Faculdade de Engenharia da Universidade do Porto

Multicriteria evaluation as a tool for decision support in the design of sustainable routes

Joana Sofia Campos Santos

FINAL VERSION

Dissertation completed in
Mestrado Integrado em Engenharia Eletrotécnica e de Computadores
Major Automação

Supervisor: Tânia Daniela Lopes da Rocha Fontes
Co-supervisor: Jorge Manuel Pinho de Sousa
08/07/2021

Resumo

Nas últimas décadas, o transporte público tornou-se uma componente muito importante da mobilidade, principalmente em grandes áreas metropolitanas. No entanto, as atividades de transporte têm criado diversas consequências negativas, como emissão de poluentes, dependência energética, acidentes, ruído e congestionamento. Estes têm aumentado nos últimos anos levando a uma preocupação crescente com sua eliminação e minimização. Uma forma de resolver esse problema é desenvolver redes de transporte público com base numa avaliação integrada de seu desempenho de sustentabilidade. Assim, o objetivo principal deste trabalho é desenvolver uma ferramenta para realizar uma avaliação multicritério de rotas de transporte público em relação às três principais dimensões da sustentabilidade: económica, social e ambiental.

A estrutura de análise foi desenvolvida a partir de uma relação hierárquica entre dimensões, critérios e indicadores. Nesse sentido, para cada dimensão, foi realizada uma seleção de indicadores incluídos nos diferentes critérios escolhidos, considerando a literatura desta área. Cada indicador foi quantificado e normalizado antes de lhes serem atribuídos pesos. Nesta última etapa, os pesos atribuídos aos níveis das dimensões e dos critérios foram recolhidos da literatura. Já a nível dos indicadores, os pesos foram atribuídos de forma uniforme.

A ferramenta desenvolvida foi aplicada a um caso ilustrativo formado por três rotas de autocarros. Para aproximar o caso à realidade, a criação do conjunto de dados teve como base a principal empresa municipal de autocarros que opera na área metropolitana do Porto (STCP), em Portugal.

Esta aplicação validou a ferramenta, resultando num índice de sustentabilidade para cada rota da rede desenhada, considerando períodos de pico e períodos fora de pico. A flexibilidade da ferramenta também permite uma análise completa dos níveis dos critérios e das dimensões. Uma análise mais aprofundada demonstrou o potencial da ferramenta para lidar com situações mais realistas, contribuindo assim para melhorar a sustentabilidade urbana.

Palavras-chave — indicadores, multicritério, transporte público, rotas, sustentabilidade

Abstract

In the last decades, public transport has become an important component of mobility, particularly in large metropolitan areas, Nonetheless, transport activities have originated several negative consequences such as pollutant emissions, energy dependency, accidents, traffic noise, and congestion. These have been increasing over the past years leading to a growing concern on their elimination and minimization. One way to address this problem is to design public transport networks based on an integrated assessment of their sustainability performance. Thus, the main goal of this work is to develop a tool to accomplish a multi-criteria evaluation of public transport routes regarding the three main sustainability dimensions: economic, social, and environmental.

An analysis structure has been developed based on a hierarchical relation between dimensions, criteria, and indicators. Accordingly, for each dimension, a selection of indicators within different chosen criteria was performed, taking into account a considerable number of proposals and suggestions from the literature. Each indicator was quantified and re-scaled before having weights assigned to them. In this last step, the weights assigned to the dimensions and criteria levels were selected from the literature in this area. On the other hand, equal weights were assigned to the indicators level.

The developed tool was applied to an illustrative case formed by three bus routes. To emulate reality, another result of this dissertation was the creation of a virtual dataset was created based on the main municipal bus company that operates in Porto’s metropolitan area (STCP), in Portugal.

This application validated the tool by resulting in a sustainability index for each route of the designed network, considering both peak periods and off-peak periods. The flexibility of the tool also allows a complete analysis of the criteria and dimensions levels. Further studies demonstrated the potential of the tool to address more realistic situations, thus contributing to improving urban sustainability.

Key-words — indicators, multi-criteria, public transport, routes, sustainability

Acknowledgments

I want to thank my supervisors, professors Tânia Fontes and Jorge Pinho de Sousa, for supporting my work during the past semester. I want to thank FEUP for providing me an office, the FEUP's library, to work on this dissertation.

I want to thank my mum and my dad for paying for my course and raising me to be an independent woman with values and free to make my own decisions. I must thank my sister, according to her, who is always there for me and does me the biggest favours. "See you in a while crocodile". To the rest of the family, I could not picture a better one.

I want to thank my friends that I can count on at my best and worst moments. Joana, you put up with me for a long time and I have no doubt that you will keep doing so for many decades. To the lovely weirdos from class 7 that became my friends and with I have created incredible memories over the past 5 years, you are one of the best things FEUP gave me.

This work is financed by the European Regional Development Fund through the Operational Programme for Competitiveness and Internationalisation - COMPETE 2020 Programme and by National Funds through the Portuguese funding agency, FCT - Fundação para a Ciência e a Tecnologia within project PTDC/ECI-TRA/32053/2017 - POCI-01-0145-FEDER-032053.

Index

List of Figures

List of Tables

Abbreviations

A	Accidents
A_D	Accidents' deaths
A_{DP}	Accessibility related to disabled people
A_{EP}	Accessibility related to elderly people
AHP	Analytic Hierarchy Process
A_{IP}	Accidents' injured people
AM	Alternative modes
A_{MP}	Accessibility related to the majority of people
ANP	Analytic Network Process
AS	Average speed
CH_4	Methane
CL	Congestion level
C_{NOx}	Concentration of NO_x
C_{PM10}	Concentration of PM_{10}
D	Delay
E	Expenses
EC	Energy consumption
Eco	Economic
E_{NH4}	Emissions of NH_4
E_{NOx}	Emissions of NO_x
Env	Environmental
E_{PM10}	Emissions of PM_{10}
E_{VOC}	Emissions of VOC
F	Frequency
GIS	Geographic Information System
IPM	Ideal Point Method
ISM	Interpretive Structural Modeling
MOEA/D	Multi-objective Evolutionary Algorithm based on Decomposition

N_D	Noise level during the day
N_N	Noise level during the night
$\mathrm{NO_x}$	Oxides of nitrogen
NSGA-III	Non-dominated Sorting Genetic Algorithm III
OPP	Off-peak period
OR	Occupation rate
PC	Pathway circulation
PC_i	Partial criteria case number i
PCM	Pairwise Comparison Model
PE_{PT}	Public expenditures of public transport
PLS	Partial Least Squares
PM_{10}	Particulate matter with diameters of 10 micrometers and smaller
PP	Peak period
PR_{CC}	Profit rate considering capital costs
PR_{PC}	Profit rate considering personnel costs
PS_C	Passengers' satisfaction considering comfort
PS_R	Passengers' satisfaction considering reliability
PS_S	Passengers' satisfaction considering security
PT	Public transport
RD	Route's density
SD	Stops demand
Soc	Social
SPEA2	Strength Pareto Evolutionary Algorithm 2
STCP	Sociedade de transportes coletivos do Porto
TT	Travel time
TTP	Travel ticket price
UW_i	Unequal weights case number i
VOC	Volatile organic compound
WT	Waiting time
θ-DEA	Effective θ Dominance based Evolutionary Algorithm

Chapter 1

Introduction

1.1 Overview

According to the United Nations, 68 % of the world population will live in urban areas by 2050 [1]. Urban areas have an everyday increase of vast economic activities including transport systems. The increase of population will create bigger cities, rising the mobility levels of people, that will increase road transportation. The complexity of such transport systems will be greater when the cities are not effectively managed [2].

Road transportation includes certain modes of public transport, that have been used by society for many decades. Even though public transport is essential to society, it has originated several negative externalities, that involve economic, environmental, and social costs such as pollutant emissions, energy dependency, accidents, traffic noise, and congestion [3]. In the European Union, the total external transport costs, excluding active modes (cycling and walking), aviation, and maritime transport, were 841 billion € in 2016 [4].

