diesel light commercial vehicles (D-LCVs) could be substituted by refrigerated electric LCVs (E-LCVs) or hydrogen LCVs (H2-LCVs), considering both their economic and logistics performances. The economic performance is evaluated via the total cost of ownership (TCO) methodology, while the logistics one is estimated via a multi-agent simulation model. If LCVs are operated in urban contexts, we find that both alternative powertrains exhibit operational parity versus D-LCVs, irrespective of the weather conditions. In terms of TCO, however, only E-LCVs are almost competitive with D-LCVs, while H2-LCVs are by far costlier. If LCVs are used to distribute refrigerated goods in regional contexts (with longer travel distances), E-LCVs show lower logistical efficiency than D-LCVs under normal conditions, further exacerbated in extreme weather, although they have better TCO metrics. On the contrary, H2-LCVs achieved similar logistical efficiency than D-LCVs but continue to show very poor economics.

1. Introduction

Freight traffic in urban and regional areas has substantially increased due to the growth of e-commerce and home delivery services (Huang et al., 2024). Projections indicate that by 2030, the number of light commercial vehicles (LCVs) engaged in delivery operations could increase by 61 % (Gibbs & Wylie, 2024). In Europe, recent statistics by the ACEA - European Automobile Manufacturers' Association (2025) estimate that nearly 30 million LCVs are in operation, with diesel-powered vehicles accounting for 90.5 % of the total.

Diesel propulsion currently dominates the LCV segment, making it a major contributor to greenhouse gas emissions and urban air quality degradation. This exposes the sector to heightened regulatory scrutiny and decarbonization pressure. Lebeau et al. (2019) highlighted that the environmental burden per ton-kilometer of freight moved by LCVs is markedly higher than that of heavier commercial vehicles. Awan and Scorrano (2025) pointed out that in urban/regional use the social cost of environmental externalities from LCV operation is equal to 0.1686 €/km for diesel, while it is equal to 0.0803 €/km for electric, and 0.0784 €/km for hydrogen LCVs. For these reasons, battery-electric LCVs and hydrogen fuel-cell LCVs are increasingly seen as alternatives for sustainable urban freight distribution, due to their superior energy efficiency, zero tailpipe emissions, and lower noise pollution (Castillo et al., 2020). Yet their market share is still limited. ACEA (2025) reports an 8 % market share among new registrations in Europe, with large variations such as 83 % in the Netherlands and 1 % in Croatia. UNRAE (2025) reports a 4.4 % market share in Italy in the period January–November 2025 although doubling their share relative to the previous year.

The focus of this paper is on refrigerated LCVs. Within the broader topic of goods distribution, refrigerated LCVs are used to deliver chilled and frozen food. Since they require energy both for traction and maintaining the desired internal vehicle temperature of the refrigeration unit, the use of alternative powertrains appears at first sight even more challenging. Europe represents a mature refrigerated goods marketplace, with demand for fresh produce comprising 36.1 % of the market in 2024 (Maiorino et al., 2021). Serving more than 500 million consumers, the region accounts for over €60 billion in trade value—approximately 44 % of the global fresh-produce market—and hosts

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* Corresponding author at: Department of Economics, Business, Mathematics and Statistics, University of Trieste, 34127 Trieste, Italy.
E-mail address: mscorrano@units.it (M. Scorrano).

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five of the world's ten largest importers, solidifying its position as a global hub for refrigerated logistics and cold-chain operations (MarketsandMarkets, 2025). In addition, the temperature-controlled logistics segment is forecasted to expand at a compound annual growth rate of 5.8–7.2 % (Meneghetti et al., 2021). Notably, refrigerated LCVs alone account for 36 % of cold-chain freight logistics, with market value projected to reach $160 billion by 2027 (Yao et al., 2023).

Currently, the distribution of chilled or frozen food is carried out by refrigerated LVCs, equipped with refrigerated units based on a vapour compression system driven by an auxiliary diesel engine. Maiorino et al. (2021) stressed that refrigerated transportation consumes approximately 15 % of all fossil fuel energy and contributes nearly 2.5 % of total carbon emissions. The potential energy and environmental saving that could be realized with the use of alternative powertrains such as electric and hydrogen powertrains is well documented. For instance, Chen et al. (2024) estimated that large-scale adoption of battery-powered refrigeration could avoid up to 10 million tons of CO_2 and 3.7 billion liters of diesel annually. Technological improvements can help reduce the energy footprint of refrigerated transport. Meneghetti et al. (2021) considered installing solar photovoltaic panels directly into refrigerated vehicles. They found that refrigeration units and improved insulation materials can reduce energy demand by more than 28 % and decrease CO_2-equivalent emissions by approximately 66 % per vehicle per year compared to the existing diesel fleet. Segura et al. (2023) estimated that hydrogen-powered refrigeration could achieve more than 10 % fuel savings and annual CO_2 reductions exceeding 3650 kg per vehicle. Maiorino et al. (2024) estimated that the integration of kinetic energy recovery systems may further reduce refrigerated LCV energy consumption by 5.4 %, resulting in cost savings of 0.004–0.006 €/km.

In this paper, we argue that refrigerated LCVs operating with alternative powertrains can gain market penetration only when two main conditions are met: when they are economically and operationally comparable to the existing counterparts. The aim of this paper is to assess under what economic and operational conditions refrigerated electric LCVs (E-LCVs) and hydrogen fuel cell LCVs (H2-LCVs) could serve as viable substitutes for refrigerated diesel LCVs (D-LCVs) in last-mile delivery logistics.

The economic competitiveness of E-LCVs, H2-LCVs and D-LCVs has been commonly evaluated via the total cost of ownership (TCO) methodology (Danielis et al., 2024; Danielis et al., 2025). In this paper, we apply such methodology to refrigerated LCVs, whereas most of the previous literature analysis general use LCVs (Muhammad et al., 2025), apart from Awan and Scorrano (2025). Moreover, differently from most of the previous studies, we take the point of view of a delivery company managing a fleet of LCVs, whereas most literature considered the TCO of single owners. This implies that the company arrange to charge\refuel their LCVs overnight at the depot and not only at public chargers \refueling stations during the service, enjoying potential economies of scale and lower electricity\fuel prices than the ones that should be paid at public chargers\refueling stations. In addition, the delivery company could also decide to produce in-house electricity or hydrogen making the necessary investments. In such a case the TCO should incorporate the investments cost for the production and charging\refueling infrastructure.

The logistics performance of E-LCVs, H2-LCVs and D-LCVs is assessed via a hybrid multi-agent simulation model combining System Dynamics, Discrete Event Simulation paradigms and Agent-Based Modelling (ABM), and implemented with the software AnyLogic within a GIS environment. Simulation modelling provides a structured framework for analyzing complex logistics systems by replicating real operational dynamics. System Dynamics captures time-dependent interactions and feedback loops among aggregate system variables (Cimino et al., 2025; Guo et al., 2025). Discrete Event Simulation (DES) is a process-centric, event-sequenced approach that can model detailed operational workflows (as flowcharts), making it effective for micro-level processes such as order handling, vehicle dispatch, and calculating metrics like fleet utilization, dwell time, and service times (Borshchev & Grigoryev, 2020; Lyu et al., 2023). However, DES is limited in representing adaptive agent interactions. ABM simulate the interactions among individual agents (vehicles, customers, and a fleet operator) and their impact on overall system performance (Schiffer et al., 2021). Combining the three approaches into a hybrid model is particularly fruitful for evaluating alternative powertrains within a complex delivery network as many papers demonstrated (De Bok & Tavasszy, 2018; Utomo et al., 2020; Mehdizadeh et al., 2022; Samchuk et al., 2022; Lorig et al., 2022; Helo & Rouzafzoon, 2023; Vilaça et al., 2024; Cannavacciuolo et al., 2025).

Our simulation model is used to compute a range of operational metrics, including total fuel/energy consumption, number of customers served, refueling/recharging time per order, and total distance travelled. It is calibrated using real operational inputs, using data from Bofrost Italia, a temperature-controlled food distributor located in San Vito al Tagliamento, Italy. We assess the logistics performance for urban and regional refrigerated food deliveries, under normal, extreme cold and extreme hot weather conditions using two key logistics indicators: the number of customers that can be served by LCVs with a specific powertrain during an 8-h work shift and the time eventually needed for refueling\recharging. The logistics indicators are finally compared with the TCO metric cost per km driven to assess the prospects for their short term and long-term uptake.

While the analysis is centered on a specific transportation niche, its relevance extends more broadly. The quantification framework developed here—integrating both economic and logistical performance—can be readily adapted and applied to other segments of commercial transportation.

The paper is organized as follows. Section 2 summaries the literature and the specific contribution that this paper attempts to make. Section 3 details the TCO estimation methodology. Section 4 describes the architecture of the hybrid simulation model. Section 5 covers the model implementation and application. Section 6 concludes, draws some policy implications and addresses the limitations of the model.

2. Literature review

We focus the literature review on the economic competitiveness of alternative fuel LCVs and on the operational challenges they pose to the companies that adopt them.

