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COMPARATIVE ANALYSIS OF MULTI-DRIVE RAILWAY MULTIPLE UNITS PARAMETERS AND THEIR SUITABILITY FOR OPERATION ON PARTIALLY ELECTRIFIED AND NON-ELECTRIFIED METROPOLITAN RAILWAY LINES

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***Abstract**:*

In metropolitan and partially long-distance traffic, we are now seeing an increased use of multiple units characterised by the utilisation of the passenger area that is optimal in terms of interior space. The propulsion systems used in them utilise various forms of supplied energy. Technological development in the field of multi-drive systems for rolling stock offers an increasing diversity of design solutions. Among railway operators and carriers when purchasing rolling stock, this generates the problem of choosing the right type of multiple unit among the numerous types offered by manufacturers. The main purpose of the article is to analyse and evaluate railway multiple units, both classic diesel-powered and multi-drive ones. Modern three-unit trainsets in service in Europe were analysed to address the research gap regarding comprehensive comparative analyses of real-world operational functionalities under mixed-traffic conditions. On the basis of a multivariate comparative analysis, selected types of multi-drive multiple units were evaluated in terms of their selection for mixed traffic on partially electrified and non-electrified lines. Technical, economic, environmental, operational and functional parameters were used as comparison criteria. The evaluation algorithm incorporated fuzzy numbers to represent uncertain values, as well as specific weights determined by the decision-maker. The study systematically compared five vehicle categories: classic diesel multiple units (DMU), diesel-electric multiple units (DEMU), battery electric multiple units (BEMU+) and tri-mode multiple units (TMU). The analysis made it possible not only to evaluate the types of multiple units offered by manufacturers today but also provides a valuable tool in the decision-making process of selecting the optimal rolling stock for metropolitan railways. The final multi-criteria evaluation revealed that the diesel-electric multiple unit (DEMU) achieved the highest overall score due to its optimal technical performance and long range on non-electrified routes. The fuel cell multiple unit (FCMU) ranked second, emerging as the most rational choice when zero-emission transport is required. Battery multiple units (BEMU+) and tri-mode multiple units (TMU) followed in the ranking, while single-drive diesel units (DMU) ranked last overall largely due to their poor environmental performance.

Keywords: *Railway, multiple unit, multi-drive multiple unit trainset, bimodal multiple unit, non-electrified railway line, metropolitan railway transport, multi-criteria comparative analysis*

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1. Introduction

Modern cities, which are metropolises with their surrounding towns and cities, are now centres of economic and social activity. It is estimated that cities are home to about two-thirds of the world's population, and in Europe it is more than 70% of the population (Kabisch et al., 2011). In order to ensure sustainable transport, agglomerations require the provision of an efficient public transport system, where railway transport that can quickly move large streams of passengers in a relatively short period of time works best. In many major cities in Europe and the world, metropolitan railways are essential elements of transport (Li et al., 2021). As part of the policy of sustainable mobility development in urban areas and reducing the negative environmental impact of internal combustion vehicles, local governments and operators are taking a number of measures to increase the use of the railway mode of transport. These measures include increasing the capacity of railway lines, building new stops, offering attractive metropolitan tickets and promoting trains as an environmentally friendly mode of transport.

Local and suburban traffic in European conditions is carried out almost exclusively by railway multiple units (Wolfram, 2003). Due to European policies aimed at reducing greenhouse gases in the atmosphere, the 21st century has seen the development of multi-drive rolling stock. More and more operators are opting to operate services with fuel-cell, diesel-electric or battery-powered multiple unit trains.

A notable feature of the railway lines that carry metropolitan railway traffic is the relatively short distances between stops (Pyrgidis C. N., 2021). For this reason, on such routes, in addition to the maximum speeds achieved, speed, acceleration and braking times and rolling stock capacity are primarily important (Far, 2021). New designs of multiple units for distances between stops of 1000 m show parameters that ensure the achievement of a commercial speed of 35-40 km/h for a standstill time of 18-20 s. This is achieved as a result of the large share of the driving mass, in some cases up to 100% of the total mass, as well as significant unit powers reaching more than 20 kW/t. The highest speeds depend on service zones and range from 120-160 km/h (Wolfram, 2003).

The use of modern rolling stock affects travel comfort, the perception of the quality of the services offered, the operator's image and environmental friendliness. In metropolitan transport, the key features of the rolling stock are high starting acceleration, large capacity, single-space layout of the interior of the cars, a large number of doors facilitating quick exchange of passengers, space for luggage and bicycles, and adaptation to the needs of people with limited mobility. Manufacturers are meeting all these challenges by offering multi-drive multiple units, which are becoming the primary means of transport in metropolitan transport.

On electrified lines, electric multiple units are the cheapest to operate, while on non-electrified lines (Heininger P. et al., 2019), diesel multiple units are still the most heavily used (Durzyński Z. et al., 2020), which, given the European Union's policy of reducing vehicle emissions, are being replaced by multi-drive multiple units, such as:

a) fuel cell multiple unit and hydrogen multiple unit (FCMU/HMU)
   Hydrogen and fuel cells are an ideal combination from the point of view of climate protection and revolutionising energy and transport. They enable energy storage and zero-emission railway transport (Caparrós M. J. et al., 2021).
b) diesel-electric multiple unit (DEMU/EDMU)
   The diesel engine is connected to a traction generator, which converts mechanical energy into electrical energy and, through an inverter, powers the asynchronous traction motors located on the driving bogie. The generated current is fed to electric traction motors. In addition, an overhead current collector or third rail used on an electrified section is built onto the rolling stock.
c) battery electric multiple unit and independently powered electric multiple unit (BEMU/BEMU+/IPEMU)
   The batteries can be charged from regenerative braking and from the overhead line while driving and at a standstill. It uses the energy stored in batteries on the non-electrified section and the current drawn from the overhead line by the current collector on the electrified section (Schirmer, T. et al. 2020).

