Advanced Logistic Systems – Theory and Practice, Vol. 18, No. 3 (2024), pp. 43-57
https://doi.org/10.32971/als.2024.027

AN INNOVATIVE OPERATIONAL MODEL FOR COMPANIES OPERATING BUS FLEETS

VINCE KRUCHINA[1] – PÉTER TAMÁS[2] – GYÖRGY TIBOR SÁRKÖZI[3] – BÉLA ILLÉS[4]

Abstract: *The organization and operation of public transport have not escaped the impact of changes taking place worldwide which are driven and influenced by the rapid spread of disruptive technologies and efforts related to climate protection and sustainable development. The challenges posed by the proliferation of electric vehicles (EVs) – including electric buses (BEBs) – require new solutions and new ways of thinking, and a more holistic and innovative operating model for road transport companies using buses. In this model, the authors present a methodology for the delivery of contracted scheduled services that, as part of a systems approach, links a mixed fleet and its appropriate route plan within a data-driven circular operational model, allowing room for innovative energy solutions, the use of renewable energy sources and for satisfaction of increasingly demanding climate and sustainability requirements, all using a logistics science approach.*

Key words: *Battery Electric Buses, BEB, TCO, mixed fleet, data driven, sustainability*

1. INTRODUCTION

The aim of this paper is to provide a logistics model with which public transport operators can decide to integrate electric buses into their fleet, thus contributing to carbon neutrality and sustainable development. With the model we are presenting, environmentally conscious public bus transport will be sustainable not only from an environmental point of view, but also from a corporate, operational and economic point of view.

The spread of electric vehicles (EVs) – including electric buses (BEBs) – has been increasing rapidly since the 2010s, accompanied by the appearance of numerous publications on their introduction and integration.

In an article published in 2016, BORÉN et al. stressed that, from a theoretical point of view, electric buses can be a cheaper and more sustainable option for urban transport than fossil-fuelled buses. At that time the authors could not find any tests under real operating conditions that evaluated the reliability of electric buses in local transport in Sweden under extreme winter weather conditions. Also unavailable was updated noise measurement data for electric buses on the European market. The purpose of this follow-up study was therefore to test and verify the energy efficiency and quietness of electric buses in a real environment. The sound impact study measured that the noise emissions of electric buses (63dBA) are lower than those of diesel (68dBA) or biogas (70dBA) buses [1].

[1] PhD student, University of Miskolc, Institute of Logistics, Hungary
Vince.Kruchina@volanbusz.hu
[2] University professor, University of Miskolc, Institute of Logistics, Hungary
peter.tamas@uni-miskolc.hu
[3] PhD, University of Miskolc, Institute of Logistics, Hungary
dr.sarkozi.gyorgy.tibor@outlook.hu
[4] University professor, University of Miskolc, Institute of Logistics, Hungary
bela.illes@uni-miskolc.hu

In 2019 PELLETIER et al. addressed the electrification of bus fleets as a topical issue and considered transition alternatives that set the number of electric buses that should be in the fleet within a given period [2].

2019 LI et al. examined solutions for the adoption of electric buses in cities around the world and produced a summary and guidance report for organisations operating urban transport and bus operators [3].

Research published in 2021 by the McKinsey Center for Future Mobility found that electric vehicles are transforming the car industry and helping to decarbonise the planet. At that time, the public transport system in the city of Shenzhen in China was already being served by a fleet of 16,000 all-electric buses. Based on the growth in the number of electric vehicles, a twenty-fold increase in battery production capacity in Europe was forecast by 2030, with the industry estimating that up until 2030 it would need to install more than 15,000 chargers per week in the European Union. Simplified regulation is needed to facilitate the installation of electric chargers, as experts say that it can currently take up to three years to obtain authorisation to expand the network of fast-charging stations [4].

In 2021 AAMODT et al. published a guidance publication on the integration of battery electric buses into bus fleets in the United States of America, highlighting that the use of these vehicles is becoming increasingly attractive for cities seeking to reduce emissions and congestion. But they pointed out that while electric bus fleets can bring benefits such as lower fuel and maintenance costs, improved performance, lower emissions and energy security, a number of challenges to their integration need to be overcome. These include upfront cost premiums, design difficulties, range, and lack of knowledge of the associated technology. Decision-makers, transport managers, public service providers and other stakeholders need to consider many factors before deployment [5].

In 2021 SHAH et al., noting increasing air pollution problems in large cities, identified the sustainability of urban and suburban transport systems as one of the most important factors in urbanisation. In the interest of introducing green and sustainable solutions, changes in the transport system need to be planned carefully and globally [6].

Therefore, together with a thematic assessment of the literature on these issues, a complex, holistic design of the whole ecosystem is needed to address the economic, environmental and social sustainability of vehicle fleets and the services they provide. This should not only take into account aspects related to the organisation of transport (e.g. vehicle fleet, transport infrastructure, route, etc.), but also the creation of optimal operating conditions for electric buses: integration of the charging network into the route plan; location of the charging network; choice of charging modes; energy-optimised solutions for the supply of fuel; and sustainability issues related to the traction batteries of electric buses (degradation, recycling and second life cycle). The review of thematic literature presented in the following section includes publications identified as relevant for the topic's keywords.