2.1. *The economic competitiveness of alternative fuel LCVs*

Table 1 provides a comprehensive overview of recent literature assessing the TCO of LCVs across different countries, vehicle segments, and alternative powertrains relative to the conventional ones, i.e. diesel in Europe, petrol in the US or compressed natural gas in the case of Spain (Castillo & Álvarez, 2023).

Overall, the studies show a growing competitiveness of E-LCVs, particularly in small and urban-oriented segments, while heavier and box-type LCVs generally remain less competitive. Financial incentives emerge as a key determinant of E-LCV competitiveness in most regions, although some recent studies indicate that E-LCVs can already be cost-competitive without subsidies in specific markets (Awan & Scorrano, 2025; Barroso et al., 2023; Gil Ribeiro & Silveira, 2024; Guo et al., 2025; Lal et al., 2023; Scorrano et al., 2021; Siragusa et al., 2020).

Hydrogen-based LCVs (H2-LCVs and FCEVs) tend to be less competitive in the short term, with their viability often dependent on future uptake, infrastructure availability, and policy support. Castillo and Álvarez (2023) investigated H2-LCVs in detail in the case of Spain. They found that range extender hybrid fuel cell LCVs (FC-EREVs) are best option when using purchased hydrogen, while they are inferior to E-LVCs when hydrogen is produced onsite via electrolysis drawing the electricity from the grid.

The findings highlight significant regional and segment-specific differences, underscoring the importance of localized analyses when

Table 1
Summary of the literature on the TCO of LCVs.

Study	Reference country	Alternative powertrains	LCV Segments	Main conclusion
Lebeau et al. (2019)	Brussels, Belgium	E-LCV	small, heavy	• Small E-LCVs almost competitive • Heavier LCVs less competitive • Financial incentives essential
Jones et al. (2020)	London	H2-LCV, E-LCV		• E-LCVs and HFC competitive only with incentives • Green Hydrogen does not dampen competitiveness
Rottoli et al. (2021)	Europe	H2-LCV, E-LCV, e-fuel LCV		• E-LCVs have an advantage over H2-LCVs or e-fuel LCVs
Scorrano et al. (2021)	Italy	E-LCV	city, panel and box	• City and panel E-LCVs are cost competitive • Box E-LCVs (Maxus EC80) are not
Watabe and Leaver (2021)	Japan	H2-LCV	new and used	• H2-LCVs competitive with uptake, after 2030 • Incentives strengthen competitiveness but not essential
Siragusa et al. (2020)	Milan, Italy	E-LCV		• E-LCV could be competitive
Mulholland (2022)	USA	E-LCV	different battery size	• E-LCVs with a range of up to 200 miles is achieved in the next five years
Sendek-Matysiak et al. (2022)	Poland	E-LCV		• E-LCVs not competitive yet • Financial incentives needed
Barroso et al. (2023)	Brasil	E-LCV	theoretical models	• E-LCVs could be competitive
Bhutani et al. (2025)	India	E-LCV, CNG		• E-LCVs are already the most competitive option
Lal et al. (2023)	Germany and California	H2-LCV, E-LCV	panel	• E-LCVs are already cost-competitive in both the studied regions, H2-LCVs are not • Financial incentives needed
Castillo and Álvarez (2023)	Spain	H2-LCV, E-LCV, FC-EREVs, CNG		• FC-EREVs best option when using purchased hydrogen • BEVs best option when onsite hydrogen production via electrolysis using the grid
Gil Ribeiro and Silveira (2024)	12 European countries	E-LCV	small, medium and large	• E-LCV competitive in 9 out of 12 countries • Financial incentives are necessary in most countries
Guo et al. (2025)	7 American States	E-LCV	small, medium and large	• Small and large E-LCVs competitive, even without financial incentives
Awan and Scorrano (2025)	Italy	H2-LCV, E-LCV	refrigerated	• City and panel E-LCV competitive without financial incentives • Box LCV segment barely competitive • FCEVs require refueling infrastructure and financial incentives
Our paper	Italy	H2-LCV, E-LCV	refrigerated	

FC-EREVs: range extender hybrid fuel cell LCVs.

evaluating alternative powertrains for LCVs.

We envisage two potential limitations of the existing literature. First, the LCV economic competitiveness is studied in general terms, abstracting from the various cases, for instance, whether the LCV is used for last-mile distribution in an urban context or for regional distribution. The two use cases imply very different annual distance travelled (ADT), with large implications for competitiveness as resulting from the studies' simulations. The second relevant one is that it remained often unspecified whether LCVs are part of a larger fleet operated by a company or by a single LCV owner. Such a distinction has implications on charging facilities and the charging costs. In the case of a company, it is likely that when a company opts for alternative fuel LCVs, it would invest own charging infrastructures (EVSE) at the depot, involving high capital costs but potentially lower variable costs for the electricity or hydrogen and the possibility of overnight charging. In the case of a single LCV owner, charging cost would be linked to home charging costs or charging at public chargers. In the latter case, there is a trade-off between charging time and charging costs, fast charging being usually more expensive than slow charging.

Our study aims to address these gaps by:

- Considering a specific use case: the distribution of cold and frozen food via refrigerated LCVs both in urban and regional contexts.
- The company-level focus required accounting for the costs associated with the infrastructure needed to charge E-LCVs and refuel H2-LCVs. In the latter case, we considered both the costs associated with in-house production of green hydrogen and the purchase of (grey) hydrogen from external suppliers.
- Consequently, E-LCVs and H2-LCVs could be charged\refueled overnight at the depot or during the service on public chargers depending on the delivery routes.

2.2. Operational challenges

Notwithstanding their potential for reducing emissions, improving urban air quality, and lowering operating costs, the literature has indicated that alternative powertrain LCVs, both E-LCVs and H2-LCVs, raise a unique set of challenges that must be carefully managed (Anosike et al., 2023).

One of the most significant challenges of E-LCVs is their limited driving range. While modern alternative E-LCVs may offer ranges of

150–300 km under ideal conditions, the actual range achieved in real-world operations is often lower. Factors contributing to this variability include: a) the payload since carrying heavy cargo increases energy consumption and reduces the effective range; b) climate effects since cold or extremely hot weather significantly affect battery efficiency; and c) auxiliary systems, e.g., refrigeration units draw energy from the same battery, further limiting distance. Because of this, fleet managers must carefully plan routes to ensure vehicles can complete their deliveries without running out of charge. This constraint can reduce operational flexibility, particularly for ad hoc jobs or multi-stop delivery schedules. Operators may need to include contingency trips or even maintain a larger fleet to ensure coverage (Anosike et al., 2023). At this regards, Skarlis et al. (2023) examined whether early available hydrogen fuel cell vehicles have the potential to overcome the range anxiety limitation, provided that there exists an extended H_2-refueling network.

A second big challenge is associated with charging\refueling infrastructure constraints. In fact, while public charging networks are expanding, chargers\dispensers can be unavailable due to high demand, maintenance issues, or technical faults. Even with DC fast charging, recharging a large battery can take 30–90 min, far longer than the 5–10 min it takes to refuel a diesel van. Unlike diesel or petrol vehicles, E-LCVs require chargers which might be challenging to accommodate since many depots were not originally designed to handle high-power electrical loads. Moreover, installing multiple fast chargers may require costly upgrades to the grid connection or transformer capacity. In order not to reduce fleet utilization, effective scheduling and smart charging strategies become essential for minimizing downtime. Encouragingly, Iwan et al. (2021) found that in their specific case of handling courier deliveries with a Nissan eNV200, there was no need to recharge the battery. In a recent survey among fleet managers, Axsen and Pickrell-Barr (2024) found that the lack of charging or fueling infrastructure is still among the most serious concerns, together with high capital cost of vehicles, the limited market availability of alternative powertrain LCVs, and vehicle range concerns.

Next, one needs to consider potential payload and vehicle configuration trade-offs (Christensen et al., 2024; Morganti & Browne, 2018). A large battery pack can weigh hundreds of kilograms, reducing the legal payload the vehicle can carry. In addition, while many traditional diesel LCVs have a wide range of body configurations, the options for E-LCVs \H2-LCVs are still more limited, which can restrict their suitability for certain trades. Operational performance in refrigerated delivery fleets has been widely modelled through routing optimization frameworks, particularly the vehicle routing problem (VRP), which minimizes distance or cost under fixed conditions (Qin et al., 2021). However, as noted by Bac and Erdem (2021), VRP-based models often lack the capacity to capture stochastic demand, infrastructure constraints, or dynamic vehicle behavior, limiting their real-world applicability. In contrast, agent-based modelling (ABM) enables the simulation of heterogeneous fleets (Ballano et al., 2023), varying charging/refueling behaviors, and route-specific operational uncertainty.