Regarding human health, up to 30 % of Europe's urban citizens are potentially exposed to levels of air pollution that exceed some of the European Union air quality standards [5]. Urban transportation is responsible for about a quarter of CO_2 emissions [6]. As a result, the European Commission has defined the goal of reducing greenhouse gas emissions in the transport sector, at least 60 % by 2050 with respect to 1990 [6].

Congestion is an ancient challenge and a prevalent issue in cities with a population above a threshold value of about one million inhabitants [2]. The European Commission states that congestion costs will increase around 50 % by 2050 [6]. Circumstances, such as public transport sharing road space with other vehicle categories, originate an increase of congestion that affects the transit system efficiency [2]. Moreover, 69 % of road accidents occur in cities [6].

Generally, people choose the most convenient and fast transport mode, as it results in the minimization of the total time spent travelling or commuting. From a certain income threshold, private automobile is the most chosen mode creating high levels of automobile dependency [2]. Alternative modes, such as public transport, do not meet the convenience level provided by private automobile. Accordingly, by transforming sustainable transport in a convenient and fast service, people may switch to a public transport mode [4].

Several authors explain that to promote sustainability in transport systems, a mixed strategy involving land-use planning and efficient public transport services is required [6]. For instance, the introduction of alternative propulsion systems and fuels in urban buses fleets could make a substantial contribution in reducing the carbon intensity of urban transport. However, road traffic emissions are influenced by several factors such as road slope, vehicle speed, load, and meteorology [5]. Hence, this strategy should be complemented with other land-use planning related aspects. Therefore, to reach the necessary improvements, infrastructure of transport systems, such as roads, pathways, and stations, must change since it shapes mobility. With a suitable network, it is necessary to work towards positive impacts on economic growth, social equity, and environmental issues.

1.2 Motivation

With the increase of negative externalities costs of transport over the past decades, a bigger concern for eliminating and minimizing them has been growing [7]. This concern has led to pursue sustainable strategies for transport management. Thereby, a sustainable transport system that targets economic development, environment protection and social equity, has the ambition of optimizing the use of transportation systems to accomplish economic, social, and environmental goals, without preventing the ability of future generations to do the same [7].

Even though the previous definition is generally used as the main sustainability description, sustainable development is very complex and has many perspectives due to its numerous criteria, interconnections, and consequences [2]. Nonetheless, the considered sustainable transportation objectives are to increase the people quality of life and economic prosperity of cities, as well as to diminish environmental impacts by managing energy consumption and pollution [8].

Accordingly, it is possible to name the main dimensions of the sustainability concept as economic, social, and environmental [7]. Related to each dimension, the involved stakeholder groups' perspectives should influence the decisions concerning urban transportation [9]. In the public transport scope, these groups may include passengers, operators, and local authorities. Such share conflicting interests that can be handled by adopting approaches capable of determining the respective trade-offs and assigning importance weights.

To manage resources efficiently, cities need tools that can estimate sustainability indicators, particularly concerning the design of routes for public transport. This development requires a multi-criteria approach to balance the sustainability dimensions. For this end, decision-makers must have access to all possible information related to the city's environment, the public transport system and its social usage and costs, as well as to their direct and indirect impacts [3]. This information will contribute and justify selecting certain indicators and criteria, within each dimension, as a basis for a successful creation of a tool to support decision-making.

A research worth of approximately three decades of studies found that 84 % of those articles worked with criteria only related to the strategic level, while others considered the tactical decision-making level [3]. Through the many different multi-criteria decision-making techniques, the most used dimensions and criteria in urban passenger transport studies were economic, technical and logistics, environmental, safety, social, and land use [3].

Even though these studies have been focusing on these dimensions, the authors do not combine all of them simultaneously. This is an insufficient approach if the aim is to design transit networks towards sustainability. Additionally, the involved stakeholders' perspectives must be considered and combined into the creation of a fair and decent compromise between the different groups of stakeholders [9].

1.3 Objectives

Due to the amount of irreversible damage already caused by unsustainable decision-making and behaviour, cities and individuals must start to take action in order to prevent further issues. Therefore, using public transport to travel and commute inside urban areas is seen as desirable sustainable behaviour that could benefit everyone. Hence, working to make public transport more sustainable is necessary.

This dissertation aims to develop a tool able to perform a sustainability multi-criteria evaluation of public transport systems, particularly buses' networks. Given the numerous points of view and the stated context in which this dissertation fits in, the problem being treated is of a complex and multi-criteria nature. The tool proposed can be integrated with a decision support system or included in network design projects. Furthermore, it can assist decision-making by identifying and determining the main sustainability obstacles and issues related with the management of public transport services.

To properly perform an extensive sustainability evaluation, a micro approach is adopted by assessing each network route individually. This approach combines several indicators relevant for many criteria related to the sustainability dimensions, economic, social, and environmental, and considers the respective trade-offs and constraints.

To demonstrate the applicability of the proposed tool, a small network was created to reproduce a real public transport system. This was mainly based on the STCP company that provides a public transport service of buses at Porto's metropolitan area.

1.4 Dissertation structure

This dissertation is organized into six chapters. The context, motivation, and objectives are presented on Chapter 1.

To frame the work proposed, an extensive study on the related topics was performed on Chapter 2. Some studies, related to network design, were selected from the literature and the respective analysis was divided into three subsections: introduction and scope of the studies (subsection 2.1.1), the input data required by the research application (subsection 2.1.2), and the presentation of the methods and criteria used and respective highlights (subsection 2.1.3). Section 2.2 consists of a brief literature review on studies focused on sustainability indicators.

The proposed methodology to assess a public transport route sustainability performance is presented on Chapter 3. Every step of the proposed methodology is detailed including the selection of indicators (section 3.1), the quantification of indicators (section 3.2), the scale normalization (section 3.3), and the assignment of weights (section 3.4).

The tool was applied to the illustrative case created and described on Chapter 4. The chapter defines the illustrative case and justifies the creation of the dataset, that is later used to obtain the tool application results. It starts with the description of the designed network (section 4.1) and of the used software (section 4.2). To complete the illustrative case, a dataset was created, and it is explained in section 4.3. For the specific generated data, it was required to determine particular values for the references used on the scale normalization process (section 4.4).

The obtained results from the application of the illustrative case to the adopted methodology are presented and discussed in Chapter 5. The first three sections consist of the criteria (section 5.1), dimensions (section 5.2), and sustainability index (section 5.3) results obtained for each route and type of period. The following sections explain further analysis that were performed to study the sustainability index regarding the variation of the indicators' values (section 5.3.1), unequal weights for the indicators' level (section 5.3.2), and partial criteria (section 5.3.3).

At the end, Chapter 6 states the main conclusions, contributions, and future work. This is followed by two appendixes. Appendix A presents a Portuguese public transport contextualization, that consists of the analysis and comparison of three transport companies. Appendix B consists of the research paper submitted in the 7th IEEE International Smart Cities Conference (ISC2 2021).

Chapter 2

Context and preliminary literature review

To frame the work described in the introductory chapter, an extensive study on the related topics was performed. For this purpose, the “Engineering Village” search engine, from Elsevier, dedicated to engineering and scientific content was used. The research focused on documents published from 2014 to the present. No restrictions related to the document type was defined, however most of the literature found were articles in scientific journals.

The key words used on the research translate the related topics, such as multi-criteria, sustainability, public transport, decision support systems, and network design. Most of the analysed studies were obtained from the combination of the keywords “network design” and “public transport” as well as from the combination of “multi-criteria”, “public transport”, and “sustainability”. Accordingly, two main topics were analysed: studies of network design, presented in section 2.1, and studies of sustainability indicators, presented in section 2.2.

2.1 Network design

The group of studies analysed are focused on the use of multi-criteria decision support methods to design alternative routes for a public transport network considering one or more sustainability dimensions. The following subsections introduce those studies and respective scope (2.1.1), explain the data used for the multi-criteria evaluation (2.1.2), and analyse each method and criteria applied, and state the main highlights (2.1.3).