2. Thematic review of literature on the operation of electric buses

In recent years there have been very many studies on the return on investment and the correct methodology for electric buses, which have correctly examined the total cost of ownership (TCO) of the means of production; but these analyses have mostly focused on the location of the charging infrastructure, battery performance or the optimisation of routing policy.

In 2010 OFFER et al. published a comprehensive sensitivity analysis on several vehicle platforms (BEV, FCHEV, FCV, ICE) which showed that by 2030 FCEVs will be able to achieve life cycle cost parity with vehicles using conventional fuel [7].

In 2013 FENG et al. calculated that, based on contemporary US market values, the energy costs per mile for electric commercial vehicles (ECVs) were almost four times lower than those for conventional diesel trucks. In terms of vehicle purchase costs, however, ECVs are approximately three times more expensive. While maintenance of electric vehicles is easier and cheaper, there is more uncertainty about the lifetime and long-term costs of ECV batteries [8].

In 2014 LAJUNEN, had already addressed the issue of energy consumption and cost-benefit analysis for hybrid and urban electric buses, and in a 2018 article the same author analysed the lifetime costs of electric buses by examining different charging methods. [9].

In 2014 NURHADI et al. conducted a sensitivity analysis of the total cost of ownership (TCO) of public transport systems using electric buses in medium-sized cities in Sweden [10].

In 2016 ZHOU et al. investigated the life cycle characteristics of electric buses under real operating conditions, with a focus on energy consumption and carbon dioxide emissions. They calculated that, over the entire life cycle of vehicles, the use of electric buses reduces fossil energy consumption by 85–87% and CO_2 emissions by 19–35%. The power supply for electric buses can be produced entirely from green energy: solar, wind or geothermal. Therefore reducing emissions need no longer be just a local objective, but a global one [11].

In 2017 KUNITH et al. developed an optimisation model for the cost-effective design of charging infrastructure for electric buses in urban bus networks. They emphasized that key factors in minimizing the total cost of ownership (TCO) and managing available energy resources are the efficient layout of charging infrastructure and the appropriate sizing of battery capacity. Various scenarios were tested in order to assess the impact of charging performance, weather and changing operating conditions [12].

In 2018 LAJUNEN, 2018, focused on the impact of charging demand and charging methods on life cycle costs, and developed a specific simulation tool for a comprehensive assessment of the operation of electric buses under different conditions. The charging modes considered included charging at night, at terminuses, and on an ad hoc basis. The simulation results are presented for four operational routes for bus services in Finland, in California and across the United States. The results show that the key factor for the proper daily operation of buses charged during the night is the battery system's energy capacity, while for buses using fast chargers the battery size has little impact on energy consumption and life cycle costs. The life-cycle costs of electric buses are strongly influenced by capital costs, including the purchase costs of buses and charging equipment. Assuming a twelve-year life cycle, electric buses charging at terminuses may have a somewhat shorter life cycle than diesel buses, but on average the life cycle costs are 7% higher. Buses charged during the night have an average lifetime that is 26% longer than diesel buses and the corresponding figure for alternatively charged buses is 35% longer [13].

In 2018 LOZANOVSKI et al. carried out a sustainability assessment of fuel cell buses used in public transport. As part of this assessment, fuel cell buses' operational performance was evaluated against diesel buses in terms of both sustainability and real-world performance. The study concluded that H2FC buses meet the operational and performance criteria and are environmentally friendly when using "green" hydrogen [14].

In 2018 VORA et al. found that in the design of electric vehicle operations the impact on the total cost of ownership (TCO) made by battery degradation and replacement has hitherto been insufficiently emphasized, even though the battery is the most expensive and least robust part of the powertrain [15].

In 2020 JEFFERIES et al. presented a comprehensive TCO assessment method for electric bus operation based on discrete-event simulation, including route plan design and charging infrastructure optimisation. As a result of their work, a model based on a complex economic and technical ecosystem was developed to determine the return-on-investment indicators for electric buses. The eFLIPS (Electric Fleet and Infrastructure Planning/Simulation) model they published is illustrated in Fig. 1. The economic framework presented in their study is logical and highly detailed, as it calculates the following: battery capacity; route lengths; charging options, whether on-site, at terminuses or in transit; fleet composition; charging times; operating and investment costs, and other economic indicators [16].

