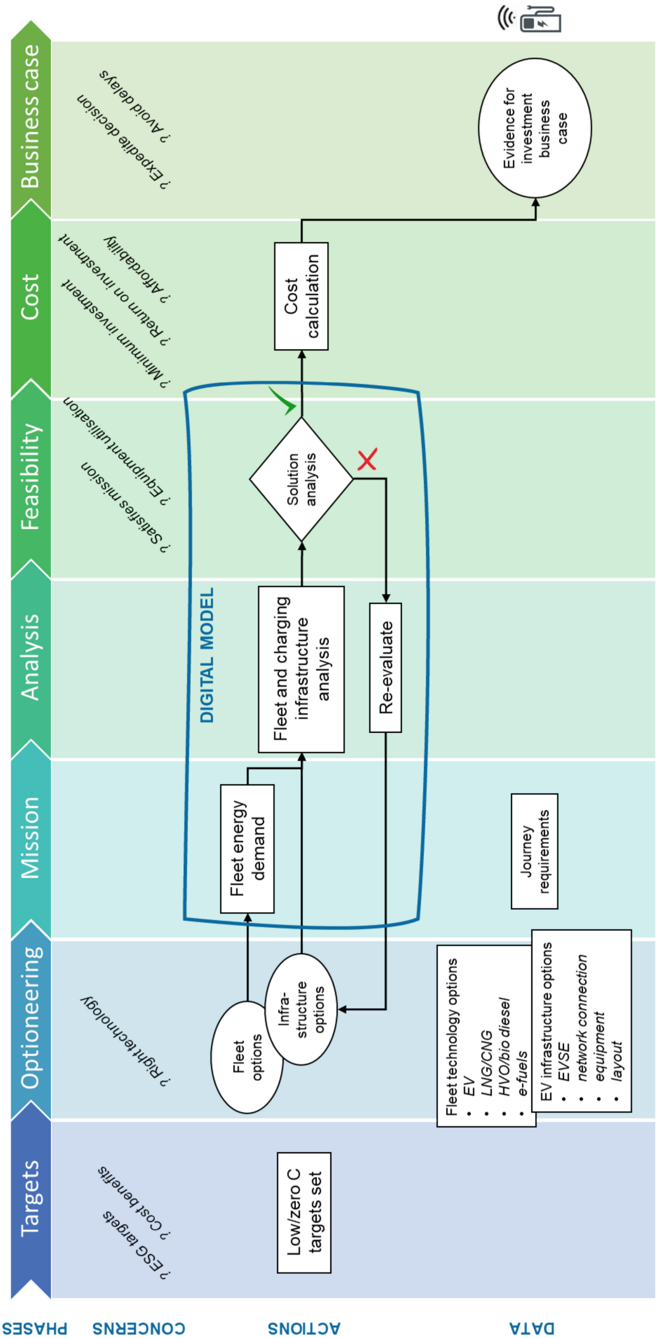

Fig. 1. Infrastructure investment decision journey.

Quak et al. [6] validated electric HGV economics, but with low power overnight chargers. Drake et al. [7] examined electric HGVs' cost effectiveness using depot and destination charging up to 250kW and example network connection cost. Basma et al. [8] included equipment cost for 100kW and 350kW chargers, and service and maintenance in the TCO calculation, but without installation civils, electricals, nor financing.

1.3 Technical and Operational Challenges

Charging Speed and Time. Electric HGVs have battery sizes of 500kWh and larger [9]. Fast recharging is necessary to minimise dwell time, with a technical standard for megawatt charging (MCS) to be published shortly by CharIN [10].

Infrastructure Availability. Electric HGV recharging infrastructure is scarce. Investment will focus on key freight routes [11], leaving fleet operators to plan electric HGV recharging at depots.

Electricity Distribution Network Capacity. Recharging multiple vehicles concurrently requires to import substantial power from the electricity distribution network. For most locations, a connection reinforcement request is needed to the distribution network operator (DNO), which incurs complex costs and lead times [7].

1.4 Investment Decisions

The flow diagram in Fig. 1 describes the decision journey of a Fleet Director (or a Facilities or Finance Director), to arrive at a business case for charging infrastructure. Identifying both the fleet and infrastructure options requires experience but the analysis of the fleet mission, and the potential for each fleet and infrastructure option to satisfy the fleet mission, are too complex and require computer simulation.

2 Digital Model

2.1 State-of-the-Art

Digital models of public recharging infrastructure offer operational benefits to drivers and CPOs, and support urban planners to optimise investments [12]. Digital models also enable grid edge management for peak demands and flexibility/off-peak recharging [13].

Francisco et al. [14] used a MATLAB digital model to optimise charging process management for EV fleets through time window allocation. Korotunov et al. [15] introduced a virtual prototype to support charger predictive maintenance.

A new digital model will assess the feasibility of fleet and infrastructure options.

2.2 Methodology

A new digital model has been developed with MATLAB/Simulink Simscape Electrical [16], using input data including the following:

- Fleet vehicle operations, therefore calculating fleet energy consumption (demand),
- Charging infrastructure options,
- Depot site power equipment and/or energy storage options (depot energy network),
- Electricity distribution network connection and reinforcement options.

The new digital model calculations determine the feasibility of options to satisfy the fleet mission, the equipment utilisation, and the profile for energy imported from the electricity distribution network from which the energy consumption costs can be calculated. The overall capital and operational cost outputs then support the investment calculations and the business case for fleet and infrastructure decisions.

2.3 Depot Energy Network

Together, the recharging infrastructure power equipment and further infrastructure, such as new local energy storage or local generation, create a new energy network at the depot. Modelling recharging infrastructure options involves:

Integration of Renewable Energy Sources. With rising energy costs, local renewable generation is attractive to reduce electricity import from the distribution network [17]. Integration involves historical data and advanced forecasting (e.g., [18]) to predict the intermittent generation (location, season, weather) for energy planning.

Energy Storage for Operational Resilience. Local energy storage aids integration of local renewable generation, by peak shaving and load shifting. Local energy storage also provides network stability during supply and demand dynamics, and will ensure uninterrupted recharging service during supply disruption, improving overall operational resilience [19, 20]. Local energy storage may also mitigate reinforcement [21].

Commercial Opportunities. Local energy storage offers economic opportunities through energy price arbitrage and flexibility services to the distribution network [17].

Bidirectional charging vehicle-to-grid is a promising additional network flexibility service (exporting vehicle energy to the distribution network). Predicable usage patterns of electric HGVs make this an attractive future possibility.

Site Consumption and Energy Management. Existing depot loads to balance with the electric HGV recharging demand include for example lighting, heating, ventilation, industrial plant, material handling equipment, security systems, and offices.

Figure 2 illustrates charging and depot energy network management strategies for the above listed considerations.

2.4 Fleet Operator Findings

The new digital model supported evaluation of depot sites with electric HGV fleets up to 50 vehicles, including both shuttle and multi-drop operation, with either dockside or remote recharging. The optimum number of chargers per vehicle and the potential for local energy storage (investment) varies from depot to depot, often depending on the distribution network connection and reinforcement cost.

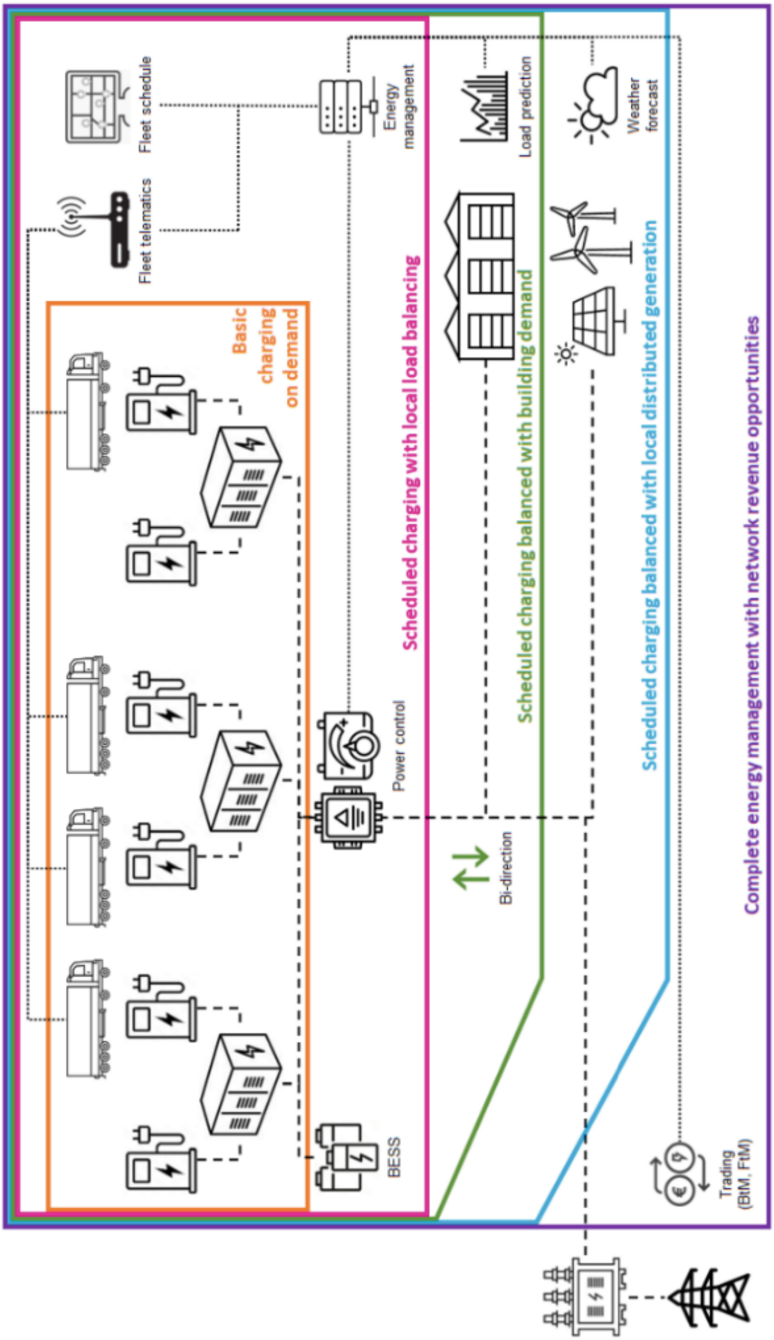

Fig. 2. Depot energy network schema including electric HGV charging and strategies.

The new digital model helped to understand daily profiles for energy import (costs). Fleet consumption costs dominate the cost calculation, highlighting the critical importance of fleet operation and recharging regime according to tariff. A positive return on local energy storage investment has been shown [22].

3 Conclusion

Prior TCO research for electric HGVs has focused on vehicle and energy costs rather than recharging infrastructure, but this investment is significant. Computer simulation is needed to evaluate the fleet and infrastructure options facing Fleet Directors.

The new digital model described facilitates this evaluation of options, and feeds into an overall infrastructure investment decision journey to arrive at a business case. Cost assumptions and forward-looking statements cannot be avoided, so care must be taken in applying results. All HGV fleets and depots are unique.

Suggested future work should look at how key costs will reduce with adoption, and the role of public funding for depot and destination recharging.

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Business Model Implications of Innovative Solutions for Sustainable Urban Freight Transport

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Abstract. Urban freight transport faces significant environmental and societal challenges, necessitating innovative solutions. This paper explores the business model implications of such solutions, drawing insights from research trials conducted in Bremen, Mechelen, and Groningen as part of the "Urban Logistics as an on-Demand Service" (ULaaDS) project. While many proposed solutions are technologically ready, their integration into existing business practices and scaling for impact remains challenged. Key findings highlight the tension between innovative solutions and entrenched business-as-usual models. The interplay between private business and public authorities emerges as an important factor, with mutual expectations shaping the trajectory of these solutions. The research underscores the need for a holistic approach, integrating technological, business, and regulatory facets, to ensure sustainable urban freight transport solutions can compete effectively.

Keywords: Urban Freight Transport · Sustainability · Scalability · Public Policy · Commercial Viability

1 Introduction

The urban freight transport research community has proposed and studied a wide array of innovative solutions over recent decades [1–3]. These solutions strive for different ends: some primarily address environmental concerns while others focus on the impact of urban freight transport on public space, noise pollution, and safety. The means to meet these ends are diverse. Broad strategies include decarbonization, consolidation, and the spatial or temporal separation of freight transport from people living, working, or visiting the city. Solutions target the vehicles and the logistics facilities involved in urban freight transport, through technological innovation, the introduction of novel business models, and changes in regulations. Some are driven by private enterprises; others find their genesis in public organizations or in public-private partnerships.

Given the scope of urban freight transport and the magnitude of the environmental and societal challenges, innovative solutions must be deployed at scale to make considerable impact and be viable in the long term. Yet, scale and long-term viability have been

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challenging. Pilot tests with urban consolidation centers, for example, often handle shipments of only a few suppliers, carriers, or receivers [4] and seldom make it past the pilot stage [5]. And, despite broad attention and long-term testing, the use of cargo cycles remains challenging [6]. These, and other, innovative solutions in urban freight transport typically rely on proven technology, maybe except for autonomous freight transport vehicles. The real challenge for deployment at scale, then, lies not in the technological readiness, but rather in the way the solution is integrated into existing business practice.

This paper explores the business model implications of innovative solutions for sustainable urban freight transport. Insights are drawn from research trials in Bremen, Mechelen and Groningen, as part of "Urban Logistics as an on-Demand Service" (ULaaDS), a project within the European Union's Horizon 2020 research and innovation programme. The research trials provided critical lessons learned about the integration of innovative solutions into existing operational processes, competition with business-as-usual, and the role of rigorous regulations to ensure long-term viability.

2 Research Trial Descriptions

The ULaaDS project focused on five innovations in on-demand and sustainable urban freight solutions, namely the integration of (1) containerization and (2) cargo bikes into last-mile delivery, the development of platforms for (3) the integrated management of urban freight transport and (4) vehicle sharing, and (5) the sharing of location and infrastructure for passenger and urban freight transport.

Different innovations were trialed across three lighthouse cities involved in the project: Groningen (the Netherlands), Mechelen (Belgium), and Bremen (Germany). While different in aspects such as population size and regulatory context, these three European cities have in common a historic city center and a bike-friendly infrastructure and attitude. The three research trials focused on different solutions and are described below.

2.1 Groningen Research Trials

The Groningen research trials focused on the implementation of a platform for shared zero-emission urban freight vehicles and the placement of parcel lockers on public transit hubs.

The platform for shared zero-emission urban freight vehicles was aimed at providing shopkeepers in the city center of Groningen with access to zero-emission vehicles for the on-demand supply of their shops and delivery to consumers in and around Groningen. Different vehicle types—a cargo bike, a light electric freight vehicle, and an electric van—and their use by entrepreneurs with a different urban freight transport demand were tested. Shopkeepers in need of a zero-emission vehicle can reserve one via an app, pick the vehicle up from its parking location, use it, and afterwards return it to the same parking location. During the trial, vehicle reservation and use was possible for a select group of shopkeepers and free of charge, but with the explicit purpose of gaining insight into the business model of the platform. Reservations and vehicle use were closely monitored and discussed with the shopkeepers during several sessions.

The scope of the parcel locker research trial was changed and expanded from placing a few parcel lockers to developing a policy framework for parcel locker placement in public spaces in general. As the ULaaDS project was being developed and initiated, parcel lockers had become a mature solution, deployed at scale by many logistics service providers across Europe. While being actively involved in the placement of a locker proved challenging, an increasing number of actors sought permission to place parcel lockers in public spaces without financial support. The trial therefore shifted its focus to better facilitating parcel locker placement requests through the development of a policy framework [7]. The process included several public-private dialogues, a benchmark of solutions across Europe potentially relevant for the framework, and a spatial analysis.

2.2 Mechelen Research Trials

The Mechelen research trials focused on setting up a platform for collaborative urban freight transport and the piloting of an autonomous vehicle sharing passenger and freight transport services.

The collaborative urban freight transport platform was aimed at consolidating parcel pickups at local shops in the inner city of Mechelen. The fragmented nature of these pickups, with few parcels per stop for each logistics service provider and few stops in relation to the size of the area, leaves ample room for improved cost-effectiveness through consolidation. Under the proposed platform, parcels from several well-known logistics service providers would be picked up by a third-party cargo bike company and transported to a hub for sorting and further transport and delivery by the logistics service providers. Using cargo bikes for pickups, combined with the benefits of consolidation, aligns well with the city's sustainability goals. Ultimately, the research trial did not reach full deployment, mainly due to the complexity involved with clearly outlining the business processes as well as the sharing of costs and benefits across the partners involved.

The pilot testing of an autonomous vehicle with shared passenger and freight transport services included a preparation phase and an operational trial with the vehicle. In the preparation phase, several scenarios were considered to integrate passenger and freight transport, and the final solution included an autonomous shuttle for passenger transport on a business park with a small parcel locker being installed in the vehicle for freight transport. The vehicle, with a capacity for nine passengers, traversed a 2-km route with six stops operating between 11 AM and 6 PM. From June 2022, the operational trial ran for one month with passengers only and then for one month with the parcel locker installed. The parcel locker that was installed had three small and three medium-sized compartments, and functioned like a traditional parcel locker in that customers could simply select it as delivery location during checkout at a web shop.

2.3 Bremen Research Trials

The Bremen research trials focused on scaling up containerized urban freight transport and exploring solutions for integrating passenger and urban freight transport.

Containerized urban freight transport relies on the "Physical Internet" metaphor [8]. Here, seamless material handling because of standardized containers should lower the cost of transshipment and hence facilitate transshipment to smaller-sized vehicles in an urban context. In the research trial, the notion of containerized transport included two container sizes: The smallest container fits exactly on the back of a cargo bike and can be loaded onto the bike in one go; the larger one fits exactly nine of the smaller ones. By pre-loading the smaller containers at an upstream facility based on their last-mile delivery sequence and then loading these into the larger container in the same order, the time spent on downstream material handling is minimized, which enhances the efficiency of using cargo bikes for the final stages of development. After successful pilot tests with smaller, mostly B2C parcels, the trial expanded the scope of the containerized solution to larger B2B shipments. The goal was to study if the solution fits this broader scope.

The integration of passenger and urban freight transport was pursued in two ways. First, a community-based cargo bike lending scheme was rolled out with the aim to introduce cargo bikes to citizens in Bremen. Each cargo bike is assigned a "host", typically a local shop or coffee bar. The host provides a parking spot, manages reservations, and assists with maintenance. Users can reserve a bike online—free of charge—and use it for transporting goods for which they would otherwise use a car. Second, a digital pilot explored the potential for combining parcel pickup and delivery with on-demand passenger transport services. Based on real-world data from reference cities, a digital environment was created to test different ways in which parcel transport could best be integrated in the on-demand passenger transport services. The final solution that was tested aimed at picking up parcels from local businesses and delivering them to locations nearby, and utilizing vehicles needed for passenger transport in that same area whenever idling.

3 Business Model Implications

The ULaaDS research trials in Groningen, Mechelen, and Bremen provide valuable insights into the challenges and opportunities of implementing sustainable urban freight transport solutions.

Like many of its sister EU projects, the ULaaDS research trials mostly deployed and studied innovative solutions at a relatively small scale. Achieve meaningful environmental and social impact, however, requires scaling these solutions to city-wide or regional levels. While the technology underlying many solutions is, in essence, ready for large-scale deployment, taking them from 'proof-of-concept' to widespread application remains a key obstacle in the journey towards sustainable urban freight transport. Scaling up raises complex questions around infrastructure investment, operational feasibility, and commercial viability.

A notable observation across the trials is the relationship between private businesses and public authorities. When deploying sustainable solutions, private businesses often expect public support—either implicitly or explicitly—through resource allocation or regulatory adjustments. In Bremen, for example, the containerized urban freight transport solution involved public support for the micro-hub operations in terms of finding suitable locations and enabling space on a private parking lot. The cessation of this support led to a halt in activities, raising concerns about the long-term viability of these solutions in the absence of continuous public support.

Another challenge emerges from the juxtaposition of these innovative solutions against business-as-usual. Existing urban freight transport models are characterized by externalized negative environmental and societal impacts. While these negative impacts are widely recognized, this recognition alone does not impede actors in this sector to continue with their operations as they have done for a long time. Indeed, time has allowed business as usual to evolve into a highly cost-effective way of operating, and the business models of innovative, more sustainable solution will likely have a hard time competing on cost—especially before they reach deployment at scale. The challenge for urban planners lies in creating an environment where sustainable alternatives can compete fairly.

The Groningen research trial with shared vehicles highlights the importance of a supportive regulatory environment in influencing business decisions. The introduction of the time-access restriction zone, combined with the launch of the shared vehicle platform, created a unique situation where shopkeepers were more inclined to explore sustainable urban freight transport options. This suggests that policy measures can act as catalysts, nudging businesses towards sustainable practices. This may entail reassessing regulatory frameworks and economic instruments to ensure they encourage sustainability and do not inadvertently sustain harmful practices.

4 Discussion and Conclusions

Each of the innovative solutions tested in Bremen, Mechelen, and Groningen have been the focus of prior academic studies [9–12]. In the ULaaDS project, the aim was to gain insights into the scalability and business model implications when innovative sustainable urban freight transport solutions are deployed in medium-sized European cities.

Insights from the ULaaDS research trials offer a roadmap for sustainable urban freight transport. They underscore that the transition to sustainable urban freight transport requires more than just technological advancement and reveal important challenges when scaling innovative solutions for meaningful environmental and social impact. Notably, these challenges lie in the competition from business-as-usual and the interplay between private business and public authorities, each with mutual expectations about the trajectory towards deployment of innovative solutions at scale. A successful transition hence calls for collaboration among businesses, public authorities, and other stakeholders—creating a comprehensive approach that encompasses technological, business, and regulatory considerations, ensuring that sustainable solutions can compete with business-as-usual on a level playing field. This calls for a reevaluation of regulatory frameworks and economic instruments, ensuring they foster sustainability and do not perpetuate unsustainable urban freight transport practices.

Acknowledgements. This paper summarizes three deliverables related to business and operating models of the ULaaDS trials (D3.1, D3.3, D3.5) published on https://ulaads.eu/. ULaaDS is a project under the CIVITAS initiative and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 861833.