Transitioning to E-LCVs thus requires new operational disciplines such as route optimization for range, energy management to coincide with off-peak electricity pricing, new software requirements for battery state-of-charge monitoring, charging alerts, and predictive range calculations. Fleet managers need advanced digital tools, real-time data monitoring, and staff training to maintain efficiency. This adds complexity compared to operating diesel or petrol fleets. For instance, Utomo et al. (2020) evaluated energy use of battery-electric trucks via an agent-based model study aimed at establishing whether a fleet of electric vans with different charging options can match the performance of a diesel fleet. They concluded that technological interventions alone are not sufficient to match the performance of a diesel fleet. Hence, reorganization of the urban delivery system is required in order to reduce carbon emissions significantly.

Finally, there are challenges in scaling up from small pilot fleets of E-LCVs\H2-LCVs to larger fleets since more vehicles require more chargers and higher electrical capacity, shared depots or public charging points may cause delays, larger fleets require more sophisticated scheduling to avoid downtime and optimize utilization.

Mimicking real world operations, we attempt to add to the literature by examining the performance of refrigerated E-LCVs, H2-LCVs and D-LCVs in terms of total customers served in a working shift and total time needed for charging\refueling under different scenarios.

3. The total cost of ownership methodology

The Total Cost of Ownership (TCO) is an economic methodology that accounts for all costs associated with owning, operating, and disposing of an LCV. Three main cost components can be identified: the capital expenditures (*CAPEX*), the operational expenditures (*OPEX*) and the salvage value (*SV*) (Danielis et al., 2025). The capital expenditure includes the manufacturer's suggested retail price (*MSRP*), covering both the base glider cost and the cold-box, along with any manufacturer discounts (*MD*) at the time of acquisition, the registration costs (*RC*), the potential subsidies (*SUB*) - and infrastructure expenses for charging equipment installation (*INF*).

$$CAPEX = MSRP - MD + RC - SUB + INF$$

The operational expenditures (*OPEX*) encompass a broad spectrum of cost factors associated with the expenses incurred during the vehicle's operational lifespan (*T*). Most of them depend on the annual distance travelled (*ADT*). For any given year $t \in [1, T]$, $OPEX_t(ADT)$ is formulated as:

$$OPEX_t(ADT) = CT_t + INS_t + MAIN_t(ADT) + FE_t(ADT) + FE_{coldbox}(ADT)$$

where CT_t represents the circulation tax, INS_t the insurance premium, $MAIN_t$ (ADT) the repair and maintenance costs, FE_t (ADT) the fuel \electricity expenditures, and $FE_{coldbox}(ADT)$ corresponds to the fuel expenses in fuel\electricity consumption required to maintain the refrigeration unit of the LCV. FE_t (ADT) can be further specified as follows:

$$FE\,(ADT) = EFF_{FE} \cdot P_{FE}$$

where (EFF_{FE}) is the fuel\electricity efficiency (expressed in liters, kWh, or kg), P_{FE} is the average price of fuel\electricity (expressed in €\liter, €\kWh, or €\kg).

Since total operational expenditures and salvage value (SV) occur at different points in time, we applied the appropriate discount rate to determine their present values. Accordingly, the TCO expressed in present value terms is given by:

$$TCO = CAPEX + PV_{OPEX} - PV_{SV}$$

where

$$PV_{OPEX} = \sum\nolimits_T \frac{OPEX_t}{(1+i)^t}$$

and

$$PV_{SV} = \frac{SV}{(1+i)^T}$$

Finally, the metric TCO/km is calculated as:

$$\frac{TCO}{km} = \frac{TCO}{\sum_t \frac{ADT_t}{(1+i)^t}}$$

3.1. Application for the Bofrost Italia case study

Bofrost Italia is the Italian branch of Bofrost A.G., a German frozen food home-delivery company. Bofrost A.G. operates in twelve European countries with around 240 branches, serving approximately six million customers. The Italian subsidiary is headquartered in San Vito al Tagliamento, located in the northeastern Italian Friuli-Venezia Giulia (FVG) region. For our application, we made reference to LCV segment with a gross vehicle weight of up to 3.5 tons. In agreement with Bofrost Italia, we selected Maxus Delivery 9 as a reference model (Fig. 1). The technical specifications of the Maxus Delivery 9, as E-LCV, and its counterparts as H2-LCV and D-LCV are presented in Table 2.

Table 3 summarizes the assumptions made in estimating the TCO of the three LCVs. The MSRPs of the E-LCV and D-LCV are sourced from the manufacturer's websites, while that of the H2-LCV is based on the literature. The appropriate value added tax in Italy is 22 %. Although the Italian government offers occasional purchase subsidies and manufacturers' or retailers' grant discounts, in our analysis, we opted not to include them in the base case scenario. In Italy, the vehicle registration and circulation taxes are administered at regional level; we calculated those in force in the FVG region. Note that the alternative fuel LCVs are exempt from the annual circulation tax. The insurance premium is assumed to be equal to 600 EUR per year and is not differentiated by powertrain, consistently with the Italian current empirical evidence (Danielis et al., 2025). Fuel prices are set equal to the average price observed in Italy in 2025; we distinguished between prices at the public station and at the depot, the latter assumed to be lower. The salvage value and repair and maintenance costs per kilometer are sourced from the literature (Awan & Scorrano, 2025). Note also that toll charges are not considered, since LCVs are expected to operate exclusively in urban areas.

Estimating infrastructure costs presents a special challenge, especially for H2-LCVs, due to high technological uncertainty and limited real-world deployments. Most of the TCO estimates presented so far in the literature do not fully account for this issue (Awan & Scorrano, 2025; Basma et al., 2022), an exception being Lal et al. (2023). Yet, the issue of recharging the LCVs using alternative fuels is crucial for their adoption at fleet level.

We researched this topic in depth and devoted an extensive Supplementary Material to detailing the equipment needed at depot level, the associated costs and what would be the cost per LCV depending on the fleet size. It is widely recognized that the transition to E-LCVs or H2-LVCs requires re-thinking the existing organization of depots (Awan & Scorrano, 2025). Similarly to electric buses, E-LCVs are more conveniently and efficiently charged at the depot overnight or during the idle periods. However, this requires companies to install charging infrastructure, including physical charging stations (with power conversion and connectors), high-capacity electrical supply (grid connection, transformers, switchgear), software and network systems (for managing operations, billing, and diagnostics), and ancillary equipment (like energy storage and land-use components). Each cost component should be priced appropriately and the best configuration selected, depending on the fleet size (Wang et al., 2025). The detailed calculations are reported in Section 1 of the Supplementary Material.

In the case of H2-LCVs, we considered two possibilities: in-house hydrogen production or external sourcing. In the former case, we considered the possibility to build an on-site photovoltaic (PV) plant to feed the PEM electrolyser, located near the depot, to produce green hydrogen; and to acquire a hydrogen storing tank, a compression system, pre-cooling unit and a dispenser. The cost modelling, based on Masutti (2025), is detailed in Section 2 of the Supplementary Material. Alternatively, hydrogen can be sourced by external suppliers, not necessarily generated by renewable sources only.

Table 2
Vehicle technical specification.

Technical Specification	E-LCV	H2-LCV	D-LCV
Manufacturer's Suggested Retail Price (10^3)	67.2	100	33
Battery/tank Capacity	74 kW	6.5 kg	80 l
GVW (tons)	3.5	3.5	3.5
Max Speed	100	140	140
Cargo Volume m^3	12.3	12.3	12.3
AC Charging Time (5 % ~ 100 %) (h)/ Charging power (kW)	5.2/22 kW	N/A	N/A
DC Charging (Fast Charging)	51 min/90 kW	N/A	N/A
Energy Consumption (per 100 km)	30 kW	1.5 kg	11 l
Vehicle Range (km)	225	~350–400	624
Dimension length x width x height (mm)	5940 × 2062 × 2730	5940 × 2066 × 2755	5940 × 2066 × 2755
Source	MAXUS, 2024	Awan & Scorrano, 2025; Motornet.it, 2024	MAXUS, 2024

For D-LVCs, fueling infrastructure includes a storage tank, ancillary equipment and safety upgrades, a fuel management system, and dispenser units. For details, see Section 3 of the Supplementary Material.

The cost estimates that we obtained are illustrated in Table 4. H2-LCVs exhibit the highest infrastructural costs if hydrogen is produced in-house, followed at a large distance by E-LCVs and D-LCVs. In all cases, there are considerable economies of scale.

3.2. TCO estimates

Based on the assumptions outlined in the previous section, we obtained the estimates TCO illustrated in Table 5.

H2-LCVs have the highest total cost per kilometer, with both green H2 produced in-house or (most likely grey) bought from external sources at the current market prices. Such cost disadvantage is primarily driven by elevated CAPEX, which is much higher than for the other powertrains, while the annual OPEX is slightly lower than that of D-LCV only in the case of green H2 (which is estimated to be cheaper than grey H2).