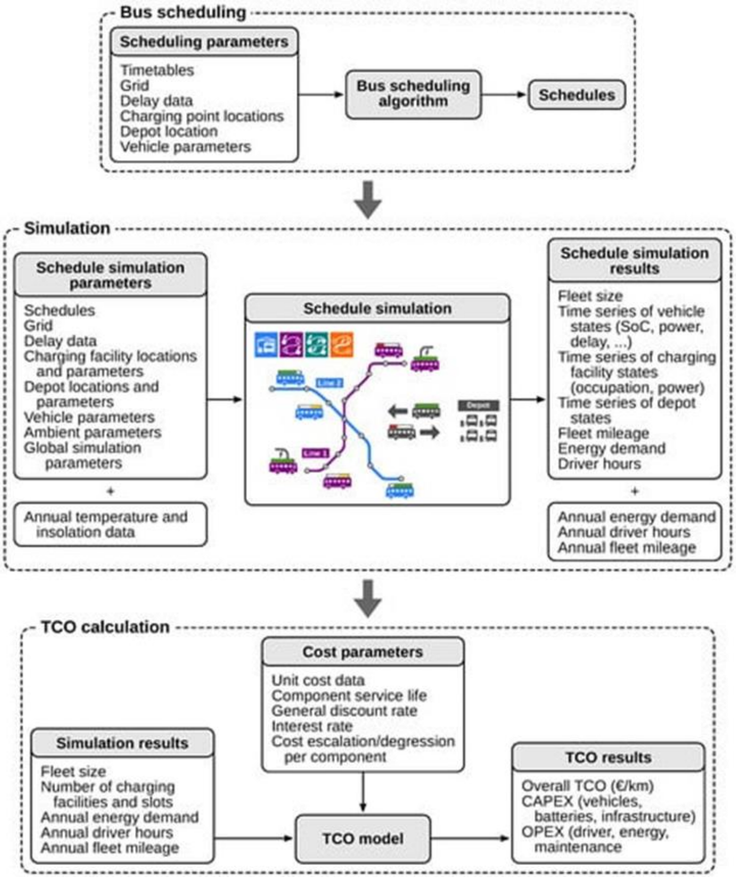

Figure 1*. The so-called "eFLIPS" (Electric Fleet and Infrastructure Planning/Simulation) model (Jefferies, 2020)*

In 2021 BARRAZA et al. developed an efficient design and cost comparison procedure for battery electric bus networks for various powertrains. In their paper's model input data they identify the relevant cost parameters for comparison of diesel and electric powertrains on rigid and articulated buses. These include distance-related costs (e.g. specific fuel and maintenance), labour costs and specific infrastructure costs [17].

In 2021 KIM et al. conducted a comparative TCO analysis of battery electric and hydrogen fuel cell buses for public transport systems in small and medium-sized cities. In addition, a structural analysis of a given city's public transport system was carried out, assessing the most suitable bus routes for the use of electric or hydrogen buses [18].

In 2021 POLOM et al. evaluated the experiences and directions of development of public transport services utilizing electric buses in Poland. The authors concluded that the transformation of public transport was achieved mainly by supporting the purchase of electric buses and the charging infrastructure, ignoring the country's energy balance and the possibility of combining various energy sources [19].

In 2022 AGER-WICK ELLINGSEN et al. established that battery electric buses (BEB) use a variety of Li-ion battery technologies and sizes, but there is little knowledge or data about the environmental impacts of the possible alternatives. The environmental performance of BEBs was evaluated over the ten-year life cycle typical of bus tenders, as well as over a twenty-year extended life cycle. Extending the life of a BEB from ten years to twenty years improves both environmental performance and the relative contribution to the potential environmental impacts of BEB alternatives [20].

In 2023 ABDELATY et al. investigated the potential for a robustly designed battery electric bus network based on disruptive evolution of the charging infrastructure, using network analysis theory. In contrast with conventional BEB infrastructure optimization models that aim to minimize the total system cost, utility impacts and component size, their study seeks to determine how the operability of the transport system can be maintained in the event of a disruptive event such as power outage or equipment failure, and which parameters of the charging process can significantly affect this [21].

In summary, most economic modelling shows that in the medium term the profitability of operating electric buses is still in doubt. But we question whether we can really accept the veracity of the national and international calculations which have been presented. The models and methodologies that have been developed and presented are excellent within their own logical parameters, but in our view, they are not sufficiently wide-ranging. The economic frameworks presented in the studies are themselves logical and highly detailed, as they take account of battery capacity, route lengths, charging options (whether at depots, terminuses or in transit), fleet composition, charging time, operating and investment costs and other economic indicators. In our view, the shortcoming of the models is that their authors are content with a solitary economic schema and have not placed them within a complex ecosystem in which isolated systems are connected.

Therefore, in this publication we are presenting a much more complex model, which is an ecosystem built according to the methodology of logistics science. In it we not only consider the TCO, investment (CAPEX) and operating (OPEX) costs of electric buses; we also provide a very complex, but more realistic, picture of the potential for the deployment of electric buses by examining the revenue aspect of other business opportunities in electric buses, spent batteries and charging stations, and the potential for the production and commercialisation of the fuel itself – i.e. electricity.

