Avaliação multicritério de sistemas de transporte urbano com foco no sistema Personal Rapid Transit

Aplicação à ligação Estação do Oriente - Aeroporto de Lisboa

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Abstract

Sustainability and optimization are pivotal elements in urban development, gaining increasing complexity and significance as cities continue to grow. Over the past decade, there has been substantial growth in both transport mode selection and developments related to automated guided transit. This article aims to evaluate various transport modes in the context of the connection between Lisbon Airport and Gare do Oriente Train Station. The study area encompasses the zone modernized during Expo 98, including commercial and residential zones adjacent to Berlin Avenue, which serves as the central axis for this case study.

Keywords: Multi-Criteria Decision Analysis, Urban Transport Mode Selection, Urban Terrestrial Transports, Personal Rapid Transit.

1 Introduction

Urban expansion poses challenges to the core systems that sustain a city, including its transportation network. As demand for passenger and freight transport within cities increases, planning processes become more complex, with significant impacts. Decision-making must consider factors such as environmental impact, social well-being, and quality of life. To explore alternatives, some entities have revisited the concept of 'mass customization,' commonly applied in other industries, within the transportation sector. By combining cutting-edge technologies with concepts from the 1950s, the discussion around autonomous transportation systems, particularly Personal Rapid Transit (PRT), resurfaces. This paper focuses on studying decision-making problems, specifically applied to the link between Lisbon Airport and Oriente Train Station to analyse and select transportation modes in a complex and numerous stakeholders and evaluation criteria environment.

The complexity arises from considering various technical aspects, especially those related to environmental and societal impacts.

2 Case Study

The case under study in this project is the connection between Lisbon Airport and Gare do Oriente Train Station.

The route covers a distance of 2.45 km, with an average incline of 3.8% and a maximum incline of 15.5%, with a minimum crossroad section of 21 meters and a max of 80 meters (Google, 2016). Some of the limitations include two viaducts with 5.2 meters of clearance to the ground.

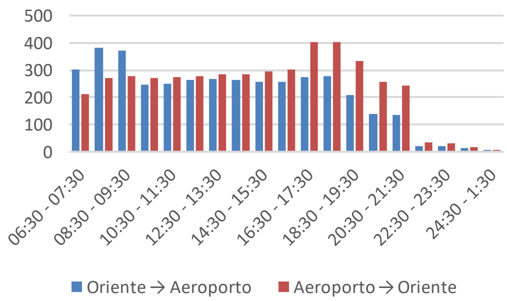


Figure 1 - Histogram of the daily average joint demand on weekdays of the Lisbon Metro and Carris lines 744 and 705 for the connection between Lisbon Airport and Oriente Station in both directions in 2015 (Transportes de Lisboa, 2016)

The demand in presented in Figure 1 for the route, is a result of combining demands of the three alternatives that provide transport in the current route (Carris route 744 and 705 and Lisbon Subway). Demand is expected to increase at a rate of approximately 3000 passengers per year (ANA, 2016).

3 Urban Transport

Urban transportation technologies ware grouped by modes, each mode is defined by three basic characteristics: Right-of-Way, system technology and type of service.

The Right-of-Way (ROW) is the way/lane in which the vehicle operates and is divided by categories, A, B and C. Being A fully controlled and exclusive, B longitudinally, physically separated by curbs, barriers, or others, and C for surface streets with mixed traffic (Vuchic, 2007).
The System Technology is defined by support (the vertical contact between vehicles, e.g., steel rail), guidance (e.g., driver, rail), propulsion (including the type of power unit and traction system) and control (e.g., signals, automated control).
The Types of Service are defined by the types of routes and trips served (short to long-range coverage), by stopping schedule (all-stops to direct route) or by type of operation and time of operation (related to the schedule that it operates).

3.1 Urban Terrestrial Transport Modes

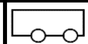
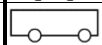
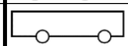
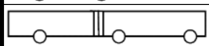
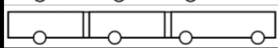
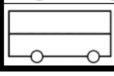
3.1.1 Railways Transport Modes