Drive systems in rolling stock are being improved all the time to increase their efficiency, durability, and reduce emissions. Work is also underway to develop rolling stock designs to improve passive safety and make more efficient use of passenger space while maintaining the utmost comfort for users.

Regional railway operators are constantly replenishing their rolling stock base with new multi-drive multiple units. There are many models and solutions available on the market, however, the problem remains the selection of the type of multi-drive multiple unit for partially electrified and non-electrified routes. Due to the interaction of many phenomena, analysis of a numerous group of factors is required to reach an optimal decision. Making the right selection is a multi-criteria task, and during the decision-making process it is necessary to make sure that the chosen solution is the best and most effective as a function of the criteria adopted. It is therefore recommended to use specialised tools to support and facilitate decision-making (Mertler C. A., 2021). This article presents the results of a functional and operational analysis of the use of different types of railway multiple units, for mixed traffic on electrified and non-electrified lines.

2. Literature review

In recent years, the scientific literature has increasingly addressed the topic of alternative propulsion systems in regional and suburban rail transport, with particular attention given to battery-electric, multi-power, and hydrogen-powered units. Numerous studies and reports focus on assessing the energy, cost, and environmental efficiency of these technologies in comparison to conventional diesel multiple units. However, there remains a noticeable gap in comprehensive comparative analyses that examine the functional and operational performance of various traction units currently offered by manufacturers for deployment on partially electrified and non-electrified lines, which are typical of many metropolitan rail networks.

One of the few studies to undertake such a comparison is the article (Kaspar B., 2022), which presents an analysis of different alternative propulsion technologies, such as hydrogen fuel cells, traction batteries, and hybrid multi-power vehicles, taking into account their compatibility with existing infrastructure across six key regional rail routes in Germany and the United Kingdom. The author places particular emphasis on the alignment of these solutions with climate policy objectives and explores implementation barriers. While the study identifies the most suitable propulsion solution for each of the analysed regional lines, it does not consider the deployment of specific traction unit types under mixed-traffic conditions common to metropolitan rail operators.

The report (Guckes N. et al., 2020), by contrast, focuses on the economic aspects of implementing zero-emission alternatives to diesel traction units. While this document provides valuable data concerning both capital and operational costs, it considers only selected operational scenarios within a limited regional context and does not offer a comprehensive comparison of the functional capabilities provided by different manufacturers of multi-power vehicles.

A similar approach is evident in the study (AERRL, 2022), which outlines a general strategy for phasing out diesel use within the European rail network. This document identifies overarching directions for technological transition as well as organisational and infrastructural aspects; however, it does not include a practical comparison of vehicle types, nor does it offer operational performance analyses.

The article (Karkosiński D. et al., 2023) analyses the use of hybrid energy storage in electric multiple units operating on the Gdynia–Hel line. The authors focus primarily on a technical and energy analysis of a solution based on supercapacitors and lithium-ion batteries. This study serves as an example of a practical implementation analysis, concentrating on the selection and integration of energy storage systems within existing traction units. While the research provides important insights into energy strategies, its scope is limited to a single railway line and a single vehicle type.

A study of similar scope is presented in (Pugi L. et al., 2024), which examines the use of battery-powered trains on regional lines in Italy. Although the authors address the issue of operation on partially electrified lines, the study is restricted to a single propulsion technology and does not consider the broader range of available technologies or their operational characteristics. Furthermore, the absence of references to specific vehicle models offered by manufacturers significantly hinders the applicability of the findings to real-world investment decisions.

In contrast, the article (Fabri G. et al., 2024) examines the application of hydrogen-powered rolling stock on a specific urban route. The analysis focuses on environmental and technological aspects. Despite its practical orientation, the publication is limited to a single propulsion type and a single design scenario. It does not include a comparative analysis

with other technologies, which hinders a comprehensive assessment of implementation effectiveness under varied operational and topographical conditions.

The article (Heininger P. et al., 2019) outlines the main directions in the development of alternative solutions to conventional diesel multiple units in regional rail services, including battery, hybrid, and hydrogen technologies. Despite its broad scope, the study lacks an in-depth operational analysis encompassing reliability, operational flexibility, and lifecycle costs. Furthermore, it does not reference specific vehicle models currently available on the market, which limits its practical applicability for decision-making processes.

It is also worth noting the design and engineering approach presented in the article (Kolář J., 2023), which discusses the evolution and current development trends of lightweight multiple units for regional rail services. Although the author introduces several interesting concepts for battery-electric and multi-power vehicles, the comparative analysis is limited to selected parameters of diesel and hydrogen units, without offering a comprehensive operational perspective in relation to the range of products currently available on the market.

A review of the existing literature indicates that most studies focus either on selected propulsion technologies or on individual implementation case studies. Comparative aspects related to the functionality and real-world operation of vehicles are frequently overlooked, particularly in the context of infrastructure constraints, the specific characteristics of metropolitan traffic, and the availability of particular vehicle models from manufacturers. In this context, there is a clear need for an in-depth analysis that systematically compares the operational parameters of multi-power units, their operational flexibility, interoperability, and their impact on transport efficiency. The objective of this study is to address this gap.