3. PRESENTATION OF AN INNOVATIVE OPERATING MODEL

The theoretical background to the innovative operating model is presented in the following structure:

- Identification of the boundaries of the system, scope of utilisation, exclusions and limitations
- Logistical interpretation of the system model
- Logistics processes (flows) and entities within the system
- System links between flows and entities
    - Definition of the role of the data centre and identification of the related logistical entities
    - Identification of the scope and types of data processed in the data centre
    - The technological relationship between the data centre and the data
    - Description of the role of the data centre in terms of enterprise resource planning (ERP)

3.1. Boundaries and utilisation scope of the logistics system

The logistics model can be applied to local, suburban and interurban public transport bus operating companies that aim to achieve a significant degree of mixture within their fleets by efficiently integrating electric buses into them, taking into account the entire lifetime cost of the fleet and diversified energy supply solutions, while in the longer term addressing problems associated with the sustainability and economic viability of batteries.

Based on the thematic literature review, we found that various publications, research projects and studies have developed models which operate at different levels. These models were arranged into a hierarchy – from Level 1 to Level 5 – according to their impact on total cost of ownership (TCO).

Level 1 model: comparison of the TCOs within fleets for buses of different makes, types and powertrains,

Level 2 model: based on the findings of the Level 1 model, the proportion of vehicles with different powertrains was determined in order to create a mixed fleet, taking into account basic fuel costs, the ratio of various powertrains to the total fleet composition, and ranges,

Level 3 model: in addition to the above considerations, this model also takes into account the charging infrastructure options and charging modes,

Level 4 model: this also addresses the second life cycle of batteries and their potential for use in terms of decarbonisation.

Level 5 model: the data-driven innovative solution presented in this paper, which also integrates the energy logistics flow in a holistic way into a circular economic and logistics model, exploiting the potential of Industry 4.0.

3.2. Logistics interpretation of the system model

Using graph theory and network theory as a starting point to theoretically ground a holistic model, we apply these theories in a special way, connecting previously unconnected processes and entities into a logistics network.

In mathematics, graph theory is the study of graphs, which are mathematical structures used to model pairwise relationships between objects. In this context a graph consists of vertices (also called nodes or points), connected by edges (also called arcs, links or lines). A distinction is made between undirected graphs, where edges symmetrically connect two vertices, and directed graphs, where edges asymmetrically connect two vertices. Graphs are a major object of study in discrete mathematics.

Network theory is the study of graphs as representations of either symmetric relations, or – more generally – asymmetric relations between discrete objects. Network theory is part of graph theory: a network can be defined as a graph in which vertices and/or edges have attributes (e.g. names). It is used in a number of disciplines, including statistical physics, particle physics, computer science, electrical engineering, biology [1], economics, finance, operations research, climatology and sociology.

According to GLISTAU (2024), logistics is an application-oriented science that analyses, models and quantifies the functioning of human, technological and organisational systems in space and time based on the flow of objects that form networks. Flows can be of a physical type (e.g. materials, commodities, etc.), or related IT, financial and energy flows [22].

The model presented in this paper aims to improve the economic, environmental and social sustainability of a mixed fleet company by examining the full life cycle cost of an electric vehicle fleet – a group of transport assets integrated into the transport logistics flow. To this end it integrates into the complex model the energy supply and battery reverse logistics flow system and flows of electric vehicles. This is done in a way that is circular and data-driven, based on information from Industry 4.0 IT tools.

3.3. Logistics flows and entities

The system shown in Fig. 2 combines three logistics flows in order to justify the integration of electric buses (BEB) into a mixed fleet from a TCO perspective. These flows, which will be presented in more detail at entity level, are the following:

- Processes and entities of the transport system served by a mixed bus fleet
- The energy supply system for electric buses managed as an ecosystem
- Reverse logistics system for electric bus batteries

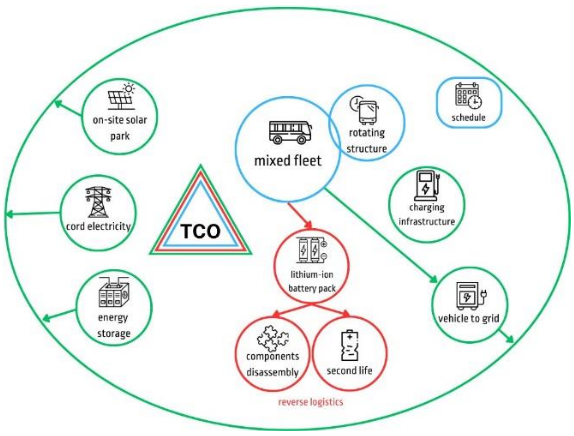

Figure 2. *Logic diagram of the 3 logistics flows*

3.3.1. Transport system served by the mixed bus fleet

The integration of electric buses – part of the larger sector of electric vehicles (EVs) – into the passenger transport fleet has been a challenge for transport operators that previously operated with diesel and gas-fuelled vehicles.