Streetcar / Tramway - A streetcar or tramway, is a type of light rail that operates mostly on shared roadways, typically consisting of a single vehicle, and stops occur directly on the shared roadway, using catenary power wires (Neff & Dickens, 2014; Vuchic, 2007).
Light Rail (LRT) - Its rolling stock resembles traditional trams, LRT operates at higher capacity and speed, often on an exclusive right-of-way combining features of trams and rapid transit (FICCI, 2013; Neff & Dickens, 2014; Vuchic, 2007). If it operated in rapid transit are called Light Rail Rapid Transit (LRRT) (FICCI, 2013).
Ultra-Light Rail – is a rail system even lighter than standard light rails, often fully automated (FICCI, 2013).
Metro - (aka urban train, rapid rail, metropolitan railway, or heavy rail) is a high-capacity rail transport mode that operates on exclusive tracks and vehicles with multiple units (four to ten cars). Metro systems have sophisticated signalling, elevated platforms, and dedicated operation (Dearien, 2004; Neff & Dickens, 2014; Vuchic, 2007).
Monorail - vehicles (usually trains) that run on a single rail, beam, or tube. Most monorails fall into the heavy rail category or automated track systems. Common monorails use rubber-tired wheels on top of a cement beam (Neff & Dickens, 2014; Vuchic, 2007).
Subway - operates exclusively in underground tunnels. Its primary characteristic is functioning underground, providing advantages in visual impact and minimising disruption to urban fabric. However, subway infrastructure costs are higher (4 to 6 times higher than at the ground level, and 2 to 2.5 more than elevated tracks) (Flyvbjerg et al., 2008; Vuchic, 2007).

3.1.2 Road Transport Modes

Road transport is essentially defined by BUS, they normally are divided by chassis type, as presented in Table 1, by type of operation, and power unit/energy source.
Conventional BUS operate with fixed schedules on streets in mixed traffic (ROW C), BUS Transit System operates in a coordinated system and Rapid Transit operates as a system of distinct buses and separate infrastructure.
For the power unit/energy source, the term trolley appears, for the ones using catenary, other terms such as “electric” are used to differentiate from the usual petrol and diesel versions (in this case for ones using batteries) (Vuchic, 2007).

Table 1 - Different types of bus per chassis, adapted from Vuchic (2007)

Type		sketch	Length (m)
Minibus			6-7
Midbus			8-10
Conventional			10-12
Articulated	Normal		16-18
	Double		22-24
Double-decker			10-12

The name of the mode is generated by adding the three categorizations. E.g., Minibus Trolley Rapid Transit (minibus vehicle using catenary and operating as rapid transit).

3.1.3 Cable-propelled transit

As part of the Cable-propelled transit vehicles are grouped by the support type, as the group is specifically related to the propulsion system. The modes are:
Aerial Tramway - a system of aerial cables and towers with non-motorized suspended vehicles. Propulsion is carried out by motors located centrally rather than on the vehicle itself. They can overcome steep slopes, but require significant ground space for its stations (Alshalalfah et al., 2013; Clement-Werny et al., 2011; Neff & Dickens, 2014; Vuchic, 2007).
Cable Car - This is a type of rail system with individually controlled vehicles. These vehicles move by coupling to an underground cable, and the cable’s motors are located outside the vehicle (Neff & Dickens, 2014; Vuchic, 2007).
Funiculars - These are rail-based systems where vehicles are pulled by a cable. They are known for their ability to handle steep inclines, with a motor typically located at the highest

point of the route (Clement-Werny et al., 2011; Vuchic, 2007).

3.1.4 Automated Guideway Transit (AGT)

Automated Guideway Transit (AGT) is defined by (Kutz, 2011) as a class of transportation systems where fully automated.

They are divided by vehicle capacity/size, in:

Automated People Movers (APMs) - are driverless units operating on fixed tracks, with a capacity of up to 100 passengers. APMs are commonly used in airports for short-distance lines (up to 13 km) with shuttle operation. Most vehicles use rubber-tired wheels (tires) and have capacities ranging from 15 to 80 passengers per vehicle, often in compositions of two or three cars. They are normally Light Rail Transit based modes, with full automation (Kutz, 2011; Vuchic, 2007).

Group Rapid Transit (GRT)- is an automatic vehicle type with capacities ranging from 6 to 18 passengers per vehicle. GRT stations feature platforms and non-stop passageways, and vehicles stop according to passenger needs. Morgantown GRT in the USA is an example of this systems (Raney & Young, 2000).

Personal Rapid Transit (PRT) – In Vuchic (2007), Personal Rapid Transit was defined as "An imaginary transit mode consisting of small-capacity (2 to 6 passengers cabin-type vehicles travelling automatically over an elaborate system of guideways; individuals or small acquainted groups would use a cabin to travel between origin and destination stations without stopping. Meyer and Morache (2010) defines PRT as: "very small vehicles with a capacity of three to five persons per car or 'pod'." Anderson (2000) defined PRT as "a system of small, fully automated vehicles that carry people nonstop between off-line stations on a network of exclusive guideways."

The definition now proposed for PRT is an automated system of small-sized vehicles, with a capacity of 2 to 6 seats, that operate automatically on an exclusive or shared network of guideways, using an advanced and redundant computer system, and in vehicles (that in normal operating conditions) go from their origin to their destination without stopping, thanks to stations with stopping tracks diverted from the circulation track. The PRT transport studied in this work was designated in Furman, Ellis, Fabian, and Muller (2015) as Automated Transit Networks (ATN) including the following main characteristics:

- Direct transport service between origin and destination without stops or transfers.
- Small-sized vehicles for individual use or small groups.
- On-demand service rather than fixed schedules.
- Fully automated vehicles operating 24/7.
- Reserved lanes for PRT vehicles.
- Small guideways compared to other transit systems.