Obviously, these results depend on all the assumptions we made regarding economic factors such as MSRP, fuel prices, insurance costs, residual value and political decisions concerning the value added tax, subsidies, and circulation tax. National governments may use these levers to promote alternative powertrains. In Fig. *2*, we performed a simulation analysis estimating the critical value associated with changes in MSRP and the annual distance travelled, two of the variables that, according to many authors (Basma et al., 2022; Muhammad et al., 2025), influence the relative competitiveness of the powertrains. The MSRP of the E-LCV and of the H2-LCV might decline considerably as economies of scale are gained in the production of batteries and fuel cells. The ADT depends more simply on the logistical tasks performed by

Fig. 1. Maxus delivery-9 (E-LCV, H2-LCV and D-LCV).

Table 3
TCO assumptions.

Parameter	E-LCVs	H2-LCVs	D-LCVs	Ref.
MSRP (€) (without VAT)	67,123	100,000	33,000	(Awan & Scorrano, 2025; MAXUS, 2024; Motornet.it, 2024)
VAT (€) (22 %)	14,767	22,000	7260	(Awan & Scorrano, 2025; MAXUS, 2024; Motornet.it, 2024)
Subsidy (€)	0	0	0	–
Retail Discount (€)	0	0	0	–
Registration Cost (€)	342	342	342	(Automobile club d'Italia, 2025)
Charging Equipment Cost per vehicle (€) *	8806	73,450	3503	(Nicholas & Wappelhorst, 2022; Wang et al., 2025)
Annual Circulation Tax (€)	0	0	59	(Automobile club d'Italia, 2025)
Insurance Premium (€)	600	600	600	(Scorrano et al., 2021)
Fuel Price at Public Station	0.60 €/kWh	15 €/kg **	1.8 €/l	(Awan & Scorrano, 2025; Danielis et al., 2025; ENI, 2022)
Fuel Price at Depot	0.35 €/kWh	11.8 €/kg	1.5 €/l	(Danielis et al., 2025; Scorrano et al., 2021)
Fuel Efficiency per 100 km	30 kW	1.5 kg	11 l	(MAXUS, 2024; Motornet.it, 2024; Scorrano et al., 2021)
Maintenance Cost (€/100 km)	3.0	3.97	3.67	(Awan & Scorrano, 2025)
Residual value of the vehicle (€)	6712	10,000	6600	(Awan & Scorrano, 2025)
Residual value of the charging infrastructure (€)	2641	18,000	1992	Our Assumption
Number of Years	10	10	10	Our Assumption
WACC	2 %	2 %	2 %	(Danielis et al., 2025)

[*] Charging equipment cost is calculated with DC-150 kW configuration.
[**] Our assumption is based on several sources including information collected from direct communications with Italian providers. Note that Castillo and Álvarez (2023) make a very different assumption: they assumed that hydrogen purchase costs are equal to 4.2 €/kg.

Table 4
Infrastructural cost per LCV (€).

Fleet size\type	E-LCV	H2-LCV	D-LCV
10 LCVs	17,613 (DC 150)	146,900	7006
20 LCVs	8806 (DC 150)	73,450	3503
50 LCVs	4862 (DC 350)	58,760	1401
70 LCVs	3473 (DC 350)	41,971	1001

Table 5
TCO estimates for refrigerated LCVs (ADT = 40,000 km).

Powertrains	Electric	Diesel	Hydrogen (in house production)	Hydrogen (external sourcing)
Total CAPEX (€)	91,038	44,105	195,792	122,342
Annual OPEX (€)	8018	11,476	10,486	12,406
TCO (€)	155,389	140,339	263,704	225,577
TCO/km (€)	0.43	0.39	0.73	0.63

the LCVs.

Fig. 2 shows that E-LCVs are cost competitive with D-LCVs if their MSRP decreases to around EUR 55,000 or when the ADT is higher than 55,000 km\year, or intermediate combinations of the two values. Green H2-LCVs, by contrast, would become cost competitive only at ADTs above 80,000 km\year and at prices almost half of current MSRP levels.

Traditional TCO metrics do not account for differences in logistical performance across powertrains, raising a critical question: how do different propulsion systems compare in real-world logistics operations? To address this question, we developed a multi-agent simulation model to assess the logistical efficiency (delivery capability, refueling downtime, etc.) of each powertrain under various operational scenarios.

4. A multi-agent simulation model for logistical operations

4.1. The environment

The Environment acts as the main agent or the top-level agent in the simulation model, orchestrating the interactions and dynamics of the system. It contains information on the geographical settings, the routes and the locations where the charging\refueling stations are positioned (Fig. 3).

Multiple refueling and charging stations were placed along the routes to support vehicle operations; for E-LCVs, the public charging stations provide up to 150 kW power (the technical charging limit of the electric Maxus Deliver 9).

4.2. Model description

The logistical operations of LCVs are governed by three agent types (Fig. 4). Customers generate order requests at a predefined rate, while Bofrost is assumed to manage a mixed fleet of LCVs categorized by powertrains. Each vehicle type responds to orders following the same operational framework. The LCV agent-type manages vehicle movement and dynamically monitors fuel/energy levels throughout the journey. A detailed description of agent behavior regarding order request within the simulation model follows.

The model is initiated by customer order requests generated through static assignment approach at a uniform rate. Upon receiving the order request, the fleet operator (single fleet-operator Bofrost Italia) assigns these orders to LCV Agent-type representing different powertrain technologies (diesel, battery-electric, and hydrogen), ensuring comparative operation under identical logistical conditions. Although the model architecture supports multiple independent fleet operators, in this study it has been instantiated with a single operator managing all three powertrains under the same depot. The customer pool comprises up to 50 fixed clients mapped on the GIS (Geographic Information System) environment in both urban and regional scenarios, representing areas actively served by Bofrost Italia in the region. All agents—including customers, the fleet operator, and LCVs—interact dynamically within a shared environment, enabling real-time logistical coordination.

Upon receiving an order, the LCV Agent autonomously determines the shortest route (accessing OpenStreetMap library) and schedules refueling or recharging stops based on predefined threshold levels. Charging/refueling stations are positioned along the route. LCVs access the nearest facility based on its proximity. At each customer location, the LCV stops for 10 min to unload consignments. The vehicle journey is carried out until all consignments are served and then returns back to the fleet operator's location.

The Environment serves as the top-level agent within the simulation model, governing interactions and overall dynamics while encapsulating its structural and functional components (Christensen et al., 2024). It defines the geographical landscape, positioning GIS-based locations for each agent type.

4.3. Customer agent

Bofrost has a list of orders they must fulfill from their customers' base. Daily, they assign a given number of orders to each LCV driver. We modelled it via an event-based mechanism.

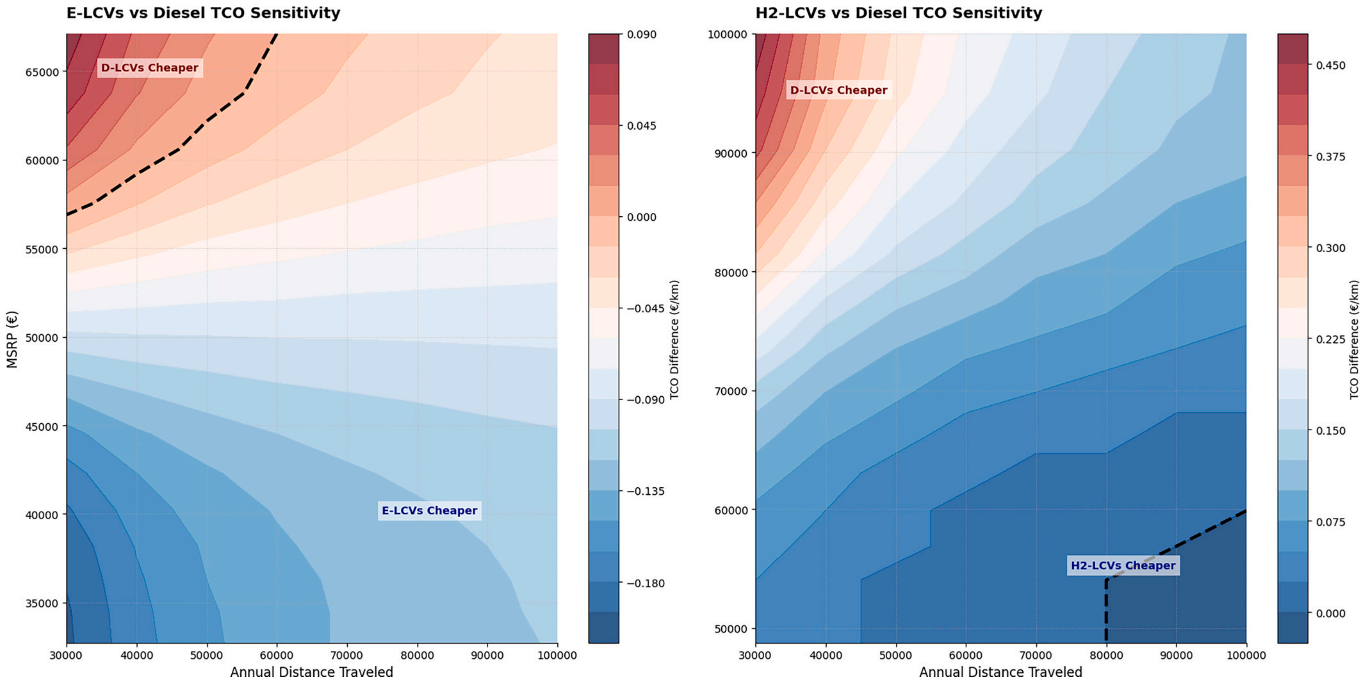

Fig. 2. Critical value curve for E-LCVs or H2-LCVs relative D-LCVs.