The entities of the transport logistics system are the following:

- A mixed bus fleet, including battery electric vehicles
- The timetable served by the mixed fleet
- The route plan needed to comply with the timetable

In addition to their environmental benefits, the characteristics of electric buses that are subject to examination include range, specific energy consumption and overall lifetime. In the design of a route plan suitable for the implementation of a timetable expected from the service provider, a key issue is that the range of the electric vehicles and the way in which their batteries are charged should be appropriate for the safe operation of the route. In the context of electrification and decarbonisation as a process, the technical composition of a mixed fleet will also continuously change according to the proportion of electric buses that can be integrated, based on a comparison of whole lifetime costs.

3.3.2. Energy supply system for electric buses

The entities that make up the system are the following:

- Electric bus charging infrastructure and system
- Vehicle-to-grid
- Photovoltaic system
- Mains electricity
- Energy storage

The batteries of electric buses need to be recharged according to the daily journey length so that they are ready for the next daily journey length. The battery capacity may allow for charging and the depot, while for longer journey lengths it may be necessary to add a charging session mid-route. The energy stored in the electric bus battery can be fed back into the electricity grid with a so-called "V2G" system. Renewable energy is an obvious means of generating the energy used in the process of electrification. Among the available energy supply options, the implementation of the buy and sell options can be optimised through connection to the grid. Electric vehicles with batteries that are no longer suitable for the powertrain can also play a role in developing the energy flow.

3.3.3. Reverse logistics system for electric bus batteries

The entities of the reverse logistics system are:

- Electronic, electrical waste treatment, dismantling into components
- Use as storage for external parties (also)

While electric batteries enable electric buses to operate with zero emissions, the use of used batteries can also green the manufacturing process for new batteries and create important energy storage opportunities through a second life cycle. A reverse logistics flow can be designed by optimising the way batteries are charged and monitoring their degradation.

3.4. Information and management flow

Entity of the information flow
- Logistics entities connected to the data centre
- Scope, type and source of data generated in the logistics entities
- Relationship between the data centre and ERP

The scope, type and source of data are fundamentally related to the entities involved in the flows. The way in which information is transmitted is based on the use of IoT tools, exploiting the potential of Industry 4.0. This provides the opportunity for the data centre to perform the computations required for the management and control functions and to operate a data-based and data-driven management system.

3.4.1. Logistics entities related to the data centre

The logistics entities associated with the data centre are shown in Fig. 3. The figure shows that all entities are connected to the data centre through the capabilities of Industry 4.0, ensuring that these entities flow into the data centre.

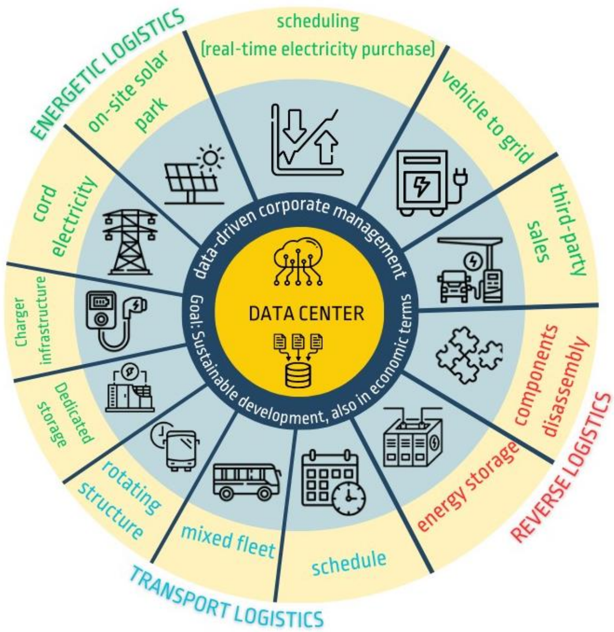

Figure 3. *Logistics entities linked to the data centre*

3.4.2. Scope and types of data

In the transport sector, data is not only an integral part of day-to-day operations, but also serves as a strategic tool for business decision-making, enhancing operational efficiency and improving passenger service. To create an efficient operational business process, it is essential to define the primary sources of data and the core systems that produce it, where the data required for operations is generated. Data map of the core processes required to operate electric buses:

The range and types of data sent to the data centre from the logistics entities named in Fig. 3 are shown in Table I.

Table I.