In comparison with GRT, PRT performs non-stop trips, while GRT stops at all required stations. PRT can become cost-competitive exploiting mass production and infrastructure benefits (Anderson, 2000). Some of the locations where PRT is operational include Heathrow Airport (London), Masdar City (Abu Dhabi), Suncheon Bay (South Korea) and Tianfu Airport, China. PRT is still in the early stages of commercialization.

4 Transportation Planning and Transportation projects

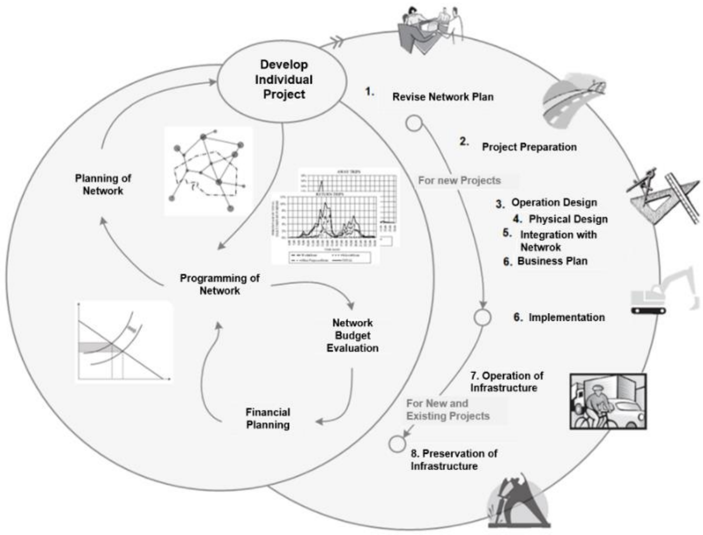


Figure 2 - Phases of overall transmission system development process and the implementation projects of sub-networks or transport corridors (Hook & Wright, 2007; Sinha & Labi, 2011)

The implementation and maintenance of a transportation network involve a set of steps, which are presented in Figure 2 within the smaller circumference.

These steps encompass all the aspects that contribute to the network's complexity and the development of transportation projects. The sequence of steps may vary depending on the country, considering the practices and regulations applicable by the responsible entities.

Transportation planning and network in scope of the work, are driven by Lisbon Metropolitan Area (AML). AML aims to make urban transportation sustainable from social, environmental, economic, and financial perspectives, addressing the mobility needs of the population (AML, 2016), being responsible for planning, organizing, operating, financing, supervising, promoting, and developing public passenger transport (República, 2015). As transportation projects derives from the network planning and is performed by a sequence of activities related to the planning, design, construction, management, operation, and evaluation of a single transportation facility / infrastructure project, the decision process must include its main objectives as part of the scope of the decision making (Ceder, 2007; Sinha & Labi, 2011).

5 Decision-making on transport mode and vehicle selection

5.1 Methods

The most used decision methods in transportation projects, whether individually or in combination, are described below.

5.1.1 Environmental Impact Assessment (EIA)

EIA is an activity designed to identify and predict the impact on the environment, human health, and well-being resulting from legislative proposals, policies, programs, projects, and operational procedures (Kassim & Simoneit, 2005). EIA is mandatory or must have for transportation projects according with legal requirements (PE & CE, 2001) and (CUE, 1997; PE & CUE, 2003, 2009).

5.1.2 Cost-Benefit Analysis (CBA)

CBA is an approach that quantifies the costs and benefits of a project by measuring positive and negative impacts and comparing the benefit-to-cost ratio between alternatives (Shang et al., 2004). As advantages it includes: strong Theoretical Basis economic foundation, and simplicity for decisions based on existing market value criteria (tangible factors) (Shang et al., 2004). CBA still faces specific challenges when applied to transportation projects for example when applied to infrastructure life cycles, focuses on short-term travel savings, which may not align with long-term user strategies (Macário, 2014). Furthermore, CBA often treats travel time as a cost, emphasizing increased average speed as a primary strategy to reduce this cost. To mitigate these, Salling and Banister (2009) suggest a combined use of CBA and Monte Carlo simulation, as simulation serves as a sensitivity analysis for the model.

5.1.3 Total Cost Analysis (TCA)

TCA can be used as a method for comparing transportation alternatives, it aggregates all costs for each alternative, including environmental and travel time costs.

TCA offers two advantages over CBA: simplifying understanding for stakeholders and allowing more judgment in decision-making regarding intangible factors (DeCorla-Souza et al., 1997).