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Performance Assessment of Multi-articulated Flexible Vehicle Platforms in Realistic Road Infrastructure Models

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Abstract. This paper explores the application of modeling and simulation techniques to evaluate the performance of multi-articulated vehicle combinations in real-world scenarios within the context of the ZEFES (Zero-emission flexible vehicle platforms with modular powertrains serving the long-haul freight eco-system) project. ZEFES aims to address transport sector emissions, by pioneering zero-emission vehicle technologies. Assessing the capabilities of these vehicles in challenging real-world conditions, such as roundabouts and sharp turns is necessary, since long vehicle combinations (up to 33.5 m) require large road width for maneuvering. Rollover tendencies in highway entry and exits are also considered. This assessment aides in determining the right vehicle in the right duty for cross border operation. An automated workflow identifies critical road sections using GPS data and constructs digital road models using the OpenCRG framework. GPS data is interpolated for feature extraction, focusing on analyzing heading angle changes. To perform swept path analysis, the available road-width is extracted using computer vision and known road design standards. Realistic vehicle reference trajectories are generated, and driver behavior is modelled to simulate maneuvering, considering the unique characteristics of multi-articulated vehicles, based on empirical methods.

Keywords: Digital Twin · Vehicle Infrastructure Interaction · Computer Vision

1 Introduction

1.1 ZEFES Digital Twin Architecture

As part of the Green Deal, Europe aims for carbon-neutrality by 2050, with a 55% CO_2 reduction by 2030 [1]. The road transport sector targets a 30% reduction, requiring efficient heavy-duty vehicles like Battery Electric Vehicles and Fuel Cell Electric Vehicles. Advances in battery technology, ZEV (Zero Emission Vehicle) allowances, and falling battery costs aid emissions reduction. However, widespread adoption relies on a robust charging infrastructure, which introduces route optimization challenges. The ZEFES project explores real-world ZEV adoption and efficiency enhancements through demonstrators.

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An objective of the ZEFES project is to develop a digital twin platform (in the form of a user interface), with tools for logistics operations, including buying decision, mission planning, right vehicle in the right duty (RVRD), predictive maintenance, etc. The HAN University of Applied Sciences is developing a sub-tool in the RVRD tool to assess the feasibility of using a particular vehicle combination in an arbitrary route/mission. These vehicles suffer from maneuverability and stability constraints, startability and gradeability issues during reduced friction conditions.

1.2 Vehicle-Infrastructure Interaction Simulation

In the sub-tool, Global Positioning System (GPS) data from a mapping/routing Application Programming Interface (API) is analyzed with respect to the performance of ZEVs. Critical sections in routes are classified as roundabouts, sharp turns, highway entry/exits, and steep slopes. Roundabouts and sharp turns are challenging due to the need for large turning radius, while highway entry/exits pose rollover risks. Steep slopes are dangerous due to vehicle gradeability limitations at particular loading conditions. PTV API is used for ZEV charging-optimized routes [2]. These critical sections are simulated with the user's vehicle combination with the following workflow:

1. Perform multi-body simulations using known ZEV parameters and European road infrastructure specifications.
2. Create a simulation result database, with each result signifying a Key Performance Indicator (KPI) for specific infrastructure elements like roundabouts and sharp turns (requiring swept path analysis), highway entry/exits (requiring rollover analysis), and steep gradients (requiring gradeability analysis).
3. The sub-tool running in a Docker environment will obtain the route data, detect critical sections in the route and use the results database for assessing the safety.
4. Safety is then categorized into three levels: green, orange, and red according to the KPI results and this is published back to the API which can possibly replan.

The results database is formulated as a multi-dimensional look-up table of KPIs in order to assess the safety. In [3], the authors present a complete methodology for multi-body modelling and performance assessment. This methodology was then used in [4] to assess the performance of longer and heavier vehicles. With this, the highway entry/exits and sharp slopes can be assessed. However, simulating a ZEV, especially a multi-articulated ZEV with real-world infrastructure conditions has not been achieved in published literature. In [5] and [6] for instance, software such as Autodesk® Vehicle Tracking© and AutoTURN© were used to perform swept path analysis on known roundabouts. These software packages use kinematic models of various vehicle combinations to estimate trajectories. While offering comprehensive customization, these software can only be used manually, and not programmatically, which is required in ZEFES since:

- Simulating every possible ZEV combination, in every possible roundabout size and exit can result in 1000s of simulations, which would be extremely time consuming to perform manually in the kinematic software packages.
- Although kinematic models can provide accurate results in low acceleration, low steering angle simulations, multiple studies have shown that the trajectory errors

increase when highly dynamic maneuvers are performed. In [7], a kinematic model of a car, a 9 degree of freedom (DoF) model and actual test vehicle are compared using a combination of curves and straight line driving. The results indicate that the errors increase with the length of the maneuver. The mean error was 32.5% lower in the 9 DoF model compared to the kinematic model. In conclusion, for a 4 wheeled vehicle, the more turns executed, the higher the errors will be. When considering a multi-articulated ZEV such as an A-Double (tractor-semitrailer-dolly-semitrailer) consisting of tens of wheels, the errors will be significantly higher if kinematic models are used for swept path analysis. Hence, purely kinematic models used in the aforementioned software are not feasible for this methodology.
– Weather conditions significantly influence the road grip. Such tools do not take this into account.

Furthermore, automating the process of determining locations of critical sections along a route is an open problem. Services such as Google Maps provide turn-by-turn directions in their APIs, but lack the ZEV focused logistics optimization.

1.3 Research Objectives

Existing swept path analysis methodologies are unsuitable and hence this paper explores on the following research questions:

– How can specific road infrastructure features such as roundabouts, highway entries and exits be detected in GPS route data?
– What methodologies can be used to extract the usable road width and perform swept path analysis?

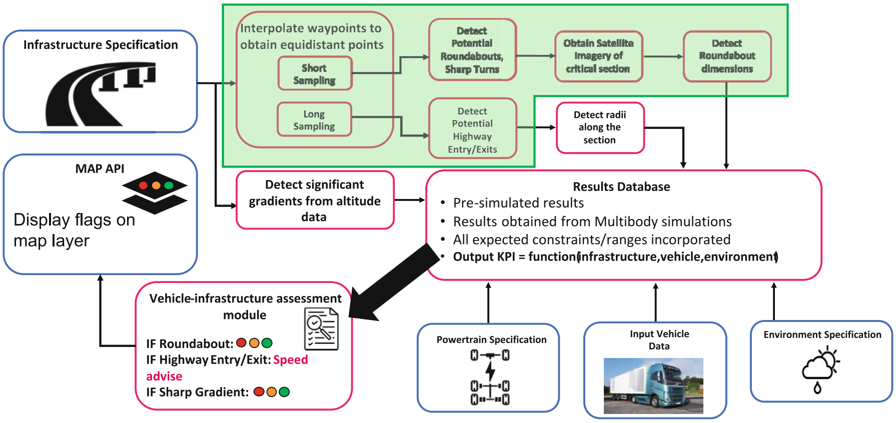

Fig. 1. Methodology to identify critical sections, extract road boundaries and perform vehicle-infrastructure assessment.

Section 2 describes the sub-tool workflow and the detection of critical sections in GPS data, Sect. 3 explores empirical and analytical techniques to extract usable road width.

2 Methodology

The methodology for detecting critical sections in GPS data (see Fig. 1, green portion) involves interpolating the route data, since GPS coordinates along a route are logged as a function of speed and not distance. Equidistant data points are essential for the application of identification algorithms consistently across diverse regions. Data at equidistant query points are interpolated linearly (due to fast computation time).

Two datasets are generated during interpolation, one sampled in 10 [m] steps and another with 50 [m] steps. Shorter steps capture sharp direction changes, while longer steps are ideal for detecting large curve radii. A detection algorithm assesses heading changes between consecutive points. Detecting sharp turns and roundabouts is straightforward, but highway entry/exit detection is complex due to diverse designs. European guidelines specify road section dimensions [8], with motorways having 750–900 [m] radius curves and expressways as low as 35 [m]. Interpolating in 50 [m] steps ensures the presence of at least 2 data points in the sharpest curves, making it suitable for highway entry/exit detection. To detecting highway entry/exits:

- Group consecutive large heading ($>10^{\circ}$) changes data points
- Compute radius of curvature for every 3 points along the group:
  - If the group's mean radius of curvature is < 1000 [m] & length of group is > 250 [m], save as highway entry/exit
  - Else, ignore outlier radii (due to imperfect GPS data) and recompute

Similarly, the algorithm for detecting sharp turns and possible roundabouts:

- Group consecutive large heading ($>20^{\circ}$) changes
- Compute length of the group:
  - If length of the group is $< = 40$ [m] & difference between initial and final heading in the group is $> 60^{\circ}$, save as sharp turn
  - Else, compute radius of curvature for every 3 points along the group:
    - If the group's mean radius of curvature is < 200 [m], perform image detection for detecting a possible roundabout

3 Satellite Image Analysis

After grouping critical sections and identifying possible roundabouts, their satellite images are analyzed to extract the road sections by segmentation. A generalized vision artificial intelligence model OpenGVLab [9], and K-means clustering are considered. While the latter method is simpler, both are sensitive to the image resolution available. To detect a roundabout, as shown in Fig. 2, where the original image (a) is segmented (b), and in its gray scaled image (c), MATLAB's *imfindcircles()* is used to detect circles. This uses Hough's transform, which looks for certain shapes in the image. Using the detected circle's radius, the roundabout boundaries are reconstructed due to known design regulations.

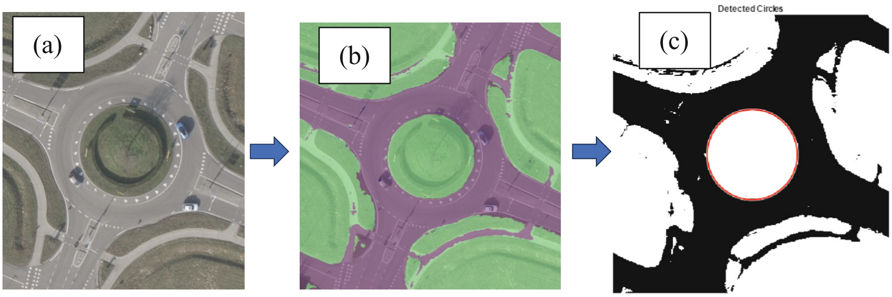

Fig. 2. Extraction of road and non-road pixels and detection of circles. Original image (a); Segmented image (b); Detected circle in red (c). Original image retrieved from MATLAB's Mapping Toolbox [10].

3.1 Swept Path Analysis

After extracting road features, the next step involves simulating a high-fidelity multi-body model on the road surface for swept path analysis. These models use the Magic Formula tire force and torque equations, which implement the combined slip steady-state, and the optionally the turn slip effects [11]. These tire models require a compatible road model. OpenCRG, a widely used road surface file format framework is used to build a road models for each critical section, considering the detected road features. Truck driver behavior at sharp turns and roundabouts indicate that as much of the available road width is to be utilized, see Fig. 3(a), that needs to be reflected in simulations. Hence, a reference path that represents realistic trajectories are created (see e.g., Fig. 3(b)).

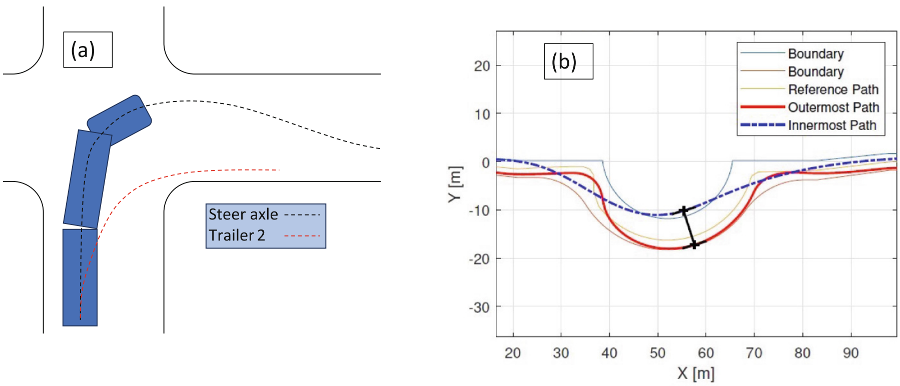

Fig. 3. Truck driver behavior and simulation results. Overshooting the curve [12] (a); Simulation results of an A-Double in a roundabout (b).

With these set of models, numerous model (vehicle and road) parameter permutations are taken into account and the results database is populated for every possible critical section.

4 Conclusions

This paper presented analytical techniques based on heading angles and curvature to detect critical road sections due to the need for programmatic analysis. Road features segmentation was explored using computer vision and data techniques. Additional techniques are required to improve the robustness of circle detection with varying image quality. The results database can be populated with the developed methodology of multi-body simulations which utilize the actual infrastructure information. Although the empirical method to define reference paths in critical sections provide a solution, the path is not optimized for each specific vehicle combination. In future work, a model predictive control based path optimization technique will be pursued.

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Circularity of Reusable Packaging

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Abstract. As part of circular economy, reusable packaging is a key to reduce waste. In order not to ruin the intended sustainability impacts one must take care on the return transport of the reusable packaging and the according logistic concepts. This paper takes a first step in defining a catalogue of use cases to structure the different opportunities of the trip back of reusable packaging to senders. This catalogue is the base terminology to design, optimize and compare concepts regarding their impacts and to derive the according consequences for the entire logistic chain.

Keywords: Circular Economy · Reusable Packaging · Transport Chains · Logistic Concepts · Environmental Footprint

1 Motivation

Packaging, especially for the delivery of goods in the CEP (courier, express and parcel services) domain, results in a lot of waste. It is estimated that packaging accounts for approximately 46% of global plastic waste [1], which is especially true if the parcel's packaging is used just one time. The EC defined several targets for reducing waste in its Directive 94/62/EC of 20 December 1994 on packaging and packaging waste [2]: 65% by 2025, 70% by 2030. To further prevent packaging waste, the European Commission published a proposal for a revision of EU legislation on Packaging and Packaging Waste on 30 November 2022.

Circular economy, and especially reusable packaging, like reusable cardboards, plastic boxes, etc. may constitute a solution. But more stable and robust materials and constructions are needed, which results in a higher environmental footprint for production and maintenance than for single-use packaging. Furthermore, there is an additional transport demand if the packages go back to the sender. This paper focusses on this perspective and contributes to find clever logistics solutions to integrate returns into delivery processes.

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As part of the national research project ReKEP [3], this study structures the opportunities how delivery of goods and the return of packaging can be combined. So far, there is no terminology or catalogue of these options for combined package/goods transport available in the literature. Therefore this paper provides this contribution and build this important first step to a common terminology to enable the selection and optimization of solutions for sustainability logistics with reusable packaging.

2 Definition Process

The first step to structure use cases of trips of reusable packaging was inspired by a more general principle in the priorization of measures for sustainable mobility. Like in Austria's 2030 Mobility Master Plan [4] the highest priority 1 is to **_avoid_** transport entirely wherever possible. As priority 2, the transport that is left should be **_shifted_** to the most sustainable mode of transport. And as priority 3, within each mode, traffic should be **_improved_** to reduce energy consumption.

The translation of this priority concept to classes of use cases of trips of reusable packaging is as follows:

Class 1: No additional trip / transport. In this class, the reusable package is only transported with a good in it.

Class 2: Existing transport, without goods. In this class, the empty reusable packaging is taken along by an already existing trip.

Class 3: Additional transport. In this class, additional trips are performed to return the reusable package into further delivery processes. Especially these use cases need investigation to minimize the additional transport milage.

With this first classification in mind an iterative process on exploration / brainstorming and feedback sessions within the research team have been performed to come up with a first set of use cases. Each use case has been enriched with a description, one or more examples, comments for clarification and potential variations that are covered in the use case category. This edited collection has been revised in a project workshop by experts and practitioners in logistics and reusable packaging. With this feedback the final catalogue of use cases of trips of reusable packaging was created.

3 Resulting Categories

To visualize the different use cases small figures according to the legend presented in Fig. 1 are attached.Due to text limitations the identified variations are not described in this paper. Such variations are regarding the point in time and the location between the delivery of the good and the start of the return transport of the reusable packaging, the type of packaging as well as the actors involved. Exemplary, the return transport could be performed via a return station.

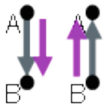
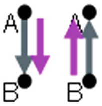


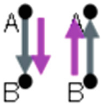
Fig. 1. Legend for the visualizations of the use cases.

3.1 Class 1: No Additional Trip / Transport



[UC 1a] Returns (from the delivery spot). *Description:* Goods delivered in reusable packaging are sent back in reusable packaging without having been used.

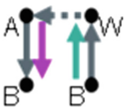
Example: The customer buys clothes from a mail-order-company and sends unsuitable items back to the retailer in the original packaging.



[UC 1b] Sharing of goods. *Description:* When sharing goods, the goods are picked up from a warehouse in reusable packaging and brought to the place of use. After a limited period of use, the goods are returned to the warehouse in a reusable packaging.

Example: The customer receives a tool for use for a limited amount of time and sends it back in a reusable packaging after use.

Comment: In terms of transport, this use case is the same as [UC 1a].



[UC 1c] Waste. *Description:* After delivering a good, rubbish is transported away in the reusable packaging of the delivery.

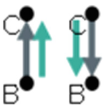
Example: After a good has been delivered, the reusable packaging is used to transport pre-sorted plastic waste.

Comment: The destination of the removal is very diverse and depends heavily on the type of waste (e.g. organic waste, batteries) and the corresponding recycling strategy (reuse, recycling, composting, waste incineration,…).

[UC 1d] Second-hand goods. *Description:* A good is transported after it is used for a longer time from a consumer to the next consumer in a reusable packaging.

Example: To transport goods sold via an online marketplace, reusable packaging that is available at the private seller is used.

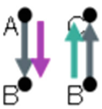
Comment: The Use Case does not pre-define, where the seller takes the reusable packaging from.



[UC 1e] Repairs. *Description:* An item is sent by the user for repair in reusable packaging. After repair it is sent back to the user in reusable packaging.

Example: A laptop is sent by the customer for repair to the dealer in reusable packaging, who then sends the repaired laptop back to the customer a reusable packaging.

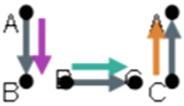
Comment: The difference to [UC 1a/b] is that the starting point for repairs is with the user.



[UC 1f] Onward transport / transport chain. *Description:* The same reusable packaging is used for the delivery of raw materials as well as for shipping the refined product.

Example: The housing of an electronic product is delivered, and the assembled product is sent to retailers in the same reusable packaging.

Comment: When reusing reusable packaging, attention must be paid to the suitability of the packaging for both transport trips (purity, weight, size,…).



[UC 1g] Real circular systems. *Description:* At real circular systems, the reusable packaging is reused in a continuous chain of transport, always filled by the same or different goods.

Example: A company receives intermediate products in reusable packaging, which it reuses when transporting waste products to a processing point. There the reusable packaging can be used to send the processed materials back to the producer of the intermediate products.

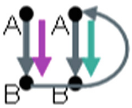
Comment: There are hardly such cycles in traditional product life cycles that allow such a closed chain of transports with the same reusable packaging. This will change soon as circular economy progresses.

3.2 Class 2: Existing Transport, Without Goods

[UC 2a] Unpack and return straight away. *Description:* The goods delivered in reusable packaging are unpacked immediately and the reusable packaging is returned to the supplier.

Example: When receiving the delivery, the customer removes the goods directly from the reusable packaging, which remains with the supplier.

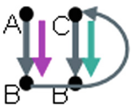
Comment: This is only possible in the case of a personal hand-over.



[UC 2b] Return next time. *Description:* A good is delivered in reusable packaging. With the next delivery from this supplier, this reusable packaging will be given back to the supplier.

Example: The customer hands over to the supplier reusable packaging from a previous delivery from this supplier.

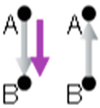
Comment: Of course, starting from the second delivery onwards the reusable packaging from the previous delivery(s) can be returned.



[UC 2c] Give back to someone. *Description:* A good is delivered in reusable packaging. The next time a supplier delivers, this reusable packaging is given back to the supplier.

Example: The customer gives the supplier reusable packaging from an earlier delivery from (any) supplier.

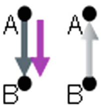
Comment: The difference to [UC 2b is that the supplier of the different deliveries doesn't need to be identical. This asks for standardization of the reusable packaging.



[UC 2d] Return on their own. *Description:* The reusable packaging of a delivery is returned to the sender by the recipient himself.

Example: Filled deposit bottles are returned by the recipient to the sender (e.g. department store) after they have been used/emptied.

Comment: In this use case, there is no CEP like return/onward transport of the reusable packaging.

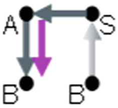


[UC 2e] Shopping Street concept. *Description:* The reusable packaging of a home delivery of a shopping street is returned by the recipient himself.

Example: After purchasing products all goods of all shops of a single customer are collected (e.g. in a delivery center of a shopping street) and delivered to the customer's home in reusable packaging. The customer takes the reusable packaging(s) with them the next time they visit the shopping street.

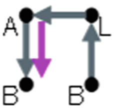
Comment: This is a special version of [UC 2d or UC 2f].

3.3 Class 3: Additional Transport



[UC 3a] Via collection points. *Description:* The return transport of the reusable packaging always takes place via a dedicated collection point. The transport from the recipient to the collection point is carried out by the recipient himself.

Example: The customer transports the reusable packaging received at a delivery to a collection point (e.g. a department store).



[UC 3b] Collection by reusable packaging logistics provider. *Description:* The reusable packaging is collected from the recipient by a reusable-packaging-logistics-provider, bundled and transported to the senders of goods.

Example: Pallet logistics – eg. EUR-pallet [5].

Comment 1: This Use Case is a special case of [UC 2a/b/c]. The main difference is that the return transport of the reusable packaging is coordinated centrally by the reusable packaging logistics provider and can return to the any sender. A pool of predefined reusable packaging is made available if required and collected from the recipient.

Comment 2: In this use case the standardization of reusable packaging, including the qualities necessary for return, is essential.

Comment 3: The role of the reusable packaging logistics provider is usually taken over by a transport company.

[UC 3c] Broker/matchmaker for reusable packaging. *Description:* The demand for reusable packaging from senders as well as offers of no longer used reusable packaging from recipients are coordinated from an intermediary office (exchange/matchmaker). Also, the corresponding transports are organized by this agent.

Example: Company A receives many preliminary products in reusable packaging, but they cannot reuse this packaging any further. The brokerage office now links this offer with a company B that needs this reusable packaging for sending goods.

Comment 1: In this use case, too, the standardization of reusable packaging, including the qualities necessary for return, is essential.

Comment 2: The role of the matchmaking agency can be performed by very different players, from a central, possibly even public, body to a free competition at an (online) stock exchange.