Scope and types of data from logistics entities

LOGISTICS FLOWS	DATA PACKAGE	ENTITIES	Volume	DATA		
TRANSPORT						
	TE–RP	ROUTE PLAN	number of units	route length		
				geographical route		
	TE–MF	MIXED FLEET				
		Vehicle types by powertrain				
		– BEB	number of units	specific consumption by type kW/km		
				battery capacity kW		
				range km		
		– DIESEL	number of units	specific consumption by type 100 litres/km		
		– CNG	number of units	specific consumption by type 100 kg/km		
	TE–MR	TIMETABLE		planned timetable distance		
				deviations from timetable		
ENERGY ASPECTS						
	EE–CI	CHARGING INFRASTRUCTURE				
		– charging at depot	capacity limit		location on route	
		– charging at terminus		yes/no	location on route	
		– charging at stops		yes/no	location on route	
		MAINS ELECTRICITY				
		– off-peak price electricity		cost: Ft/kWh – real-time data	calculated purchased volume	
		– peak price electricity		cost: Ft/kWh – real-time data	calculated purchased volume	
		– normal		cost: Ft/kWh – real-time data	calculated purchased volume	
	EE–PV	PHOTOVOLTAIC SYSTEM AT DEPOT		total installed capacity PkW		
				real-time performance (kW)	calculated amount of energy kWh	
				consumption characteristic curve kWh/period		
	EE–EP	ELECTRICITY PURCHASE SCHEDULING				
				storage characteristic curve kWh/period		
	EE–ES	ENERGY STORAGE	full capacity		calculated amount of energy from charging/offtake	
	EE-VG	VEHICLE-TO-GRID		amount of energy from traction battery that can be sold to the grid kWh		
BATTERY	BE–OB	BEB IN OPERATION	capacity of number of units			
				charging state		
				SOH	SOC	
	AE-VA	– for storage battery purposes	unit	SOH		sales revenue (HUF)
			capacity			
		– waste broken down into components	quantity	technical composition		sales revenue (HUF)

3.4.3. Link between data and the data centre

Data from the entities is transferred to the data centre repository, where it is processed. The information output based on real-time information is transmitted to traffic management, energy management and maintenance specialists, and enables immediate intervention in a given area.

The data centre is served by several logistics flow entities, where data models needed for optimal operation are created and updated in real time.

The main logistics flows and their entities:

- Traffic Management – Data Sources
  - On-board IoT devices
  - Passenger counting devices
  - Coordination, route plan, ticketing, central dispatching system
- Traffic management – Logistics flows
  - Route plan
  - Fleet composition

    - Timetable
- Operation – Energy data sources
    - Charging infrastructure
    - Mains electricity
    - Photovoltaic system at depot
    - Power scheduling
    - Energy storage
    - Vehicle-to-grid
- Operation – Battery related data sources
    - BEB in operation
    - Recycled batteries
- Operational – logistics flows
    - Infrastructure operational flows
    - Electric charging flows (energy-charging-usage)
    - Vehicle operational flows
    - Primary data management
    - Energy flows (solar panels, storage, mains electricity, etc.…)
- Reverse logistics flows

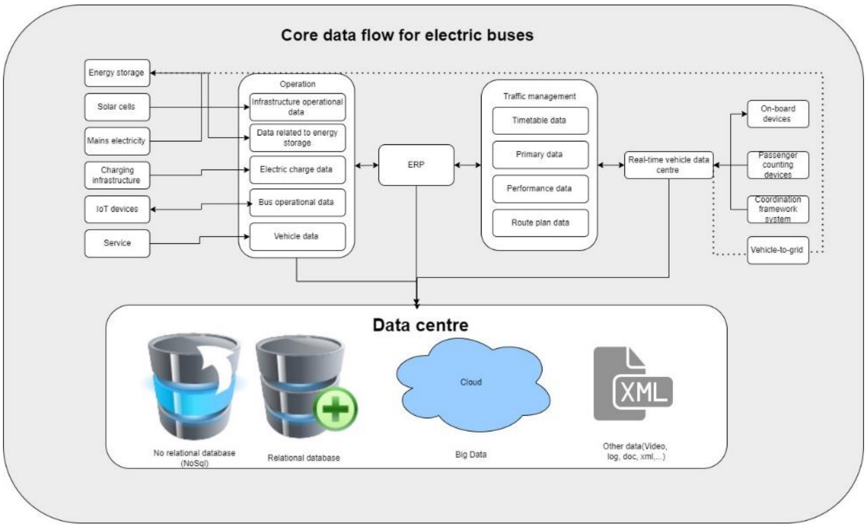

Figure 4. *Core data flow for electric buses*

If we look at logistics flows from an electric bus operational perspective, we can see that three main data flow entities can be distinguished:

- Data derived from energy logistics information flows
- Transport logistics data
- Reverse logistics data

For each of these three entities, data is generated along defined business processes and arrives independently and incommensurably at a central data silo. In order to make this data available for later use, it must first be consolidated and assigned a uniform metastructure, and moved to a data centre so that it is available for later business intelligence analysis. This data centre and metasystem will ensure that no information distortion occurs at any level of business decision making.

3.4.4. The role of the data centre in ERP

In order to build on the existing data assets generated in logistics flows and the big data generated by the introduction of new technologies (IoT, real-time data from the bus, event-driven management data), there is the need for development of a modern, service-oriented and sufficiently flexible data analytics platform. To be able to manage this data coming from existing logistics entities, the following is necessary:

- Creation of a unified data analysis layer over real-time data and data stored in existing static systems. Unified management of data with different structures and formats, and unified management of multiple data storage solutions. Consolidation of data set metadata. (E.g. does the consumption measured on CAN buses include the recuperation energy, or where is the electric drive consumption measured?)
- Ensure data purity and produce reliable business data (extreme data filtering, log parsing with AI).
- Perform statistical and AI-based analysis efficiently.
- Feedback from the results obtained allows optimisation of bus journeys, analysis of bus driver styles and habits, and predictive decisions on energy saving and electricity purchase.
- Improve passenger transport services based on trends and forecasts.
- Create driver dashboards.
- Create a central data asset catalogue with which business-classified metadata can be accessed, organised into data security categories, searched, and viewed masked by role.