Table 2.1 and Table 2.2 outline the main research studies analysed. For each one, Table 2.1 introduces its study type, whether it is applied to a literature benchmark or a case study, its scope, mainly focused on characteristics of the case study such as city, city size, and network “size”. Additionally, the type of transport is described along with the considered sustainability dimensions. Table 2.2 presents the methods, input data, and criteria used to evaluate solutions and respective highlights.

Table 2.1 – General characterization of the design network studies.

Reference	**Study type**		**Scope**							**Type of transport**			**Sustainability dimensions**		
			City	**City size**			**Network**								
	L	**CS**		**B**	**M**	**S**	**A**	**P**	**OR**	**C**	**B**	**M**	**Eco**	**Soc**	**Env**
Cipriani et al. [10]		x	Foligno (Italy)			x	x				x		x	x	
Feng et al. [11]		x	- (China)		x			x			x			x	
Camporeale et al. [12]		x	Molfetta (Italy)			x	x				x		x	x	
Nayeem et al. [13]	x		-										x	x	
Duran-Micco et al. [14]	x		-												x
Owais et al. [15]	x	x	Rivera (Uruguay)		x		x				x		x		
Chao Wang et al. [16]	x	x	Zhaoyuan (China)		x		x			[1]	x	x		x	x
Amiripour et al. [17]		x	Mashhad (Iran)	x			x				x		x	x	

Study type: L: literature, CS: case study
City size: B: big, M: medium, S: small
Network: A: all, P: partial, OR: one route
Type of transport: C: car, B: bus, M: metro
Sustainability dimensions: Eco: economic, Soc: social, Env: environmental
[1]: Different modes of public transportation

2.1.1 Introduction and scope

The analysed studies conducted the development of alternative and better solutions for transport based on multi-criteria evaluation that were applied to case studies [10–12, 17] and literature benchmarks [13, 14]. The case studies represented mainly urban areas and buses' networks in Italy [10, 12], China [11, 16], Iran [17], and Uruguay [15]. On the other hand, literature benchmarks were defined by the number of nodes and edges, bus routes, nodes per route, and trips [13, 14]. Yet, some researchers tested their developed method for both a literature benchmark and a case study [15], [16]. Wang et al. [16] and Owais et al. [15] intended to validate their method with the well documented Mandl's benchmark and to demonstrate how it can solve real world transit network design problems.

These studies are related to the Transit Network Design Problem (TNDP), which is part of the transit planning process. The TNDP has two phases: route design and frequency setting [15]. Once these two phases are completed, the transit planning will then focus on developing the timetable and scheduling vehicles and crew necessary to the network [15]. Most of the reviewed articles focus more in the first phase. According to the considered criteria, different methods are proposed to solve the public transport network design problem by optimizing certain indicators for, mainly, buses networks [10–12, 15–17].

Usually, regarding network design, different perspectives are considered. Nayeem et al. [13] introduced a multi-criteria optimization method to solve a transit network design problem while considering the users', bus operators' and local authorities' perspectives. Owais et al. [15] presented a multi-criteria algorithm to create an efficient bus network from the beginning and a frequency setting algorithm that considered both the user and operator points of view.

Transit demand can be affected by different attributes such as travel conditions, seasonal impacts on peoples' lifestyle, economic conditions, population characteristics, and opportunity of alternative modes [17]. Amiripour et al. [17] opted to focus their work on an algorithm able to design a bus network while considering seasonal demand variation, since this is generally neglected even if, practically, it is quite an important factor.

Feng et al. [11] developed a transit network optimization model focused on the effect of the transfer time, that is part of the total time of a transit travel. Similarly, Cipriani et al. [10] proposed a method to solve the network design problem for public transport applied to small-medium size cities, aiming to reduce the number of transfers, and travel and waiting time. These cities are defined by the presence of both jobs and residences, common transport demand origins, and a low number of connections in its road network [10].

Camporeale et al. [12] aimed to enhance social inclusion of vulnerable social groups that can benefit when accessing public transport. Thus, public transport systems pose an important role in everyday life to the social groups that lack access to private transport and, consequently, face more difficulties to get to desired destinations. By including the social dimension in the TNDP formulation, desirable level of equity could be improved.

Focusing on the environmental dimension, Duran-Micco et al. [14] developed a solution for the transit network design problem considering CO_2 emissions. Among other indicators, Wang et al. [16] used an emission factor to combine more than one type of emission. Following another point of view, Wang et al. [16] presented a multi-level and multi-mode optimization model. Its objective was to translate properly the various modes of public transport in urban areas. Consequently, according to the city size, a type of transport mode was associated to each level. This way, Wang et al. [16] divided the transport system in a skeleton network, as the part of the system that covers the larger areas, an arterial network, as the center of urban public transport, and a feeder network, as the part that provides transfer services between the previous networks. As the case study chosen by the authors focused on a medium size city, Wang et al. [16] considered the arterial network and aimed to solve a bus route network design problem through a hybrid optimization model with fewer assumptions and some simplifications.

In these studies, the achieved solutions depend mostly on the considered objectives and criteria, that can be provide an association between the study and the sustainability dimensions such as economic, social, and environmental. The economic dimension appears to be the one most included [10, 12, 13, 15–17]. This is followed by the social dimension, as authors consider the total travel time [10, 11, 16], different stakeholders' perspectives [13] and respective demand costs [12]. There were only two studies directly implicated with the environmental dimension [14, 16].

Hence, instead of focusing on one dimension only [11, 14, 15], some studies have focused on two dimension [10, 12, 13, 16, 17]. However, in order to assess sustainability and obtain a solution that provides a sustainable public transport network, all three sustainability dimensions must be considered. This way, all stakeholders' perspectives can be portrayed through different indicators, similarly to what Nayeem et al. [13] did.

Table 2.2 – Method topics of the selected network design studies.

Reference	Methods used	Input data	Criteria used to evaluate the solution	Highlights
Cipriani et al. [10]	Heuristic procedure	Origin-destination matrix (O/D), road network, bus capacity and network terminals	Total distance and TT by buses, the total number of vehicles used and the negative effect on the user	The method reduced by 68 % of the number of transfers, by 3 % of the passengers' TT and 13 % of the passengers' WT
Feng et al. [11]	Genetic algorithm	Acceptable maximum transfer times for a bus trip, bus trip data and transfer walking and waiting time of the bus trip	Total time cost of the bus trip and TT from one stop to another	The model improved the average pure TT per bus trip by 3 % and the ratio of bus trips with no transfer by 4 %
Camporeale et al. [12]	Genetic algorithm	Number of routes, headway feasibility, fleet size, demand coverage and equity	Combination of the passengers, operators, and unsatisfied demand costs	Reduction of the unwanted demand from 40 % to 1.7 % and of the overall costs from 78053 to 23944
Nayeem et al. [13]	Evolutionary algorithm combining SPEA2, MOEA/D, NSGA-III and θ-DEA	Road network (undirected graph), passenger demand	User perspective: in-vehicle TT, WT, percentage of transfer. Bus operator perspective: fleet size and route length. Local authorities: unsatisfied demand and degree of route overlap	Multi-objective optimization proved to be more effective when compared with other methods
Duran-Micco et al. [14]	Bi-objective memetic algorithm	Fixed infrastructure network, fixed demand between each pair of nodes, types of buses (size, technology, capacity, CO_2 emission factor)	Total travel time and CO_2 emissions	Reductions of approximately 30 % of the CO_2 emissions can be achieved by compromising the total travel time by 1 %
Owais et al. [15]	Genetic algorithm	Urban network as a non-directed graph and total transit demand	Demand coverage, network directness, user cost, and operator cost	Trade-offs required since it is not possible to minimize the operator and user costs at the same time
Chao Wang et al. [16]	Hybrid heuristic (simulated annealing and artificial ant colony optimization)	Safety score, green ratio, frequency of service, line length and fleet size	Passengers' total in-vehicle TT, passengers' WT and transfer time, vehicle emission cost and bus operating cost	This method presented a reduction of 21.51 % of the total travel time and provided 85.23 % direct travels
Amiripour et al. [17]	Hybrid heuristic (heuristic and genetic algorithm)	Four demand scenarios, data related to policies and level of service	Passenger waiting time, empty seat/space time, time difference from the shortest path and fleet size	As this approach achieve optimal results for different seasons, these are practically not acceptable

TT: travel time. WT: waiting time.