4 Outlook

This paper is just the first step to enable future investigations in the selection and optimization of solutions to achieve the intended sustainability goals originally intended by reusable packaging. Based on this catalogue of trip use cases of reusable packaging, optimization concepts can be developed. In doing so, the established common terminology enables to compare different logistic concepts and their impact on transport mileages, payload-distances as well as energy demand and CO2 emissions.

To take effect it is important to make it known in the research as well as operator and governance community. This paper as well as dissemination activities of the underlying project ReKEP [3] will undertake this task.

From a scientific point of view there is potential to generalize the catalogue beyond the CEP sector and extend it to all applications of reusable packaging. In this way it will create an important contribution to speed up of the introduction of circular economy and the success of the physical internet.

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Circular Economy and Life Cycle Assessments

Laboratory and Field Study of High-Rate Recycled Asphalt Pavement Rejuvenated with Waste Cooking Oil

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Abstract. Europe generates a large amount of site-won asphalt annually. European Union (EU) promised to increase circular economy policies, considering the concerns related to the efficient use of non-renewable resources and the struggle against climate change. Innovative technique's contribution to those goals is of primary importance.

This paper summarises the results of the CoolAsphalt project, aiming to study an innovative process to reuse RAP – reclaimed asphalt pavement – with a high incorporation proportion, up to 100%. High rates of RAP in new asphalt mixtures for pavements require a rejuvenating agent to recover the lost bitumen's volatile components. This study involved the addition of waste cooking oil (WCO) collected from restaurants, canteens and collecting points around municipal territories. Vegetable oil consumption is growing annually worldwide, resulting in a large amount of WCO that needs to be valorised.

The laboratory studies consisted of designing the asphalt concrete blends to apply in real-scale trial sections and assessing their mechanical and functional properties because resistance to ageing could be an issue for the lifecycle of these asphalt mixtures. An accelerated long-term ageing procedure simulated a five-year in-service period for Lisbon's climatic conditions.

The results show that the mechanical and surface properties of the hot (HMA) and warm mixtures (WMA) are suitable for low/medium traffic pavements. During the blends' manufacturing in a conventional drum plant, some issues related to the RAP's water content and the mixing temperature arose. These events allow the authors to highlight some recommendations on producing high RAP content asphalt mixtures with WCO as a rejuvenating agent.

Keywords: waste cooking oil · RAP · mechanical performance · long-term ageing · surface properties

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1 Introduction

Placing value on non-renewable materials has become a critical priority within public policy to attain specific goals related to a circular economy and the sustainable utilization of natural resources. Given the growing emphasis on these societal issues within the construction and maintenance of transport infrastructure, there is a pressing requirement to study and reuse materials for consecutive lifecycles in road pavements to minimize their environmental impact. Reusing of RAP – reclaimed asphalt pavement - has been widely used, but the ratio between manufacturing asphalt mixtures from virgin raw materials and those incorporating RAP is still low in Europe [1]. Hence, practitioners must intensify the incorporation rate of RAP in daily operations to align practice with the ongoing policies. Rising the RAP rate into new asphalt mixtures requires restoring the aged binder properties, such as reducing hardness and the propensity to cracking, and enhancing the capacity to bond to aggregates [2]. In this context, waste cooking oil (WCO) as a rejuvenator for the RAP's aged bitumen emerges as an opportunity to value another waste whose production is increasing globally [3]. This technique diminishes the improper disposal of waste materials like RAP and WCO in unsuitable locations, such as landfills and sewage systems, and reduces energy consumption.

Many relevant papers on the use of WCO to produce bio-bitumen have been published over the last decade [3]. Since most of these studies available mainly involved characterising the resulting bio-bitumen from mixing WCO and bitumen with promising results [3], it is advisable to conduct additional performance assessments on asphalt mixtures manufactured with a high content of RAP and WCO as a rejuvenating agent added during the mix blending process (dry method). This paper exposes the findings on the properties of asphalt mixtures produced in the laboratory and at an industrial scale regarding the recycling of up to 100% RAP while employing WCO as a rejuvenator.

2 Materials and Methods

2.1 Materials

The studied mixtures were based on a typical asphalt concrete for pavement surface layers, AC 14 surf 35/50, considered as reference, with 5% of 35/50 penetration grade bitumen content by mass of the total mixture. The blends with 60 and 80% of RAP and WCO were developed to the same type of layers. Because the asphalt plant could not produce 100% RAP mixes, the study considered 80% RAP for WMA and 60% for HMA as the practicable maximum. The RAP was milled in a 14-year-old pavement with 4.5% aged bitumen content. Figure 1 shows the gradations of RAP and the blends with 60 and 80% RAP superposed to the grading envelope generally used in Portugal.

As the project focuses on investigating cost-effective asphalt mixtures with high RAP rates, the gradation of the blend with 100% RAP had no adjustments to fulfil the gradation specification limits. After some initial studies [4], the results focused in this paper refer to different compositions: a hot-mix AC with 60% RAP, 10% WCO and 1% virgin bitumen (H-60RAP); a warm-mix AC with 80% RAP, 10% WCO, 1% virgin bitumen and 1.5% of organic wax (melting point of 100–110 ºC) as warm-mix additive (W-80RAP). The WCO content was selected based on previous studies [4].

The percentages of RAP and virgin bitumen refer to the blend's total mass, whilst the proportions of WCO and organic wax indicate values by the mass of the total binder. The WCO for the laboratory studies was domestic waste with acidity values between 0.359 and 0.426 mg KOH/g and a 919 kg/m^3 density. The WCO used in the plant at a real scale was collected from urban containers and had acidity values between 3.8 and 4 mg KOH/g.

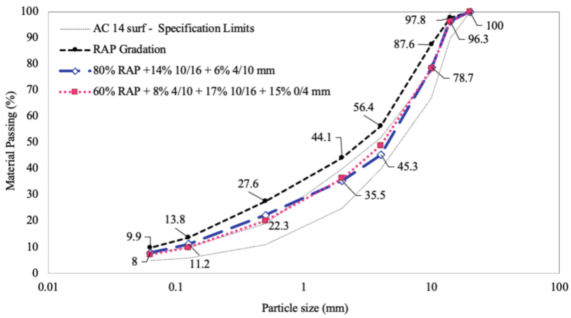

Fig. 1. Gradation of RAP and blends with 60 and 80% RAP

2.2 Methods

In the laboratory, the blends' components were preheated in an oven before mixing at 150ºC for the hot mixes and 130ºC for the warm mixes. After the mixing phase, the blends were placed in an oven at the mixing temperature for 30 min to allow the WCO to interact with the binder. Testing on cylindrical specimens with 102 mm in diameter and 64 mm in height, compacted with 75 blows per face, delivered the volumetric properties and Marshall properties of the studied blends used to determine the initial blend's compositions [4] considering Marshall values of 26.5 kN and 5.0 mm for stability and flow, respectively. These thresholds considered an increase of 25% over the maximum values currently applied for Portuguese specifications for virgin raw materials. The same type of specimens compacted with 50 blows per face supplied the results for water sensitivity in indirect tensile strength (ITS) tests conducted at 15 °C. The indirect tensile strength ratio (ITSR), as specified in EN 12697–12, was considered to evaluate the water sensitivity. Roller compacter moulded slabs to cut prismatic beams with 410 × 50 × 50 mm^3 to evaluate stiffness (EN 12697–26) and fatigue resistance by conducting the four-point bending (4PB) test, performed under controlled strain conditions at 20 °C (EN 12697–26). These tests were performed before and after an accelerated ageing procedure of specimens on TEAGE [5] to simulate a 5-year in-service time. Similar slabs with 40 mm thickness were moulded to assess rutting resistance in wheel-tracking tests according to EN 12697–22 by applying 10,000 loading cycles of a wheel at 50 °C.

The British pendulum test evaluated skid resistance using EN 13036–4 to measure the surface's PTV (pendulum test value). The measurement of texture depth (MTD) was conducted by the volumetric patch method by EN 13036–1.

Cylindrical cores and slabs taken from the pavement prototypes were also tested: cores for water sensitivity, beams from slabs for stiffness and fatigue resistance. Tests conducted directly on the pavement surface evaluated the surface's skid resistance and texture depth.

3 Results and Discussion

3.1 Water Sensitivity

Figure 2 presents the results of ITS and ITSR obtained for laboratory specimens and field cores.

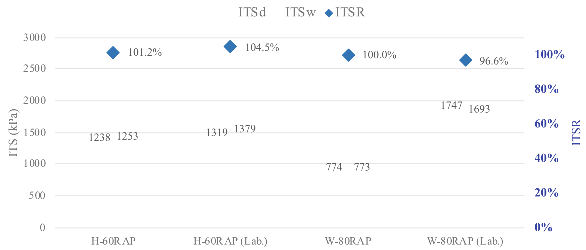

Fig. 2. Water sensitivity in indirect tensile strength tests.

The results obtained for the laboratory and field mixtures tested show low sensitivity to water because the ITSR values are higher than the 80% usually required. However, the ITS values were relatively low for the cores taken from trial sections with W-80RAP. The higher void content (5.7%) measured for field cores for W-80RAP may explain the lower ITS values for these compared with those from laboratory specimens (air voids of 0.2%).

3.2 Rutting Resistance

Figure 3 presents the variation of rut depth with the number of wheel passes for the slabs taken from the pavement trial sections. These curves allowed us to determine RDair (rut depth) and WTSair (slope of the wheel tracking curve in the quasi-linear region), comparing them with similar tests on the laboratory moulded slabs. The results show that the specimens revealed suitable resistance to rutting, notwithstanding the specimens from the field resist less than the compacted in the laboratory (ratio above 1.0). This tendency is verified for RDair and WTSair. In the case of the 80 RAP blend, the highest air void in the field justifies the more significant deformation observed. The mix with 60% RAP exhibited better resistance to rutting regarding RDair and the worst for WTSair. Despite having similar volumetric properties in the field and the laboratory, the different aggregate structures in both situations are likely to explain the worse behaviour shown by the slabs from the field.

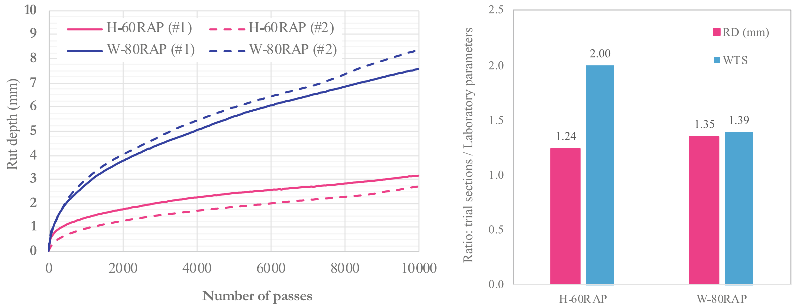

Fig. 3. Rutting resistance of field specimens (left) and ratio between trial sections and laboratory resistance (right).

3.3 Stiffness and Fatigue Resistance

The stiffness moduli measured to field specimens were 2250 MPa and 3770 MPa, at 10 Hz, respectively, for the warm mix W-80RAP and hot mix H-60RAP. These values are approximately 10% less than those of laboratory specimens. Therefore, it seems that the differences mentioned above regarding air voids of the specimens from the field and the laboratory had low influence on the stiffness results.

In what ageing is concerned (simulation of 5 years of exposition to in-service conditions), for the blend W-80RAP, the field mixtures were more sensitive to ageing than those from the laboratory. The "aged stiffness / unaged stiffness" ratio varied from 2 to 2.9 (frequencies from 30 to 1 Hz) for the field specimens, while this variation was from 1.4 to 2 for the laboratory mixture. The higher potential of water and UV radiation access into the specimens through the voids for the field specimens may be the reason behind the observed behaviour.

Fatigue resistance results revealed suitable behaviour for laboratory and field specimens. The results for ε6 – strain needed to attain fatigue failure of specimens after 1 million loading cycles – rising from the fatigue laws of the studied blends revealed the results presented in Table 1.

Table 1. Fatigue resistance of the blends based on the ε6 (μm/m) parameter.

Blend designation	Laboratory specimens	Aged laboratory specimens	Field specimens
H-60RAP	234	179	268
W-80RAP	198	132	251

The results show that the fatigue resistance of the mixtures obtained in the trial sections is adequate and even considerably higher than that observed for the laboratory samples. Moreover, the hot-mix asphalt (H-60RAP) performed better than the W-80RAP, revealing less ageing sensitivity.

3.4 Surface Properties

The surface characteristics of laboratory slabs and the trial sections' surface are summarised in Table 2.

Table 2. Surface properties.

Blend designation	Laboratory specimens	Field specimens	Laboratory specimens	Field specimens
	Skid resistance (PTV)		Texture depth (MTD)	
H-60RAP	80	85	0.91	0.77
W-80RAP	77	85	1.78	1.12

All blends met the standard requirements for texture depth (typically 0.7 mm in Portugal) and skid resistance with a minimum PTV of 60. H-60RAP exhibited a lower texture depth compared to W-80RAP. It should be noted that the surfaces of the slabs produced in the laboratory did not undergo any action to remove the surface bitumen film, which impairs skid resistance. On the contrary, vehicles circulated on the field pavement before skidding resistance was assessed. This situation explains the slightly higher PTV in the field.

4 Conclusions

The results presented in this paper allow the following main conclusions on warm- and hot-mix asphalt with high rate of RAP and WCO as a rejuvenator: 1) low sensitivity to water; 2) Adequate resistance to rutting, with the hot mix showing better behaviour than the warm mix; 3) Suitable stiffness and fatigue resistance, even after being subjected to a long-term ageing process; excellent surface characteristics (skid resistance and texture depth).

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Rejuvenation of High-Content Reclaimed Asphalt Mixtures with Bio-Heating Oil: Laboratory and Plant-Produced Experience

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Abstract. Habitually, bio heating oil – BHO – is valorised to generate energy as fuel for boilers. This matter is a by-product derived from biodiesel production containing mainly volatile elements. These compounds could be beneficial to recover the lighter fractions of aged bitumen of RAP – reclaimed asphalt pavement – to be added in high-rate incorporation in new asphalt mixtures. Although RAP has excellent potential to be reused in pavement construction and rehabilitation actions, the available data for Europe shows that there is a need for additional efforts to achieve higher levels of RAP reuse.

This paper presents results from the project CoolAsphalt, which aims to develop low-cost asphalt concrete on an industrial scale with up to 100% of RAP reuse, meeting appropriate requirements for medium / low-traffic roads. This 30-month ongoing project was funded by the European Union and the Portugal 2020 programme. It involved the study of different hot and warm asphalt blends in the laboratory in terms of empirical, mechanical, and functional properties. Since most of the binder within the blends suffered ageing due to solar radiation and climate exposure, the effect of secondary long-term ageing on mechanical and functional properties was assessed on asphalt mixtures specimens moulded with a high proportion of RAP and BHO as a rejuvenator.

The laboratory results revealed that BHO effectively contributed to recovering the aged binder's properties, considering the results obtained for water sensitivity, rutting resistance, stiffness, and fatigue cracking resistance. Even though practically no gradation adjustment was performed for the resulting asphalt mixtures, the surface and mechanical properties of the asphalt mixtures were suitable. Moreover, the production, laydown and compaction on an industrial scale to build the necessary pavement prototypes allow us to propose some relevant recommendations for using this type of mixture.

Keywords: bio heating oil · RAP · mechanical properties · accelerated ageing · surface properties

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1 Introduction

Despite policies to increase the circular economy in transport infrastructures, available figures indicate further efforts are needed to increase the reclaimed asphalt pavement (RAP) reuse in European road pavements [1]. As RAP is a valuable end-of-life material and its use reduces the consumption of non-renewable virgin raw materials, many authors have been testing it [2]. However, a high content of RAP requires a suitable quantity of a rejuvenating agent to restore the aged bitumen [3]. The literature uses several bio-oils [4], such as those obtained from a biodiesel production plant, where waste cooking oil and animal fats are used as the primary raw materials. The production process involves esterifying the free fatty acids, followed by transesterification. Bio Heating Oil (BHO) is a low-viscosity black oily liquid from biodiesel distillation. This residue mainly comprises less volatile organic compounds and residual Fatty Acid Methyl Ester (FAME).

Several authors have been evaluating the effect of bio-oil on binder's properties and rheology performance [4, 5]. By incorporating bio-oil, the binder's rotational viscosity and softening point generally decrease while the penetration and ductility increase. It also decreases the complex modulus and increases the phase angle. In terms of mixture, the literature mentions that the laboratory mixing time to add bio-oil to virgin binder varies from 10 to 40 min, and the temperature range is 130 to 180ºC [6]. A study using bio-bitumen produced with BHO in asphalt mixtures [7] showed that although the materials' resistance to water damage was suitable, it slightly decreased as the percentage of BHO increased. The same tendency was observed in the wheel tracking test at 60ºC. Results for fatigue revealed some inconsistency because the blend with the bio-bitumen with the highest content of BHO revealed the best fatigue performance. However, the resistance for lower BHO contents blends was lower than that made with the virgin binder.

Despite existing studies, additional laboratory tests should be carried out to assess the behaviour of asphalt mixtures (warm and hot) with a high proportion of RAP and BHO as a rejuvenating agent, even after long-term ageing. This paper presents the findings of a study conducted as part of the ongoing CoolAsphalt project that aims to create an economical paving material for medium to low-traffic roadways while minimising changes to the original properties of RAP and BHO.

2 Materials and Methods

2.1 Materials

The studied mixtures were based on a typical asphalt concrete for pavement surface layers, AC 14 surf 35/50, used as a reference, with 5% of 35/50 penetration grade bitumen content by mass of the total mixture. The blends with 60 and 80% of RAP and BHO were developed to the same type of layers. The RAP was milled in a surface layer with 4.5% aged bitumen content. The gradations of the RAP's aggregates, the blends with 60 and 80% RAP, and the gradation limits generally used in Portugal are presented in Fig. 1.

As the project's primary focus centres on the exploration of cost-effective asphalt mixtures featuring high RAP rates, it's worth noting that the gradation of the blend containing 100% RAP required no adjustments to meet the specified gradation limits.

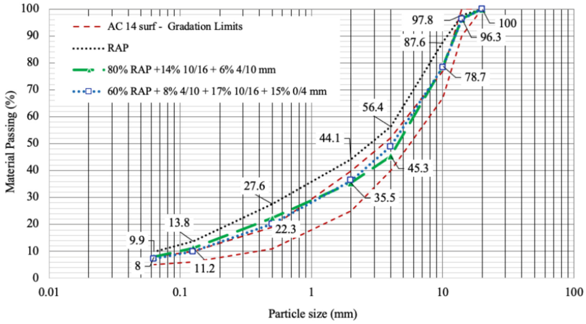

Fig. 1. Gradation of RAP and blends with 60 and 80% RAP.

The compositions evaluated in this paper include a hot-mix asphalt concrete (AC) with 60% RAP, 10% BHO, and 1% neat bitumen (referred to as H-60RAP), as well as a warm-mix AC featuring 80% RAP, 10% BHO, 1% neat bitumen, and 1.5% of organic wax serving as a warm-mix additive (designated as W-80RAP). The contents of RAP and neat bitumen are expressed as a fraction of the total blend weight, whereas the contents of BHO and organic wax are indicated as a percentage of the total binder weight.

2.2 Methods

An oven heated the blends's constituents to allow mixing them at temperatures of 150ºC and 130ºC for hot- and warm-mix asphalt, respectively. Afterwards, the blends were kept in an oven at the mixing temperature for 30 min to allow the contact between the binder and the BHO.

Cylindrical specimens with 102 mm in diameter and 64 mm in height, compacted with 50 blows per face, were tested in indirect tensile strength (ITS) tests at 15 °C, before and after water conditioning to assess water sensitivity, as defined in EN 12697–12. Similar cylindrical cores delivered these results taken from pavement prototypes.

Tests applying 10,000 passes of a wheel at 50 °C (recommended temperature in Portugal [8]) on slabs assessed permanent deformation resistance in wheel tracking tests following EN 12697–22. This type of roller-compacted slabs was sawed to obtain prismatic samples with $410 \times 50 \times 50\ mm^3$ to measure the blends' stiffness (EN 12697–26) and fatigue resistance based on four-point bending tests conducted under controlled strain conditions at 20 °C (EN 12697–24). These tests were repeated after subjecting the specimens to an accelerated ageing procedure to reproduce a long-term period of in-service conditions, with UV radiation and moisture. Cut slabs from the pavement provided results for the pavement prototypes. The pavement surface was evaluated regarding skid resistance with the British Pendulum (EN 13036–4) and texture depth using a volumetric patch method (EN 13036–1).

3 Results and Discussion

3.1 Water Sensitivity

Results of ITS and indirect tensile strength ratio (ITSR) obtained for laboratory specimens and field cores are summarized in Fig. 2. No results are available for W-80RAP from the pavement prototypes.

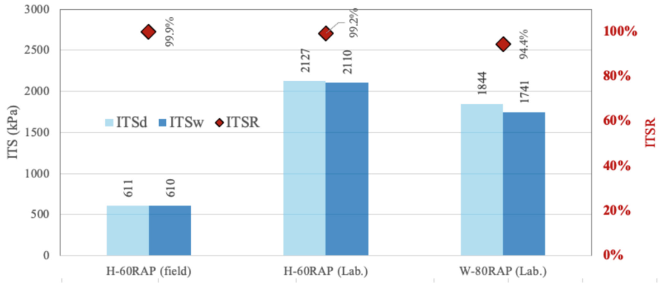

Fig. 2. Water sensitivity in indirect tensile strength tests.

The results show that the studied blends revealed limited susceptibility to water, as evidenced by ITSR values exceeding the typical 80% requirement. However, it's worth noting that the ITS values were comparatively lower for cores extracted from trial sections. This disparity in ITS values may be attributed to the higher void content observed in the field cores, measuring at 3.7%, in contrast to the laboratory specimens with significantly lower air voids (around 0.5%).

3.2 Permanent Deformation Resistance

The wheel tracking tests conducted on slabs of the different compositions provided curves that represent the growth of rut depth with the number of loads. RDair is the rut depth at 10,000 cycles, and WTSair represents the mean curve's slope between cycles 5,000th and 10,000th (Fig. 3). Additional results of H-80RAP-0.6NB are also presented to show that the resistance increases by reducing the neat bitumen content from 1.0% to 0.6%. No results are available for W-80RAP from the pavement prototypes.

Although the observed resistance is suitable, i.e., all the blends achieved low rut depth values), the slabs sawed from the pavement prototype (60% RAP) revealed less resistance than the corresponding slabs moulded in the laboratory. The higher void content achieved in the field may explain the difference. As expected, warm-mix asphalt blends with 80% RAP performed worse than hot-mix.