3. Methodology

3.1. Selection of the comparative analysis method

Methods of multi-criteria comparative analysis allow to support the decision-making process in situations of choosing between multiple options. In the case of this analysis, the objects of study are specific models of multiple units available on the European market, which are collected into groups according to the type of drive source. What is important here is the appropriate selection of evaluation criteria and the proper assignment of weights to them, as a function of what characteristics or criteria of a given object are important to the decision maker (Dean M., 2020).

For the case of multidimensional comparative analysis of types of multi-drive railway multiple units, an algorithm was used that assumes the analysis of multiple units from a finite set of MUs of the considered rolling stock (1).

$$MU = \{MU_1, MU_2, MU_3, MU_i, \dots MU_N\}, \quad \text{for } i = 1, 2, 3, \dots N \tag{1}$$

where:
MU – a set of objects,
$MU_1, MU_2, \dots MU_N$ – elements of the set,
i – based on a set of criteria Kg,
g – specifies the criterion number (g = 1,...G).

Both non-measurable criteria, which cannot be directly expressed by numbers, and measurable criteria, which are expressed by numerical quantities, were allowed to be used in the evaluation process under each criterion. Non-measurable criteria were quantified at a later stage so that they would eventually be expressed in numbers for calculations (Geneletti et al., 2005).

The analyses use fuzzy numbers (2) as a representation of uncertain values, which allow to determine not only fully possible values of a given and quite impossible values, but also possible values in different degrees (Gawrońska, 2014). Fuzzy numbers are characterised by three parameters A = (m, α, β). The parameter m is a real number, called the average value. While α, β are the left- and right-side dispersions, respectively (the interval defined by the decision maker or the parameters of different models).

$$A_{ij} = \left(m_{ij}, \alpha_{ij}, \beta_{ij}\right) \tag{2}$$

where:
i– group of criteria,
j – individual criteria.

A fuzzy set is characterised by a membership function that assigns a degree of membership to each object (Zadeh, 1965). The significance of the parameters in the group, was determined by the decision maker in the form of the variable V_g (3). It was assumed that the significance of the criteria is

determined on the interval [0,1], which is related to the condition that the sum of the weights of the criteria in the group expressed by the decision maker must be 1.

$$\sum_{j=1}^{J} V_{gj} = 1 \tag{3}$$

where:
V_g – significance of parameters in a group.
Based on the presented values of the criteria evaluation, fuzzy criterion evaluation values were determined for each of the types of multiple units analysed.
Since the values of the evaluation of types of multiple units are considered as the degree of fulfilment of a certain ideal state in light of a given criterion, normalisation of the values of these evaluations (4) and (5) was carried out. For this purpose, the nature for the adopted criteria was also determined. It was assumed that a criterion is considered a stimulant if higher values allow it to qualify as better from the point of view of the study conducted. A destimulant is called such a criterion, high values of which indicate a low position of the unit in the set and negatively affect the global quality assessment of the object (Mertler C. A., 2021).
For the maximised criterion:

$$\hat{A}_{ij} = \frac{A_{ij}}{maxA_i} \tag{4}$$

For the minimised criterion:

$$\hat{A}_{ij} = 1 - \frac{A_{ij}}{maxA_i} \tag{5}$$

where:
A – fuzzy criterion evaluation value.
In order to make the comparison, it was necessary to normalise the evaluations against each criterion. Next, evaluations of the types of multiple units against a higher level criterion were determined.
On the basis of evaluations against individual groups of criteria, it was possible to evaluate against a global criterion and perform normalisation of evaluations. Due to the reliance on fuzzy cumulative evaluations in determining the real ratings of types of multiple units, it was necessary to defuzzify them using the centre of gravity method (Gawrońska, 2014), assigning a real number to the membership function (6).

$$x = \frac{3 \cdot m - \alpha + \beta}{3} \tag{6}$$

where:
m - a real number, called the average value,
α, β - left- and right-side dispersion.
The obtained values for each type of multiple units, together with the values for groups of criteria, made it possible to evaluate a given solution with an indication of its strengths and weaknesses. The developed tool is an element that supports decision-making, which ultimately belongs, of course, to the decision maker.

3.2. Selection of evaluation criteria for railway multiple units for comparative analysis

The groups of criteria characterizing the railway multiple units for the comparative analysis were selected to cover as many aspects as possible that are relevant to the decision to choose a particular type of rolling stock (Gawrońska, 2014). The criteria also refer to the conditions of a given route, such as the length of the non-electrified section, the slope of the line, rolling stock maintenance points, distances between stops and the passenger offer. It should be clarified that while these infrastructural and operating conditions are not evaluated as separate criteria in the subsequent multi-criteria analysis (which focuses strictly on the vehicles), they served as essential boundary assumptions. They directly determined the selection and significance of the assessed functional and technical parameters of the rolling stock, such as the required range on non-electrified routes, initial acceleration and top speeds.
The first proposed group of criteria is economic. They include the cost of manufacturing the rolling stock, the cost of installing a refuelling station or charging facilities, the cost of fees and repairs, the cost of spare parts, the unit consumption of electricity and fuel, and the cost of electrification of the railway line. Nowadays, economic analyses based on life-cycle cost methodologies are commonly used in decisions on the purchase and modernisation of rolling stock. However, due to the nature of business-to-business transactions, cost data is not shared and is the result of negotiations between companies. Nonetheless, for up to 30 years of rolling stock