5.1.4 Social Cost-Benefit Analysis (SCBA)

SCBA compares marginal benefits (utility increments) with marginal costs (utility losses). Values are expressed in monetary terms and based on what consumers are willing to pay or derived from other methods (e.g., revealed or stated preference methods) (De Brucker et al., 2011).

5.1.5 Cost-Effectiveness Analysis (CEA)

CEA selects the alternative with the lowest cost that achieves a predefined level of effectiveness.
Effectiveness reflects the operationalization of a specific policy objective, subject to critical evaluation of its appropriateness (De Brucker et al., 2011).

5.1.6 Regional Economic Impact Study (REIS)

REIS aims to measure additional production (linked to production concepts), quantifying the value added causally related to the project.
These methods provide valuable insights for decision-making in transportation projects, considering both tangible and intangible factors (De Brucker et al., 2011).

5.1.7 Multicriteria Decision Analysis (MCDA)

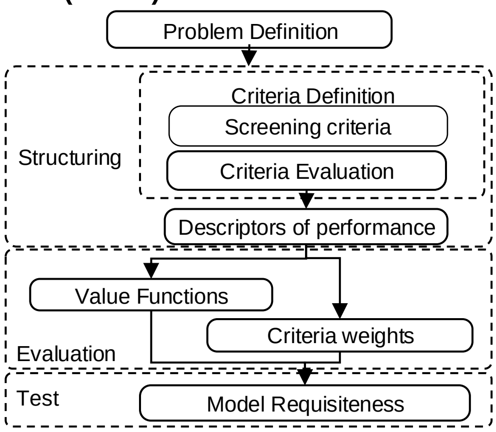


Figure 3 - Structure of the multicriteria methodology, adapted from (Bana e Costa et al., 2008)

MCDA can be defined as the study of methods and procedures by which conflicting viewpoints and multiple criteria can be formally incorporated into the decision-making process (Sinha & Labi, 2011). MCDA and CBA are the most commonly used evaluation methodologies of transportation in Europe (Bristow & Nellthorp, 2000).

A MCDA process can be divided into three main stages: structuring, evaluation, and model testing. The structure of these stages and their sub-steps are presented in Figure 3.

5.2 Evaluation Approach

Several methods for evaluating alternatives use outranking, comprise-based methods, or the additive value model, which is the most used.

Table 2 - Simplified comparation between methods

Outranking method	Compromise-based methods	Additive value model
PROMETHEE, ELECTRE, REGIME, and SIR	**TOPSIS and VIKOR**	**MAUT/MAVT**
More complex methods than additive value model. Methods: **ELECTRE:** great traceability and use of high number of criteria's but very complex method; **PROMETHEE:** avoids trade-offs between good and poor scores in criteria; **-SIR:** fusion of methods and simpler method compared to other's; **-REGIME:** wide range of use but not designed to enhance decision transparency. Difficult to track evaluation evolution and with high non-proportional computational complexity complex and sensitivity analysis.	**VIKOR:** consider the relative importance of attractiveness. **TOPSIS:** cannot consider the relative importance of attractiveness.	**MAUT/MAVT:** simple and most versatile - most widely applicable. Several weighing methods can be used and incorporate as: **Delphi Technique, Swing Weighting Method, Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), and MACBETH.** **AHP and ANP:** enable decision-markers to learn; facilitate conflict resolution and allow inclusion of tangible and intangible elements. However, AHP include high pairwise comparation, is time consuming and theoretical errors have been identified in the construction of the AHP methodology.

Table 2 presents a general description of methods with the pros and cons of each one. Based on the comparison and evaluation, a recommended approach is to use group decision-making methods, such as the one conducted by Bana e Costa et al. (2014), employing an additive value model, decision-making tools, and software tools like M-MACBETH.

6 Decision process

6.1 Alternatives

The alternative modes have been selected based in capacity and ground space requirements, and they are:
Tram - Mixed-traffic rail solution (ROW C).
Light Rail Street Car (LRs) - Similar to the previous alternative but with most of the route in a reserved lane (ROW B)
Mini BUS RT Electric (BUSe) - A Mini BUS "Rapid Transit" alternative (limited by available space, resulting in lower speeds than a dedicated system). The choice of the electric version is based on the current demand for the connection.
Mini BUS RT Fuel (BUSf): Similar to the previous alternative but with a combustion engine.
GRT street: A Group Rapid Transit (GRT) road vehicle capable of operating in shared lanes. It combines features of a low-capacity automated minibus with GRT system capabilities, serving as an intermediate solution between fully automated and shared systems with a driver.
GRT rail**:** An alternative in a reserved lane with mixed GRT and PRT operation.
PRT "rail**":** Operates in reserved lanes (ROW A) with customized operation. The term "rail" refers to a fixed-route PRT with a defined reserved lane.
PRT street: A PRT alternative in ROW B, using an autonomous vehicle.