3.3 Stiffness and Fatigue Behaviour

The hot mix H-60RAP blends and specimens produced in the laboratory achieved stiffness values of 5,287 MPa (10 Hz, 20 °C) before accelerated ageing and 6,370 MPa

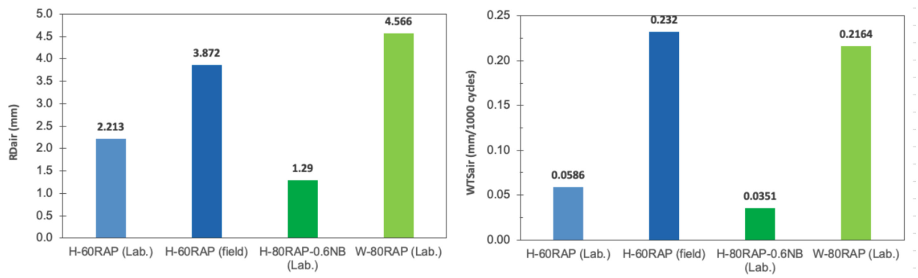

Fig. 3. Permanent deformation resistance of laboratory and field specimens: RDair (left); WTSair (right).

after being subjected to this conditioning procedure. Nevertheless, specimens cut from the pavement prototype only reached 1,290 MPa. The voids obtained for the pavement trial sections were probably responsible for the low performance obtained for the field specimens. For the same temperature and frequency conditions, the laboratory-produced warm-mix W-80RAP attained 3,192 MPa and 4,159 MPa, respectively, before and after ageing. No field specimens were available for this blend. Although the H-60RAP blend exhibits a comparatively higher level of rigidity when compared to the W-80RAP, both are suitable for use as a pavement surface layer. The better aggregate structure of H-60RAP and the presence of organic wax in the W-80RAP likely explain those results.

Regarding fatigue resistance measured in four-point bending tests, the material's showed suitable behaviour. Table 1 summarizes the regression equations parameters *a* and *b* ($\varepsilon = a.N^b$), the determination coefficient (R^2) and the values for ε_6 (μm/m) – strain needed to get specimens failure at 10^6 loading cycles.

Table 1. Fatigue resistance performance of blends.

Mixture name	Laboratory specimens			Laboratory specimens after ageing			Field specimens		
	a	b	R^2 (%)	a	b	R^2 (%)	a	b	R^2 (%)
H-60RAP	1799.0	−0.152	91.8	1504.7	−0.171	87.7	1773.8	−0.134	78.6
	$\varepsilon_6 = 220$			$\varepsilon_6 = 140$			$\varepsilon_6 = 279$		
W-80RAP	3773.3	−0.215	95.3	1303.1	−0.141	88.5	---	---	---
	$\varepsilon_6 = 194$			$\varepsilon_6 = 186$			---		

Despite the slight decrease in fatigue performance after ageing, the blends revealed suitable behaviour. The mixture with 60% RAP also showed adequate fatigue performance. As generally occurs, the hot-mix asphalt (H-60RAP) better-resisted fatigue than the warm-mix, W-80RAP, but revealed higher ageing sensitivity regarding fatigue behaviour.

3.4 Texture Depth and Skid Resistance

The mean texture depth (MTD) and the skid resistance (PTV) of the pavement prototypes' surface are presented in Table 2.

Table 2. Surface properties (laboratory / field).

Mixture name	Skid resistance (PTV)	Texture depth (MTD) (mm)
H-60RAP	80 / 79	0.79 / 0.90
W-80RAP	77 / 83	1.09 / 1.71

The results adhered to the standard criteria in Portugal, with minimum values of 0.7 mm and 60 for MTD and PTV, respectively. H-60RAP had a shallower texture depth when compared to W-80RAP. Although there is no significant difference in PTV results for the laboratory and pavement surfaces, MTD was higher for the latter, considering its higher void content, resulting in a more textured surface than the laboratory compacted slabs.

4 Conclusions

The findings presented in this paper lead to the following critical conclusions regarding warm- and hot-mix asphalt that incorporates a high percentage of RAP (Recycled Asphalt Pavement) and utilises BHO (bio-heating oil) as a rejuvenator: a) low susceptibility to water damage; b) sufficient resistance to permanent deformation, with the hot mix displaying superior performance compared to the warm mix; c) appropriate stiffness and fatigue resistance even after undergoing an extended ageing process; d) outstanding surface attributes, including skid resistance and texture depth.

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Towards a Sustainable Design and Circular Economy for Hybrid EV Batteries

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Abstract. The HELIOS European project, funded by the H2020 Programme, aims to develop lighter, modular hybrid Li-ion battery packs for EVs that combine same-size modules with high-power and high-energy cells to meet customer demands for fast charging and long-range capabilities. Nevertheless, it is important to consider the potential environmental impacts associated with the disposal of such hybrid batteries. This includes the consumption of a wider range of raw materials, the release of hazardous substances, and the emission of greenhouse gases. To address these concerns, the HELIOS project also focuses on improving the sustainability of the battery pack by creating designs for easy reuse in second-life applications and by developing recycling strategies at the End-of-Life (EoL) of the battery pack. The project has progressed in three key research areas: 1) Designing the battery pack to incorporate possible second-life scenarios using a modular configuration and enhanced dismantling techniques. 2) Froth flotation experiments were carried out to study whether graphite could be recovered in a reusable form and to create data for future LCA calculations. 3) Parallel to the froth flotation experiments, LCA methodology supported by the ISO 14040 series was used to create a baseline to evaluate the environmental impacts of the hydrometallurgical recycling of the NMC811-graphite cells. This baseline could be used later to assess the impact of graphite recovery by froth flotation, as the current LCA baseline excludes the recovery of anode materials (graphite and LTO).

Keywords: Hybrid EV Battery · Recycling · 2nd Life · Dismantling · Refurbishment · Life Cycle Assessment · Environmental Impacts

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1 Introduction

The growing electric vehicle (EV) markets have increased the demand for raw materials needed in the production of lithium-ion batteries (LIBs) to power the transition towards transportation sector electrification [1]. Furthermore, this fast-growing rate of raw material consumption also raises concerns regarding material availability, for which recycling offers a potential solution to narrow the gap between the supply and demand of lithium-ion battery (LIBs) raw materials. Consequently, the European Union has imposed new stricter recycling requirements for critical materials and from 2030 onwards, 70% of LIBs materials need to be recovered to reduce impacts due to mining [2]. However, the efficient separation of the active components and their recovery from battery wastes remains a challenge.

In addition to the regulations encompassing a wide array of requirements designed to encourage the recycling of key battery raw materials [3, 4], the European Union has introduced new targets aimed at promoting sustainability [5]. These include carbon footprint performance class requirements, applicable from 1 July 2025, for electric vehicle batteries and the reduction of battery weights [6]. The new EU laws underscore the importance of designing batteries for easy reuse in second-life applications, thereby paving the way for a more sustainable future in energy storage. Compared to directly recycling lithium-ion batteries after their electric vehicle use, the carbon footprint and energy use of batteries recycled after their second life can be reduced by 8 to 17% and 2 to 6%, respectively.

Utilizing Second-Life batteries can provide numerous advantages that contribute to their overall sustainability. Firstly, they extend the useful life of EV batteries, delaying their disposal and reducing waste [7]. Moreover, they can offset the need for new battery production and its associated environmental impact [8]. Finally, they can provide affordable energy storage solutions that support the integration of renewable energy into the grid [9]. At the European level, the potential for Second-Life batteries is significant. With millions of EVs expected to be on the roads in the coming years, a vast number of batteries will eventually reach their End-of-Life (EoL) [10]. These batteries often retain a substantial portion of their original capacity and can still provide valuable service in second-life applications prior to the final EoL recycling [11].

Currently, lithium-ion batteries are constantly undergoing development to improve EVs performance requirements for higher power density, fast charging, and longer cycle life. Therefore, a large variety of cell chemistries as well as pack, module and cell designs have entered the market to meet these demands [12]. Nonetheless, designs that are being developed to offer improved LIBs performance and longer lifetimes often result in new material selections and combinations that may not have established recycling strategies. For example, material selection can include raw materials with low economic value, which can create challenges for their separation within existing metallurgical recycling infrastructures. The wide variety of cell chemistries and module and cell designs in the market means that pyrometallurgical treatment is currently the only economically viable option, as it offers enough flexibility in terms of process feed, although with the caveat that materials such as graphite or Li are lost. [13–15].

The HELIOS project, funded by the European Union's Horizon 2020 program, has developed a series of modular and lightweight hybrid Li-ion battery packs. These packs combine high-power cells comprised of NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) cathode and a $Li_4Ti_5O_{12}$ (LTO) anode, with high-energy cells featuring an NMC811 cathode and graphite anode. The aim of the project is to explore suitable solutions for recycling these battery modules at their EoL, as well as dismantling and refurbishment approaches to promote second-life usage and recycling. The outcomes of these efforts will be integrated into Life Cycle Assessment (LCA) models to support a sustainable and circular design for hybrid batteries.

2 Methodology

Three approaches are outlined in this study following strategies that are being developed in HELIOS project to improve the sustainability of the hybrid battery pack:

- Novel manufacturing and dismantling processes enable second life use and new methodologies for recycling and metal recovery.
- Graphite recovery from mixed NMC811-graphite-LTO chemistries is studied experimentally by froth flotation. The experiments simulate the behaviour of a perfectly liberated model NMC811-graphite-LTO system in the froth flotation process without the effect of binder, electrolyte, solid electrolyte interphase (SEI), current collector pieces and plastics to test froth flotation's potential for inclusion as part of battery recycling strategies.
- The environmental impacts of recovering Co, Ni, Mn, and Li from NMC811-graphite cells by hydrometallurgical processes were simulated and an LCA was performed to obtain an overview of the environmental impact of recovering these elements.

The outcomes of these three approaches are planned to be included in more detailed cradle-to-grave LCA models. Furthermore, an additional LCA focused on a process to recover the nickel by using a hydrometallurgy process is also to be undertaken.

3 Novel Manufacturing and Dismantling Processes for Hybrid Battery Packs

This section explains the methodological strategies to enhance the efficiency and safety of recycling processes, with an emphasis on circular design principles. The principles of the circular economy revolve around designing out waste and pollution whilst maximizing the useful life of products and materials. The main principles where the HELIOS actions are focused are as follows:

- Design Out Waste and Pollution [16]: In a circular economy, resources are used efficiently, and waste is designed out of the system from the beginning. This means that products are designed and optimized for a cycle of disassembly and reuse, which can significantly reduce waste and pollution.
- Keep Products and Materials in Use [16]: The focus is on creating a "closed loop" system where resources are not just consumed and discarded but are reused, repaired, or refurbished to extend their life. This includes considering second-life applications for products or components that can no longer serve their primary purpose.

- Rethinking of Business Models [16]: Companies are encouraged to rethink their business models to support longer product lifetimes, modular design, product sharing, leasing or take-back schemes that can help keep products and materials in use for longer. By aiming to improve the efficiency of each stage, new methods to design products via a holistic approach are applied, taking into consideration their entire lifecycle, from disassembly to manufacturing and (re)assembly - the main methods are described as follows:

The new procedures are based on a thorough Analysis of Existing Techniques used in the industry that include:

Robotic Battery Disassembly: currently battery packs are manually dismantled, which requires skilled labour and specialized tools. The introduction of robotic disassembly based on current approaches will improve the performance of the process, reduce the risk of harm to workers and decrease costs, making recycling more economically viable. Another advantage is that robots can perform tasks with extremely high precision, which will reduce the risk of damaging valuable components and will ensure that valuable battery cells are handled carefully. During the disassembly process valuable data about aging, and reliability. Etc. could be collected and analyzed.

Process Optimization: development of new procedures for dismantling and refurbishment to streamline and automate the recycling process. by involving deconstruction planning where CAD design is used for pre-planning the disassembly process where the robot follows a predefined plan to remove components in a specific order. This approach includes also exploiting the modular design where the process is simplified because robots remove not only components but entire modules. Another advancement in process optimization is that the design is done in such a way that at almost all steps disassembled components are designed to be manufactured from the same material. This will facilitate second life use and introduce new methodologies for recycling and metal recovery.

The HELIOS battery pack prototypes represent a significant advancement in battery technology, a unique combination of performance, flexibility, and cost-effectiveness through the combination of high-energy (HE) cells for increased range and high-power (HP) cells for faster charging in separate modules. By utilizing a modular design with the same size and shape plastic housings or "egg-box" (each cell inside is separated like eggs in a cardboard box), these battery packs provide a versatile solution that can be seamlessly integrated into different EV models to accommodate various power and energy demands (Figs. 1 and 2).

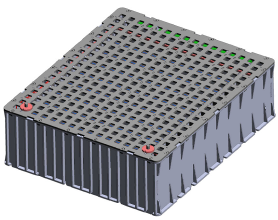

Fig. 1. HE module in "egg-box"

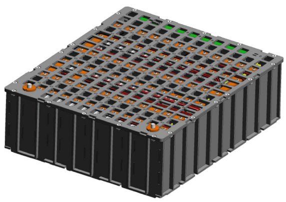

Fig. 2. HP module in "egg-box"

Either four HE or HP modules are then packaged into the so-called "subpack" that contains its own cooling circuit (Fig. 3).

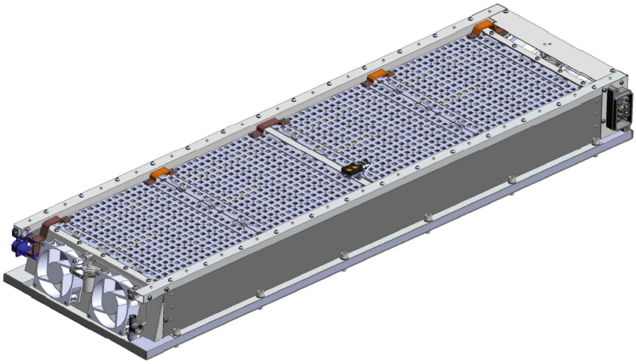

Fig. 3. Helios subpack with 4 identical modules inside

According to the needs of the original equipment manufacturer (OEM) and end-users, these subpacks can be combined in any way to meet the demands of a specific application, hence they are customizable to drivers' requirements and scale-up for different size of EVs. The interconnections between the subpacks inside a full HELIOS battery pack are quite simple and based on high voltage (HV) copper busbars and wires, which allows easy removal of individual subpacks for reuse in second-life applications like energy storage.

Furthermore, at the ultimate EoL, the complete dismantling of a subpack for the final recycling of all materials inside the "egg-box" modules is planned to be a straightforward and mainly automated process.

4 Froth Flotation as a Potential Strategy for Graphite Recovery from NMC811-Graphite-LTO Chemistries

The recycling of LIBs is primarily linked to the economic worth of the metals they hold. At present, only the most valuable metals, including Cobalt, Nickel, and Copper, are commonly extracted. [15]. From the HELIOS battery cells, Ni and Cu are predicted to face future supply risks [17] whereas Co, natural graphite and – more recently - Li, Ti, Mn and Al are also categorized as critical raw materials by the EU [2] highlighting the importance of developing strategies for the optimal recycling of these elements.

The material selection of the HELIOS battery pack poses challenges for critical raw materials recovery based on the industrial-scale extractive options currently employed for recycling spent LIBs. Pyrometallurgical processes, widely used for their high reaction rates and lack of requirement for passivation or dismantling, produce a metal alloy and a slag that contains the various oxides from Li-ion battery modules. However, this approach significantly loses critical battery materials and graphite, which is reduced to CO_2. [12, 14, 18]. Furthermore, the loss of these components will make it difficult to reach the future EU battery recycling requirements.

Consequently, research has shifted more towards hydrometallurgical recycling as a larger number of elements can be recovered, often with high selectivity [19]. Traditional hydrometallurgical recycling uses acidic media to leach metals from waste Li-ion battery electrodes, producing a solution for purification and recovery through precipitation and solvent extraction. These processes can be complex, yielding high-purity metals, but also significant secondary pollution [20, 21]. In addition, hydrometallurgical recycling is not an optimal method to recover graphite spent LIB mixtures. Graphite is porous and adds volume to the feed material, increasing water and acid consumption and producing a viscous slurry that is difficult to filter and wash [22]. Graphite particles may also get damaged during leaching, preventing its reuse it as an anode material [23, 24].

Although graphite recovery has not been the focus of most recycling processes so far, anodic graphite represents 14 – 22% of a LIBs weight and can help to satisfy the future EU recycling requirements [17]. Thus, froth flotation has recently attracted the attention for use in graphite recycling, since it is a physical separation method in which the graphite structure can be maintained, thereby allowing the direct reuse in new batteries manufacturing [17, 23, 25, 26]. Froth floatation is able to separate lithium metal oxide powder from the graphite in Li-ion batteries, by exploitation of their different wettability characteristics. Bubbles introduced into a stirred vessel containing the black mass collect hydrophobic materials, producing a graphite-rich froth. Additional reagents can enhance froth stability and promote wettability differences [27]. Direct recycling of graphite could be economically attractive if its structure were preserved and if it could be recovered with battery grade purity (> 99%). [26].

Material and methods, discussion, and preliminary results by application of this novel method in the HELIOS context are described in the following sections.

4.1 Materials and Methods

Pure battery-grade graphite, NMC811 and LTO particles were mixed according to the expected active material composition of the HELIOS battery modules, i.e., 50% of NMC811—as cathodes in both cell types contain this active material—25% of LTO and 25% of spherodized graphite particles. The particle size distributions of these model materials (shown in Fig. 4) were measured with a laser diffraction particle size analyser (Malvern Panalytical Mastersizer 3000, Malvern, UK) and the sources of chemicals used are listed in Table 1.

A laboratory-scale, 1 L flotation cell (Lab Cell-60mm FloatForce mechanism, Outotec, Espoo, Finland) was used for the flotation experiments. 40 g of the active particle mixture (50% NMC811; 25% graphite; 25% LTO) was added to 1 L of ion exchanged water and mixed by impeller at 1000 rpm for 3 min, after which the rotation speed was reduced to 850 rpm and 8 ppm of MIBC frother was added to the cell. The pulp was conditioned with MIBC for 2 min, and then air was introduced to the cell through the impeller at a flowrate of 2 l/min, to create bubbles and initiate the flotation experiment. Collection of the froth started when the froth rose to a suitable level and it was then sampled at time intervals of 0–1 min, 1–3 min, and 3–8-min to study the flotation process kinetics. The collected concentrate samples and the remaining pulp in the flotation cell were filtered and dried in a convection oven.

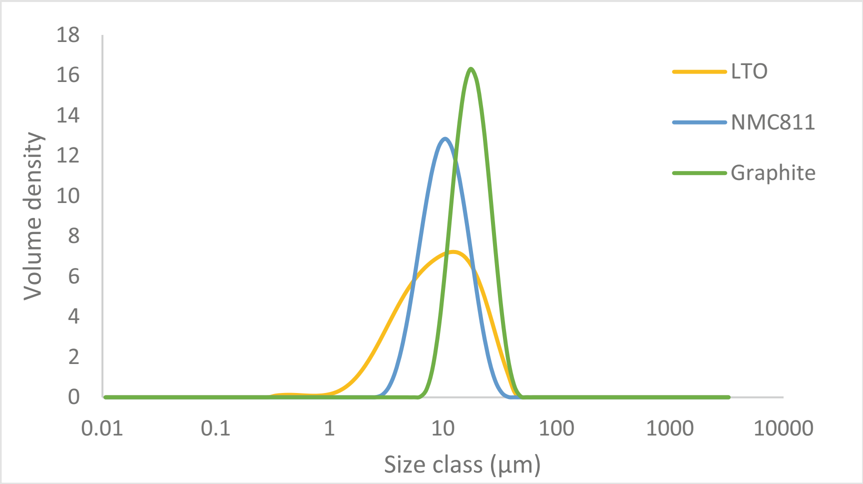

Fig. 4. Particle size distributions of model black mass.

Table 1. Materials and reagents used in froth flotation experiments of model black mass.

Distributor	Chemical	Purity [%]
MSE Supplies, Tuscon, AZ, USA	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	Battery grade
MSE Supplies, Tuscon, AZ, USA	$Li_4Ti_5O_{12}$	Battery grade
ProGraphite GmbH, Untergriesbach, Germany	Spherodized graphite	99.95
Sigma-Aldrich, St. Louis, MO, USA	Methyl isobutyl carbinol	98

These dried samples were subsequently weighed, and their composition analysed by XRF (Oxford Instruments, X-MET 5000, Abingdon, UK) and SEM-EDS (Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy) (MIRA3 SEM, Tescan, Brno, Czech Republic and UltraDry Silicon Drift Energy Dispersive X-Ray Spectrometer combined with NSS Microanalysis Software (Thermo Fisher Scientific, Waltham, MA, USA)). A schematic representation of the froth flotation experimental procedure is presented in Fig. 5.

4.2 Findings and Analysis

The hydrophobic graphite particles are collected in the froth phase, while the hydrophilic lithium metal oxides remain in the tailings. Nevertheless, with increased flotation time, the grade of the recovered graphite was found to decline - as shown in the SEM images presented in Fig. 6.

Rinne et al. [28] and Vanderbruggen et al. [17] have attributed this lowering of graphite grades to entrainment, which occurs as lithium metal oxide particles are carried with process water to the froth layer. Entrainment is an unselective recovery mechanism

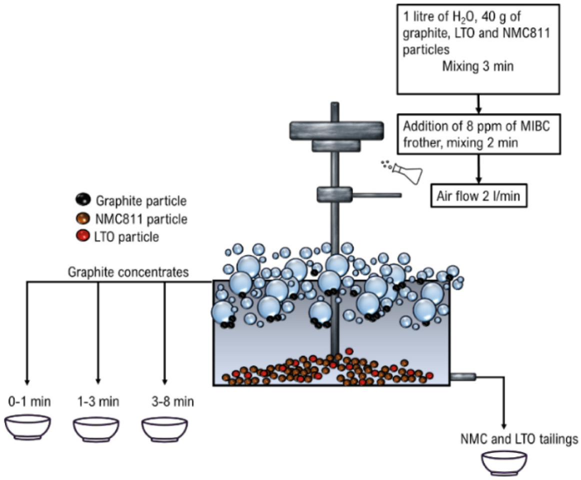

Fig. 5. Flowsheet of the froth flotation experiments.

and fine particles are more prone to be recovered by this mechanism since their settling rate is slower cf. Large particles [27]. Vanderbruggen et al. [17] measured a linear correlation between NMC111 contamination in the recovered graphite and water pulled from the flotation cell, indicating that graphite grade declines due to entrainment of particles below 10–15 µm size range. Interestingly, Vanderbruggen et al. [17] also measured significant amounts of pure NMC111 particles attaching to air bubbles in their captive bubble experiments. It is therefore possible that NMC811 and LTO particles exhibit both entrainment and true flotation behavior. The improvement of graphite grade therefore depends on the prevention of lithium metal oxide recovery by any of these mechanisms. For example, Rinne et al. [26] improved the grades of recovered graphite by increasing LCO particle sizes with selective flocculation.