operation, the cost of maintenance is essentially equal to the cost of purchasing rolling stock (Idris M. F. M., 2022). Therefore, the following analysis only considers the cost of the rolling stock purchased by a public company through an open tender.
The technical criteria take into account parameters related to the design of the rolling stock and the propulsion system used - partly also linked to the operating conditions of the railway lines.
Traffic work issues are included in the functional criteria. These include, for example, the number of seats, which should be matched to the streams on the route, as well as travel speeds on electrified and non-electrified lines. Initial acceleration, which is important especially on regional and metropolitan lines where the distance between stations is short, was also taken as one of the parameters (Abril M. et al., 2008).
Also included in the analysis are operational criteria and those that determine drive power. Range on a non-electrified route and refuelling or recharging times affect the placement of operating points and technical stops (Hernandez A. et al., 2023).
The last group is the environmental impact criterion. It was assumed that the environmental impact, such as noise emissions or emissions of pollutants and toxic compounds, is important when choosing a rolling stock propulsion source. It is the subject of many separate studies and is closely related to the source of electricity generation used (Culemann et al., 2018), such as clean renewable energy.
The quantitative criteria adopted for the comparative analysis of railway multiple units are shown below (Fig. 1).

3.3. Selection of research objects

Standard-gauge, three-unit trainsets currently in service in Europe or at an advanced test stage were used as the criterion for selecting the rolling stock for the multi-criteria comparative analysis. All rolling stock meeting the accepted conditions were selected.
For the multi-criteria comparative analysis of multiple units, rolling stock with the same number of units and the same wheelbase were put together. Rolling stock running on track with a standard gauge of 1435 mm was chosen, as this is the most common in the world (about 60% of railways).
European metropolitan railway networks typically operate multiple units consisting of 2 to 6 units. It was decided to compare three-unit rolling stock since the multi-drive multiple units produced to date are the most numerous in this configuration. Only for hydrogen-powered rolling stock, to check the correctness of the values, rolling stock with a different number of units was also put together, since the most tested design is a two-unit one.

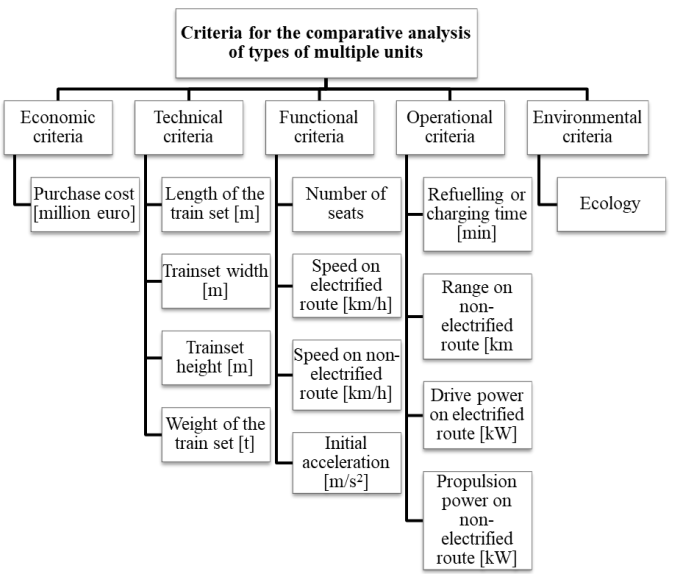


Fig. 1. Hierarchical structure of analysis criteria [own elaboration]

3.4. Identification of parameters of railway multiple units for comparative analysis

Input data for the comparative analysis was obtained from publicly available excerpts from tender proceedings, media coverage, promotional materials and brochures from manufacturers. They were then successively revised and supplemented on the basis of information obtained from users, operators and available subject literature. Some of the data could not be obtained due to company secrets

The list of parameters includes contemporary multiple units in service or at the design and prototype stage in Europe (Table 1-4). Included is the widest possible range of models offered, from various manufacturers. In the table, "n.d." means no data available, and "n.a." means that the parameter is not applicable to the type of rolling stock.

The first group of the rolling stock analysed were diesel multiple units, which are offered by almost all rolling stock manufacturers. The list included popular models produced by Stadler, Bombardier (now Alstom) and PESA. Table 1 shows the data for these vehicles.

The second group of the rolling stock analysed were battery electric multiple units (BEMU+). Most are still in the prototype stage, and regularly run only in Austria (though recently also in Germany, Czechia and Italy). The list included popular models produced by Siemens, Stadler, Bombardier (now Alstom) and Alstom. Data for the analysed rolling stock are shown in Table 2.

The third group of the rolling stock analysed were fuel cell-powered multiple units. One of the longest-tested is the iLint made by Alstom - but it is a 41.8-metre-long two-unit model. Hydrogen-powered three-unit versions are in the prototype stage at Siemens and CAF (according to preliminary findings, they are capable of 800-1,000 kilometres at a time). The refuelling time is 15 minutes and is comparable to that of diesel multiple units. Technical data for the rolling stock is shown in Table 3.

The last group analysed included tri-mode multiple units. They are currently in operation only in the UK. The Class 756 model has diesel, battery and electric propulsion from a pantograph, while the Class 799 model uses hydrogen and electricity from the overhead line and batteries on board. Data for this group of rolling stock is shown in Table 4.