6.2 Objectives, criteria, descriptors, and value tree

The definition of objectives was developed through a cognitive map and constructed based on the works of Bryson et al. (2004).
The map allowed the identification of evaluation criteria, which were defined considering that they should be consensual, isolable, operational, and intelligible, and that their set in the multicriteria model should be exhaustive, non-redundant, concise, decomposable, and consensual (Bana e Costa & Beinat, 2005).

Table 3 - Criteria, Descriptors, Metrics, and Upper and Lower Levels of Reference

Criteria – Descriptor of performance	Upper level	Lower level
Air Pollution - Air pollution (gCO2/pax-km)	0	124
Biodiversity - Potential impact on biodiversity comparing options	Low Impact	High Impact
Soil Pollution - Comparison of pollution generated (e.g. oils and fuels).	Low Impact	High Impact
Noise - Noise in decibels	0	80
Soil usage - Lowest possible land use	No additional soil	More than available
Visual Impact - comparison between the options.	Low Visual Impact	High Visual Impact
Mix Network (Mobility) - Network support to transport passengers and goods	Network supports freight transport equally	The network must be segregated
Congestion (Mobility) - Impact on congestion on existing infrastructure	Congestion reduction	Increased congestion
Personal Space (Comfort) - Comparison of the feeling of available space for each passenger	Total privacy / similar to a private vehicle	No Privacy / No Personal Space
Feeling of Comfort - Temperature, humidity, pressure, contact surfaces, and cleanliness sensation	High feeling of comfort (fully controlled and user-adjustable	No comfort (affected by weather conditions and

Criteria – Descriptor of performance	**Upper level**	**Lower level**
with impact to passenger comfort.	environment in the vehicle and station)	vehicle movements)
Exposure to Climate (Comfort) - Passenger's level of exposure to outdoor elements	No exposure to the environment	Fully exposed (transitions with vehicle, station)
Seating - Comparing seating availability as a % of vehicle capacity.	100% Seating / Total Seating	0% Seating / Total Seating
Integration with complementary transportation systems - Integration of infrastructure and vehicles with other mobility solutions such as bicycle	Full integration (no unevenness, with visual and functional integration)	Complete disruption (unevenness, distances of more than 2 minutes on foot)
Network Expandability - Network Expandability (System under Study)	Easy, no infrastructure changes required	Total loss of investment / infrastructure
Network Schedule Integration - Ability to adjust and integrate with existing network schedules.	Full integration of schedules is possible	No synchronization
Integration with network routes - Integration and adjustment to existing and potential network routes	Full integration with the other routes (of the other networks)	No integration or negligible
Traveling Time - Average travel time in minutes per passenger.	0 average min/pax	18 average min/pax (≈ cycling time)
Availability - System availability in normal operation (% of time [24h] with at least one vehicle above 20% capacity)	100%	0%
Demand Adjustment - Ability to adjust to the daily demand maintaining numbers of vehicles.	300% adjust pax/h capacity	0% adjust pax/h capacity
Current Facilities (Demand) - Capacity to adjust the current infrastructure as % of the expected passenger	100% possible variation	0% possible variation
Future Facilities (Demand Adjustment) – Ability adjust to future demand in % only adding necessary vehicles	1000% possible variation	0% possible variation
Usage (Easiness) - Comparison of the user-friendliness of the system.	Very Easy	Very Hard
Usage as group (Easiness) - Comparison of ease of use as a group (e.g. w/ children)	Very Easy	Very Hard
Baggage Transport (Easiness) - Comparison of the ease of carrying luggage	Very Easy	Very Hard
Facility Service Lifetime - Installation expected lifetime	100 years	0 years
Vehicle Service Lifetime - Lifespan of vehicles.	100 years	0 years
Reliability - Predicted system reliability.	100%	0%
Impact real estate value (Externalities) - Impact on the value of real estate.	100%	0%
Relocations (Externalities) - Expropriations and relocations.	0	10
Business impact (Externalities) - on other economic activities as a percentage of its activity.	100%	-20%
Costs - Total costs with: Capital, Intangibles, Fixed assets, and Risk (financial)	0,1 €/pax.km	1 €/pax.km
Chemical, Radiologic and Biologic Risk (Safety) - Comparison of the risk of disease spread and biological contamination, and related others.	No risk (no passenger and no impact)	Very high risk (all passengers being exposed and with high impact)