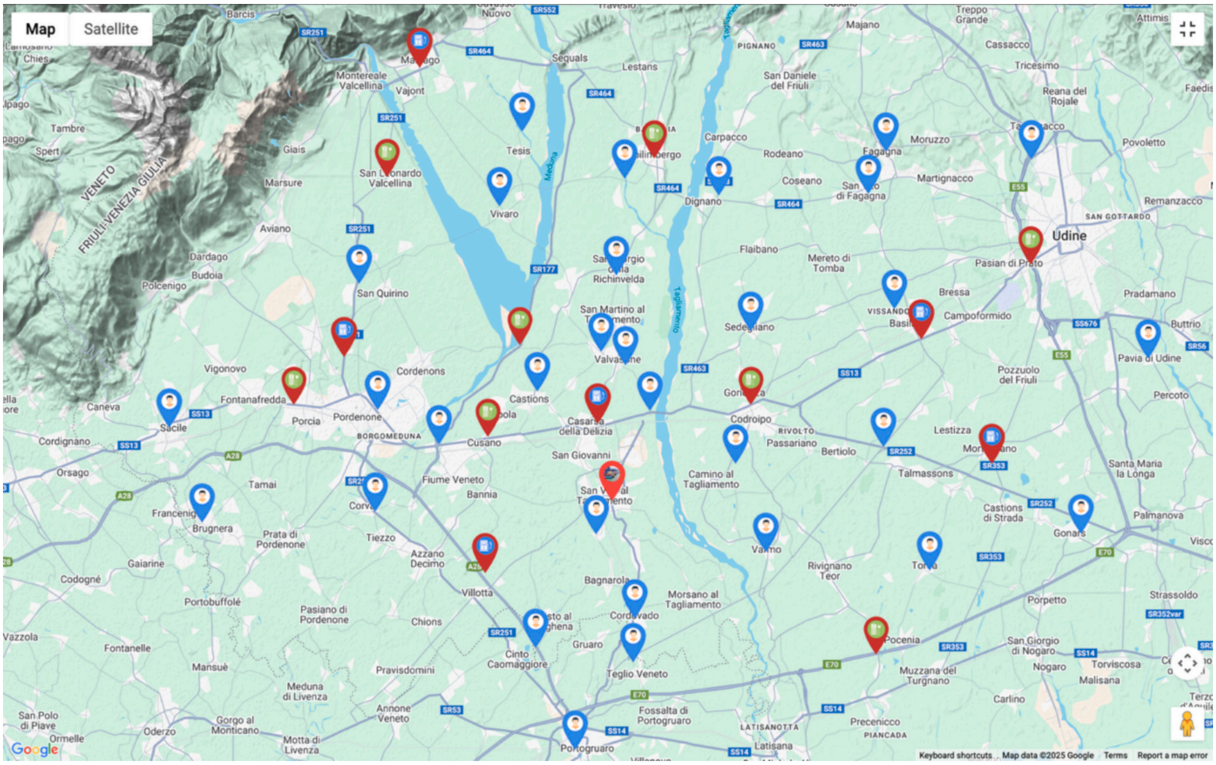

Fig. 3. The geographical environment with the customers' locations in the regional scenario and the charging\refueling stations.

4.4. *The fleet operator*

In this simulation model, Bofrost Italia is designated as the sole fleet operator, managing three distinct LCV fleets: diesel-powered, hydrogen-powered, and electric vehicles. The fleet operator processes customers' order requests and coordinates the delivery of the consignments from the warehouse to the customers' locations via LCVs Agent.

Order processing, a core function of Bofrost Italia (fleet-operator), is inherently process-centric and requires micro-level event handling. To accurately simulate this, a discrete-event simulation (DES) paradigm is employed. The sequence is illustrated and explained in Fig. 5.

4.5. *The LCV agent*

Order requests are assigned to the LCV agent type, that is primarily responsible for the order delivery on specified routes. LCV agents govern

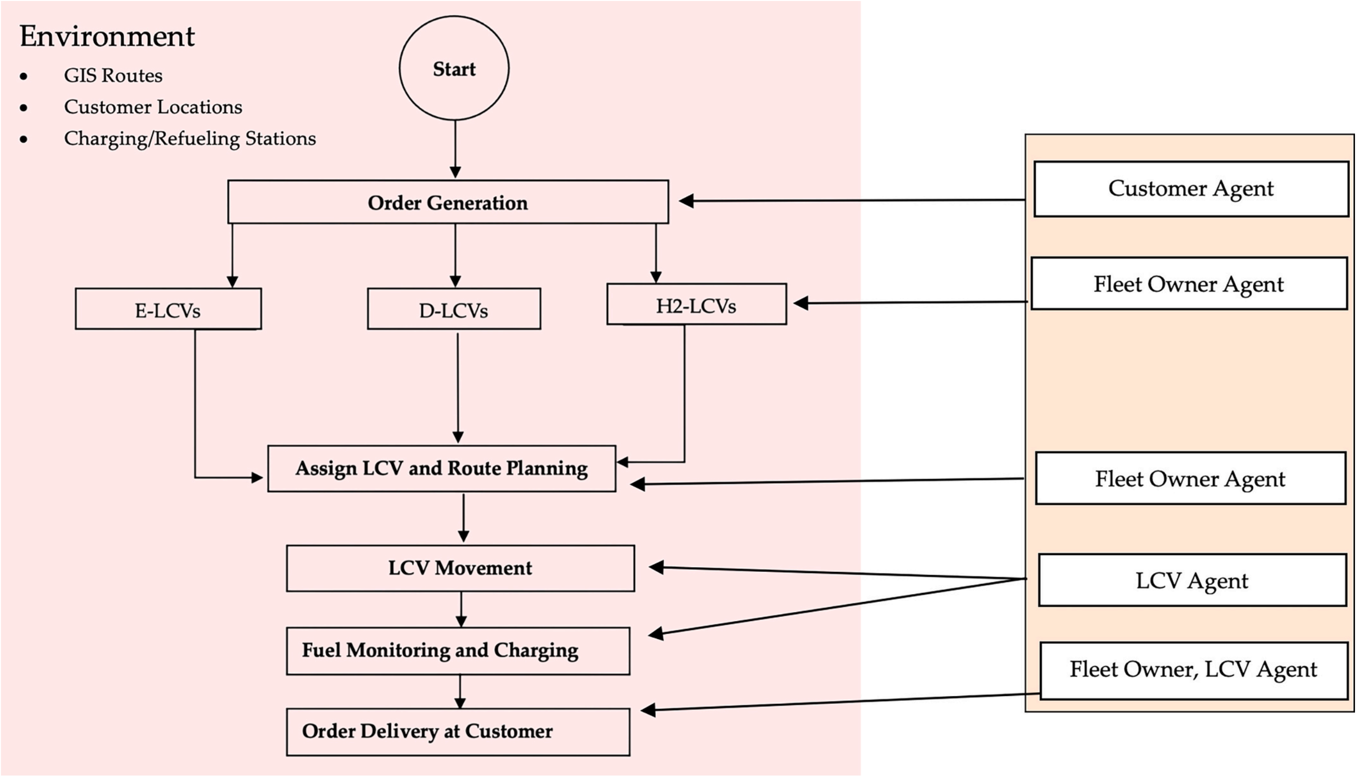

Fig. 4. Overview of the model.

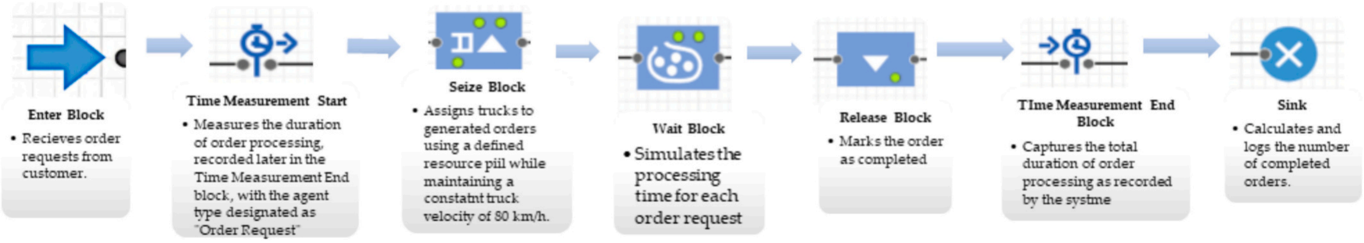

Fig. 5. The discrete-event model of order management.

vehicle movement using an agent-based modelling paradigm incorporating stock-and-flow dynamics (Fig. 6). LCVs are assumed to be preloaded overnight and fully charged at the Bofrost Italia facility and begin deliveries at 8 AM. Upon reaching each customer's location, the vehicle halts for 10 min to complete the unloading process. Throughout the journey, fuel/energy consumption is continuously monitored. If the minimum refueling/recharging threshold is triggered, the vehicle dynamically calculates the optimal route to the nearest available station.