Fig. 5 summarises the top-down hierarchy of data-driven ERP.

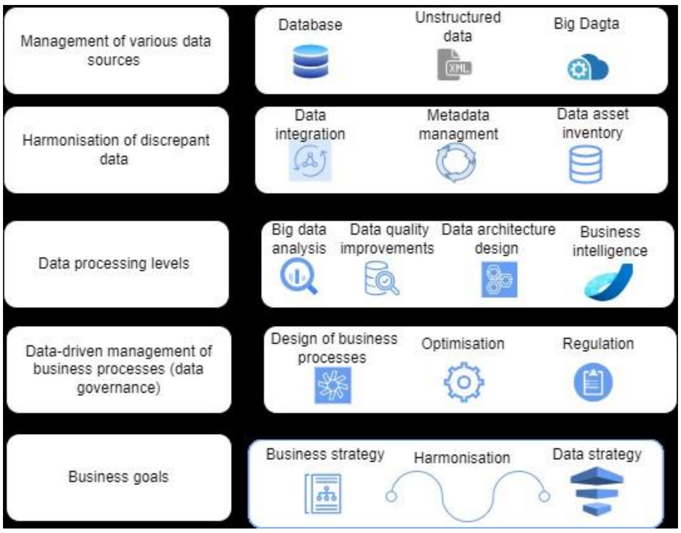

***Figure 5**. Logic diagram of a data-driven ERP system*

4. Holistic model of the operational system

Fig. 6 illustrates the innovative ecosystem that enables data-driven and sustainable operations. This figure shows the system, IT and data relationships between the flows and their entities described in Section 3.

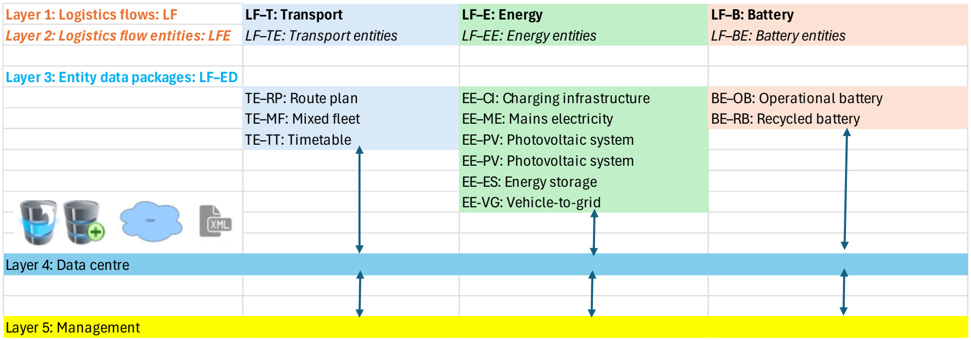

Figure 6. *Innovative operational model for a company operating a bus fleet*

The economic calculations based on the data presented in Section 3 and their use in the ERP system are presented in Section 5 in the form of a case study for Volánbusz Zrt.

5. Summary

Using the innovative model presented in this paper, we have created an ecosystem that allows bus operating companies to develop an optimal operating system choosing between internal combustion and electric powered vehicles, taking into account environmental and economic sustainability considerations. The novelty of the model we present lies in the fact that, instead of the univariate models presented in the international literature which is cited, we have created a complex ecosystem which enables us to take into account energy, transport and IT logistics flows. In the flowchart presented by us we have drawn the logistics flows, their related entities and data flows that, after having provided the basic data, allow bus transport operators to create their own optimal operational frameworks.

In summary, the model presented in this paper takes into account and incorporates all logistical factors that may affect the optimal operation of electric buses, thus demonstrating that environmental and economic sustainability objectives can be met.

References

[1] Borén, S., Nurhadi, L. & Ny, H. (2016). Preferences of Electric Buses in Public Transport; Conclusions from Real Life Testing in Eight Swedish Municipalities, World Academy of Science, Engineering and Technology, *International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering* **10**(3), Retrieved from https://www.diva-portal.org/smash/get/diva2:911643/FULLTEXT01.pdf

[2] Pelletier, S., Jabali, O., Mendoza, J. E. & Laporte, G. (2019). The electric bus fleet transition problem, *Transportation Research Part C: Emerging Technology*, **109**, 174-193, https://doi.org/10.1016/j.trc.2019.10.012

[3] Li, X., Gorguinpour, C., Sclar R. & Castellanos, S. (2019). How to enable electric bus adoption in cities worldwide, World Resources Institute, Ross Center, https://doi.org/10.46830/wrirpt.18.00123