Table 1. Technical and operational data of diesel multiple units - DMUs [own elaboration]

Manufacturer	**Stadler Rail AG**	**Stadler Rail AG**	**Stadler Rail AG**	**Bombardier Transportation**	**PESA**
Train model	**FLIRT**	**FLIRT**	**GTW**	**Talent**	**Atribo**
Train type	**DMU**	**DMU**	**DMU**	**DMU**	**DMU**
Country of operation	Estonia	Italy	The Netherlands	Germany	Poland
First year of production	2013	2021	2006	2000	2010
Track gauge [mm]	1435	1435	1435	1435	1435
Number of units	3	3	3	3	3
Purchase cost [million euros]	n.d.	n.d.	3,68	n.d.	3.48
Length (m)	59.89	66.80	55.94	52.16	55.57
Width [m]	3.50	2,82	2.95	2.93	2.89
Height [m]	4.50	4.12	4.30	4.05	4.14
Weight [t]	135.0	n.d.	87.0	110.5	108.0
Number of seats	161	151	172	161	151
Speed on electrified route [km/h]	160	140	140	120	120
Speed on non-electrified route [km/h]	160	140	140	120	120
Initial acceleration [m/s^2]	0,85	0.91	1,00	1,00	0.50
Range on non-electrified route [km]	n.d.	n.d.	n.d.	1000	2000
Fuel tank capacity [l]	2800	2400	2000	n.d.	1500
Diesel drive power [kW]	n.d.	700	600	500	764
Sources of information	(Knjazev, 2016)	(Stadler Rail Group, n.d.a)	(Stadler Rail Group, n.d.b; Heininger et al., 2019)	(Kroma et al., 2014)	(Kroma et al., 2014; Brancewicz, 2015)

Table 2. Technical and operational data of multi-drive multiple units - BEMU+ [own elaboration]

Manufacturer	**Siemens Mobility**	**Bombardier Transportation**	**Alstom SA**	**Stadler Rail AG**
Train model	**Desiro ML**	**Talent 3**	**Coradia Continental**	**Flirt Akku**
Train type	**BEMU+**	**BEMU+**	**BEMU+**	**BEMU+**
Country of operation	Austria	prototype / Germany	design	prototype
First year of production	2018	2019	2023	2017
Track gauge [mm]	1435	1435	1435	1435
Number of units	3	3	3	3
Purchase cost [million euros]	n.d.	n.d.	6.32	n.d.
Length (m)	75.5	56.2	56	58.6
Width [m]	n.d.	n.d.	2.92	2.88
Height [m]	n.d.	n.d.	4.28	n.d.
Weight [t]	132.5	114	n.d.	n.d.
Number of seats	144	169	150	154
Speed on electrified route [km/h]	140	140	160	140
Speed on non-electrified route [km/h]	120	140	160	140
Initial acceleration [m/s^2]	0.77-1.00	1.1	n.d.	n.d.
Range on non-electrified route [km]	n.d.	40-150	100-120	80-220
Charging time [min]	n.d.	7-15	n.d.	15-20
Electric drive power [kW]	2600	1520	n.d.	1000
Battery drive power [kW]	975	1520	n.d.	1000
Sources of information	Reimann S., 2020; Siemens Mobility GmbH, n.d.	Dolecki, 2018; Mach, 2017; Laperrière, 2019; Heininger et al., 2019	Miller, 2020	Saeed M. et al., 2023; Stadler Rail Group, n.d.d

Table 3. Technical and operational data of multi-drive multiple units - FCMU, TMU [own elaboration]

Manufacturer	**Alstom**	**Siemens**	**CAF**	**Stadler Rail AG**	**Porterbrook**
Train model	**iLint**	**Mireo H**	**Civia H2**	**FLIRT UK Class 756**	**HydroFLEX Class 799**
Train type	**FCMU**	**FCMU**	**FCMU**	**TMU**	**TMU**
Country of operation	Germany	design / Germany	prototype / Spain	prototype / UK	prototype / UK
First year of production	2019	2022	2022	2023	2019
Track gauge [mm]	1435	1435	1435	1435	1435
Number of units	2	3	3	3	4
Purchase cost [million euros]	6.6	n.d.	n.d.	6.43	n.d.
Length (m)	41.8	70	n.d.	65	79.3
Width [m]	2.75	n.d.	2.9	2.7	2.82
Height [m]	4.34	n.d.	4.3	3.92	3.58
Weight [t]	n.d.	n.d.	n.d.	n.d.	n.d.
Number of seats	138	160	n.d.	144	n.d.
Speed on electrified route [km/h]	120-139	160	n.d.	120	140
Speed on non-electrified route [km/h]	120-140	160	n.d.	120	140
Initial acceleration [m/s^2]	n.d.	1.1	n.d.	1.1	n.d.
Range on non-electrified route [km]	600-800	800-1000	800	80	1000
Fuel tank capacity [kg]	180	n.d.	160	n.d.	277
Refuelling/charging time [min]	15	15	n.d.	n.d.	15
Diesel drive power [kW]	n.a.	n.a.	n.a.	1300	n.a.
Electric drive power [kW]	n.a.	n.a.	n.a.	2600	400
Battery drive power [kW]	544	1700	n.d.	1300	400
Hydrogen drive power [kW]	544	1700	n.d.	n.a.	400
Sources of information	Varney, 2018; Böhm M., 2022	Voß, 2022	CAF, 2022; Dittus H, 2022	Stadler Rail Group, n.d.e	ExpressDigest, n.d.