If refueling or recharging is required during the journey, LCVs utilize public fast-charging stations. The delivery process is halted at 04:00 PM (after 8 h of operations), and LCVs remain stationed at the fleet operator's facility. If additional refueling\recharging is necessary ($\leq$70 %), LCVs are refueled\recharged overnight at Bofrost Italia facility. An order is considered completed once the consignment is unloaded at the customer's facility, while a trip is deemed completed only when the vehicle returns to its base, ensuring delivery accuracy and operational efficiency.

4.6. Fuel management

Fuel management is modelled using a System Dynamics (SD) framework, integrated into LCV Agent-type. This allows for dynamic representation of fuel consumption under varying operational conditions (Cimino et al., 2025). The model incorporates refueling and recharging events, which are triggered when LCVs reach designated public charging stations or the Bofrost depot at the end of the service. Additionally, E-LCVs are configured with a fast-charging protocol activated exclusively at public charging stations, whereas diesel and hydrogen LCVs employ standardized refueling rates.

Each powertrain is equipped with a dedicated fuel management module, designed to simulate real-world operational behavior. The SD framework for H2-LCVs is depicted in Fig. 7, while a similar approach is applied to all powertrains.

The stock module represents the vehicle's fuel tank or battery capacity (H2-Tank), while the inflow accounts for refueling/recharging events occurring at public stations or at the fleet-operator's facility. Conversely, the outflow represents energy consumption when the vehicle is in motion. Fuel consumption is influenced by fuel efficiency, speed, and refrigeration energy demand, with refrigeration accounting for 19 % of overall fuel consumption across all refrigerated LCVs (CoolKit, 2022). During unloading at customer locations, propulsion-related fuel outflow halts, while refrigeration energy consumption remains active.

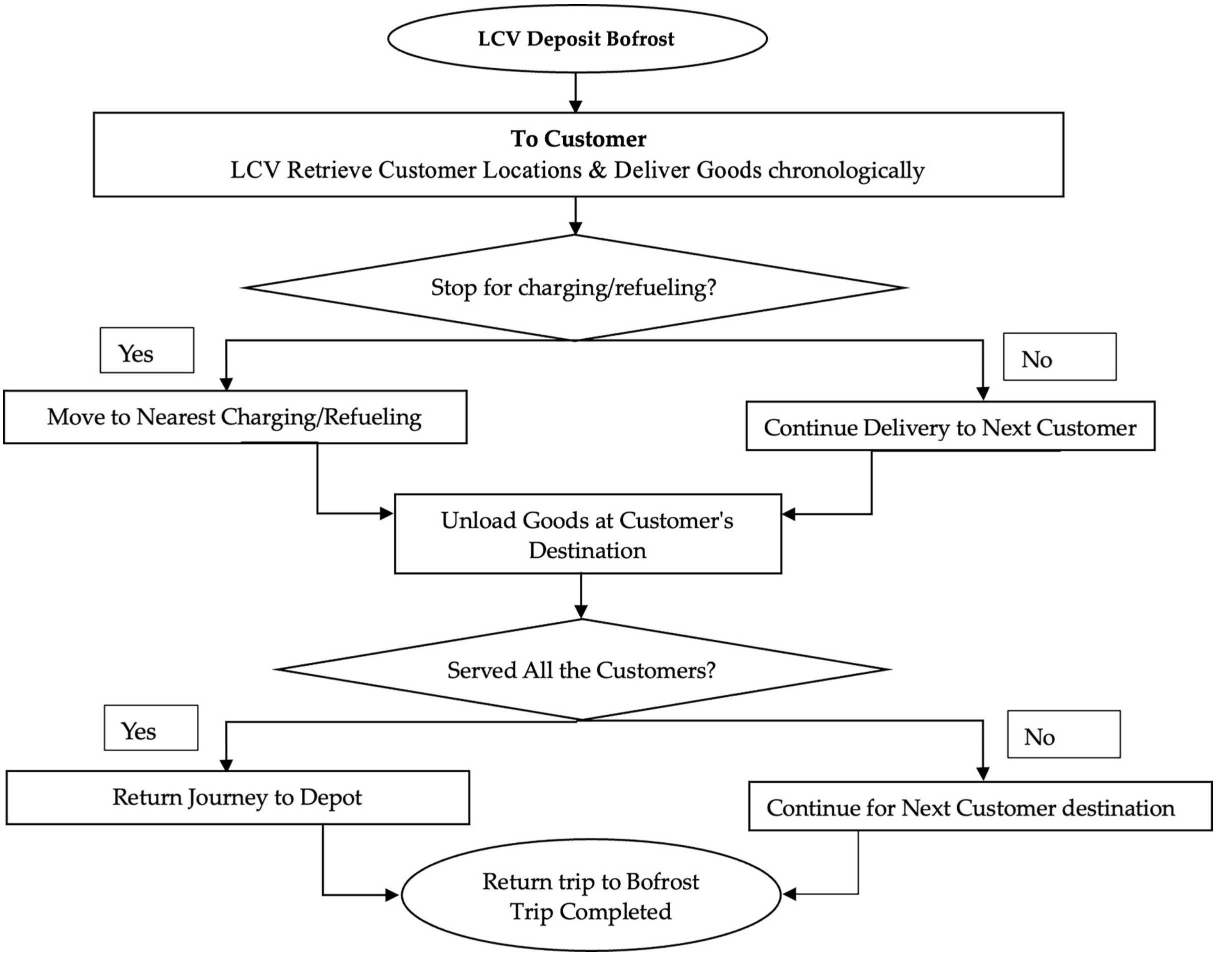

Fig. 6. Overview of LCV behavior along with fuel management.

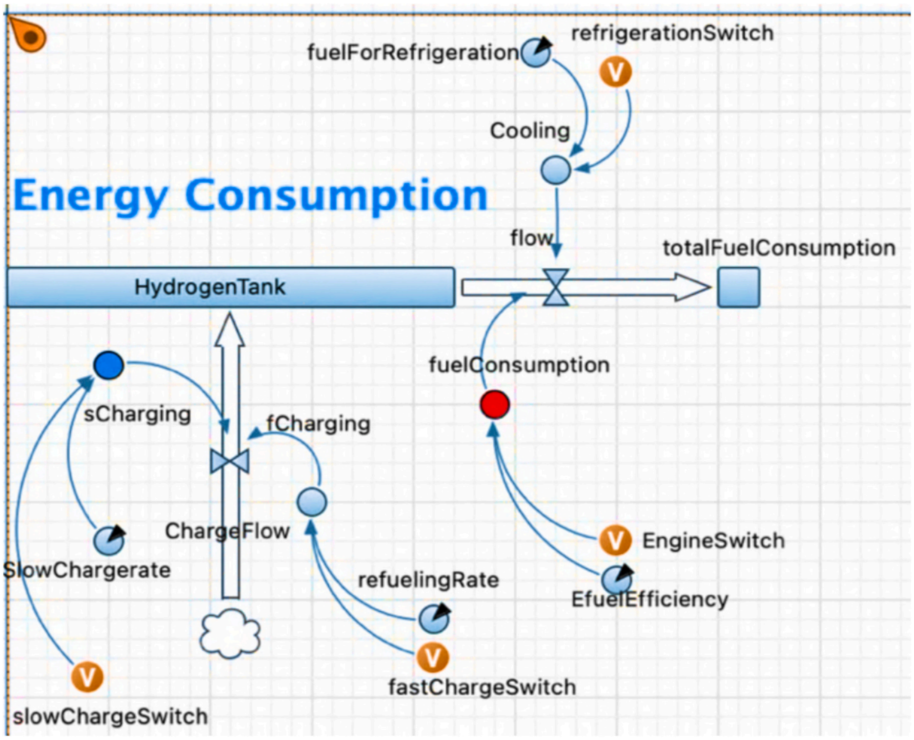

Fig. 7. The fuel-consumption system-dynamics model.

5. Model implementation and application

The multi-agent simulation model is developed using a case study approach. The operational timeframe is constrained to 8-h daily shifts (8 AM to 4 PM), to mirror Bofrost's delivery shift. For geospatial data processing, the model incorporates MeteosatSG satellite projections via the GeoTools Library. The fleet size is defined within the fleet-owner agent population, with the baseline scenario specifying a given number of 20 LCVs per fleet, though the model is scalable to accommodate varying fleet sizes.

In order to quantify the logistical performance of each powertrain we selected two indicators: the total orders completed and total refueling time.

The model's parameters are summarized in Table 6. The model's behavior is assessed for its ability to emulate real-life logistical operations, considering expected speed, charging time, unloading time, and fleet operator dwelling time.