Use of selective depressants targeting the LTO and NMC811 particles could also improve the graphite grades by reducing true flotation [17]. Lithium is known to leach to the process water and Li + ions have been shown to stabilize froths, thereby increasing water recovery and entrainment. Therefore, washing the black mass before flotation has resulted in improved graphite grades. [26, 28] Other options for reducing entrainment include lowering solid-liquid ratios [29] and selectively flocculating lithium metal oxides into larger particle clusters [26].

Figure 7 shows the cumulative grade vs. cumulative recovery curves and flotation kinetics of the 50% NMC811–25% LTO-25% graphite mixture. The data points represent the arithmetic mean from four repeated experiments under identical conditions and the standard deviations of the results. The large experimental variation can be partly attributed to the manual froth collection. On average 87.8% of the graphite could be recovered with 94.8% grade and 50% of the graphite can be recovered with 98% grade. These results show that froth flotation has the potential to be used for the direct recycling of LIBs, although further research to optimize the froth flotation process is needed to achieve consistently $>$ 99% grades.

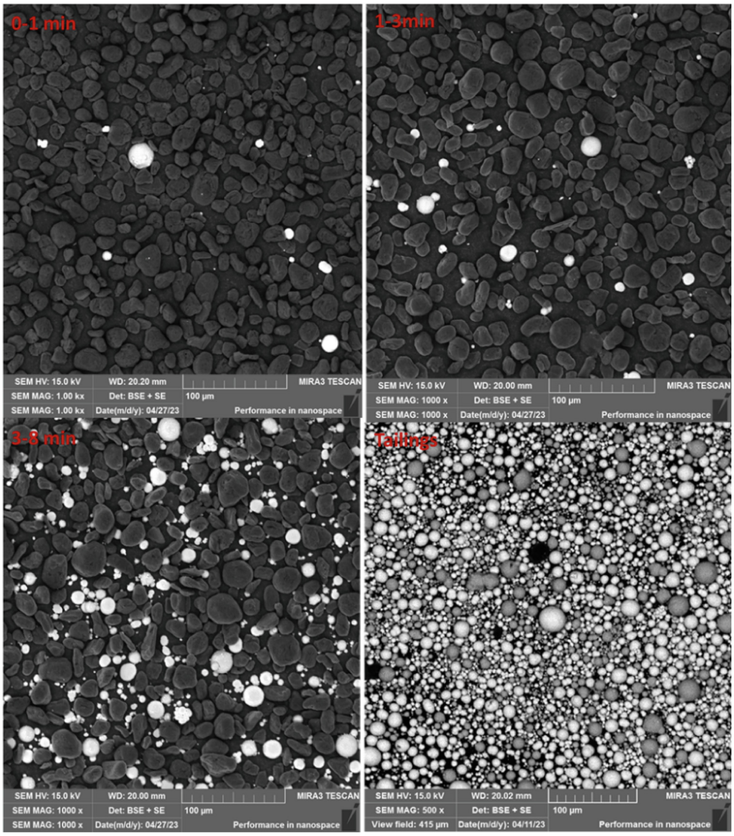

Fig. 6. Comparison of the graphite concentrates collected during 0–1 min, 1–3 min and 3–8 min flotation times and the remaining tailings. Black particles are graphite, grey particles are LTO, and white particles are NMC811.

The kinetics of graphite flotation were determined by fitting the graphite recoveries collected at different time intervals to the classical first order kinetic model according to Eq. (1) [27, 28] to obtain the rate constant k = 0.85 for the electrode mixture studied.

$$R(t) = R_{max}\left(1 - e^{-kt}\right) \tag{1}$$

where, R(t) is the recovery of graphite at time (t), Rmax is the maximum recovery after the experiment and k is the rate constant.

Such kinetic data, graphite grades information and recoveries could be utilized in the HSC simulations and LCA calculations related to the recycling of HELIOS modules.

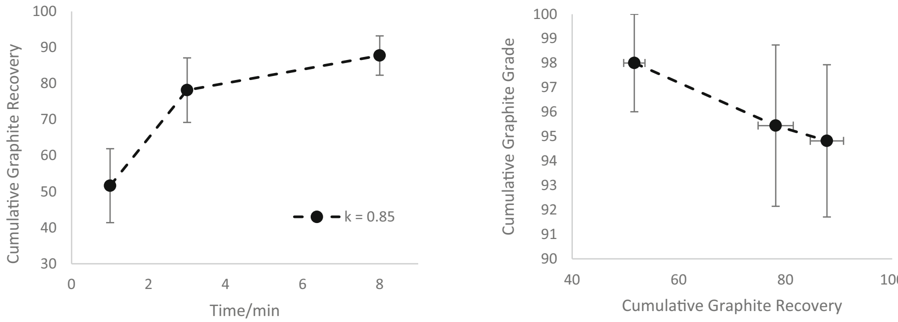

Fig. 7. Cumulative grade of graphite as a function of graphite recovery and graphite recovery as a function of flotation time during froth flotation of model black mass composed of 50% NMC811, 25% graphite and 25% LTO. The curves represent repeated experiments under identical conditions.

5 Environmental Impacts of Recovering Co, Ni, Mn, and Li from NMC811-Graphite Cells by Hydrometallurgical Processes: A Simulation and LCA Study

Process simulation is a useful tool when reliable industrial data is unable be obtained. In this case, the HSC Chemistry® Sim software module (METSO, Pori, Finland) was utilized to obtain the life cycle inventory (LCI) of the emerging hydrometallurgy recycling process. An extensive literature review was carried out to obtain the parameters for the process simulation and chemical reactions. Open LCA software by Green Delta was utilized to generate the life cycle analysis with the support of the Ecoivent 3.6 database developed by the Swiss Centre for Life Cycle Inventories.

5.1 Goal and Scope

The goal of the study was to understand the environmental impacts of recycling black mass with a high content of nickel. The functional unit selected is 1 kg of recycled black mass. For the environmental impacts it was planned that the LCA-related work undertaken as part of HELIOS would not only cover the carbon footprint of the EV batteries, but also consider additional impact categories of relevance for the actors involved in their mining, manufacture, and use by a grave to gate study. Preliminary treatment of the black mass by crushing, magnetic separation, and sieving is not included in the scope of this study along with the binder and electrolyte effects on the system.

5.2 System Boundary

The system under study is shown in Fig. 8 and depicts the hydrometallurgy process for battery recycling proposed for the black mass with high nickel content. The study boundary is composed of leaching, copper cementation, iron and aluminium removal by hydrolysis, manganese solvent extraction and precipitation, cobalt and nickel solvent extraction and crystallization, and lithium precipitation. The effluents from the system are collected and treated via a neutralization step. Nonetheless, the environmental impacts associated with waste management and further wastewater treatment associated with the overall process were beyond the scope of this work.

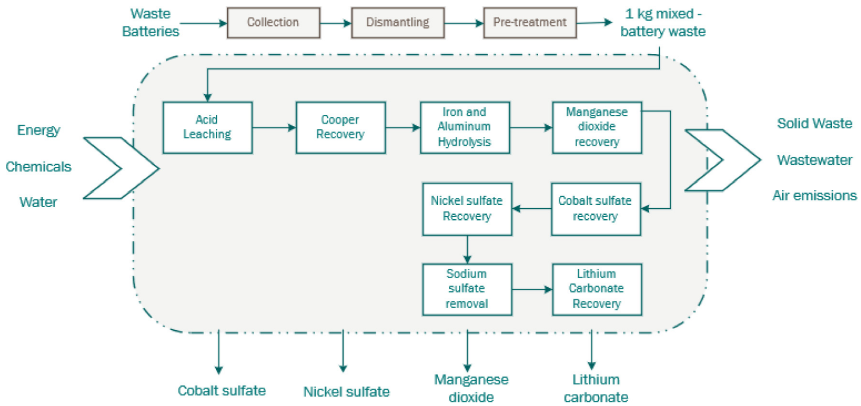

Fig. 8. System boundary and flowsheet diagram of the battery recycling process to study.

5.3 Impact Assessment Methods and Indicators

An LCA was carried out using Open LCA software, and the Ecoinvent database 3.6, with three different impact methods selected to analyse the impact categories. Under this context and aligned with the recommendations in ISO 14044 [29], the Environmental Product Declaration, EPD® system [30] and the PEF method [31], the impact categories shown in Table 2. Are suggested to study the environmental behaviour of the battery solutions. Table describes the environmental category analysed the method used and its description.

5.4 Process Descriptions

The black mass underwent preliminary treatment involving crushing, magnetic separation, and sieving, to achieve a particle size smaller than 0.125 mm. The material that was taken as a reference was investigated previously by Roy et al. (2019) who studied NMC 111 [32]. Nonetheless, the mass percentage of the LCO, LNO, and LMO were modified to stoichiometrically increase the LNO content to match the NMC811 composition. The chemical composition of the black mass fed to the system is outlined in Table (Table 3).

The black mass was fed to a leaching system that comprised of 2M H2SO4 and 4% of H2O2. The pregnant leaching solution (PLS) was further treated in a complex battery recycling circuit to recover copper as metallic copper powder through cementation, manganese recovery as oxide (MnO2), through solvent extraction and oxidative precipitation, recovery of cobalt and nickel respectively as nickel sulphate (NiSO4·6H2O), and cobalt sulphate (CoSO4·7H2O) through solvent extraction and crystallization, and

Table 2. Impact categories analysed, the method used, and units.

Abbreviation	Impact category	Unit (Method)
GWP	Global Warming Potential	kg CO_2-eq (CML)
ADP	Abiotic depletion (elements)	kg Sb-eq (CML)
ADPf	Abiotic depletion (fossil)	MJ (CML)
AP	Acidification potential	kg SO_2-eq (CML)
EP	Eutrophication potential	kg PO_4 3—eq (CML)
FW-AE	Fresh water aquatic ecotoxicity	kg-DCB-eq (CML)
MA-EX	Marine aquatic ecotoxicity	kg-DCB-eq (CML
ODP	Ozone depletion	kg CFC-11-eq (CML)
POCP	Photochemical ozone creation potential	kg ethene-eq (CML)
T-EX	Terrestrial ecotoxicity	kg-DCB-eq (CML)
FPM	Particulate matter	kg PM2.5 eq (ReCiPe)
LU	Land use	m^2 x yr annual crop land (Recipe)
HT-C	Human toxicity potential – Cancer	CTUh (USEtox 2.01)
HT-NC	Human toxicity potential – Non-Cancer	CTUh (USEtox 2.01)

Table 3. Chemical composition of the black mass fed to the system.

Component	$LiNiO_2$	$LiCoO_2$	$LiMnO_2$	Cu	Al	Fe	C	Total
wt%	54.66%	6.57%	6.85%	3.56%	0.78%	1.23%	26.35%	100%

lithium carbonate (Li2CO3). After every stage, all effluents collected and subject to a simple neutralization step were metals (except lithium, calcium, and sodium) which were removed at pH 7. Additionally, the flowsheet removes Glauber salt by increasing the concentration of Li through evaporation to remove (Na2SO4·10H2O) through crystallization, whereas aluminium and iron are taken out of the system as oxides via hydrolyzation (Table 4).

5.5 Process Performance

The selected mass flow for the study was 7000-ton of black mass/year as Rinne et al. (2021) previously proposed in their study where a LIBs and NIMH battery recycling system was investigated [21]. The flowsheet simulation was successfully recovered. ~92% Li, 95% Co, 94% Ni, and 94% Mn. The estimated purity of the recovered materials is shown in Table 5.

Table 4. Simulation parameters for flowsheet simulation in HSC-Sim

Leaching	Unit	Value	Reference
H_2O_2	%	5	[33] [5]
H_2SO_4 concentration	gr/L	196	[33]
S/L ratio	g/L	100	[34]
Mn solvent extraction	Unit	Value	Reference
pH	-	4	[35]
O/A ratio in extraction	vol/vol	1:1	[35]
O/A in stripping	vol/vol	8:1	[35]
H_2SO_4 concentration in stripping	mol/L	0.5	[35]
$MnSO_4$ concentration in scrubbing	g/L	4	[35]
O/A ratio in scrubbing	vol/vol	10	[35]
Mn precipitation	Unit	Value	Reference
SO_2 partial pressure in SO_2/O_2	p.%	6	[36]
pH	-	3–4	[36]
O_2 utilization efficiency	%	33	Estimate
Al and Fe removal	Unit	Value	Reference
pH in neutralization	-	4	[20]
Co solvent extraction	Unit	Value	Reference
pH	-	5.4	[20]
Co loading in extractant	g/L	~17	[37]
O/A in extraction	vol/vol	1:1	[20]
O/A in stripping	vol/vol	1:4	Estimated
H_2SO_4 concentration in stripping	g/L	10	[20]
O/A scrubbing	vol/vol	10:1	Estimated
$CoSO_4$ concentration in stripping	g/L	10	[20]
Ni solvent extraction	Unit	Value	Reference
pH	-	6.5	[20]
O:A in extraction	vol/vol	1:2	Estimate
O:A in stripping	vol/vol	4:1	Estimate
H_2SO_4 concentration in stripping	g/L	10	[20]
O:A in scrubbing	vol/vol	10	[20]
$NiSO_4$ concentration in scrubbing	mol/L	0.3	[20]
Sodium sulphate crystallization	Unit	Value	Reference

(*continued*)

Table 4. (*continued*)

Leaching	Unit	Value	Reference
Li concentration	g/L	20 g/L	[38]
Na_2SO_4 solubility	g/L	12	[38]
Lithium carbonate crystallization	Unit	Value	Reference
Li concentration	g/L	1	[38]
pH	-	12	[38]

Table 5. Material recovered from the software simulations and their purities (%)

Material	Purity	Unit
MnO_2	98.41	%
Li_2CO_3	97.79	%
$NiSO_4$	99.61	%
$CoSO_4$	99.34	%

5.6 Life Cycle Inventory

A comprehensive life cycle inventory is presented in Table 6. It must be noted that even though life cycle assessment using Ecoinvent 3.6 is an optimal tool to understand the environmental impacts of a process when industrial data is not available it has its limitations. For example, solvent extraction chemicals (D2EHPA, Cyanex 272, TBP) were not included in the LCI, moreover, cobalt sulphate had to be replaced stoichiometrically with metallic cooper and oxygen gas was excluded from the LCI due to lack of data availability in the Ecoinvent data 3.6. Due to these reasons, no results related to the excluded materials were generated to analyse a more comprehensive life cycle assessment, nevertheless, this investigation was conducted using the most up-to-date information accessible during the period of this study.

5.7 Impact Analysis

The total environmental impacts are summarized in Table 7, while the contribution of every material to each category is depicted in Fig. 9. It is interesting to observe that through the impact categories nickel sulphate, sodium hydroxide, and sulfuric acid had the highest contribution to the environmental impacts. Nickel sulphate is used in minimum amounts for the purification of the recovered nickel while sodium hydroxide and sulfuric acid are used in several different steps of the flowsheet.

For GWP, the more important contributors were associated to the use of sodium hydroxide (35%), nickel sulphate(20%), hydroxide peroxide and the generation of steam (~11%). ADP contributions were nickel sulphate 50% and sodium hydroxide and sulfuric acid with ~19%. For ADPf contributions were related to the use of sulfuric acid

Table 6. Life cycle Inventory (LCI)

Input			Output		
Leaching					
Black mass	1.00	kg/kg	Leaching Residue	0.22	kg/kg
Sulfuric acid	1.49	kg/kg	$O_{2(g)}$	0.12	Nm^3/kg
Hydrogen peroxide	0.29	kg/kg	$H_{2(g)}$	0.01	Nm^3/kg
			$H_2O(g)$	2.86	Nm^3/kg
Cu Cementation					
Iron scrap	0.02	kg/kg	Cu	0.03	kg/kg
Iron-Aluminum removal					
$O_{2(g)}$	0.01	Kg/kg	O2(g)	0.01	Nm^3/h
NaOH	0.56	kg/kg	$Fe(OH)_3$	0.06	kg/kg
			$Al(OH)_3$	0.02	kg/kg
Mn Recovery					
Manganese sulphate	0.01	kg/kg	MnO_2	0.07	kg/kg
Sulfuric acid	0.10	kg/kg	$O_{2(g)}$	0.01	Nm^3/h
NaOH	0.14	kg/kg			
$O_{2(g)}$	0.03	kg/kg			
$SO_{2(g)}$	0.00	kg/kg			
Co Recovery					
Cobalt Sulphate	0.01	kg/kg	Cobalt Sulphate	0.15	kg/kg
Sulfuric acid	0.11	kg/kg			
NaOH	0.09	kg/kg			
Ni Recovery					
Ni	0.12	Kg/kg	Nickel sulphate	1.25	kg/kg
Sulfuric acid	0.76	kg/kg			
NaOH	0.62	kg/kg			
Lithium Recovery and Na_2SO_4 Removal					
Na_2CO_3	0.27	kg/kg	Lithium carbonate	0.19	kg/kg
NaOH	0.00	kg/kg	Sodium sulphate(anhydrite)	3.16	kg/kg
Effluent Treatment					
Lime	0.01	kg/kg	Wastewater	8.41	kg/kg
			Solid Waste	0.04	kg/kg

Table 7. Life cycle assessment impact categories with total results

Impact category	Unit	Value
GWP	kg CO_2 eq	3.66
ADP	kg Sb eq	2.14×10^{-4}
ADPf	MJ	50.40
AP	kg SO_2 eq	0.19
EP	kg PO_4-eq	1.15×10^{-2}
FW-AE	kg 1.4-DB eq	15.80
MA-EX	kg 1.4-DB eq	17458.86
ODP	kg CFC-11 eq	1.39×10^{-6}
POCP	kg C_2H_4 eq	7.69×10^{-3}
T-EX	kg 1.4-DB eq	1.78×10^{-2}
FPM	kg $PM_{2.5}$ eq	4.91×10^{-2}
LU	m^2a crop eq	3.04
HT-C	cases	3.43×10^{-10}
HT-NC	cases	2.72×10^{-10}

(21%), sodium hydroxide (28%), steam and hydrogen peroxide (~11%). AP contributions were primarily the result of nickel sulphate usage (80%) and sulfuric acid (13%). EP contributions were related to nickel sulphate and sodium hydroxide usage (~36%). For the FW-AE category, 81% is associated with nickel sulphate and 9% with sodium hydroxide. While, for MA-EX nickel sulphate(66%), sodium hydroxide (17%), and sulfuric acid (7%) are the primary associations. ODP contributions are associated to the usage of nickel sulphate 85%. POCP contributors were associated to nickel sulphate80%, and 13% of sulfuric acid. T-EX contributions were nickel sulphate 50%, sodium hydroxide at 25%, and sulfuric acid at 8%. FPM impacts were associated with the usage of nickel sulphate with 78% and sulfuric acid with 13%. In contrast, LU associated impacts were nickel sulphate(70%), and sodium hydroxide and cobalt production (~11%) each.

It was observed in the results of the environmental impacts related to toxicity (HT-C and HT-NC) the main contributors were sodium hydroxide, hydrogen peroxide and nickel sulphate use throughout the categories. It must be highlighted that the units of these categories are quantified in several cases. For HT-C Sodium hydroxide 23%, hydrogen peroxide 27%, nickel sulphate 19%, steam, soda ash and sulfuric acid ~8%. For HT-NC the biggest contributors were sodium hydroxide 32%, nickel sulphate 16% production and sulfuric acid 35%. Additionally, soda ash contributions through the categories were > 7% except for HT-C. Electricity contributions were > 5% in every category, therefore, it can be concluded that the battery recycling system is not highly energy dependent.

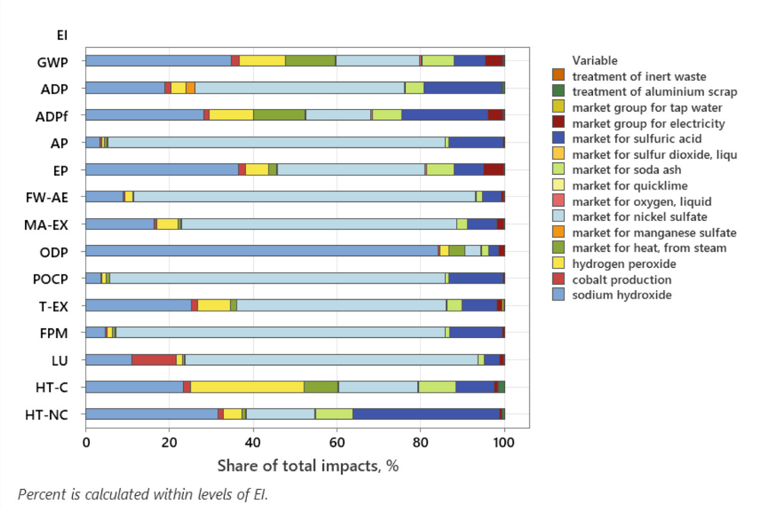

Fig. 9. Depicts the environmental impacts of every impact category assessed by Recipe hierarchy (H), CML IA baseline and USEtox

6 Conclusions

This study presents a preliminary comprehensive approach towards enhancing the efficiency of battery recycling processes within the HELIOS project. The study focuses on a set of integrated strategies that consist of three distinct actions to improve the environmental sustainability of hybrid batteries. The findings and main conclusions are outlined below:

1. The design for Disassembly/Manufacturing/Assembly focuses on creating efficient and safe methods for each stage of the battery lifecycle. This includes an analysis of existing techniques, the introduction of robotic disassembly, and the optimization of recycling processes. These methods are expected to reduce waste, lower costs, and increase worker safety.
2. Results of the froth flotation experiments demonstrate good separation between fully liberated graphite-NMC811-LTO electrode mixture. 88% of the graphite could be recovered with 94.8% purity and approximately 50% of the recovered graphite was recovered with a 98% grade. The kinetic flotation data aids in simulating the HELIOS battery pack recycling process. Removing graphite reduces environmental impact and acid use, and recovered graphite can be reused. Optimization of flotation parameters and pretreatment steps are needed to increase graphite grade. This process also enables TiO_2 recovery.
3. The results show that HSC sim process simulation baseline for recycling NMC811 cathodes provides an optimal basis for future LCA calculations for designing a recycling flowsheet for the HELIOS battery modules. It successfully recovered battery-grade lithium, cobalt, nickel, and manganese. LCA results suggest that most of the environmental impacts come from the use of nickel and sodium hydroxide. The results

from the froth flotation experiments can be incorporated into the baseline to broaden the scope of the flowsheet.