2.1.2 Input data

When developing a method to evaluate and obtain alternative routes, it is necessary to collect data to determine indicators that may be necessary for the objective function or other criteria of the used method. Thus, as part of the process, researchers define the required input data for the application of their methods.

Generally, in this type of studies, the road network represented as a non-directed graph and an origin-destination (OD) matrix is always used, as it is fundamental information for the assessment and design of a transit network. Additionally, the peripheral terminals [10], the number of routes [12], and the length of the routes [16] are also considered.

Related to the buses used to provide the transport service, the input data includes bus capacity [10, 14] and fleet size [12, 16]. Particularly, when the problem is directed to the environmental dimension, more buses' characteristics, such as the technology involved, bus size (small, medium, large), and CO_2 emissions, are provided [14]. Duran-Micco et al. [14] focused only on one type of pollutant emissions. Instead, it would be advantageous if different types of emissions, that are harmful to the humankind and have a negative impact on the environment, were considered. These could result on a ratio or value that would establish a constraint for the problem formulation [16]. Accordingly, Wang et al. [16] used an emission factor at different speeds and vehicles' types, resulting in a "green" ratio. The emissions included were hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NOx).

Regarding the users of the service, the amount of time related to the users' experience from the provided service, such as the in-vehicle travel time, waiting time and transfer time are widely used, mainly in studies that aim to minimize the total travel time [10, 11, 13, 16]. The demand is also a popular indicator [12–15, 17]. In some studies, the demand represents a fixed value between two bus stops, that is between each pair of nodes of the OD matrix [12–15]. Hence, the variability of the passengers' demand during the day and seasons throughout the year was not considered, which decreases the proximity to the transit networks reality. Amiripour et al. [17] address this limitation by including a seasonal demand variation and creating four demand scenarios. For each scenario, the respective possible transit networks were analysed by an optimization framework. Moreover, they used as input information the level of service provided and data related to local policies.

In general, the surveyed studies consider both operators' and passengers' perspectives [10, 12, 15]. The passenger perspective can include the times associated to the passengers' travels [10] and associated costs [12, 15] as well as aspects that may affect the passengers' comfort during the travels [10]. For the operators' perspective, the main indicator is costs [10, 12, 15]. Hence, information is acquired through surveys to determine, for instance, the acceptable maximum transfer time for a bus trip [11] and the equity factor [12]. This equity factor is an indicator that combines both spatial distribution and social needs' aspects. It contributes as a constraint that limits the level of both spatial distribution and social needs aspects according to the information provided from the surveys generated [12]. Since the lack of equity evidenced in public transport is a social problem, it is an appropriate factor to consider for the social dimension of sustainability.

2.1.3 Methods and criteria

To reach the proposed and stated objectives, different methods and criteria have been considered. When solving the transit network design problem, even when the goal is to optimize an existent one, both meta-heuristics [10–17] and exact methods can be used. While exact methods assure optimality, these are generally considered unmanageable [15]. Alternatively, meta-heuristics assure efficiency in treating the TNDP, yet without guarantying optimality [15]. Regarding computation, meta-heuristics appear to be more efficient [16]. Therefore, there is a tendency to use meta-heuristic methods instead of exact methods.

For network design, the genetic algorithms are the most popular approach [11, 12, 15, 17]. While providing a powerful search and a near-optimal solution in a feasible amount of time, these algorithms can be simply adapted and have the ability to find good solutions [12]. Other (meta-)heuristic methods used were a specific heuristic procedure [10], an evolutionary algorithm [13], a bi-objective memetic algorithm [14], and a hybrid heuristic [16].

Using a genetic algorithm, Feng et al. [11] evaluated the total time[1] cost of a bus trip and the travel time from one stop to another. The connecting times were not analysed by these authors, as the integration of factors related to land use, bus route operation, and individual travel characteristics is complex and defines each connecting time of a bus trip. This study achieved a reduction of 3 % of the average travel time per bus trip and an improvement of 4 % of the number of bus trips with no transfers.

Even though the passengers' costs and total travel time are generally related to the social dimension, the quantitative equity is not usually referenced [12]. By combining the passengers, operators and unsatisfied demand costs, Camporeale et al. [12] were able to reach a higher equity level, by reducing the unsatisfied demand from a current value of 40 % to 1.7 %, and an improvement of the overall costs by 70 %.

The transit network parameters considered by Owais et al. [15] were the demand coverage, network directness, user costs and operator costs. The objective function consisted of the combination of both user and operator costs with the respective assigned importance weights. The minimization of both operators' and passengers' costs at the same time was not possible without trade-offs [15]. Therefore, when developing the methods, weights were considered to capture their relative importance and to reflect the trade-offs between the stakeholders' associated costs [10, 12, 15].

Amiripour et al. [17] claim their method is different as their genetic algorithm is integrated with a heuristic method. The constructed hybrid approach has two optimization levels: the route level and the network level. While the route level has a heuristic method generating routes based on certain constraints, the network level is focused on applying the genetic algorithm and, subsequently, a heuristic method to increase each route demand.

Cipriani et al. [10] developed a heuristic procedure considering the total distance and time travelled by the buses, the total number of used vehicles and the negative effects on the user. This method was able to reduce the number of transfers by 68 %, the passengers' total travel time by 3 %, and the passengers' waiting time by 13 %.

Nayeem et al. [13] evolutionary algorithm combines four selected literature algorithms. These are the strength Pareto evolutionary algorithm 2 (SPEA2), the multi-objective evolutionary algorithm based on decomposition (MOEA/D), the non-dominated sorting genetic algorithm III (NSGA-III), and the effective θ dominance-based evolutionary algorithm (θ-DEA).

---

[1] The total time is composed by the two connecting times and the pure travel time. As the pure travel time refers to the time that takes riding the bus and making transfers, the connecting times refer to the time spent from the origin point to the bus stop and from the bus stop to the destination.

In transit networks, there are typically three different stakeholders involved: passengers, operators, and local authorities, with different perspectives and, consequently, with different concerns and factors. Nayeem et al. [13] considered all these stakeholders and created a multi-criteria function in light of the related factors. From the user perspective, the goal was to minimize the in-vehicle travel time, the waiting time, and the percentage of transfer. For the bus operator, it was important to minimize the fleet size and the route length. Finally, the local authorities were interested in the minimization of the percentage of unsatisfied demand and of the degree of route overlap. When applying this method to the selected and well-known literature benchmark, the method proved to be more effective when compared to other methods found in the literature.

Regarding the environmental dimension, the purpose of Duran-Micco et al. [14] was to minimize the total travel time and the CO_2 emissions, thus obtaining a compromised solution. When applying the developed method to the literature dataset, they were able to reduce approximately 30 % of CO_2 emissions if the total travel time was compromised by 1 %. However, considering the goals presented from the European Commission for 2050, studies directed to the environmental dimensions should combine more greenhouse gases and harmful emissions.

Supporting this idea, Wang et al. [16] focused in more than one type of emission, that resulted in a “green” ratio. While this ratio was considered as a constraint, they developed a hybrid heuristic combining simulated annealing and artificial ant colony optimization. Besides minimizing the total travel time, their objective function included minimizing the bus emission and operating costs. As result, the applied method was able to reduce the total travel time by 21.51 %, to provide 85.23 % direct travels, and 14.65 % one transfer travels.