5.1. *Urban vs. regional scenario*

Next, we performed a series of scenario analysis. Firstly, we simulated the logistical performance of the three powertrains under an urban and a regional scenario. In the Urban Scenario, customers are located within a metropolitan area. The total distance to be travelled to serve customers would be about 190 km/day, equivalent to an ADT of approximately 49,590 km\year (261 working days). In addition, we assumed that each consignment to the customer would take 10 min, accounting for the need to find off-side parking, delivering the product to the customer, collecting payments, potential reordering, and so on. In the Regional Scenario, customers are spread out in a regional\rural area. The total distance to be travelled to serve customers is about 346 km, for an ADT of approximately 90,400 km\year (261 working days). Using the model to simulate consignments in the two scenarios, we obtained for each LCV type the results reported in Table 7.

In the urban scenario, all three powertrains demonstrate similar operational capability, i.e. serve on average about 43–45 customers. However, E-LCV is slightly worse (43 instead of 45, i.e. -4 %) and might need a 22-min charging time. In the Regional Scenario, the difference in the average number of customers served increases to 3 out of 34 (i.e. -9 %) and the charging time to about 27 min.

5.2. *Urban vs. regional scenario in different weather conditions*

Next, we simulate the impact of climatic extremes on the above-described scenarios. The climatic extremes are categorized as the Cold Weather Scenario when temperatures fall below 0 °C, and the Hot Weather Scenario when temperatures exceed 28 °C. Table 8 presents the simulation results under these extreme cold and hot conditions, for both urban and regional settings.

In the Urban Scenario, extreme temperatures had no impact on daily delivery differential: E-LCVs are able to serve two customers less than the other powertrains due to the 22-min charging needs. In the Regional Scenario, E-LCVs experience a performance degradation in extreme temperatures: the difference in the average number of customers increases from 3 to 7 customers with cold weather and to 4 with hot weather. This reduction is a consequence of additional charging needs and reduced efficiency in those conditions. H2-LCVs exhibit also a small performance loss.

Table 6
LCVs Parameters. Source:(CoolKit, 2022; Danielis et al., 2025).

LCV Parameters	E-LCV	H2-LCV	D-LCV
Fuel Efficiency per 100 km	30	1.5	11
Battery/Tank Capacity	74 kW	6.5 kg	80 l
Refrigeration Impact	0.1785 kW/min	0.0089 kg/min	0.06545 l/min
LCV Range (km)	225	365	664
Recharge Threshold	20 %		
LCV Speed	30 km/h		
Refueling Rate	–	350 kg/h	3000 l/h
Charging Power	150 kW	–	–

Table 7
Results for 8 h operational time for each LCV (differentiated customer location, normal weather conditions).

	Urban Scenario			Regional Scenario		
	E-LCV	H2-LCV	D-LCV	E-LCV	H2-LCV	D-LCV
Average number of customers served per LCV\day	43	45	45	31	34	34
Total refueling time (min) per LCV\day *	22:06	00:00	00:00	27:18	00:00	00:00

* "Total Refueling time per LCV/day" is the average delay per LCV due to mid-route refueling/charging, in minutes: seconds.

Table 8
Results for 8 h operational time for each LCV (similar customer location, differentiated weather conditions).

	Cold Weather Scenario			Hot Weather Scenario		
	E-LCV	H2-LCV	D-LCV	E-LCV	H2-LCV	D-LCV
One day (8 Hours) Simulation under Urban Scenario						
Average number of customers served per LCV\day	43	45	45	43	45	45
Total refueling time (min) per LCV\day	22:34	00:00	00:00	22:09	00:00	00:00
One day (8 Hours) Simulation under Regional Scenario						
Average number of customers served per LCV\day	27	33	34	30	33	34
Total refueling time (min) per LCV\day	28:18	03:15	00:00	27:09	03:14	00:00

5.3. *A Monte Carlo simulation for regional deliveries*

The deterministic version of the model assumes fixed parameters. However, real world implementation of deliveries is subject to various uncertainties related to traffic variability and the use of the charging infrastructure. To incorporate some of these uncertainties, we conducted a Monte Carlo analysis. Specifically, we assumed that model parameters illustrated in Table 9 are normally distributed. Efficiency might vary depending on payload, driving behavior, traffic conditions and weather. The charging rate might vary according to the chargers' technical characteristics and the occupancy level. The *E*-LCV battery capacity might degrade over time, and the H2-LCV tank capacity might vary depending on the pressure and technical features of the dispenser (Utomo et al., 2020).

We report only the results for the regional scenario because it is the one that presents the largest differences in the performances among

Table 9
Parameters assumptions.

	Parameters	Mean	Standard Deviation
E-LCVs	Efficiency	0.300 kWh/km	0.40
	Charging rate	2.5 kWh/min	0.25
	Battery Capacity	74 kWh	7.0
H2-LCVs	Efficiency	0.015 kg/min	0.015
	Refueling rate	5.83 kg/min	0.50
	Tank Capacity	6.5 kg	1.5

powertrains. The results indicate that E-LCVs are able to complete between 18 and 33 orders (on average 29.23), with a probability of 45 %, 23 %, 20 % of being equal to 30, 33, 25 orders and so on, respectively (Fig. 8). Conversely, H2-LCVs are able to complete a similar number of orders, ranging from 18 to 33, but with a different probability distribution, i.e. 78 % of the time the number of orders delivered is equal to 33, and on average it is equal to 31.28 orders (Fig. 9).

In terms of charging time, on a daily basis E-LCVs need between 1- and 124-min charging time, on average 32.01 min (Fig. 10), while the time loss is much lower for H2-LCVs (Fig. 11).

6. Discussion and policy implications

This study evaluated the economic and logistics viability of refrigerated LCVs with alternative propulsion systems using Italian market prices from the point of view of a large frozen food delivery company, such as the case of Bofrost Italy. Despite environmental advantages of substituting conventional refrigerated D-LCVs with more environmentally friendly powertrains such as E-LCVs and H2-LCVs, their market penetration is still in the initial phase.

The TCO analysis includes the infrastructural costs required to charge the E-LCVs at the company's premises, in addition to the possibility of charging them at public chargers during the daily operations if needed. Similarly, we have considered the possibility to produce internally green H2-LCVs (an option that might be reasonable for large fleets) or to buy hydrogen from external providers. We find that refrigerated *E*-LCVs are nearly cost-competitive with D-LCVs, depending on many factors among which acquisition costs (potentially benefiting from financial incentives) and ADT are particularly relevant. By contrast, H2-LCVs are not yet economically viable, unless very high ADTs and substantial financial incentives are assumed. However, although very important, economic competitiveness is not the only metric considered by fleet managers of logistics distribution companies handling refrigerated goods. Range is a critical factor, as refrigerated LCVs have to complete as many orders as possible, making vehicle uptime crucial; time spent recharging\refueling translates directly into lost business. Based on our hybrid simulation model, we found that when deliveries occur mainly in urban environments with limited distances between customers, the operational performance loss of E-LCVs relative to D-LCVs, measured by the number of customers served, is about 4 %. This loss increases to 9 % in regional distribution scenarios, as E-LCVs may require stops of about 30 min for recharging. Additionally, uncertainties related to traffic, weather, driving behavior or waiting times at the charging stations may further impact E-LCV performance. This is not the case for H2-LCVs, whose operational performance appears comparable to that of D-LCVs.

In conclusion, we find that refrigerated E-LCVs are close to being competitive both in economics and logistics terms. In order to reach full competitiveness without the need for financial incentives, range and acquisitions costs need to further decrease. Innovations in battery technology and market competition from Chinese manufactures are likely to be the main drivers of change, alongside developments in the passenger car market. The outlook for H2-LCVs is less optimistic. In fact, while their logistics performance is comparable to that of D-LCVs, the economic competitiveness is hampered by the high acquisition costs and the relatively expensive price of hydrogen.

Admittedly, the reliability of modelling results depends on the realism of the model's parameters and its ability to incorporate the complexities of a logistics organization. A limitation of this simulation model is its simplified representation of depot-based refueling\recharging infrastructure, which assumes that the company is able to smoothly and simultaneously perform such operation jointly with the replenishment of the LCVs to satisfy the next day deliveries (Christensen et al., 2024). Such assumption introduces another constraint regarding charging station load management, as real-world charging efficiency may decline when multiple vehicles charge simultaneously.

Discussions with Bofrost fleet managers revealed that depot-level infrastructure remains a central barrier. Electrifying refrigerated fleets or introducing hydrogen vehicles requires substantial organizational and spatial adjustments (Awan & Scorrano, 2025). While the public bus sector has already undergone this transition with significant public support, refrigerated LCV operators—mainly private firms and SMEs—face greater financial and logistical constraints. Existing evidence and sectoral experience suggest that deployment hurdles for electric charging infrastructure are likely to be resolved earlier than those related to the very expensive deployment of hydrogen production and refueling equipment (Danielis et al., 2025). Consequently, refrigerated E-LCVs are more likely to replace diesel vans in the near to medium term.