Table 4. Technical and operational data of multi-drive multiple units - DEMU/EDMU [own elaboration]

Manufacturer	**Bombardier Transportation**	**Stadler Rail AG**	**Stadler Rail AG**	**NEWAG S.A.**
Train model	**AGC B 81500**	**FLIRT 3 (BTR 813)**	**FLIRT**	**Impuls 36WEh**
Train type	**DEMU**	**DEMU**	**DEMU**	**DEMU**
Country of operation	France	Italy	UK	Poland
First year of production	2004	2019	2019	2020
Track gauge [mm]	1435	1435	1435	1435
Number of units	3	3	3	3
Purchase cost [million euros]	n.d.	8.62	13.37	5.34
Length (m)	57.4	66.8	65	59.3
Width [m]	2.95	2.82	2.72	2.84
Height [m]	4.02	4.12	4.12	4.15
Weight [t]	134.9	140	n.d.	120.5
Number of seats	168	159	144	160
Speed on electrified route [km/h]	160	160	160	160
Speed on non-electrified route [km/h]	160	140	160	120
Initial acceleration [m/s^2]	n.d.	1	0.7	0.4-1.1
Range on non-electrified route [km]	n.d.	n.d.	n.d.	1000
Fuel tank capacity [l]	3000	n.d.	n.d.	1440
Diesel drive power [kW]	890	700	960	1600
Electric drive power [kW]	1800	2600	2600	1600
Sources of information	(Bombardier Transportation, n.d.)	(Stadler Rail Group, n.d.f; Ferrovie, 2017)	(Stadler Rail Group, n.d.c)	(Railvolution, 2020)

4. Multi-criteria comparative analysis of different types of multi-drive railway multiple units

Fuzzy set theory was used in the calculations, as it allows both different types of qualitative and quantitative criteria to be taken into account. Table 5 shows the fuzzy numbers characterised by the three parameters, which were determined based on the presented parameter set values of modern multiple units. The quantitative criteria were presented in the form of ranges of values, due to uncertainty due to the small number of multi-drive rolling stock in operation to date and difficult access to data.

To evaluate fuzzy values, criterion weights have been introduced that take into account placing greater emphasis on certain relevant criteria. Above all, the new multiple units are to be environmentally friendly so as not to cause negative environmental effects. Given the operators' limited budgets, the cost of purchasing the rolling stock remains important (Persson R. et al., 2024). High importance was also attached to various functional and operational parameters such as range on a non-electrified route and initial acceleration.

The arrows indicate whether the criterion is a stimulant or a destimulant. The downward-facing arrowhead indicates that the lowest possible values should be aimed for. For example, due to the dense distribution of short stations, metropolitan traffic is expected to be carried out using rather short trains with quick passenger turnaround. Another important factor is short downtime, affected by, for instance refuelling or battery charging time. The upward-facing arrowhead indicates that the highest possible values are expected. This refers, for example, to the number of seats available for passengers.

In further calculations, the fuzzy evaluations for the analysed multiple units were subjected to normalisation of values due to the degree to which a certain ideal state was met. A normalisation of the evaluations against each parameter was also performed to enable the values to be compared with each other. The criteria were grouped according to the previously adopted groups of criteria (Table 6).

The last necessary step was to determine the evaluation against the global criterion and to normalise the ratings again. In order to determine specific numerical values for each type of multiple units, a fuzzy defuzzification was performed using the centre of

gravity method assigning a real number to the membership function (Table 7).
On this basis, results were obtained to enable ranking of values and interpretation for both rolling stock types and individual criterion groups. The higher the score values, the better the rolling stock meets the set criteria.

Comparing the results obtained, it can be concluded that the diesel-electric multiple unit (DEMU) received the highest rating due to the selected criteria and the weights adopted for each criterion. It received a score of 0.78 on an evaluation scale of 0 to 1, where 1 would mean receiving an ideal condition relative to the other types of rolling stock.

5. Results and discussion

Table 5. Fuzzy evaluations for the analysed multiple units [own elaboration]

Train type	**DMU**			**BEMU+**			**FCMU**			**TMU**			**DEMU**			**Weight**	
Parameter	m	α	β	m	α	β	m	α	β	m	α	β	m	α	β		
Purchase cost [million euros]	3.58	0.3	0.3	6.35	0.5	0.5	7.1	0.7	0,6	6.72	0.5	0.5	6.8	3.5	2.5	1	↓
Length (m)	59.5	7	7	62.5	6	12	70	5	9	65.2	6	6	62.1	5	5	0.4	↓
Width [m]	2.9	0.3	0.4	2.92	0.1	0.5	2.9	0.1	0.3	2.73	0.1	0.5	2.83	0.2	0.2	0.1	↓
Height [m]	4.25	0.2	0.2	4.28	0.2	0.2	4.3	0.1	0.1	3.92	0.1	0.4	4.08	0.1	0.1	0.1	↓
Weight [t]	111	20	20	123	20	10	120	30	30	135	10	20	130	10	10	0.4	↓
Number of seats	160	10	10	155	40	50	160	10	10	144	10	10	158	12	12	0.3	↑
Speed on electrified route [km/h]	140	20	20	160	20	0	150	20	20	120	20	40	160	20	0	0.2	↑
Speed on non-electrified route [km/h]	140	20	20	140	20	20	150	20	20	120	20	20	140	20	20	0.2	↑
Initial acceleration [m/s^2]	0.75	0.25	0.25	0.93	0.15	0.19	1.1	0.2	0.2	1.11	0.51	0.09	0.92	0.08	0.25	0.3	↑
Range on non-electrified route [km]	1500	1000	1000	130	90	80	900	250	250	150	40	20	2000	1000	700	0.4	↑
Refuelling time / charging [min]	18.5	7.3	19.6	16	5.5	6.5	15	4	3	13.2	8.8	8.5	16.5	5.5	5.5	0.2	↓
Drive power on electrified route [kW]	640	140	120	1800	800	800	1700	500	500	2500	300	100	2100	500	500	0.2	↑
Drive power on non-electrified route [kW]	640	140	140	1250	300	300	1700	500	500	1300	400	200	1150	450	450	0.2	↑
Zero-emission level	0	0	0	0.8	0.8	0.2	0.7	0.7	0.3	0.6	0.6	0.4	0.5	0.5	0.5	1	↑