The analysis and understating of this framework helped decide the goals of this dissertation. Given the criteria and conclusions of the studies working towards sustainable public transport networks, the combination of the three sustainability dimensions, and respective criteria and indicators, became a focal point of this dissertation. Hence, a more related framework consisted of the sustainability indicators studies analysed in section 2.2.

2.2 Sustainability indicators

A literature review focused on the development of sustainability indicators applied to transportation was conducted in order to identify and analyse the different models and methods used. Table 2.3 summarizes the information collected from these studies including the identification of the model, the focal aspect, the scope, the considered sustainability dimensions, the methods used, and the highlights.

Considering the three sustainability dimensions, Amrina et al. [8] developed a multicriteria model to evaluate sustainable transport systems in West Sumatra, Indonesia. Duleba et al. [9] designed a model capable of including the stakeholders groups’ perspectives into the decision support system of public transport, which was applied to the city of Mersin, in Turkey. However, unlike most studies analysed, the stakeholders’ groups identified were the passengers, the potential passengers, and local government.

Related to sustainable aspects of urban transport, some studies focused on identifying and assessing specific criteria [18–20]. Gazis et al. [18] assessed the emissions impact of different routes to identify the best alternative for private vehicles considering suburban routes between the cities of Porto and Aveiro, in Portugal. Focusing on the social dimension, Corazza et al. [19] evaluated the accessibility to bus stops in Rome, Italy, and Chen et al. [20] identified the spatial gaps in urban public transport supply and demand from seniors in Edmonton, Canada.

To evaluate the sustainability performance of the transportation, Amrina et al. [8] created a methodology consisting on three different phases: identification of the indicators, determining the relationships of the indicators and their respective weights. The identification of the indicators was based on a literature study and verified by five experts from the West Sumatra transportation department. For each dimension, different indicators were selected due to the multicriteria nature of the problem.

For the determination of the indicators' relationship, Amrina et al. [8] opted to use an interactive learning process, the Interpretive Structural Modelling (ISM) method. This is able to develop a map of the indicators' relationships, which resulted in the identification of six indicators that affect and are affected by each other. These were accessibility of region, management of public transportation, infrastructure of public transportation, transportation for people with special needs, level of traffic congestion, and land use to improve transportation facilities [8].

Once the relationships of the indicators were established, Amrina et al. [8] determined the indicators' importance weights using the Analytic Network Process (ANP) and, further it was necessary to use the Analytic Hierarchy Process (AHP) for the remaining indicators, which were not related to each other. Similarly, Duleba et al. [9] also applied the AHP method. Even though the AHP cannot handle non-hierarchical relations between decision system elements, it provides a clear decision structure to the evaluators and validates consistency [9]. For the combination of the preferences of the passengers, non-passengers and government, Duleba et al. [9] used the Kendall's coefficient of concordance.

In general, the studies supported their methodologies using a set of platforms and models to compute the required indicators. The Geographic Information System (GIS) is a popular data processing platform that stores, manages, and displays map data [18–20]. To compute emissions the Vehicle Specific Power (VSP) and EMEP/CORINAIR methodologies are popular [18]. While VSP concerns the instant vehicle speed, acceleration, and slope, the EMEP/CORINAIR is an emission factor backlog which considers speed, slope, and load factor.

The criteria for this study were distinguished into two categories: time independent, considering distance, and time dependent, considering different emissions such as nitrogen oxides (NO_x), carbon monoxide (CO), unburnt hydrocarbons (HC), and particulate matter with diameter of the order of 10 µm or less (PM_{10}). With the objective of determining the best route among four alternatives, Gazis et al. [18] performed this assessment considering three strategies: economic costs, human health impact, and current atmospheric pollutant concentrations.

Table 2.3 – General characteristics of the sustainability indicators.

Reference	**Model**	**Focal aspects**			**Specific criterion**	**Scope**				**Sustainability dimensions**			**Methods used**	**Highlights**
						City	**Type of transport**							
		SD	**SG**	**S**			**C**	**B**	**M**	**Eco**	**Soc**	**Env**		
Amirina et al. 2020	Multi-criteria for evaluating a sustainable transport system	x			…	West Sumatra (Indonesia)				x	x	x	ISM, ANP	The most important indicator was land use to improve transportation facilities
Duleba et al. 2018	Inclusion of the stakeholders involved into decision making		x		…	Mersin (Turkey)		x			x		AHP, Kendall's coefficient of concordance	Service quality, approachability, and directness are the factors that decision makers should focus on
Gazis et al. 2012	Identify the best routes based on emission impacts			x	Emissions	Porto, Aveiro (Portugal)	x					x	GIS, VSP, CORINAIR	The best route depended on the strategy used: economic costs, human health impact and current atmospheric pollutant concentrations
Corazza et al. 2019	Evaluation of the accessibility to bus stops			x	Accessibility	Rome (Italy)		x			x		GIS, PCM, IPM	The facilities that lack accessibility and need adjustments are in lesser populated areas
Chen et al. 2018	Identify the spatial gaps in public transport from seniors			x	Spatial gaps	Edmonton (Canada)		1			x		GIS, PLS path modelling, Lorenz curves, the Gini Coefficient, gap measurement	Public transport services for seniors are not identical for all the population regions

Focal aspects: SD: sustainability dimensions, SG: stakeholders' groups, S: specific.
Type of transport: C: car, B: bus, M: metro, 1: bus plus 2 lines for rail train transit.
Sustainability dimensions: Eco: economic, Soc: social, Env: environmental.
Methods used: ISM: interpretive structural modelling. ANP: analytic network process. AHP: analytic hierarchy process. GIS: geographic information systems. PCM: pairwise comparison model. IPM: ideal point method. PLS: Partial least squares.

Corazza et al. [19] assessed the pedestrian accessibility to bus stops through a methodology combining three phases: areas of investigation, data process tools, and results assessment and interpretation. These resulted in a final accessibility score for bus stops. The areas of investigation consisted of the road network analysis and the transit accessibility index to bus stops. Besides a complete GIS software, Corazza et al. [19] acquired information through questionnaires as another process data tool. To assess and interpret the accessibility levels, a weight assignment process was performed through the Pairwise Comparison Method (PCM). The multi-criteria analysis was developed with the Ideal Point Method (IPM) and contributed for the determination of the final accessibility score for each bus stop.

Chen et al. [20] organized three categories around the GIS software, which consist on public transport supply, public transport demand, and relative public transport gap. To measure the comprehensive public transport supply index, Chen et al. [20] used the Partial Least Squares (PLS) path modelling and a normalization method. The proportion of seniors was used for the public transport demand index. Both indices allowed the assessment of the relative public transport gaps considering social equity among seniors. The relative gap was composed by the local relative gap, which was determined by gap measurements, and by the global relative gap, which is determined by a combined method of the Lorenz curves and the Gini coefficient [20].

Amrina et al. [8] obtained, as the most important indicators, the land use to improve transportation facilities, the level of traffic congestion, and the transportation for people with special needs, by this order. To increase the attractiveness to the potential passengers and the passengers' satisfaction, Duleba et al. [9] found factors such as service quality, approachability (directness to stop, safety of stops, and comfort in stops), and directness (need of transfer and fit connection) to be more relevant to the decision makers in the transportation department.

Gazis et al. [18] highlighted how the best route depends on the strategy used and current atmospheric pollutant concentrations. In Corazza et al. [19] study the most relevant indicators were the frequency, number of inhabitants served, and the number of lines/routes. Additionally, it was concluded that the bus stops that lack accessibility the most and need adjustments are located in the least populated areas [19]. Finally, Chen et al. [20] developed method successfully identified the populational areas with relative public transport gaps and evidenced an unidentical level of equity between different areas.

Chapter 3

Methodology adopted to assess the sustainability performance

The development of sustainable public transport system networks is complex and implies the analysis of many indicators from different sustainability dimensions. Each indicator must be identified, quantified, and evaluated in order to understand how it affects the transport system and its sustainability performance.