In conclusion, the integrated strategies proposed in this study have the potential to enhance the efficiency and sustainability of battery recycling processes. The findings suggest that the design for Disassembly/Manufacturing/Assembly, froth flotation experiments, and HSC sim process simulation baseline can significantly reduce waste, lower costs, and increase worker safety while recovering valuable materials from hybrid batteries while providing the basis to develop the further cradle-to-grave LCA models.

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List of abbreviations

ADP	Abiotic depletion (elements)
ADPf	Abiotic depletion (fossil)
AP	Acidification potential
EoL	End-of-Life
EP	Eutrophication potential
EV	Electric vehicle
FPM	Particulate matter
FW-AE	Fresh water aquatic ecotoxicity
GWP	Global Warming Potential
HE	High-energy
HP	High-power
HSC	H (enthalpy), S (entropy), and Cp (heat capacity)
HT-C	Human toxicity potential – Cancer
HT-NC	Human toxicity potential – Non-Cancer
HV	High voltage
LCA	Life Cycle Assessment
LIB	Lithium-ion batteries
LTO	Lithium, titanium and oxygen
LU	Land use
MA-EX	Marine aquatic ecotoxicity
NMC	Nickel, Manganese and Cobalt
ODP	Ozone depletion
OEM	Original equipment manufacturer
POCP	Photochemical ozone creation potential
SEI	Solid electrolyte interphase
SEM-EDS	Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy
T-EX	Terrestrial ecotoxicity

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Life Cycle Environmental Performance of Diesel, Fuel Cell, and Battery Electric Long-Haul Heavy-Duty Trucks

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Abstract. This study provides an environmental performance evaluation of heavy-duty 40-ton semi-trailer trucks from a life cycle perspective. The life cycle assessment (LCA) study was conducted as a hypothetical case study of semi-trailer trucks used in Norway. The life cycle impacts of diesel, fuel cell, and battery electric semi-trailer trucks are assessed in a cradle-to-grave attributional LCA study in terms of greenhouse gas (GHG) emissions as well as five other impact categories. Overall, we find that battery electric and fuel cell trucks offer GHG benefits compared to diesel trucks. However, across five other environmental impact categories, results are less clear-cut, with the diesel and battery trucks offering the lowest impact and the fuel cell truck having higher impacts. However, due to lower technological maturity and limited primary industry data available higher uncertainty exists for modelling of fuel cell systems. This should be taken into consideration in further studies. The preliminary results in this study offer environmental insights of electric powertrains and demonstrate the importance of holistic environmental impact understanding, beyond direct emissions and GHG assessment.

Keywords: LCA · Li-ion Battery · PEM fuel cells · heavy-duty vehicles

1 Introduction

Both fuel cell and battery electric powertrains are currently under consideration for heavy-duty vehicles and while the choice for electrification of city buses has fallen on batteries in Norway, it is still uncertain whether fuel cells or batteries offer the best alternative for heavy-duty trucks. Thus, the purpose of this study was to investigate and provide understanding of the environmental performance of different electric powertrain technologies that may be used to power long-haul heavy-duty freight trucks, and to compare against a conventional diesel powertrain.

While both fuel cell and battery powered trucks offer zero tailpipe emissions, their overall life cycle environmental performance is more complex and unclear as indirect emissions occur both upstream and downstream of operation. Thus, a holistic systems perspective is required when comparing the environmental performance of the different

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powertrain technologies. To evaluate and compare the environmental performance of long-haul diesel, fuel cell, and battery electric trucks in a holistic manner, we used the life cycle assessment (LCA) method. For this purpose, we compiled cradle-to-grave inventories to assess the environmental impacts of 40-ton semi-trailer trucks, which consists of a tractor unit and one semi-trailer used to carry freight. The powertrain technologies considered in the study includes diesel internal combustion engine (ICE), proton exchange membrane fuel cell (PEMFC), and Li-ion battery (LIB) electric.

2 Method

The goal of this paper is to evaluate and compare the environmental performance of diesel, PEMFC, and LIB electric long-haul semi-trailer trucks across various environmental impact categories. A process-based attributional and comparative approach was used to estimate the cradle-to-grave performance across six environmental impact potential categories of the diesel, PEMFC, and LIB semi-trailers trucks. Impacts in terms of global warming potential (GWP), photochemical oxidant formation potential (POFP), eutrophication potential (EP), ozone layer depletion potential (ODP), acidification potential (AP), and freshwater ecotoxicity potential (FETP) were estimated using the CML-IA baseline characterization method. The LCA is conducted as a hypothetical case study considering use of 40-ton semi-trailer trucks in Norway. The system boundaries included the energy carrier from well-to-wheel (WTW) and the vehicle equipment from cradle-to-grave as well as the energy use and efficiency of the hydrogen fueling and battery charging stations (but not the production or EOL of the shared infrastructure itself). The functional unit was set to "the use of a 40-ton semi-trailer truck per ton-kilometer (tkm)", where impacts were estimated based on a 16 ton payload and total mileage of 800 000 km. The total mileage was derived based on an assumed truck lifetime of eight years and a yearly mileage of 100 000 km.

2.1 Inventory Modelling

For production (cradle-to-gate) of the semi-trailer trucks, we relied on data from published [1–9] studies and ecoinvent 3.8 process data as well as original inventory data compiled for the study. For diesel trucks, we considered auto diesel sold on the Norwegian market in 2021, which is a blend of fossil diesel, fatty acid methyl ester (FAME), and hydrotreated vegetable oil (HVO). Based on statistics from the Norwegian Environment Agency, we estimated a biodiesel content of about 14%. For hydrogen used in fuel cell trucks, we considered green hydrogen produced via electrolysis using wind-based electricity. For battery electric trucks, we assumed use of the Norwegian consumption mix. To evaluate the sensitivity and for wider transferability of study results, we considered blue and grey hydrogen for the fuel cell truck as well average European electricity mix for battery trucks. Use of energy carriers were estimated to be 0.37 l diesel/km, 66 g hydrogen/km, and 1.35 kWh/km (including 5% losses in charger). To evaluate anticipated technology performance improvement in the electric powertrains, we performed uncertainty analyses considering how improvements in energy efficiency affect life cycle GHG emissions of the electric powertrains. Inventory data for wear emissions from breaks, tyre, and road were adapted from the *ecoinvent* database to account for differences in gross vehicle weight (GVW) of each of the semi-trailer trucks as well as regenerative breaking. Break wear was assumed to be 20% lower for electric trucks due to regenerative breaking. For maintenance we considered annual replacements for tires and fluids. For the PEMFCs, we estimated one stack replacement as the estimated operation. In an uncertainty analysis, we considered both one additional (2) and one fewer (0) stack replacements. For batteries, replacements were deemed unnecessary as the use did not exceed expectations regarding calendar life or cycle life. Even so, in an uncertainty analysis, we consider how one replacement of battery modules affects the life cycle GHG emissions of battery trucks. End-of-life (EOL) modelling was done in line with the cut-off approach, where no burden is allocated to the recycled materials (i.e., downstream products) and instead, raw material input upstream of component and vehicle production has a recycled content.

3 Results

3.1 Global Warming Potential

The total cradle-to-grave GWP emissions from the semi-trailer trucks are provided in Fig. 1, where contribution to production (cradle-to-gate) is denoted green, WTT energy carrier in a darker shade of grey, TTW energy carrier in a lighter shade of grey, maintenance in blue-grey, and EOL in yellow.

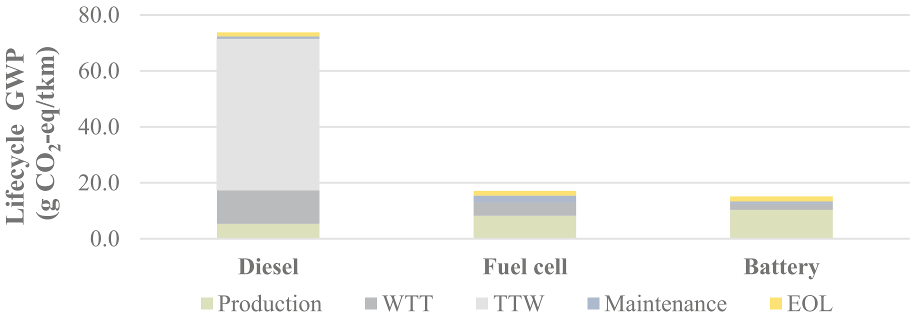

Fig. 1. Total life cycle GWP of 40-ton semi-trailer trucks with a 16 ton payload.

While the production emissions from the trailer and glider are the same for all three alternatives due to model assumptions, production emissions of the electric powertrains are significantly higher than the diesel-based powertrain. For the fuel cell truck, the higher powertrain emissions derive from the PEMFC system and hydrogen tank, which are similar in size. For the battery truck, the high powertrain emissions stem primarily from the LIB, where the modules make up about 80% of battery production emissions. For the diesel truck, the ICE contributes to approximately 65% of the powertrain emissions. Despite higher production emissions, both the electric trucks offer life cycle GHG emissions benefits compared to the diesel truck as use phase emissions are significantly lower. WTT emissions of the fuel cell truck are higher than that of the battery truck because the hydrogen production through electrolysis is energy demanding and because the fuel cell powertrain (40%) is not as efficient as the battery powertrain (70%). The fuel cell stack replacement adds to maintenance emissions for the fuel cell truck, making its maintenance emissions significantly higher compared to the diesel and battery trucks. While the battery truck has the highest EOL emissions due to battery recycling, EOL emission contributions to total life cycle emissions are low for all powertrain technologies.

3.2 Other Environmental Impact Potentials

Figure 2 presents the relative environmental performance in terms of POFP, EP, ODP, AP, and FETP. Contribution towards life cycle impact from semi-trailer truck production (cradle-to-gate) is denoted green, WTW is grey, maintenance is blue-grey, wear is red, and EOL is yellow.

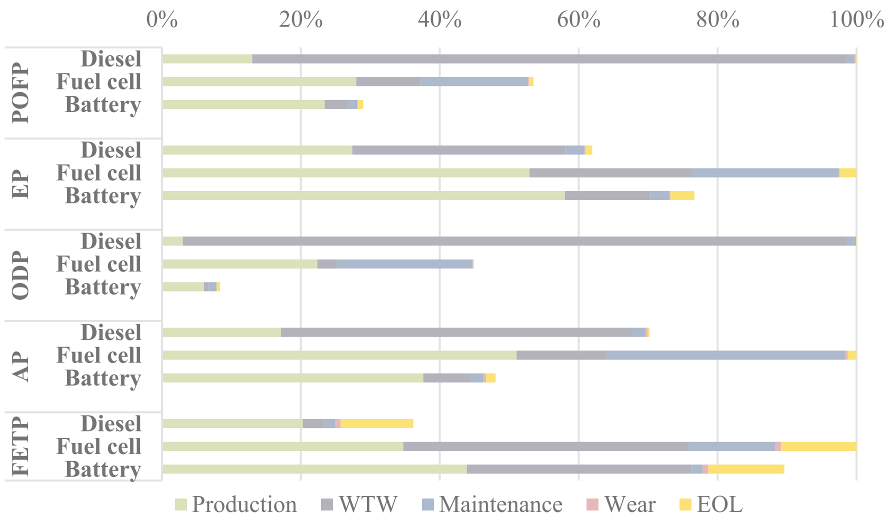

Fig. 2. Relative impact results from cradle-to-grave across multiple impact categories. Impacts are reported relative to the highest result.

When looking across multiple impact categories, we find that none of the powertrain technologies outperform the others. Generally, we find that the electric powertrains have higher production impacts. The diesel truck offers the lowest life cycle impact in terms EP and FETP; the extraction and refining processes related to battery metals tend to have particularly high contributions to toxicity impacts as well as eutrophication. It is perhaps more surprising that in terms of toxicity, the WTW impact of the battery truck is also higher than the diesel truck. The high upstream (WTT) toxicity impacts from electricity use stems primarily from copper used in the electrical distribution network. Note that because toxicity and eutrophication impacts depend on local background concentrations and chemical interactions between pollutants, caution should be applied when interpreting the results; toxicity and eutrophication results may be viewed as indications of potentially problematic aspects of the electric powertrains, rather than providing an absolute environmental ranking of powertrains. Much of the impact from fuel cell replacements is caused by the platinum loading in the catalyst, due to upstream impacts form platinum extraction and refinery operations.

3.3 Robustness Analyses

To evaluate particularly sensitive and uncertain parameters, we performed a range of sensitivity and uncertainty analyses for the electric trucks. In Fig. 3, results from the main analysis are shown in grey (diesel), turquoise (fuel cell), and orange (battery) lines, while results from the robustness analyses are shown in the lighter turquoise (fuel cell) and orange (battery) columns.

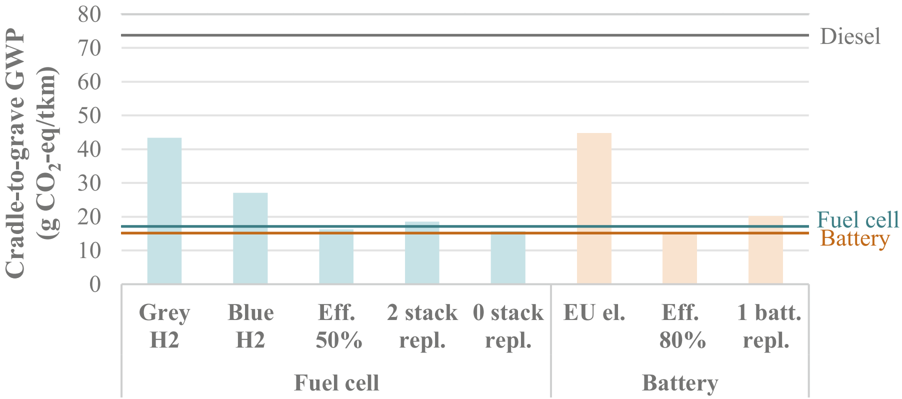

Fig. 3. Robustness analyses considering parameters for electric semi-trailer trucks.

Both electric trucks offer lower life cycle GWP than diesel trucks. Use of energy carriers from production pathways with higher carbon footprints was found to have the highest effect on life cycle emissions for both the fuel cell and battery trucks. In contrast, change in efficiency and replacement of fuel cells and batteries had less significant effects. An increase in efficiency does not offer much improvement because the carbon footprints of the green hydrogen and the Norwegian electricity used for charging are very low. With higher carbon footprints, increase in efficiency would have provided a larger relative improvement.

4 Discussion and Conclusion

Across six impact categories, we find that the different technologies offer both environmental benefits and disadvantages with no one powertrain technology outperforming the others. The results illustrate that in terms of GWP, accessibility to low carbon footprint energy carriers is more important than higher powertrain efficiency and even lifetime of fuel cells and batteries. In terms of impacts more affected by metal use (e.g., EP, AP, and FETP), it is more important ensure high lifetime to avoid or reduce replacements of fuel cell stacks and battery modules.

The results from this LCA illustrate the importance of considering all life cycle stages and numerous impact categories to obtain a more holistic understanding of the environmental performance of different powertrain alternatives. A narrower focus limited to TTW and GHG emissions, would not have identified how important the powertrain components in the electric powertrains are to their overall environmental performance. Perhaps most importantly, a TTW focus would not have captured that in Norway, battery electric trucks appear to be more environmentally friendly than fuel cell trucks. That said, there is uncertainty associated with the results of both the battery electric truck and (particularly) the fuel cell truck, mainly due to lifetime aspects of LIBs and PEMFCs as well as data quality for modelling. In particular, the fuel cell Pt loading – which is a key contributor to many impacts for the fuel cell stack – is a parameter still under high development, meaning that impacts will likely reduce as this is optimized. Further studies should seek to minimize these uncertainties, with primary industry data for PEMFC and hydrogen tank modelling, and accounting for future technological developments.

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Irish Automotive Sector Considerations for Recycling Electric Vehicle Lithium-Ion Batteries

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Abstract. The Irish transport sector has been targeted by the government as a key area where greenhouse gases (GHG) can be drastically reduced and a fundamental plan within the government's strategy is the electrification of the private car fleet.

Electric vehicles (EV) extensively use lithium-ion batteries (LIB) as an energy source, however LIBs have a limited lifespan. LIBs are subject to a chemical and physical process known collectively as battery degradation, which limits the batteries capacity to hold a charge with time.

This characteristic will bring new and unprecedented challenges for end-of-life (EoL) vehicle waste management. As well as environmental concerns, there are significant personal health and safety risks associated with EV high-voltage LIBs. This raises important questions on how the automotive sector can safely process this additional hazardous waste stream.

This study investigates the value chain surrounding EoL EV LIBs and accentuates a best practice approach for the pre-recycling phases of; battery safety, disassembly, storage, and transportation, within the context of the Irish automotive aftersales landscape.

The research findings highlight the dangers surrounding EV LIBs, and present a best practice methodology regarding the safety aspects encompassing the pre-recycling operations. They are of particular importance to businesses, operatives, technicians and transporters, who will be directly involved in the pre-recycling phases of EV LIBs here in Ireland.

Keywords: electric vehicles · lithium-ion battery · end-of-life · safety · recycling · waste management

1 Ireland's Automotive Marketplace, the Current State of Play

Transport is a key driver in the Irish economy and while gross national income increased steadily since the 1990's, a simultaneous increase in transport associated harmful emissions has ensued [1].

The Irish government have pledged to halve GHG emissions by 2030 and achieve a climate neutral economy by 2050 [2]. Transport is a crucial area where GHGs can be radically reduced, and a central plan within the government's policy is the electrification

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of 30% of the private car fleet by 2030, thereafter only permitting the sales of EVs cars in the ensuing years [3].

The LIB will underpin this strategy as they are used as an energy source for EVs [4], however LIBs have a limited lifespan [5, 6]. LIBs are subject to a chemical and physical process known collectively as battery degradation, which limits the batteries capacity to hold a charge with time [7].

The global transition to EVs has advanced exponentially over the last number of years. Worldwide the number of EVs on the road exceeded 10 million in 2020 [8]. While in Ireland EV sales surpassed diesel vehicle sales in the first quarter 2023 for the first time [9].

This growth will translate into a proliferation of EoL EV LIBs which will require waste management. Modelling predicts that globally a million spent EV LIBs will require treatment by 2030 with the number doubling by 2040 [10].

2 Lithium-Ion Battery Degradation

The life expectancy of an EV will be largely determined by its battery. Due to the chemical and physical characteristics of LIBs, they degrade naturally with age [11, 12]. LIB degradation is a complex issue affected by multiple factors such as chemical composition, calendar ageing, usage and charge-discharges cycles [13].

The degradation process is not obvious physically as it occurs within the battery cell, however its most noticeable effects are realised when the usable capacity and power of the battery diminish. Literature varies, however most research suggests that EV LIBs reach their EoL when the state-of-health (SoH) drops to below 80% [14, 16, 17]. At this point, the battery can no longer propel a vehicle efficiently.

The time taken for an EV LIB to reach EoL is difficult to predict, as competing factors will influence the SoH degradation. Studies suggests an estimated lifespan of between 8 to 13 years [12, 15].

2.1 Electric Vehicle Battery Waste Management

Current EU directives ensure EoL vehicles and their batteries enter the appropriate recycling stream. However, new regulation on waste batteries will ensure a truly circular economy.

The new EU battery regulation which emanated from the European Green Deal [18], will impose mandatory requirements for sustainability, safety, labelling, EoL management and material recovery, while assigning additional responsibility to battery manufacturers [19–21].

2.2 Electric Vehicle Lithium-Ion Battery Recycling Processes

EV LIB recycling processes can be broadly classified into the four main areas off; pre-processing (disassembly and categorisation), pyrometallurgical (smelting), hydrometallurgical (leaching) and direct recycling (physical processes).

Any process that does not alter the battery's cell structure is considered **pre-processing**. This key step may include deactivation and powering down of the vehicle's high voltage electrical system before battery pack removal. Discharging the LIB after removal and disassembly of battery pack [22, 23].

Pyrometallurgical recycling is the most straight forward process commercialised today. However, it is not selective and the recovery of specific metals is extremely difficult [24], while lithium and other cathode elements are generally lost in this process [25].

Hydrometallurgical recycling is an exceptionally selective process which can recover large amounts of the batteries elements with high purity rates. Companies such as Duesenfeld, Northvolt and Lithion maintain they can recover up to 95% of a battery's components including its black mass (lithium, manganese, cobalt and nickel) using this method [26, 27, 28].

Direct recycling promises to be the most sustainable approach because recovered materials can be used directly in new battery production [29]. However, this process has yet to be commercialised [30].

2.3 Electric Vehicle Lithium-Ion Battery Hazards

LIBs are generally considered safe, however as with any component containing an electrical power source, hazards exist.

A fire in a LIB generally stems from a process known as **thermal runaway**, which under certain conditions can lead to a build-up of pressure, causing the rupturing of the battery pack, the release of toxic gases, fire and explosion [31, 32].

The **high voltage**[1] contained within an EV LIB presents the obvious hazards such as electric shock, electrical burns, arc flash, and fatal electrocution [31, 33]. Manufactures design their EVs and allied high voltage technologies to operate safely. However extreme care is required when working on EVs, as the high voltage risk is ever-present in the battery itself, even if the vehicle is powered down.

Associated risks of EVs include electromagnetic forces that can interrupt the operation of personal medical devices and manual handling risks with battery removal, as some battery packs weigh more than 500 kg [34].

2.4 Ireland's Role in Electric Vehicle Battery Recycling

From Ireland's perspective, the pre-processing phases of the EV recycling, such as powering down and removal of the battery pack from the vehicle will be carried out onsite by an automotive dealership, repairer or Authorised Treatment Facility (ATF - commonly known as a scrap yard).

Presently the pre-processing of EV LIBs is highly manual that requires specialist tools, equipment and trained operators who are practiced to work on EV high voltage

[1] UN and EU regulation ECE R100 classifies automotive EV high voltage as; > 60 V direct current (DC) and > 30 V alternating current (AC). EV batteries operate at a typical range of 400 V DC. However, manufacturers may work at significantly higher ranges, for example Porsche [38] and Hyundai [39] uses an 800-V DC battery.

systems. The LIB will then be transported to mainland Europe to continue its journey along the recycling value chain.