Table 6. Normalised fuzzy evaluations against each group for the analysed multiple units [own elaboration]

Train type	**DMU**			**BEMU+**			**FCMU**			**TMU**			**DEMU**		
Parameter	m	α	β	m	α	β	m	α	β	m	α	β	m	α	β
Economic criteria	0.518	1.000	1.000	0.110	0.971	0.971	0.000	0.941	0.956	0.056	0.971	0.971	0.044	0.529	0.676
Technical criteria	0.137	0.953	0.949	0.083	0.968	0.937	0.040	0.951	0.916	0.051	0.997	0.946	0.077	1.000	1.000
Functional criteria	0.928	0.121	0.121	0.974	0.169	0.154	1.000	0.117	0.117	0.852	0.145	0.145	0.978	0.109	0.087
Operational criteria	0.596	0.481	0.308	0.481	0.355	0.339	0.766	0.419	0.433	0.610	0.258	0.202	1.000	0.594	0.513
Environmental criteria	0.000	0.000	0.000	1.000	1.000	0.250	0.875	0.875	0.375	0.750	0.750	0.500	0.625	0.625	0.625

Table 7. Actual evaluations against the global criterion for the multiple units analysed [own elaboration]

Train type	**DMU**	**BEMU+**	**FCMU**	**TMU**	**DEMU**
Actual values	0.59680	0.67949	0.72757	0.63736	0.78429

Second in order with a high score is the fuel cell-powered multiple unit (FCMU). It achieved a score of 0.72, only 7% below the best ranking.
Third place went to the battery multiple unit (BEMU+) receiving a score of 0.67. In doing so, he pointed out the numerous advantages of multi-drive multiple units, which are increasingly appearing in regional traffic.
The rolling stock listed so far use two types of propulsion systems, but next in the mix is a tri-mode mutliple unit (TMU). It ranked fourth with a value of 0.64.
In last place remained the single-drive railway rolling stock suitable for operation on non-electrified lines, namely a diesel multiple unit (DMU). It closed the statement rate with a score of 0.60.
Choosing the type of railway multiple unit based on the type of drive used is not easy. This is because of the variation in the characteristics that describe the types of trains in question and because of the uncertainty associated with costs during operation. The comparative analysis performed provided an answer as to which of the considered rolling stock types should best meet expectations on partially non-electrified routes (Fig. 2).
The diesel-electric multiple unit distinguished itself primarily by its achieved performance, where it was the best in this competition (Table 8). This consisted, for example, of a long range on the non-electrified route and optimal performance of drive power on each railway line. It is worth noting that it is a design based on proven solutions. It combines diesel and electric multiple units that have mastered regional traffic in every country. Multi-drive diesel-electric multiple units are already running successfully in regular traffic in several countries, including Poland. Without the overhead line, speeds of 120 km/h are achieved, and the range is over 1,000 km. However, efforts should be made to reduce production costs - which is difficult, given the use of two types of propulsion. Although prices vary depending on the customer's requirements, the purchase of the rolling stock does not require specialised work of maintenance facilities equipment. On the non-electrified route, the rolling stock still uses a classic diesel engine, which is an obstacle to receiving European Union funding for the purchase of this type of vehicle. According to the announcement, in the EU's 2021-2027 financial perspective, support will only be available for the purchase of zero-emission trains, by which is meant only electric or hydrogen-powered rolling stock (European Commission, n.d.).

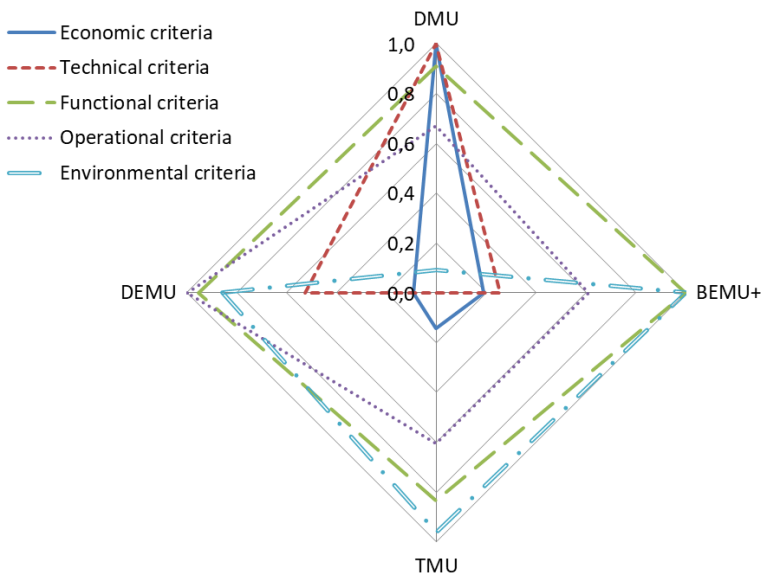


Fig. 2. Graphical representation of the results of multivariate analysis of the studied types of multiple units by groups of criteria [own elaboration]

In this aspect, it benefits from a fuel cell-powered multiple unit that is fully zero-emission while driving. Direct combustion of hydrogen produces only nitrogen oxides and steam. In contrast, when hydrogen is oxidised in fuel cells, the by-product is only steam. In the quest for climate neutrality, it is important to use green hydrogen, which is produced during the electrolysis of water using renewable energy. Alstom was the only manufacturer of fuel cell-powered multiple units until late 2024, when Siemens joined with the Mireo Plus H, while CAF remains at the prototype stage. They boast a range on a non-electrified route almost at the level of diesel multiple units while having initial acceleration values of 1.1 m/s^2. They are unrivalled in the technical performance category. They have fully proven themselves by operating services in Lower Saxony, Germany. However, they are mainly found in a two-unit configuration. Although they do not use overhead lines, they require hydrogen refuelling stations, which are not currently located along railway lines. Thus, in terms of economic parameters, they are the lowest rated.