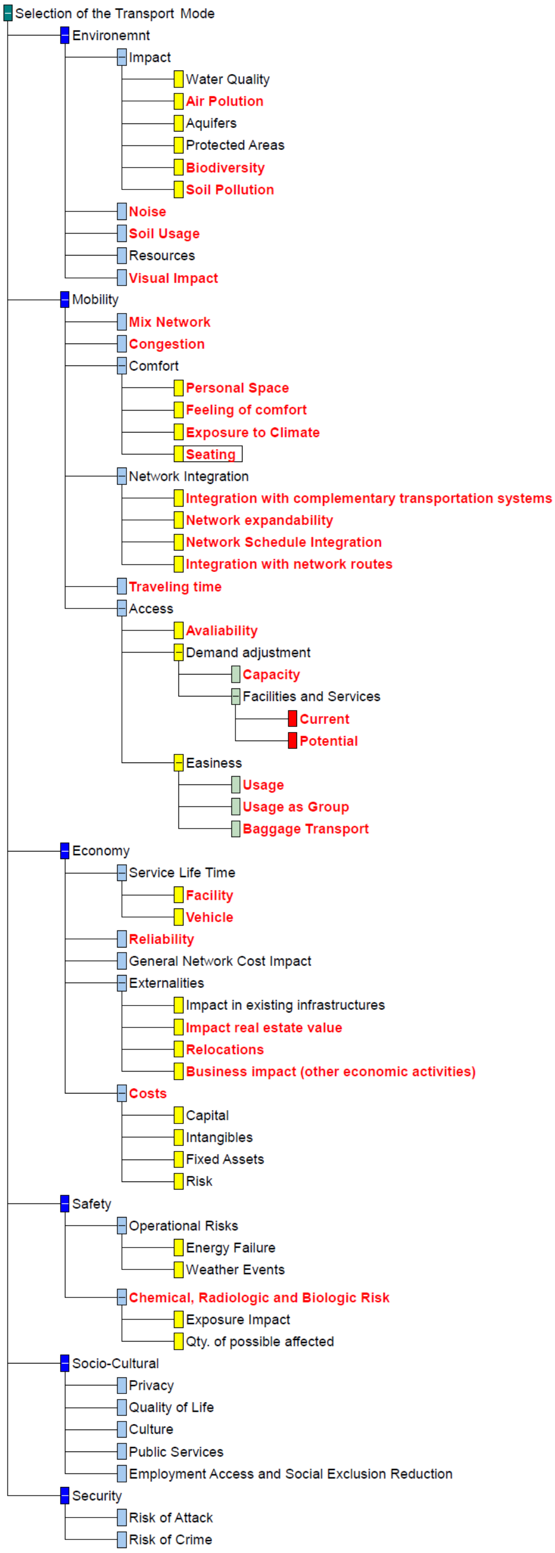


Figure 4 - Value Tree

The value tree presented in Figure 4 was constructed with all the relevant viewpoints for selecting a mode of transportation in Lisbon. It includes criterion nodes (which correspond to the criteria in red), and non-criterion nodes, which represent the areas of concern, except

for the root node (Selection of the mode of transport).
Some criteria are "inactive" in the value tree since they do not distinguish the alternatives. Therefore, they were excluded from Table 3, which presents the criteria, their descriptors of performance and reference performance levels. The expected outcome of this process involves obtaining a value scale (or value function) for each of the previously defined criteria, based on qualitative judgments of difference in attractiveness using the MACBETH semantic scale Bana e Costa et al. (2008): null, very weak, weak, moderate, strong, very strong, extreme.
Figure 5 shows the MACBETH judgment matrix used to construct the value function for the Air Pollution criterion that is depicted in Figure 6.

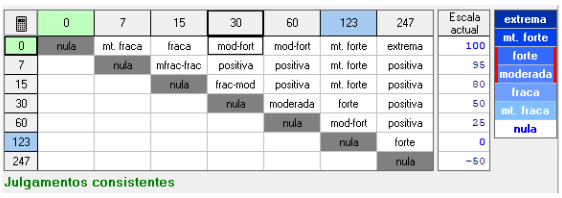


Figure 5 - Judgment matrix for Air Pollution criteria

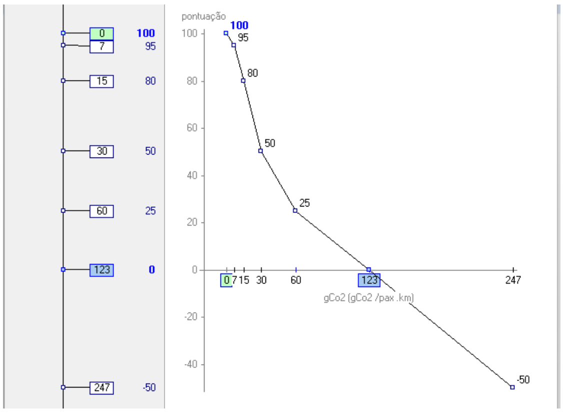


Figure 6 - Value Function for Air Pollution criteria

6.3 Performance and Criteria weights

The performance levels for each alternative are presented in Table 4. The criteria weights (Table 5) were obtained using MACBETH with judgements about the lower to upper performance improvements on the criteria.