Additionally, the model assumes the existence of an adequate network of recharging\refueling stations in the areas travelled by the LCVs (Guo et al., 2025). In fact, station occupancy, queuing times, and potential limitations in charging infrastructure availability could significantly impact the real-world operational efficiency. Although the FVG region, where the Bofrost *facil*ity is located, has a relatively dense network of charging stations, the current commercial pricing structure

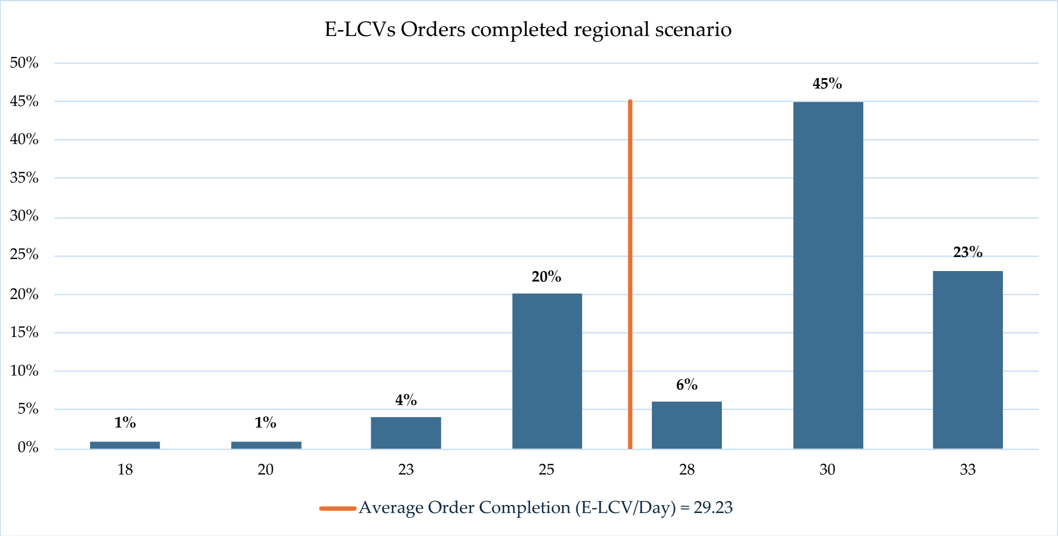

Fig. 8. Average orders completed by E-LCV during an 8-h working shift.

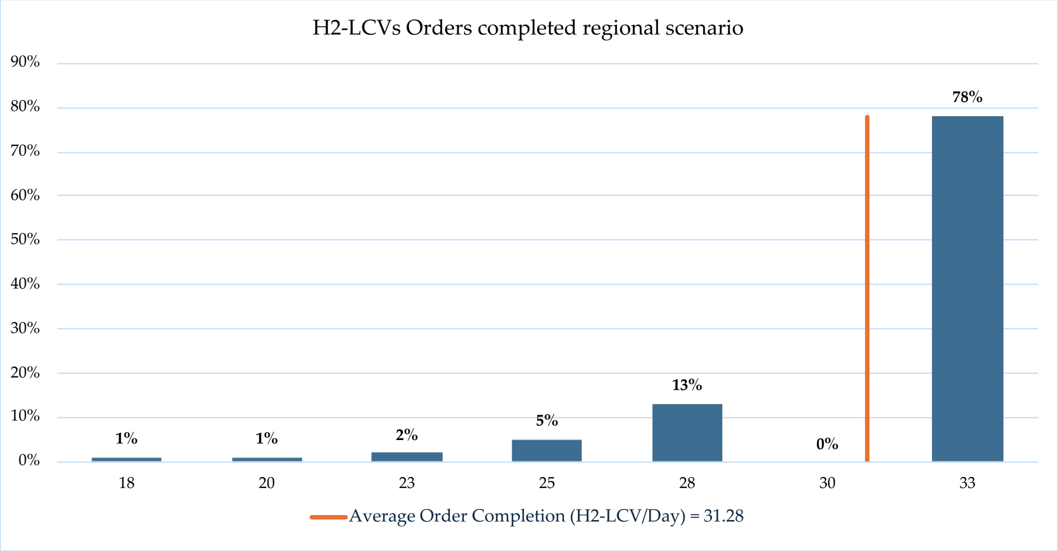

Fig. 9. Average orders completed by H2-LCV during an 8-h working shift.

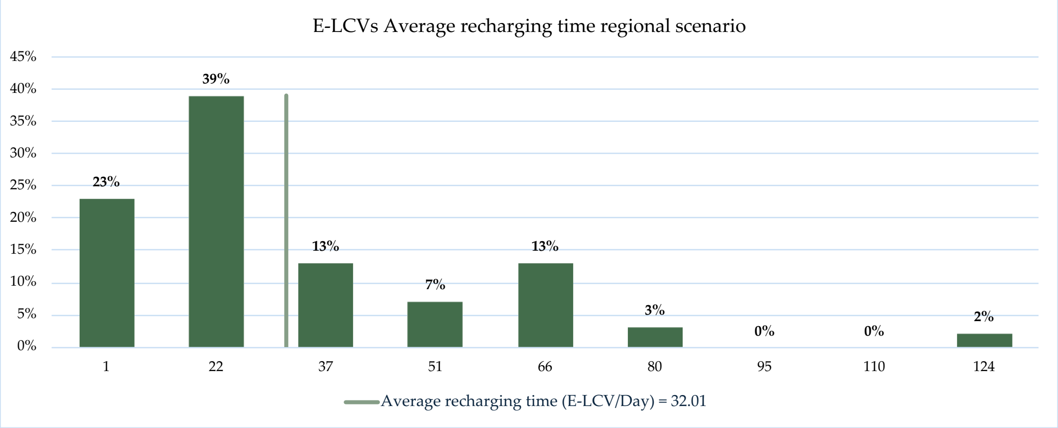

Fig. 10. Average recharging time per 8-h working shift for an E-LCV.

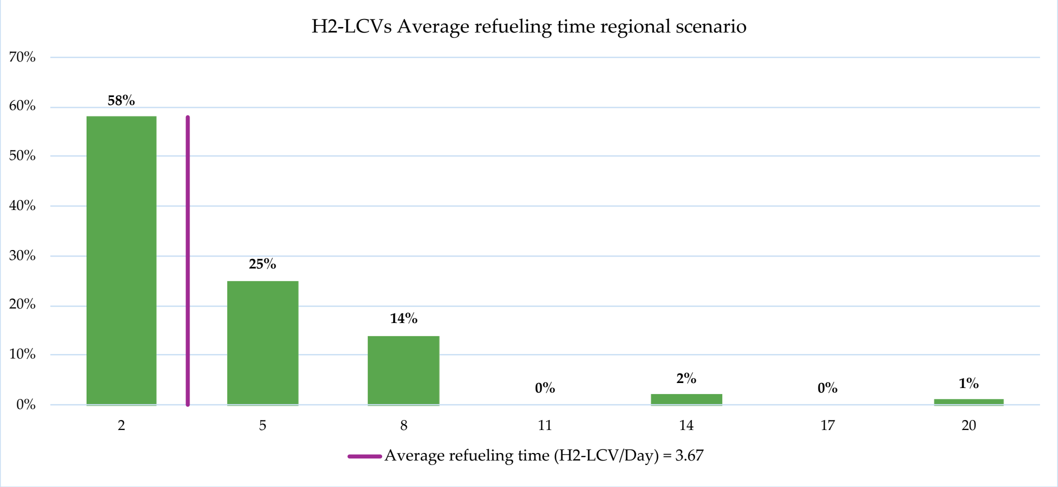

Fig. 11. Average recharging time per 8-h working shift for an H2-LCV.

substantially undermines their economic attractiveness for fleet operators. Thanks to the European funds granted by the National Recovery and Resilience Plan, the Italian government has provided generous subsidies for the expansion of charging infrastructure. Awan and

Scorrano (2025) reported that the first-ever transnational initiative, the North Adriatic Hydrogen Valley, has been created with support from the Clean Hydrogen Partnership and the Horizon Europe program. The objective is to expedite the shift to renewable energy in sectors such as transportation and industry by establishing a competitive market for green hydrogen. The 54 Hydrogen Valleys financed in Italy are expected to lead to the development of 36 hydrogen refueling stations in Italy (as of Decembre 2025, 3 are operational).

In conclusion, the decarbonization of refrigerated last-mile distribution is becoming increasingly feasible both economically and technically for urban operations through the adoption of E-LCVs, provided that targeted policy support and infrastructure development are in place. Hydrogen powertrains hold longer-term potential but require substantial cost reductions and coordinated infrastructure deployment before they can realistically compete. Aligning financial incentives, infrastructure planning, and regulatory frameworks will be essential to support a measured yet accelerating transition toward low-emission refrigerated logistics.

CRediT authorship contribution statement

Romeo Danielis: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Arsalan Muhammad Khan Niazi:** Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Mariangela Scorrano:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manuela Masutti:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rtbm.2026.101595.

Data availability

Data will be made available on request.

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