This work aims to develop a tool to develop a tool to evaluate routes from a public transport network according to a pre-defined set of indicators. For this purpose, a four steps methodology was pursued: (A) selection of indicators; (B) quantification of indicators; (C) scale normalization; and (D) assignment of weights. Figure 3.1outlines the overall methodology followed.

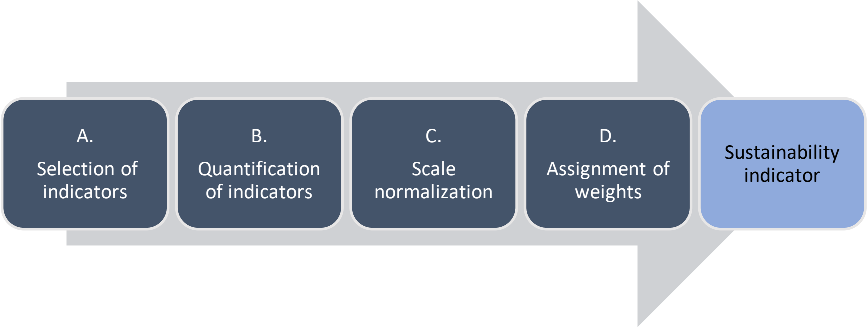


Figure 3.1 – Adopted methodology overview.

The selection of indicators of the proposed method (section 3.1) was based on an extensive literature review. Then, for the quantification process (section 3.2), data from different sources was identified and collected in order to quantify each indicator, and scales were normalised (section 3.3). Finally, as transport network design problems are of a multi-criteria nature, weights have been assigned to each hierarchical level (section 3.4).

3.1 Selection of indicators

Around the seventies, the development of policies and practices was mainly concerned with economic aspects while neglecting any environmental and social impacts [21]. In the last decade, as the correlation between these aspects evolved, sustainable urban mobility plans in European countries have been developed [22].

Most studies regarding sustainability indicators include a lot of aspects related to urban mobility [21, 23–25]. Given the public transport context, these studies consider, in general, a much more extensive range of criteria. Focusing only on the sustainability performance of public transport, a couple studies have been analysed [26, 27]. A common characteristic of these studies is their macro perspective, while in this dissertation a micro perspective is required given its context and specifications.

The analysed studies have considerably different perspectives on the type of elements to use in a hierarchical structure to define a sustainability indicator. Some authors consider dimensions that contain criteria (sometimes called themes), which will accommodate one or more indicators [21, 24]. Others relate the indicators directly to the chosen dimensions [22, 23, 25–27]. Accordingly, most of the studies consider the economic, social, and environmental sustainability dimensions (combination shown in Figure 3.2) as their dimensions [21, 22, 25–27]. However, a group of studies opted to broaden their dimensions to include other aspects, for instance, fiscal and political aspects [23, 24] or system effectiveness [26]. Regarding the selection of indicators, most researchers based theirs on expanded literature reviews [21, 23–28]. Alternatively, Burinskiene et al. [22] conducted their selection process through surveys answered by experts.

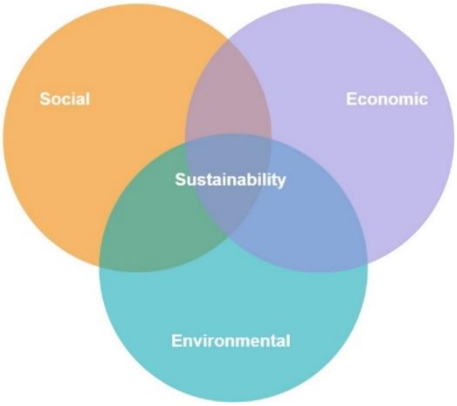


Figure 3.2 – General sustainability concept according to the Brundtland report.

Sdoukopoulos et al. [21] extensively studied sustainability indicators, “themes”, and their application, with a literature review covering 2644 indicators included in 78 studies. Out of these studies, 58 are related to the urban level, 24 to a regional/national level, and only three studies are related to the road axis/corridor level with an average number of 13 indicators proposed [21].

The Texas Transportation Department proposed similar indicators for measuring the sustainability performance of a road corridor [29, 30]. Zietsman et al. [29] focused on a freeway from the United States of America and from South Africa, while Ramani et al. [30] applied their evaluation methodology to several highway corridors in the United States. In addition, Svensson et al. [31] argue that multi-functional arterial streets, as people use those streets for different activities, should be designed and managed as such. Therefore, a group of indicators for street sustainability performance was included in their methodology. Gazis et al [18] and Fernandes et al. [32] also assessed the sustainability of alternative routes. Both focused on pollutant emissions, yet Fernandes et al. [32] additionally considered traffic congestion, accidents, noise and health impacts. However, these studies are applied to private road transport [18, 32] and include suburban axis, such as freeways, that is a type of road axis rarely used by public transport [29, 30].

In this dissertation, a hierarchical structure including "dimensions" (first level), "criteria" (second level), and "indicators" (third level) is proposed (Figure 3.3). The main sustainability dimensions compose the first level of the model: economic in purple, social in orange, and environmental in light blue. The second level represents the considered criteria with a lighter grey background colour. Each criterion requires one or a few indicators, which are introduced in the third level of the model in blue.

As the fundamental idea behind the model proposed is the sustainability concept, the three sustainability dimensions defined in the Brundtland Protocol were considered (Figure 3.2). It is important to note that even though each criterion is connected to only one sustainability dimension in the model, every criterion can influence, directly or indirectly, all the dimensions. Despite these relations, only the strongest and most evident connections were represented, to allow a simpler visualization and understanding of the model shown in Figure 3.3.

The next subsections present and justify the selection of criteria and indicators, in each of the defined dimensions. The selection of the criteria was based on a recent literature review study conducted by Sdoukopoulos et al. [21] and other sustainability studies [18, 23–26]. Accordingly, subsection 3.1.1 is related to the economic dimension, subsection 3.1.2 to the social dimension, and subsection 3.1.3 concerns the environmental dimension.

3.1.1 Economic dimension

Within the road axis/corridor level, no economic criteria were identified by the literature review conducted by Sdoukopoulos et al. [21]. However, considering the urban and regional/national level, *economic productivity* is considered in 31 % of the analysed studies. Considering the "public expenditures, investments and subsidies" (considered in 45 % of the studies) and the "transport costs and prices" (considered in 26 % of the studies) criteria identified by Sdoukopoulos et al. [21], the *transport costs and finance* criterion was created. Additionally, *transport efficiency* is included in 27 % of the proposed studies [21]. For each of the economic criterion previously identified and considered in this work, a literature review was conducted to identify the most popular indicators. Table 3.1 presents these results.