Table 4 - Performances of Alternatives

Criteria	PRT		GRT		BUS		Tram	LR
	r	s	r	s	e	f		
Air Pollution (kWh/pax.km considering 50% occupancy [10] and 251gCO2 / kWh	0,075[1]	0,072[11]	0,06[1]	0,09[9]	0,09[9]	0,14[6]	0,103	0,103[9]
gCO_2/ pax-km	19	18	16	23	23	182[10]	26	26
Noise [dB]	65[1]	65[4]	70[8]	65[3]	65[3]	71[2]	80[3]	75[7]
Feeling of Comfort	H	H	M	M	M	M	L	L
Exposure to Climate	L	M	L	M	H	H	H	M

Criteria	PRT		GRT		BUS		Tram	LR
	r	s	r	s	e	f		
Seating [5; 6; 13; 14; 15; 16] [%]	100	100	90	90	65	65	65	60
Traveling Time [min]	4	4	6	6	7	7	13	13
Availability[% h/24h] [12; 5; 6]	100	100	82	82	75	75	75	70
Capacity [12;14] [%Adjust pax/h capacity]	100	100	80	80	50	50	20	20
Current Facilities (Demand Adjustment)[12;14] [%]	40	40	60	60	60	60	60	100
Future Facilities (Demand Adjustment) [12;14] [%]	100	100	100	100	100	100	100	300
Facility Lifetime [Years]	30	30	30	30	50	50	50	50
Vehicle Lifetime [Years]	15	10	15	10	10	10	20	20
Reliability [%]	98[5]	98[5]	98[5]	98[5]	95[6]	95[6]	92[6]	95[6]
Impact real estate value [%]	20	20	10	10	5	5	0	0
Impact Relocations	0	0	0	0	0	0	0	10
Business impact (other economic activities) [%]	5	5	0	0	0	0	0	-10
Costs - Sum of operational costs [€/pax.km] [13;]	0,8	0,8	1	1	0,66	0,66	0,55	1,01
infrastructure costs [M€/km]	5.15[19]	6.5[19]	6.6[18]	5.15[18]	0.6[17]	0.6[17]	7.5[17]	27[17]
Total [€/pax.km])	0,97	1,02	1,22	1,17	0,72	0,72	0,76	1,78

Sources: (Carnegie & Hoffman, 2007)[1];(Nadri et al., 2012)[2];(Misanovic et al., 2022)[3];(Meyer & Morache, 2010)[4];(Furman et al., 2015)[5]; (Vuchic, 2007)[6];(Xie et al., 2021)[7];(Gustafsson & Lennartsson, 2009)[8];(Würtz et al., 2024)[9];(Ambiente, 2023)[10];(LocalMotors, 2016)[11]; Figure 1 [12]; (Carnegie & Hoffman, 2007)[13]; (Kutz, 2011)[14]; (Raney & Young, 2000)[15]; (Pemberton, 2013)[16]; (Alshalalfah et al., 2012)[17]; (Janić, 2014)[18]; (PRT, 2024)[19]

Table 5 – Criteria weights

Criteria	Weight
Air Pollution	46,5
Biodiversity	17,5
Soil Pollution	12,5
Noise	47,5
Soil Impact	6,5
Visual Impact	45
Mix Network (Mobility)	56,5
Congestion	6,5
Personal Space	81
Feeling of Comfort	75,5
Exposure to Climate	51
Seating	78,5
Integration with complementary transportation systems	66
Network Expandability	61,5
Network Schedule Integration	61,5
Integration with network routes	60
Traveling Time	97
Availability	80
Capacity Demand Adjustment	82,5
Facilities Current Demand Adjustment	67,5
Facilities Future Demand Adjustment	41
Usage (Easiness)	50
Usage as group (Easiness)	59
Baggage Transport (Easiness)	63,5
Facility Service Lifetime	77
Vehicle Service Lifetime	74
Reliability	72,5
Impact real estate value (Externalities)	10,5
Relocations (Externalities)	57,5
Business impact (other economic activities)	6,5
Costs	100
Chemical, Radiologic and Biologic Risk (Safety)	49

6.4 Results

Figure 7 presents the M-MACBETH thermometer graph with the overall scores of the alternatives. PRT rail is the most scored option, with 70 points.