In the criteria of environmental protection and functional parameters, the battery-electric multiple unit, which uses electricity with the possibility of using renewable energy sources during the entire route, also scored highly. It also gains maximum speeds on electrified and non-electrified lines of 140-160 km/h. While it may be charged while running under the overhead line, its biggest drawback is its short range on a non-electrified route, at just 150 km. Austria, where only 25% of railway lines are non-electrified, has opted for this solution.

The tri-mode multiple unit, which appears to combine all the advantages of the previously mentioned rolling stock, only came in fourth place. Primarily because the drivetrain occupies a significant portion of the rolling stock thus limiting seating capacity, and the complex drivetrain can cause operational problems during use (Fig. 3). After initial prototype trials, these types of rolling stock are now in regular operation in the UK.. There, they chose a multiple unit that combines a diesel engine, battery energy storage and the use of an overhead line. At the same time, a hydrogen-battery-electric rolling stock is being developed. According to existing data, a speed of 140 km/h is to be achieved with acceleration of 1.1 m/s^2. However, the range on a non-electrified route depends on a number of design and operational factors between 100 and 1,000 kilometres.

The classic diesel multiple unit (DMU), although it came last in the list, still prevails in the cost and technical performance criteria and has high scores in the functional parameters. They are the most refined design due to years of experience and are most commonly found on non-electrified lines. However, it ranked last due to its emissions and performance. The reason, for example, is the low speed of 120 km/h and an initial acceleration of 0.85 m/s^2. But above all, there is a lack of opportunity to exploit the potential of the electrified part of the railway.

6. Conclusions

During the process of selecting the rolling stock for transport tasks, it is recommended to use mathematical support tools. In the situation of selecting a type of multi-drive rolling stock, where analysis of a numerous group of factors and criteria is required, multi-criteria comparative analysis has worked well. Based on the multi-criteria comparative analysis performed, the highest evaluation value was given to the diesel-electric multiple unit for operating partially non-electrified routes. When the goal is to provide transport connections with fully zero-emission rolling stock, a fuel cell-powered multiple unit is a rational choice.

Table 8. Results of the analysis of the evaluation of types of multiple units against groups of criteria [own elaboration]

Train type	DMU	BEMU+	FCMU	TMU	DEMU
Economic criteria	1.00	0.21	0.01	0.11	0.18
Technical criteria	1.00	0.54	0.26	0.22	0.54
Functional criteria	0.88	0.94	1.00	0.86	0.95
Operational criteria	0.55	0.49	0.79	0.61	1.00
Environmental criteria	0,00	1.00	0.94	0.89	0.83

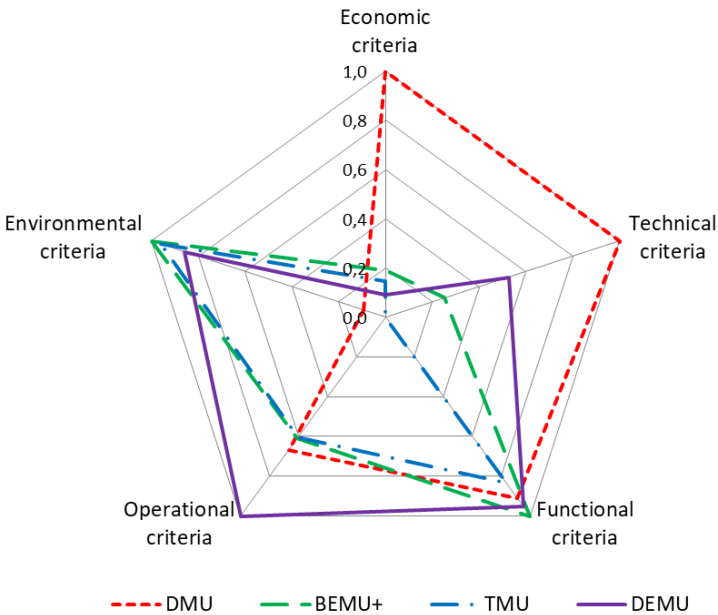


Fig. 3. Graphical representation of the results of multivariate analysis by types of multiple units [own elaboration]

The diesel-electric multiple unit is a proven design based on a combination of the most popular diesel and electric rolling stock to date. It features optimal performance depending on the drive source used. Most often, the maximum speed on an electrified line is 160 km/h and on a non-electrified line 120 km/h, and the range is approx. 1,000 km.

The fuel cell-powered multiple unit is currently the most promising solution. In terms of energy source, it moves autonomously using hydrogen stored in tanks and batteries. It, too, demonstrates a range of about 1,000 kilometres with zero-emission driving and acceleration of 1.1 m/s^2.

A battery multiple unit is a type of rolling stock that uses energy stored in batteries with the ability to recharge them while running under the overhead line. Despite good operating parameters, such as a speed of 160 km/h and acceleration of 1.1 m/s^2, the range on a non-electrified route is only 150 km.

The tri-mode multiple unit is the rolling stock with the most extensive propulsion system, which consists of three different power sources. However, the elaborate design is not conducive to performance. The number of available passenger seats is reduced while the range suffers, and maintenance requires expert workers.

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