[4] EDITORIAL: *Why the automotive future is electric*, 2021, McKinsey Center for Future Mobility

[5] Aamodt A., Cory, K. & Coney, K. (2021). Electrifying transit: a guidebook for implementing battery electric buses, *National Renewable Energy Laboratory*, https://doi.org/10.2172/1779056

[6] Shah, K.J., Pan, S-Y., Lee, I., Kim, H., You, Z., Zheng, J-M & Chiang, P-C.: Green transportation for sustainability: Review of current barriers, strategies, and innovative technologies, *Journal of Cleaner Production* **326**, 129392, https://doi.org/10.1016/j.jclepro.2021.129392

[7] Offer, G., J., Howey, D., Contestabile, M., Clague, R. & Brandon, N.P. (2010). Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy*, **38**(1), 24-29, https://doi.org/10.1016/j.enpol.2009.08.040

[8] Feng, W. & Figliozzi, M. (2013). An economic and technological analysis of the key factors affecting the competitiveness of electric commercial vehicles: A case study from the USA market. *Transportation Research Part C: Emerging Technologies*, **26**, 135-145, https://doi.org/10.1016/j.trc.2012.06.007

[9] Lajunen, A. (2013). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, **38**, 1-15, https://doi.org/10.1016/j.trc.2013.10.008

[10] Nurhadi, L., Borén, S. & Ny, H. (2014). A sensitivity analysis of total cost of ownership for electric public bus transport systems in Swedish medium sized cities. *Transportation Research Procedia*, **3**, 818-827, https://doi.org/10.1016/j.trpro.2014.10.058

[11] Zhou, B., Wu, Y. Zhou, B., Wang, R., Ke, W., Zhang, S. & Hao, J. (2016). Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions. *Energy*, **96**, 603-613, https://doi.org/10.1016/j.energy.2015.12.041

[12] Kunith A., Mendelevitch, R. & Goelich, D. (2017): Electrification of a city bus network — an optimization model for cost-effective placing of charging infrastructure and battery sizing of fast-charging electric bus systems. *International Journal of Sustainable Transportation*, **11**(10), 707-720, https://doi.org/10.1080/15568318.2017.1310962

[13] Lajunen, A. (2018). Lifecycle costs and charging requirements of electric buses with different charging methods. *Journal of Cleaner Production*, **172**, 56-67, https://doi.org/10.1016/j.jclepro.2017.10.066

[14] Lozanovski, A., Whitehouse, N., Ko, N. & Whitehouse, S. (2018). Sustainability Assessment of Fuel Cell Buses in Public Transport. *Sustainability*, **10**(5), 1480, https://doi.org/10.3390/su10051480

[15] Vora, A. P., Jin, X., Gosala, V., Shaver, G. (2018). Integrating battery degradation in a cost of ownership framework for hybrid electric vehicle design optimization. *Proceedings of the Institution of Mechanical Engineers Part D, Journal of Automobile Engineering*, **233**(6), 095440701880266, http://dx.doi.org/10.1177/0954407018802663

[16] Jefferies, D. & Göhlich, D. (2020). A Comprehensive TCO Evaluation Method for Electric Bus Systems Based on Discrete-Event Simulation Including Bus Scheduling and Charging Infrastructure Optimisation. *World Electric Vehicle Journal*, **11**(3), 56, https://doi.org/10.3390/wevj11030056

[17] Barraza, O. & Estrada, M. (2021). Battery Electric Bus Network: Efficient Design and Cost Comparison of Different Powertrains. *Sustainability*, **13**(9), 4745, https://doi.org/10.3390/su13094745

[18] Kim, H., Hartmann, N., Zeller, M., Luise, R. & Soylu, T. (2021). Comparative TCO Analysis of Battery Electric and Hydrogen Fuel Cell Buses for Public Transport System in Small to Midsize Cities. *Energies*, **14**(14), 4384, https://doi.org/10.3390/en14144384

[19] Polom, M. & Wisniewsky, P. (2021). A Review of Experiences and Evaluation of the Current Development Directions. *Sustainability,* **13**(7), 4009, https://doi.org/10.3390/su13074009

[20] Ager-Wick Ellingsen, L., Thorne, R. J., Figenbaum, E. & Wind, J. (2022). Life cycle assessment of battery electric buses. *Transportation Research Part D: Transport and Environment*, **112**(9), 103498, http://dx.doi.org/10.1016/j.trd.2022.103498

[21] Abdelaty H., Foda, A. & Mohamed, M. (2023). The Robustness of Battery Electric Bus Transit Network under Charing Infrastructure Disruption, *Sustainability*, **15**(4), 3642, https://doi.org/10.3390/su15043642

[22] Glistau, E. (2024). Logistics as a Science and the Formation of Logistic Thinking. In: Tamás, P., Bányai, T., Telek, P., Cservenák, Á. (eds) Advances in Digital Logistics, Logistics and Sustainability, CECOL 2024. *Lecture Notes in Logistics*. Springer, Cham. https://doi.org/10.1007/978-3-031-70977-7_21