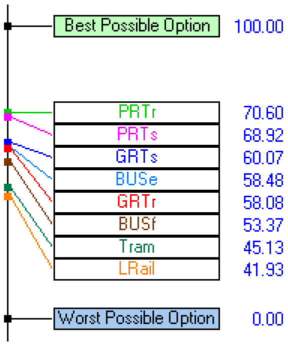


Figure 7 – Alternatives overall scores

6.5 Sensitivity and Robustness Analyses

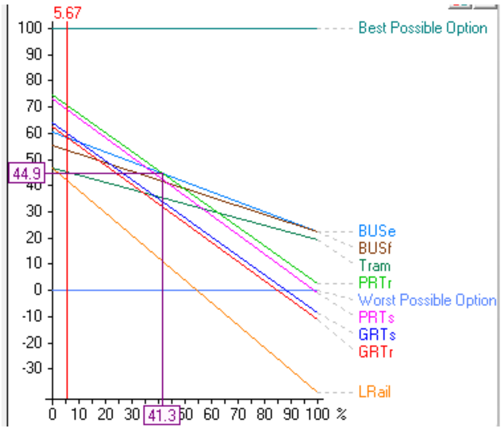


Figure 8 - Sensitivity analysis of weight to the criterion cost and considering PRTr and BUSe

The analysis of sensitivity to the weights of the criteria allows the verification of the behaviour of the overall scores versus the weight given to a criterion, maintaining the identical proportionality relationships between the weights of the other criteria.

Figure 8 shows the sensitivity analysis developed for the criterion cost. The change of the best option from PRTr to BUSe happens when the cost weight goes from 5.67 to 41.3.

Análise de robustez

	Best Possible Option	PRTr	PRTs	GRTs	BUSe	GRTr	BUSf	Tram	LRail	Worst Possible Option
Best Possible Option	=	▲	▲	▲	▲	▲	▲	▲	▲	▲
PRTr		=	+	+	+	+	+	+	+	▲
PRTs			=	+	+	+	+	+	+	+
GRTs				=	?	+	+	+	+	+
BUSe				?	=	?	+	+	+	▲
GRTr					?	=	+	+	+	+
BUSf							=	+	+	+
Tram								=	+	▲
LRail									=	+
Worst Possible Option										=

Figure 9 - Robustness analysis with global and local active variations (ordinal, MACBETH) and global cardinal variation of 40% and local variations of 30% and 20% for travel time and costs, respectively

In addition, a robustness analysis was performed to evaluate the behaviour of the ordering of the alternatives by modifying the information of the local values (scores of the alternatives in the criteria) and global values (in the criteria weights).

Only additive dominance is found, and some alternatives do not present any dominance (presented with a question mark in Figure 9).

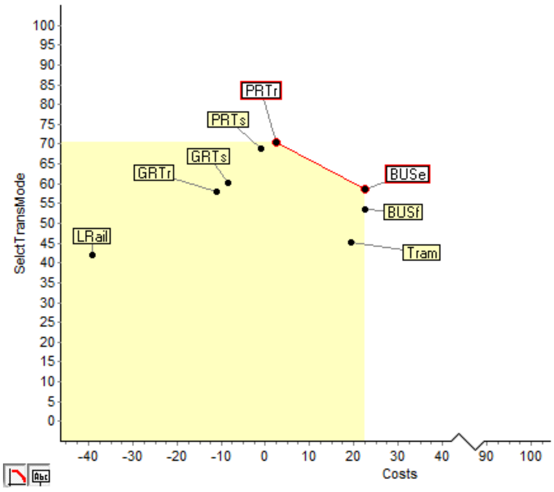


Figure 10 - Cost Benefit comparison

Figure 10 shows which alternatives are present in the efficient frontier (in red). The result of the graph allows us to identify that the PRTr and BUSe option present the best overall result within the different cost levels, and in line with the result of Figure 7.

7 Conclusions

In urban transportation decision-making processes, multi-criteria evaluation is employed, although its adoption remains limited. While cost considerations often dominate decision-making, they may not fully account for non-monetizable criteria. Multicriteria decision-making, with its ability to incorporate and reflect user expectations through weights and rankings, now presents an opportunity for more frequent use in transportation decisions.

The results obtained from the study revealed that PRT, BUS, GRT modes were the most preferred among the alternatives presented. Although not directly part of the formal evaluation process, the importance of the ability to adjust to timetables and routes was highlighted. It's worth noting that the PRTr option does not readily allow for easy route adjustments. However, since the case study was confined to a corridor, this crucial flexibility for passengers did not significantly impact the selection. Nevertheless, adaptability remains one of the strongest points of PRT systems.

PRTr mode emerged as the top choice, demonstrating minimal sensitivity to variations in the cost criterion. However, it's essential to recognize that PRT as a mode requires economies of scale - both in terms of its routes and vehicles - to achieve the expected cost-effectiveness. Currently, most PRT installations serve as demonstrations, tests, or small networks, lacking large-scale operational deployments. Nevertheless, with the advancement of automated driving technology in private passenger vehicles, the required economies of scale and technology could be harnessed by PRT. Additionally, combining vehicles as PRT shared network could revolutionize urban transport, akin to market solutions like Uber, where ticket prices and other motivations drive adjustments in supply and demand.

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