Although EVs are not new to the Irish market, they are not yet widespread and few have reached EoL. Therefore, it may be assumed that a skills gap surrounding the technology and hazards posed by EV LIBs currently exists.

3 Research Methodology

Due to the technical nature of the study, a mixed-methods pragmatic paradigm action research approach was employed. To gain a full understanding of the entire LIB value chain, a series of interviews, site visits and a convenience survey, across a diverse array of stakeholders within the electric vehicle domain were undertaken.

3.1 Qualitative Research Results

Qualitative research consisted of 14 semi-structured interviews with national and international actors. The stakeholders were categorised as public state bodies, vehicle importers and distributors, ATFs, economic actors, non-profit companies and industry experts.

543 statements relevant to this research were identified and coded using a semantic approach. Analysis of reoccurring codes led to nine key themes emerging;

1) *Transport.* Research confirmed that legislation is effective, and manufacturers are adhering to the LIB transport regulations. Concern was raised surrounding LIB transport costs to Europe ensued by Ireland's geographical nature as an island.
2) *Safety.* Stakeholders are acutely aware of the health and safety implications associated with EV LIBs. Irish actors are training and equipping their networks to work safely on EVs. Restricted access to manufacturer repair data is a concern for ATFs. A disconnect between academic study (thermal runaway) and industry (high-voltage) on the topic of safety was revealed.
3) *Knowledge.* Businesses reiterated their continued efforts to alleviate potential knowledge gaps with staff training to ensure workplace health and safety standards. The general public's ambiguous understanding concerning the second-hand market of EV LIBs was stressed as a concern.
4) *Legislation and regulations.* Current regulations are ensuring LIBs are recycled correctly. A secondary matter particular to the Irish market entails UK imported EVs which have not contributed to a central waste management fund because of a registration loophole.
5) *Recycling*. There is no standard workflow established for the EV LIB pre-recycling steps in Ireland, with different approaches being employed by organisations.
6) *Storage.* Irish stakeholders do not yet consider the storage of EV LIBs as an issue, as batteries are generally shipped from and returned to Europe on the same day.
7) *Battery removal.* Access to valid repair methods, special tooling and addressing the technician skills gap, are possible barriers for industry.
8) *Miscellaneous.* Stakeholders emphasised the new workload created in all areas of their businesses incurred by new EV operational standards. Inadequacies surrounding online training were also proffered, as working with high voltage PPE requires actual practice to achieve dexterity.

9) *Battery characteristics.* The LIB cathode type currently determines the recycling process. However, this issue is not considered during pre-recycling steps in Ireland.

3.2 Quantitative Research Results

A convenience survey among 58 light-vehicle automotive apprentice students from Technical University Dublin was undertaken, to gain an understanding of the level of awareness of front-line workers in the field.

Key findings to emerge from the apprentice survey;

1. There is a lack of understanding surrounding the electrocution threshold current.
2. Apprentices employed by a franchised dealership are more likely to have been exposed to EVs and their safe working practices when compared to those working for independent repairers.

4 Discussion

Legislation has ensured that EoL EV LIBs in Ireland are recycled correctly. However, conflicts within the different regulatory frameworks concerning EV and LIBs were cited as barriers to a correctly functioning recycling market. The EU's new regulatory framework for batteries will negate the issues raised.

The upskilling currently ongoing by stakeholders within the Irish EV field and the willingness from people to learn new skills was seen as a key enabler from an Irish perspective to bring about a safe working environment.

The financial costs of training, equipping staff with PPE and tooling is significant, which has led to different standards being employed by organisations. This is an area for concern as the hazards presented by EV LIBs are largely the same.

There is a clear knowledge divide between employees of franchised networks when compared to those from independent repairers and ATFs, suggesting a skills shortfall in the sector. The research did not reveal if this shortfall is due to under investment or an unwillingness to accept technologies that are not yet ubiquitous.

Restricted access to manufacturer specific repair documentation is a major issue for non-franchised organisations. This is of particular importance for ATFs who will be largely responsible for dismantling EoL EVs for recycling.

5 Conclusion and Recommendations

The contextual understanding gained during this research helped form the author's concept, that an industry wide standard for technicians working on EVs should be adopted and mandated by regulations.

There is currently no international standard framework for technicians who work on EVs post production [35, 36].

The author believes that a certified industry standard complying with EU regulation 1025/2012 on standardisation, is necessary to ensure all actors working with EVs are expert and fully aware of the associated personal and environmental risks to mitigate potential accidents.

The author recommends that stakeholders within the Irish EV field develop an industry-based standard in conjunction with the National Standards Authority of Ireland for technicians working on EVs. This standard should become compulsory through a statutory regulatory scheme or legislation.

The author suggests following the *Safe Electric* framework already in existence in Ireland, which is a statutory regulatory scheme for electrical contractors [37].

Such a scheme for the automotive sector would ensure only competent technicians would be eligible to work on EVs, which will lessen the possibility of serious accidents occurring while also highlighting the dangers of EVs and their batteries to the general public.

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Simulation-Based Optimization for Sustainable Textile Waste Collection Routes

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Abstract. Textile waste is all textiles and products that are dropped away. This waste comes from various sources: households, factories, and the fashion industry and significantly challenges the environmental and economic potential for sustainable waste management. This paper proposes a simulation-based optimization of textile waste collection routes, focusing on efficiency and sustainability. The model considers vehicle characteristics, collection demand, and environmental aspects. Also, it examines vehicle routes, container, and sensor technology scenarios. The results show that efficient, sustainable solutions with strategic container placement and dynamic routes can reduce travel costs and environmental impacts. As a case study, the Huesca region of Spain confirms the effectiveness of dynamic route planning and sensor technology. This method allows waste management authorities to optimize resource allocation and reduce emissions and costs, as the simulation-based method for optimizing routes can reduce costs and environmental impacts while maximizing efficiency. It highlights the urgency for waste management stakeholders to conform with recent Spanish legislation mandating. This study provides valuable insights to meet legal obligations while ensuring operational efficiency and sustainability.

Keywords: Textile Waste Collection · Circular Economy · Sustainable Logistics · Route Optimization · Agent-Based Simulation

1 Introduction

Textile waste indicates unused materials and products from the textile industry. It is a wide range of items, clothing, and other textile-based products, that are no longer needed or have gone the end of their useful life. In recent years, textile waste management has become a significant issue in the tension between environmental responsibility, regulatory compliance, and operational efficiency. These challenges highlight the urgent need for sustainable solutions in the fashion and textile industries. Waste managers now face the daunting task of complying with the new regulations in their operations to meet the operational, economic, and environmental criteria. A new Spanish law that mandates the separate collection of textile waste has highlighted the urgency of addressing this issue. This legislative reform is compelling waste management authorities to adapt their operations to the changing legal landscape. It sets the stage for a fundamental challenge:

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How can waste managers effectively manage the complexity of textile waste collection while complying with legal requirements and optimizing operational processes?

Key operational parts required by this regulatory change include understanding the waste generation profile of sites within their jurisdiction, accurately sizing collection containers, and efficiently planning collection routes. Significantly, these operational decisions must be based on more than intuition or historical practices. Instead, they must be based on data-driven insights; simulation and optimization techniques are critical. This paper addresses the demanding need for a systematic and data-driven approach to changing regulatory landscape.

Section 2 of this paper provides an overview. Following that, the methodology employed in this study is outlined. Section 4 is a description of a case study. Section 5 is discussion. Finally, in Sect. 6, conclusions are offered.

2 Literature Review

Global textile production has surged due to population growth and fast fashion trends, increasing textile demand. However, this consumption is predicted to lead to a 70% increase in global municipal solid waste by 2025, underscoring the urgent need for textile waste management, particularly in developing nations [1]. Textile waste management significantly impacts all three sustainability pillars: environmental, social, and economic [2]. A review of textile recycling technologies highlights the importance of leading economies adopting a circular approach to holistic technologies [3]. This approach is underpinned by the environmental benefits of textile reuse over incineration and landfill, with literature highlighting the superiority of reuse in reducing environmental impacts [4]. The European Union recognizes the importance of transitioning to a circular economy, highlighting trends such as digitalization and sustainability models [5]. Also, the Waste Framework Directive requires Member States to establish textile waste collection systems by 2025 [6, 7].

In response, the Guimarães municipality in Portugal conducted a comprehensive analysis of textile waste generation to prioritize separate collection routes in compliance with EU directives [8]. Furthermore, a critical aspect highlighted in the literature is the need to gather data on residents' waste generation profiles, including textile waste, to inform more effective strategies [9]. The efficiency of these systems must consider cost factors. The study introduced a management tool to calculate costs across different schemes, utilizing waste quantity and collection logistics, to optimize cost-effectiveness [10]. Studies have focused on optimizing routes using advanced algorithms, notably reducing travel distances and operational costs [11]. In the UAE, a system of smart waste collection could have a 19% reduction in operational costs [12].

Several studies have looked at innovative solutions to optimize these processes. A study presented a software system, BIN-CT, that uses computerized learning algorithms to plan optimal routes, resulting in routes that are 33.2% shorter than conventional ones [13]. Another highlighted the role of sensor technologies in dynamic route optimization, which resulted in a 7.4% reduction in pickup costs and a 10.2% reduction in CO_2 emissions [14]. In addition, the integration of ultrasonic transducers was investigated for the development of a LoRa-based smart bin architecture in the context of smart cities.

They used waterproof ultrasonic sensors to measure waste volumes in trash garbage cans [15].

This paper presents a holistic approach that combines simulation and optimization. This research seeks to provide waste management authorities with a comprehensive toolkit to address the challenges of textile waste collection while optimizing operational processes in compliance with regulatory requirements.

3 Methodology

This section provides research findings with real-world solutions. It combines data collection, optimization, and simulation components.

The first step of the methodology is obtaining relevant data from two critical sources: the locations and the available resources. The location data includes key information necessary for route planning. This includes coordinates and generation rates, measured in cubic meters per day, with the potential to be correlated with population statistics or predictive models derived from historical data. Moreover, resource data provides essential awareness for authorities and covers some aspects, including vehicle availability and economic factors such as fuel costs, labor expenses, and maintenance. It also includes vehicle details such as capacity, speed, and automation capabilities. In addition, it involves evaluating options for container sizes and exploring technologies like occupancy sensors.

The next step is route optimization. The optimization algorithm utilized is a Capacitated Vehicle Routing Problem (CVRP) algorithm, which leverages heuristic techniques to determine optimal routes. This algorithm seeks to minimize criteria, such as cost or distance, while following restrictions: including vehicle capacity limitations and other operation-specific restrictions.

To create a dynamic and flexible decision-support framework, a multi-agent simulation model has been developed using AnyLogic software. This data-driven model easily incorporates the optimization process while using the above data. The simulation allows running "what-if" scenarios based on various inputs, including location, available vehicles, container sizes, and optimization criteria. It also offers a visualization layer that dynamically represents the results. This dynamic representation gives the decision-support tool more credibility and makes it easier to visually evaluate how various factors affect the system for collecting textile waste. This comprehensive methodology is highlighted in a real-world case study, showing how it addresses problems with textile waste collection and improves operations. This illustration demonstrates the real advantages of managing textile waste. The methodology's usefulness in streamlining operations despite complex real-world situations is shown in the following section's exploration of numerous "what-if" scenarios within the textile waste collection problem.

4 Case Study

This section presents the results of a comprehensive case study conducted in the province of Huesca, Spain. Huesca is in the northeast of the country and has over 200,000 inhabitants. The case study considered 84 localities in the province that generate an estimated

0.25 cubic meters of textile waste per inhabitant per year. The map of this area is presented in Annex I.

A fundamental aspect of the case study was the simulation of diverse scenarios, characterized by distinct parameters. Notable variables included: *1-Vehicle Selection*: **The conventional van** (12m^3 capacity), while faster and more accessible to specific locations, requires manual container emptying. The van is prepared for servicing small (2m^3) containers. **The automated truck** (28m^3 capacity) is slower but operated by a single driver (compared to the van's requirement of two) and features automated container emptying. The truck can handle larger (3.7m^3) containers.

2-Route Typology: **Fixed Routes:** designed based on clustering locations, considering distance and road connectivity criteria. Suitable for weekly collection. **Dynamic Routes:** assuming the containers are equipped with IoT devices sensing occupancy levels, dynamic routes were optimized daily. The simulation detected locations requiring visits and initiated route optimization to generate optimal daily routes. **Mixed Routes:** like fixed routes, mixed routes were employed, assuming containers were equipped with occupancy sensors and executed weekly, visiting locations with containers surpassing a specified occupancy threshold.

Considering these variables, and parameters such as container occupancy thresholds and the number of containers to be placed at each site, various scenario combinations were created. Each scenario was subjected to a simulation that produced a range of results. While the system suggests the best solution in terms of distance, cost, or emissions, all scenarios remain amenable to comprehensive analysis. The following section provides an in-depth analysis of the results obtained in selected scenarios, providing valuable insight into the real-world applicability of the method and its ability to address the complexity of textile waste collection while optimizing operations.

5 Results and Discussion

Results presented in Table 1 provide a rich data set for understanding the dynamics of waste collection networks under different scenarios. These scenarios were made for several variables, including vehicle type and route typology, and to methodically assess their impact on key performance indicators such as distance traveled, costs, and emissions. The main objective was identifying the configurations that most efficiently align with the twin goals of operational efficiency and sustainability.

One significant pattern is that traditional delivery vans consistently outperform automated container loading trucks in terms of economic effectiveness and environmental impact. This pattern faces the assumption that automated technologies are always better than conventional ones. The advantages of the conventional delivery van are its maneuverability, ability to reach specific locations more efficiently, lower fuel consumption and emissions.

The mixed route typology is a favorable approach to optimize waste collection operations. This strategy mixed cluster-based route planning with the container occupancy sensors and optimized resource allocation by considering variables like distance and road accessibility, leading to decreased distances, costs, and emissions. Finding highlights the importance of using technology, data, and intelligent routing for modern waste collection.

Furthermore, selecting a scenario shouldn't be a one-size-fits-all process. The decision should allow for the specifics of the situation, the available infrastructure, and the objectives. An automated container-loading vehicle may be more advantageous in locations with vast highways and high container volumes. However, a regular delivery van may be more efficient in densely populated urban areas with little room to maneuver.

Table 1. Simulation scenarios results (three-month period of waste collection).

Scenario	Route Type	Vehicle	Distance (km)	Cost (€)	Emissions (kg CO_2)
1	Fixed	Van	14,929	25,330	4,229
2	Dynamic	Van	24,644	28,114	6,982
3	Mixed	Van	11,869	21,741	3,363
4	Fixed	Truck	14,929	52,868	11,361
5	Dynamic	Truck	16,952	56,812	12,900
6	Mixed	Truck	11,011	42,398	8,397

6 Conclusions

This paper has presented an inclusive approach to the challenges of textile waste collection, which needs to align operations with evolving regulations. The methodology integrates data collection, optimization, and simulation techniques. Through a case study in the province of Huesca, Spain, this study has demonstrated the tangible benefits of this integrated approach. By simulating different scenarios over three months, important lessons have emerged.

In addition, this study validates the value of simulation as a powerful decision-support tool. Waste management authorities can use simulation to identify necessary investments in vehicle fleets, optimal route planning, and the strategic integration of container occupancy sensors. This ensures regulatory agreement and promotes operational excellence, resource efficiency, and environmental stewardship. This research highlights the potential of data-driven, simulation-based optimization and provides practical solutions to pressing environmental challenges. As waste management stakeholders adapt to ever-changing regulations and societal demands, this study provides a roadmap for improving efficiency and sustainability while considering circular economy principles and sustainable transportation. In conclusion, integrating simulation, optimization, and data-driven decision-making in textile waste collection provides immediate benefits and positions waste management agencies for a more sustainable and responsible future. As a future line of research, the physical implementation of sensors to measure the occupancy level of the containers in the localities under study is proposed, which, in addition to serving as a lever to optimize the collection routes, will allow a better estimation of the waste generation profile of the inhabitants.

Annex I. Simulated Huesca Waste Collection Network

Annex I features a visual representation of the geographical area studied in the case, illustrating the province of Huesca, Spain (see Fig. 1). This figure, an integral part of the simulation tool's interface, displays the specific locations considered in the study, along with container placements. Notably, it utilizes a color-coded system to represent the varying occupancy levels of the containers, indicating when they exceed predefined thresholds. Additionally, the image showcases the optimized routes generated by algorithms and visually depicts the waste collection vehicles efficiently traversing these routes, offering a comprehensive visual insight into the study's waste management strategies.

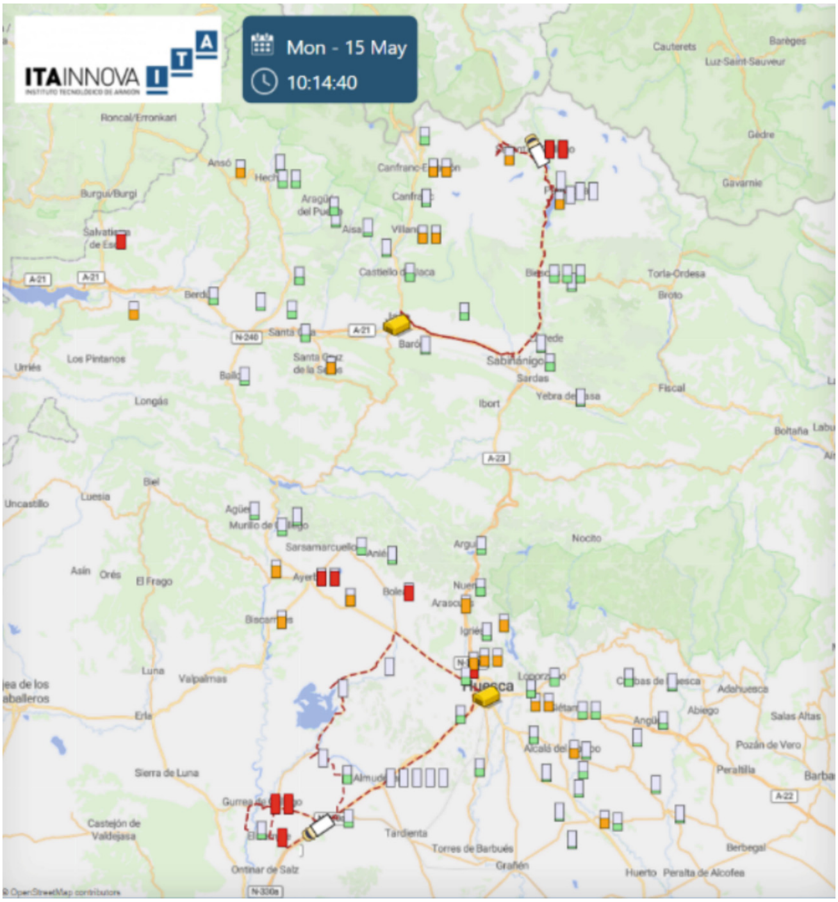

Fig. 1. Simulation visualization of Huesca's textile waste collection network. Image produced using AnyLogic simulation software and maps provided by OpenStreetMap contributors. Source: author.

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Integrating TCO and Sustainability Requirements: ESCALATE Pro-Active Design and Manufacturing Approach for Enhanced Electric Fleets

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Abstract. The European Union's plan to reduce EU-wide transport-related CO_2 emissions from heavy-duty vehicles cannot be realized without considering the GHG emissions generated during the manufacturing and electricity production phases of EVs. The European Union Funded Horizon Europe ESCALATE project approach is proposed as a proactive strategy to optimize resource utilization, minimize environmental impacts, and enhance the overall sustainability and circularity of electric vehicles (EVs) while meeting the financial aspects. ESCALATE develops solutions for 3 types of electrified vehicles (battery, fuel cell, and range extender) including the charging or refuelling infrastructure. By integrating TCO and sustainability considerations into the vehicle's design, architecture, and manufacturing processes, EV manufacturers can identify the most suitable solutions for business needs and budgets, ensuring long-term success in the competitive EV market. This paper presents the Total Cost of Ownership (TCO) and Life-cycle Assessment (LCA) approach formulated by the ESCALATE project to reveal lifetime-extended environmental and economic aspects of electrified trucks and emphasizes the importance of considering the TCO and sustainability requirements, namely life-cycle, early in the project planning phase for electric freight vehicles.

Keywords: Total cost of ownership · Electric fleets · Life-cycle Analysis · Sustainability

1 Introduction

The transportation sector significantly contributes to global greenhouse gas (GHG) emissions, accounting for 20.2% in 2021 [1]. Europe, the third largest emitter after the Asia-Pacific region and North America, contributed 16% [1]. In 2021, road transport was the main source of EU emissions, making up 26% of the total [2]. Despite constituting only 13% of the global road freight market, heavy-duty trucks (HDTs) are responsible for

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50% of worldwide road freight carbon dioxide emissions [3]. In the EU, road transportation accounted for 71.5% of all transportation GHG emissions in 2019, with passenger vehicles at 60.6% and HDTs and buses at 27.1% [4, 5].

Transitioning to electric powertrains for long-distance haul vehicles is crucial for reducing carbon emissions in the heavy-duty transportation sector, which heavily relies on fossil fuels. Over 95% of road freight trucks currently operate on fossil fuels, posing a challenge for reducing carbon intensity. The International Energy Agency (IEA) predicts that by 2050, the share of diesel and petrol vehicles could fall to 33%, replaced by alternative fuels [6]. The European Union aims to lead global emission reduction efforts in transportation, with the European Commission setting stricter targets for HDTs and buses: 45% reduction by 2030, 65% by 2035, and 90% by 2040 [7]. Battery electric trucks could significantly aid the EU's goals, potentially reducing GHGs by up to 92% if powered entirely by renewable energy [8]. The global electric truck market is expected to grow substantially, especially in the Asia-Pacific region, nearly six-fold between 2023 and 2026, and around five-fold in Europe [9].

Despite the positive outlook, a comprehensive approach to the design and operational framework of battery electric trucks, especially for heavy-duty fleets, is essential for meeting the EU's emission reduction targets. Existing literature extensively discusses electric vehicle (EV) design, life-cycle assessments (LCA), and total cost of ownership (TCO) calculations but lacks focus on the specific challenges of zero-emission heavy-duty fleet design. These fleets face unique demands and economic constraints, necessitating dedicated research. A cohesive framework addressing the lifecycle, cost, and performance complexities specific to heavy-duty vehicles is notably absent. Thus, a tailored solution for zero-emission heavy-duty fleets is essential.

The LifeCostDrive strategy addresses this gap by integrating sustainability, economic considerations, and vehicle performance, focusing on zero-emission heavy-duty fleets. Informed by the ESCALATE project's findings, this research offers detailed insights for fleet operators and manufacturers, shifting from broad EV discussions to a focused, actionable strategy for zero-emission fleets.