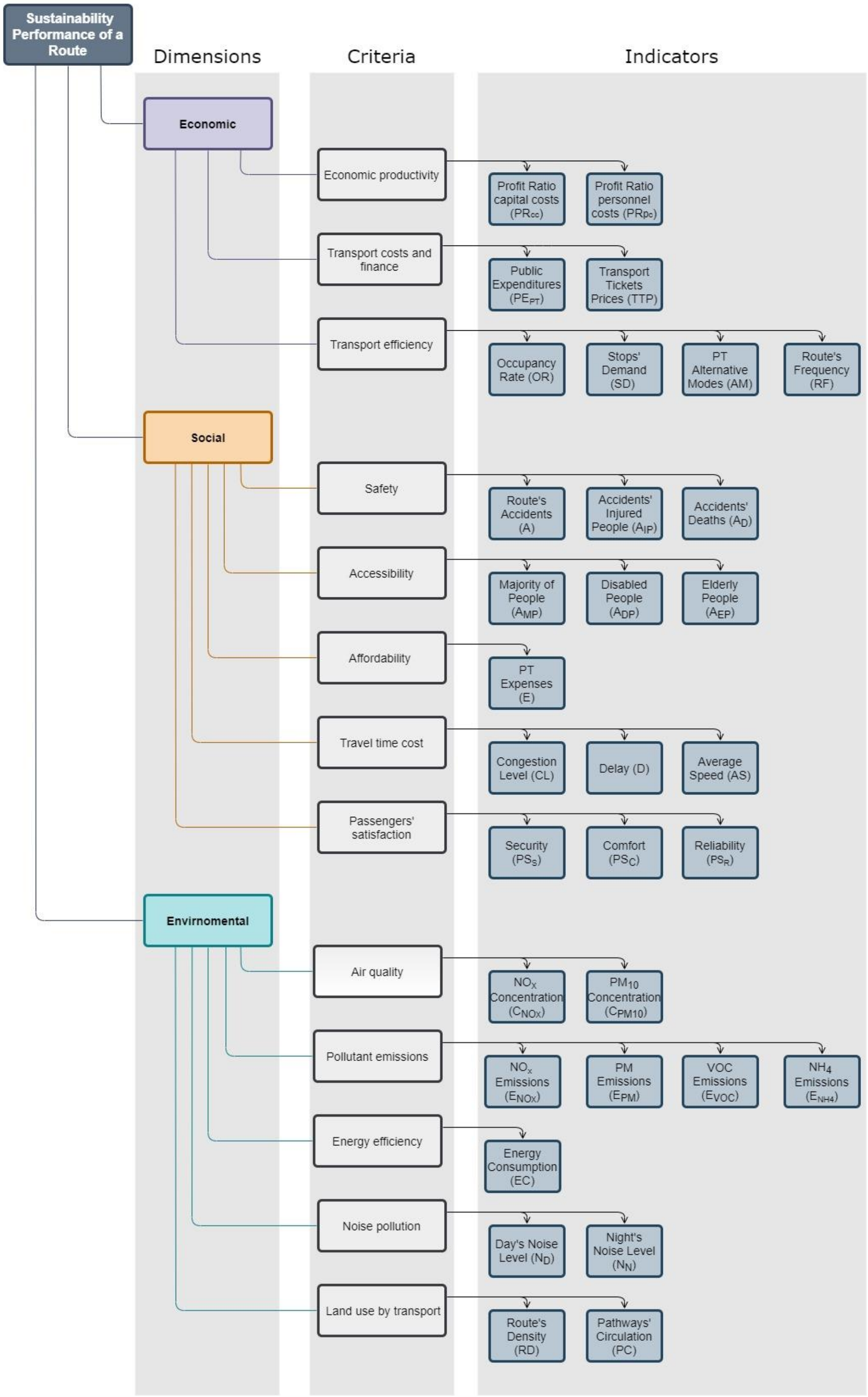


Figure 3.3 – Structure of the sustainability indicators model.

Table 3.1 – Main indicators associated to the defined criteria of the economic dimension in the literature.

Reference	**Criteria of the economic dimension**		
	Economic productivity	**Transport costs and finance**	**Transport efficiency**
This study	Profit ratio capital costs (PR_{CC}), Profit ratio personnel costs (PR_{PC})	Public expenditures (PE_{PT}), Transport ticket price (*TTP*)	Occupation rate (*OR*), Stop's demand (*SD*), Alternative modes (*AM*), Route's frequency (*RF*)
Medina et al. [23]	Operational costs of the PT system	Public expenditures, subsidies, and investment in transport systems, Financial autonomy (scale 1 to 5)	Occupation rate of private passenger vehicles, Multimodality integration level, PT frequency
Sdoukopoulos et al. [21]	Ratio of PT revenues to the respective maintenance and operation costs	Public expenditures, subsidies, and investment in transport systems, Fuel prices and taxes	Occupation rate of private passenger vehicles
Lima et al. [24]	-	Public expenditures, subsidies, and investment in transport systems, Transit fares	Occupation rate of private passenger vehicles, Multimodality integration level, Transit service frequency
De Gruyter et al. [26]	Operational costs of the PT system, Proportion of costs recovered	-	Occupation rate of private passenger vehicles, Annual PT trips per capita, PT mode split, PT fleet size

PT: public transport.

3.1.1.1 Economic productivity

Sdoukopoulos et al. [21] identified the "ratio of public transport revenues to the respective maintenance and operation cost" as the most common indicator related to *economic productivity*. Both Medina et al. [23] and De Gruyter et al. [26] recognize the "operating costs spent on the public transport system" as an indicator. Additionally, De Gruyter et al. [26] also introduced the indicator "proportion of the recovered costs". Hence, within the *economic productivity* criterion the main idea for its indicator was the profit rate in a similar way as Sdoukopoulos et al. [21] defined it. However, as two categories of costs stand out [33], this indicator was divided into two. These categories consist of personnel costs, that include every expenses directed to the company employees, and capital costs, that are applied to the transport physical assets such as infrastructures, terminals and vehicles [34]. Thus, personnel costs, identified as the biggest proportion of the total costs, originated the PR_{PC} indicator, and capital costs, as another significant proportion of the total costs, originated the PR_{CC} indicator.

3.1.1.2 Transport costs and finance

Within the *transport costs and finance* criterion, the most popular indicator is the "public subsidies invested in transport systems" [21, 23, 24]. Due to the high percentage of studies (45 %) in the literature that use the public expenditure's "theme" [21], this indicator was adjusted for public transport (PE_{PT}). Additionally, related to finance, Medina et al. [23] assessed the "financial autonomy". Sdoukopoulos et al. [21] also found the "fuel prices and taxes" to be a common indicator related to transport costs and prices. From the passenger's perspective, Lima et al. [24] considered "transit fares", that was adapted into the indicator transport travel tickets (*TTP).*

3.1.1.3 Transport efficiency

Transport system efficiency is considered by researchers in different ways. For example, De Gruyter et al. [26], additionally to the sustainability dimensions, created "system effectiveness" as a specific dimension.

Within the *transport efficiency* criterion, the most popular indicator in the literature is the "occupation rate of passenger vehicles" (private) [21, 23, 24, 26]. This supported the creation of the *OR* indicator which consists of the occupation rate of the public transport vehicles. If a bus travels a particular route that has a low occupancy rate, it can be shown that, possibly, by adopting an alternative route or adapting certain route characteristics, the route will satisfy more demand and, consequently, be more useful.

The more a person uses the public transport service, the more effective it is. Thus, based on the "annual number of public transport trips per capita", proposed by De Gruyter et al. [26], I also included in this study the stops' demand (*SD*), as a *transport efficiency* indicator.

Even though transport efficiency is also related to "multimodality integration level" [23, 24] and "public transport mode split" [26], Sdoukopoulos et al. [21] did not find multimodality to be a common criterion according to their literature review. However, when people use a transport service that cannot reach the wanted destination, it will be advantageous if that service provides connectivity points with other motorized or active modes. That way, the use of combined modes will increase the possibility of people reaching their destinations. Therefore, the number of alternative stops/stations from a stop within 300 meters, as it only corresponds to approximately a 2 to 4 minutes' walk, was considered as an indicator (*AM*).

Finally, Lima et al. [24] considered the "transit service frequency" and De Gruyter et al. [26] added the "public transport fleet size". As time is rather important in transport services, their system efficiency may be affected by the frequency of a certain route. Therefore, the route frequency (*RF*) is a *transport efficiency* indicator, that can relate to the occupation rate, time of the day or traffic congestion.

3.1.2 Social dimension

Approximately 85 % of the studies analysed by Sdoukopoulos et al. [21] between 1996 and 2018 consider the *safety* criterion, not only for the road axis/corridors level, but also for the urban and regional/national levels. Alongside the *safety* criterion, the mobility criterion is also included in 77% of the indicators' studies that Sdoukopoulos et al. [21] analysed. *Accessibility* stands out for being considered in around 68 % of those indicators' studies, while *affordability* is included in 50%. Travel time is usually addressed considering commuting travel time, and average time spent travelling under congestion [21]. Therefore, and based on the literature indicators related to time, the criterion *travel time cost* was included in this study (presented in Table 4). Even though, *passengers' satisfaction* was not a criterion identified in the literature review conducted by Sdoukopoulos et al. [21], I found several works that highlight the importance to include it [23–25]. For each of the social criterion identified, a literature review was conducted to identify the most popular indicators. Table 3.2 shows the results obtained.