This paper is structured as follows: Sect. 2 examines the environmental impacts of electric heavy-duty fleets across their lifecycle. Section 3 elucidates the financial implications of electric vehicle ownership and usage. Section 4 introduces the LifeCostDrive strategy, detailing its methodologies and emphasizing its role in sustainable fleet management within the ESCALATE project. The concluding section synthesizes key findings, discusses their implications, and considers future research directions in zero-emission heavy-duty fleets.

2 Life-Cycle Assessment (LCA) Framework –Fleet Level

The International Standards Organisation (2006) defines Life Cycle Assessment (LCA) as a method to evaluate the direct and indirect environmental, social, and economic impacts of processes and products [10] and [11]. LCA quantifies resource use, greenhouse gas emissions, environmental and health impacts, and resource depletion, facilitating direct comparisons of products and technologies based on quantitative functional performance. This is particularly important for electrified trucks, addressing sustainability challenges in transitioning from traditional to electrified heavy-duty transportation. While LCA principles are typically applied to single products, fleet-level LCA for electrified trucks necessitates a detailed exploration of sustainability across multiple vehicles. Our LCA concept considers the fleet of vehicles as the product, supported by recent studies which suggest introducing time when calculating lifecycle emissions due to changing fleet impacts over time [12], [13] and [14]. We present LCA output as total fleet emissions over a period, considering on-road energy consumption (Tank-to-Wheel) and expanding this to the fleet level by factoring in mileage and fleet composition. This dynamic approach includes future projections for energy efficiency, fleet growth, and mileage evolution (Fig. 1).

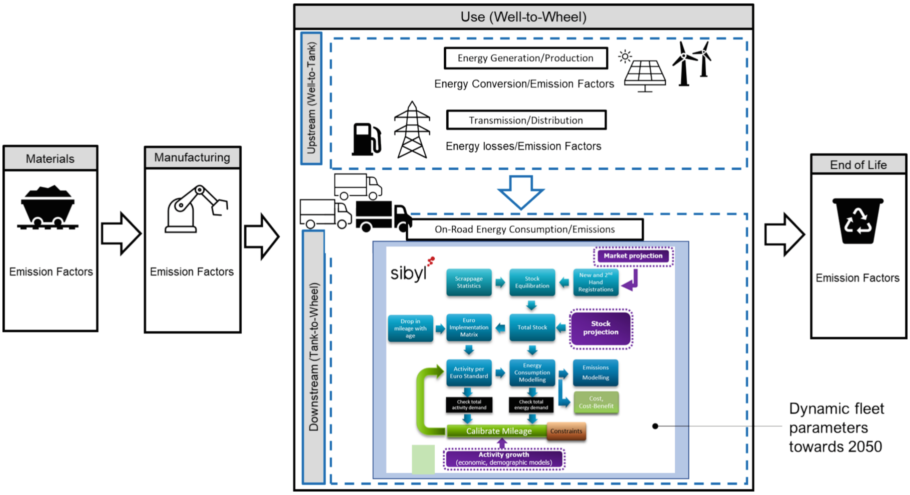

Fig. 1. ESCALATE dynamic LCA framework

Upstream impacts for energy (Well-to-Tank) include stages before on-road consumption, such as resource extraction, electricity generation, and fuel production, with emission factors accounting for the electricity mix and the efficiency of electricity transmission and fuel distribution. Vehicle manufacturing and disposal impacts are assessed from production to end-of-life, considering electrified truck components like batteries, motors, chassis, and body parts. Production country influences are also considered due to varying energy mixes and transportation distances.

Life-Cycle Costing (LCC) includes all expenses during a product's lifespan, such as purchase, operational, and end-of-life costs. Environmental-LCC assesses costs throughout the lifecycle, while Total Cost of Ownership (TCO) focuses on economic viability and performance, often excluding use and end-of-life phases unless internalised. Integrating TCO and LCC within LCA ensures a comprehensive understanding of economic and environmental impacts across the lifespan of electrified trucks, facilitating informed, sustainable decision-making in fleet management.

3 Total Cost of Ownership

As OEMs boost production and policymakers enforce new regulations, fleet owners require tools to assess the financial impact and profitability of this transition. Total Cost of Ownership (TCO) is crucial, providing insights into fleet modernisation effects. TCO facilitates comparisons with traditional ICE vehicles and identifies opportunities to enhance zero-emission heavy-duty vehicles (z-HDV) efficiency, refine powertrains, and assess economic viability. This analysis will show how TCO can be integrated into the LifeCostDrive strategy for managing zero-emission fleets. Five primary categories influence TCO: application and technical specifications, and financial parameters, including Net Present Value (NPV).

NCF (Net Cash Flow) is computed in Eq. (1) by aggregating all future costs including cost of taxes and levies ($C_{T\text{-}L}$), cost of insurance (C_I), cost of maintenance and repairs (C_M), cost of energy (C_E), cost of driver wages (C_{DW}), Cost of infrastructure (C_{In}) for year n and subtracting the residual value of the truck at the end of ownership period (RV_{Truck}).

$$\text{NCF} = \sum\nolimits_{n=0}^{n} NCF_{Year\,n}(NCF) = depreciation_{Year\,n} + C_{T-L_{Year\,n}} + C_{I_{Year\,n}} + C_{M_{Year\,n}} + C_{E_{Year\,n}} + C_{DW_{Year\,n}} + C_{In_{Year\,n}} - RV_{Truck} \quad (1)$$

Present Value (PV) is calculated by using Eq. (2) where NCF is the Net Cash Flow and R is the Rate of Return.

$$(PV)_{Year\,n} = \frac{\text{NCF}}{(1+R)^n} \quad (2)$$

The cumulative total present value of all future payments (TPV) is calculated by using below Eq. (3).

$$TPV = \sum_{n=0}^{n} (PV)_{Year\,n} \quad (3)$$

Net Present Value of Total Cost of Ownership is calculated by combining the truck's purchase cost (C_{Truck}) with the TPV of all future payments, as shown in Eq. (4).

$$NPV = TPV + C_{Truck} \quad (4)$$

4 The ESCALATE Proactive Strategy: An Overview of LifeCostDrive Strategy

The proactive LifeCostDrive (LCD) strategy integrates Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), and vehicle performance. LCA evaluates environmental impacts throughout a vehicle's lifecycle, crucial for identifying and reducing emissions in zero-emission heavy-duty vehicles (Z-HDVs). TCO examines financial aspects over the vehicle's lifespan, including long-term costs, important for stakeholders like fleet operators. Vehicle performance affects user acceptance and operational efficiency.

The ESCALATE approach analyses TCO and sustainability throughout the EV lifecycle, aiding businesses and policymakers in making informed decisions to achieve economic and sustainability goals for road transport. The framework advocates for standardised guidelines to incorporate these factors into Z-HDVs' design and manufacturing (Fig. 2).

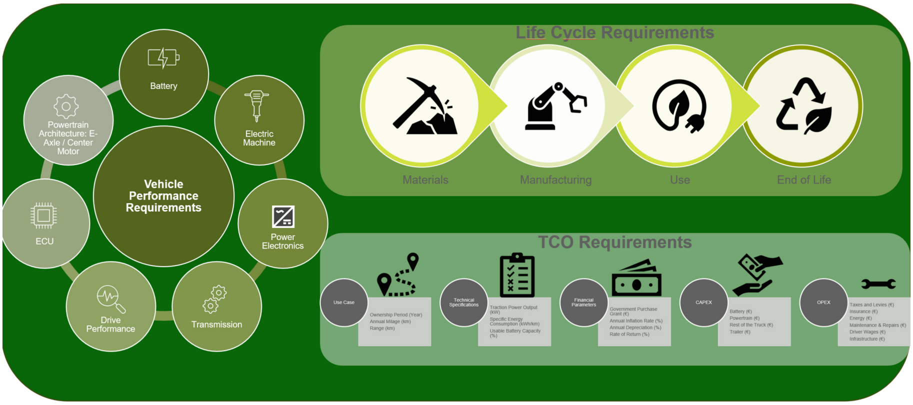

Fig. 2. ESCALATE: LifeCostDrive Framework

5 Conclusion and Future Implications

Integrating TCO and sustainability requirements early in project planning is essential for EV market success. This ensures EVs support environmental goals by reducing GHG emissions, lowering resource consumption, and promoting circular economy principles. The ESCALATE project provides a comprehensive framework to help EV manufacturers incorporate TCO and sustainability into design, architecture, and manufacturing. This proactive approach optimizes resource use, minimizes environmental impacts, enhances sustainability and circularity, and improves end-user acceptance. This research contributes to EV development literature, underscoring the importance of integrating TCO and sustainability for a greener transportation future.

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Uncertainty Sources in the Life Cycle Sustainability Assessment of Transport Infrastructure in the Context of Asset Management

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Abstract. Transport infrastructure, crucial for societal functionality and well-being, has important sustainability considerations throughout its life cycle, including resource use, emissions, and socio-economic impacts. Widely adopted life cycle thinking methodologies like LCC, LCA, and S-LCA aim to quantify these impacts, seeking to enhance the positive contributions of infrastructure while mitigating negatives. However, the reliability of these methodologies is often questioned due to the insufficient systematic consideration of uncertainties in the analyses, with deterministic assessments potentially leading to misleading conclusions. While research has progressed, with some LCC and LCA studies incorporating uncertainties, the application in the transport infrastructure field remains constrained and methodologically uneven. This paper seeks to advance the validity of sustainability assessment methodologies in transport infrastructure by reviewing sources, types, and specific triggers of uncertainty in infrastructure LCT studies, providing the reader with relevant descriptions and examples, as well as linking them across different categorizations. This research aims to advance the applicability of uncertainty analysis in the infrastructure LCT field as well as offer recommendations for future research.

Keywords: Life Cycle Sustainability Assessment · Transport Infrastructure · Uncertainty analysis

1 Introduction

Transport infrastructure forms the backbone of modern societies, facilitating global movement of people and goods. These infrastructures deteriorate over time, and as such, require interventions to restore and maintain their operational status. Today, the focus of infrastructure asset management (IAM) goes beyond merely implementing robust and safe engineering solutions, it also entails adopting and prioritizing sustainable approaches that address the negative economic, environmental, and social impacts associated with infrastructure interventions.

Life cycle costing (LCC), life cycle assessment (LCA) and social life cycle assessment (S-LCA) are life cycle thinking (LCT) methodologies developed to evaluate the

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economic, environmental, and social dimensions of sustainability [1]. In IAM, LCC enables the calculation of all agency and user costs throughout the life cycle of infrastructure networks and assets, unveiling long-term financial implications and key areas of expenditure [2]. Similarly, LCA tracks the environmental impacts of infrastructure across the asset life cycle, including the energy and resources required to carry out production, construction, demolition and waste processing tasks, as well as the emissions generated [3]. S-LCA extends this approach to the social impacts of infrastructure, covering multiple stakeholders perspectives, including workers, local community, value chain actors, consumer and overall society [4, 5].

Worldwide, transportation agencies resort to LCT methodologies to assess the performance of infrastructure interventions across the multiple dimensions of sustainability, highlighting key impacts and potential areas for improvement, and to execute comparative analysis between different options [6]. However, these methodologies are not without challenges, notably in managing the uncertainty that arises from issues related to data quality, methodological choices, or inherent variability [7, 8].

While a subset of existing studies has factored in the effects of uncertainty on infrastructure LCA and LCC analyses, this practice is far from standard. Research delivering a more comprehensive view on the subject is available, providing insights into the identification and management of uncertainties in infrastructure LCT evaluations. However, these studies tend to discuss uncertainty types and sources within a broader, more generalized framework, often with insufficient detail on uncertainty drivers specific to the infrastructure domain [9, 10]. Conversely, studies that do delve into these drivers do not explicitly frame them according to more standardized uncertainty classifications, particularly concerning their analytical level and position within the study [11].

All relevant sources of uncertainty must be considered for a thorough uncertainty analysis. This calls for a rigorous mapping of these sources, including knowing where and at which analytical level they first appear, and what triggers them. Understanding each uncertainty source is fundamental for properly managing and analyzing their effects on the assessment [7, 9]. Consequently, this study seeks to foster the development and uptake of uncertainty analysis in LCT applications in IAM by identifying and categorizing the primary types and sources of uncertainty encountered in infrastructure LCT studies, as well what triggers them.

2 Unpacking Uncertainties in Transport Infrastructure LCT Studies

2.1 Uncertainty Categorization

In LCT methodologies, uncertainties can typically be classified by either the analytical level at which they occur or the specific stage of the assessment in which they manifest [7, 10]. At the analytical level, we distinguish between parameter uncertainty, which concerns the quality and variability of the input data and scenario uncertainty, which is related to the methodological choices undertaken during the study [7, 10].

During the initial ‘goal and scope definition’ stage of an LCT study, the fundamental elements that shape the study are established. The goal and scope is underlined by precise goals and questions, steering it towards a targeted examination of impact categories and indicators that span economic, environmental, and social realms. It is at this juncture that scenario uncertainties often arise due to the pivotal methodological decisions that will influence the direction of the entire study [7, 12].

In the life cycle inventory (LCI) stage, which takes place after the goal and scope definition, executioners gather input data on economic, environmental, and social processes and flows occurring throughout the entire lifespan of the system under examination. This include indirect upstream processes in the background, as well as the direct activities under assessment in the foreground. In the ensuing life cycle impact assessment (LCIA) phase, the LCI inputs are translated into economic, environmental, and social impacts. Parameter uncertainty is usually encountered in both phases. In LCI, it stems from issues with data quality and variability of the quantities and scores characterizing the inputs [7, 10, 13]. In LCIA, it is present in the characterization factors used to compute impacts. Table 1 compiles different uncertainty sources found in literature based on the categorizations presented above.

Table 1. Categorization of uncertainty sources found in LCT methodologies.

Analytical level	Stage	Method	Uncertainties	Sources
Scenarios	Goal and scope definition	All	System definition	[11]
			Functional unit	[9, 11, 14]
			Analysis period	[9, 11, 15]
			Allocation	[16, 17]
			System boundaries	[7, 9, 11]
			Future scenarios	[14, 18]
			Goal and questions to be answered	[14]
			Impact categories and indicator selection	[5, 13, 14]
			Statistical significance of the results	[14]
Parameter	LCI	LCC	Direct and indirect costs unit costs	[12]
		LCA	Input data to describe foreground and background processes and to quantify flows	[7, 9–11, 15]

(*continued*)

Table 1. (*continued*)

Analytical level	Stage	Method	Uncertainties	Sources
	LCIA	S-LCA	Input data to describe processes and to quantify flows	[13]
		LCC	Discount rate values	[10, 19]
		LCA	Characterization, normalization, and weighting factors	[7, 9, 20]
		S-LCA	Elicitation of weight values	[13]

2.2 Uncertainty Triggers in Infrastructure LCT Studies

There are several uncertainty triggers specific to infrastructure influencing uncertainty mapping in LCT studies. Based on the literature, seven key triggers are identified: socio-demographic characteristics, analysis scale, temporal boundaries, future scenarios, the construction industry's nature, and the nature of infrastructure interventions.

In social assessments, where impacts can have different meanings in function of context, socio-demographic factors take on added importance [21, 22]. The assessment scale, whether applied at the network level—examining interventions on a group of assets simultaneously—or at the asset/project level—analysing assets in isolation—affects the system definition and data requirements of the assessment [23]. Temporal boundaries define the period over which infrastructure is assessed. They can cover single cycles—the time elapsed between one intervention to next one—multiple cycles, or all cycles until decommission in EOL. The choice of temporal boundaries thus directly influences the definition of the functional unit and the system boundaries [6, 10, 11].

Future scenarios reflect uncertainties about evolving conditions. These are mainly present in the inputs characterizing processes that are likely to change over time, such as electricity generation [18]. Future uncertainties have an important impact on the analysis, particularly when looking at life cycle phases that take place over the distant future, namely use and EOL. As a result, the importance including these uncertainties in the analysis has received increasing attention in the context of infrastructure sustainability assessments.[11, 14, 18, 24].

The construction industry's nature introduces substantial uncertainty into model inputs due to the unique nature of each construction project, affecting the characterization of foreground input quantities and processes in the model [11]. Lastly, the nature of infrastructure interventions includes specific attributes of these activities, such as post-intervention predicted service life and duration of construction time, all influencing the results [11, 18, 25]. Table 2 summarizes these key uncertainty triggers and provides specific examples applicable to transport infrastructure LCT studies.

Table 2. Uncertainty triggers in the application of LCT methodologies to infrastructure sustainability assessments. Based on [11, 18, 26].

Uncertainty triggers	Description	Examples in transport infrastructure
Socio-demographic characteristics	These features impact the assessment of infrastructure interventions by shaping the value and functions that infrastructure fulfils in its context. These factors inherently influence the way in which the social sustainability of infrastructure projects is evaluated	Social impact categories, indicators, and weights assigned to the S-LCA of restoration interventions to ageing inner city bridges in historical city centres. In this case, for example, cultural heritage aspects may heavily influence social perceptions and, in turn, social assessments
Scale	This relates to the system definition, wherein a network encompasses multiple similar infrastructure assets within a specified area, while an asset/project pertains to a specific, individual asset, each fulfilling specific functions	The analysis scale of a pavement LCA study. Is the analysis at the network level where information is limited, and uncertainty is high? Or is the analysis at the project level, where information is detailed, and more design aspects are known?
Temporal boundaries	This pertains to the analysis period over which infrastructure is analysed. In a single-cycle analysis, an asset is evaluated from construction to the next major intervention, or from major intervention to the next major intervention, considering only minor interventions in between. Conversely, a multi-cycle analysis assesses infrastructure over extended periods, incorporating both minor and major interventions, potentially up to the asset's end-of-life (EOL)	The analysis period of a given highway where a decision must be made on whether to assess the environmental impacts from the moment when rehabilitation takes place up to when it is needed again or including more than one rehabilitation cycle at a time, examining environmental impacts at the longer-term

(*continued*)

Table 2. (*continued*)

Uncertainty triggers	Description	Examples in transport infrastructure
Future scenarios	This encompasses the approach to defining future scenarios in the analysis. Infrastructure is analysed over an extended timeframe, during which changes to both the background and foreground systems are likely to occur. These changes influence the analysis and its results. A static future definition assumes continuity of current conditions into the future, while a dynamic definition accommodates expected changes	The considerations of long-term, network-level pavement maintenance and rehabilitation plans. Shifts in background systems, such as changes in electricity grids, energy sources, and waste processing techniques, as well as developments in construction materials, methods, and use (e.g., traffic volume and composition) influence the impact assessment of these assets
Nature of the construction industry	The construction industry is distinguished by the uniqueness of each project. Although construction processes and materials might share similarities across various infrastructure interventions, even of the same type, they are seldom identical due to variations in sites, contractors, and local conditions across different locations and projects	The calculation and designation of budgets for bridge restoration programs based on LCC analyses. There are no bridge projects exactly equal because, even if they share the same typology of bridge with standardized components and dimensions, different contractors might be assigned to different works, and each site has its unique conditions
Nature of infrastructure interventions	Infrastructure interventions aim to prolong the lifespan of assets, though the additional years and the activities to ensure the intended lifespan are subject to varying uncertainties regarding their timing and nature. Likewise, construction time and/or capacity are likely to fluctuate across projects, influence the analysis and its outcomes	The assessment of lifespan extension measures to rehabilitate quay walls lining inner-city canals. The actual life extension that will be granted by applying these measures is uncertain, so is the actual construction time that these works will take when applied at larger scales

3 Discussions and Conclusions

Navigating uncertainty in LCT studies is crucial for enhancing the reliability of sustainability assessments within the transport infrastructure sector. Despite a recognition of the threat of uncertainty to the reliability of LCT studies, there has been a conspicuous lack of dedicated efforts towards the development and integration of uncertainty analysis approaches in these studies [20, 27]. This underscores a pressing need for more coordinated and deliberate research efforts by the infrastructure community to address and account for the effects of uncertainty in LCT assessments. To do this, it is essential to 1) meticulously map and comprehend the sources and triggers of uncertainties that pervade the assessments, 2) establish robust methodologies for characterizing, propagating, and conducting sensitivity analyses to trace the effects of uncertainties in the analysis, and 3) encourage a collaborative research approach that standardizes the use and application of uncertainty analysis in the field.

This study contributes to improving uncertainty mapping in infrastructure LCT studies, seeking to lay the groundwork for further advancements. It focuses on outlining various types and sources of uncertainty, integrating different categorizations from existing literature, and linking them to specific triggers within LCC, LCA, and S-LCA studies in the context of transport infrastructure sustainability assessments Furthermore, it provides insightful examples illustrating how these uncertainties unfold in practice. Our work seeks to pave the way for further progress, aiming to improve the quality and reliability of sustainability assessments in IAM, facilitating more informed and sustainable decision-making and strategic planning.

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Environmental Assessment of Components for Trains Based on the Use of Fiber Reinforced Plastic

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Abstract. Sustainable development is considered one of the most important global challenges facing the world today and is an important aspect of transport development. Rail has a central role to play in decarbonising transport as the backbone of the future sustainable transport system.

Various developments have been undertaken by railway stakeholders: decarbonisation of diesel trains, noise and vibration reduction, circular economy initiatives, improving the attractiveness of passenger trains, transferring goods to freight trains, etc., i.e. different methods to further improve the energy intensity consumption (kJ/km) of rail transport. One way of reducing energy consumption is to reduce the weight of the train, and Talgo has been working intensively in this area since the beginning, pioneering the use of aluminium structures in the early 1950s and, in recent years, the use of composite materials in primary structures.

There is a lack of clear guidelines on recycling and the circular economy, or official information is outdated. This lack of clarity is an obstacle to the design of robust policies for recycling and circular economy in composites and could be an obstacle to the wider uptake of these types of materials.

In this article, we will shed light on the uptake of composites from a Life Cycle Assessment (LCA) perspective, discussing recyclability, circular economy opportunities and whole-life impacts from a cradle-to-cradle perspective.

The study is divided into two phases, starting with an LCA of the new prototypes, including the production, assembly, transport and use phases. This is followed by an LCA of conventional structures and a comparison between them. The second phase concludes with a comparison of the environmental impact of replacing conventional structures with these innovative composite structures at the end of their useful life (EoL).

The figures obtained suggest that at EoL, composites will be more economically and environmentally attractive than current materials. In addition, new developments in composite materials and recycling processes will lead to significant improvements in the circularity of these components, increasing the recyclability rate.

Keywords: composites · LCA · circular economy · recyclability · structure · lightweighting

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