Table 3.2 – Main indicators associated to the defined criteria of the social dimension in the literature.

Reference	**Criteria of the social dimension**				
	Safety	**Accessibility**	**Affordability**	**Travel time cost**	**Passengers' satisfaction**
This study	Route's accidents(A), Accident's injured people (A_{IP}), Accident's deaths (A_D)	Majority of people (A_{MP}), Disabled people (A_{DP}), Elderly people (A_{EP})	PT expenses (E)	Congestion level (CL), Delay (D), Average speed (AS)	Security (PS_S), Comfort (PS_C), Reliability (PS_R)
Medina et al. [23]	Road fatalities per 100,000 inhabitants	Share of PT vehicles that are wheelchair accessible, Percentage of people that live 500 m from a PT stop	Money spent on a trip in relation to income	Delay due to congestion, Time of indirect trips	Satisfaction with the mobility service, Proportion of PT users exposed to security incidents
Sdoukopoulos et al. [21]	Road fatalities per 100,000 inhabitants	Percentage of people that live 300-500 m from a PT stop	Money spent on transport in relation to income	Time spent commuting, Time spent under congestion conditions	PS_S
Lima et al. [24]	Number of road accidents	PT for users with special needs, Accessibility to transit	Transport use expenses	CL, AS	Satisfaction with the mobility service
Tsiropoulos et al. [25]	Number of road accidents	Number of PT accessible by disabled people, Percentage of people that live 300 m from a PT stop	E	Travel time	PS_S, PS_C, PS_R
De Gruyter et al. [26]	A_D	System accessibility (p.km/capita)	Money spent on a trip in relation to income	Average trip distance	-

PT: public transport.

3.1.2.1 Safety

Safety in public transport impacts both economic and social stability. Traffic accidents originate different types of costs that include human costs, medical costs, administrative costs, production losses, and material damages [35]. At a urban level, the most used indicator related to *safety* is the “number of road fatalities per 100,000 inhabitants” [21, 23], followed by the “number of road accidents” [24, 25]. De Gruyter et al. [26] uses the number of deaths that result from public transport accidents (A_D), that is also included in this study as a *safety* indicator.

The European Union determined that the human costs are the biggest contributor to the overall accident costs [35]. Thus, in this dissertation context, *safety* can be adequately measured by the total annually number of public transport accidents (A), whether it involves pedestrians, other buses, or vehicles, “human fault” from the operator, or machine failure. Additionally, the annually number of deaths resulted from these accidents (A_D) and the number of injured people (A_{IP}) are also of major importance.

3.1.2.2 Accessibility

Accessibility is directly related to the social dimension and largely considered as it is often used to quantify the physical ease of passengers’ (or possible passengers’) access to public transport [21, 23, 25–28]. People need access to the services that they intent to use, otherwise they cannot rely on them. Thus, the *accessibility* criterion will allow a better understanding on possible cases of social exclusion and, consequently, lack of equity. Additionally, an increase of elderly people of 10.5 % from 2017 until 2060 is expected [36]. Therefore, each indicator is referred to a certain social group: majority of people (A_{MP}), disabled people (A_{DP}), and elderly people (A_{EP}).

The most popular indicator, also used in our study, is the share of population living within a certain distance from public transport stations/stops [21, 23, 25]. Sdoukopoulos et al. [21] found the most common range of distances to be between 300 and 500 meters. However, the walking distance that a person is willing to walk depends on various factors, namely gender, age, and health [36]. Thus, this *accessibility* indicator was divided into A_{MP} for people from 14 to 64 years old, and A_{EP} for people with 65 or more years old.

Both indicators’ distances were not based on the studies presented in Table 3.2. Alternatively, these were deduced from Ribeiro et al. [36] study that focus on determining exactly the whiling walking distance for different groups of population and applying it to the transport network of Porto metropolitan area. Thus, the correspond distances for 6-, 8- and 12-minutes’ walk were determined according to age groups and gender [36]. Since only age groups were associated to each indicator, for each age group an average value of the female and male distances was calculated. Additionally, given the increasing mobility difficulties for elderly people, their 6-minute walking distance was the one considered, obtaining approximately 600 m. For the majority of people, as it included different age groups and parameters such as health issues, that might decrease their ability to walk, are not included, the chosen walking distance time was 8 minutes, and a distance of 900 m was obtained.

Some researchers consider people with special needs and their respective access to public transport [23–25]. The “share of public transport vehicles that are wheelchair accessible” [23], the proportion of “public transportation for users with special needs” [24], and the “number of public transport accessible by disabled people” [25] were used to create the A_{DP} indicator that quantifies the average accessibility level of a route’s vehicle conditions for disabled people.

3.1.2.3 Affordability

Affordability is presented in various studies as a relevant aspect to assess urban sustainability [21, 23, 25–28]. Beyond having access to public transport services, people must afford them. Practically, most of the affordability indicators relate passengers’ income with either the price of a public transport trip [23, 26], the monthly price of transport [21] or the overall price of public transport [25].

Lima et al. [24] used the transport use expenses. For our study, the proportion of the passenger income with the monthly expenses on public transport was used *(E)*.

3.1.2.4 Travel time cost

Time is an aspect that strongly influences studies related to network design, mainly the waiting time and the travel time. In congested urban areas, these times may be substantially larger due to congestion, that is originated by higher levels of road traffic in relation to road capacity depending on the location and time of day [4]. Overall, these conditions can affect transport reliability by increasing delays and consequently the travel time. In 2019, near 4 % of the world cities had a congestion level higher than 50 %, and 28 % of the world cities have a congestion levels ranging from 30 % and 50 % [37]. Accordingly, the criterion *travel time cost* was included in this study.

Many authors consider different types of time spent on travelling [21, 23–26], the congestion level (CL), and the average speed (AS) [24] when trying to define a sustainability indicator. The "congestion delay" [23], the "time spent commuting" [21], the "time spent under congestion conditions" [21], and the "time spent on the travel" [25] are time related indicators used in the literature.

Congestion and delays have a very strong relation as congestion appears to be the main cause for travel delays. However, the total travel time may be affected by other occurrences such as vehicle suppression or vehicle failures, that may justify the assessment of both factors separately, by using indicators such as the total delay (D) and the congestion level (CL). Additionally, indirect trips are very common in public transit networks and, consequently, they may create a considerable waiting time when there is a change in transport modes or routes, that can be associated to a time cost. To address this reality, some authors consider the "time spent of an indirect trip for the user" [23] and the "average user trip distance" [26]. Alternatively, the travel average speed (AS), which relates time and distance, can be used.

3.1.2.5 Passengers' satisfaction

The passengers' opinion can be very relevant as it influences directly the economical and the environmental performance of public transport operators. The more satisfied passengers are, the more passengers will rely on transport services, thus using less private transport modes. *Passengers' satisfaction* is, therefore, considered a criterion in the social dimension, and can be assessed in several levels such as security, comfort, satisfied demand, or trip duration.

Sdoukopoulos et al. [21] found that the most popular indicator in the literature is the "share of population feeling safe from relevant incidents and violations while travelling" (PS_S). Medina et al. [23] considered the "proportion of public transport users that have been exposed to security related incidents", and the overall "satisfaction with the mobility service" is also used as an indicator [23], [24]. The *passengers' satisfaction* indicators were based on Tsiropoulos et al. [25] as they assessed security (PS_S) along with comfort (PS_C) and reliability (PS_R) through a scale of 1 to 5.

3.1.3 Environmental dimension

Sdoukopoulos et al. [21] found that the most popular environmental criteria to assess road axis/corridors are related with air *pollutant emissions* and *air quality* (100 % in that type of study). However, at urban and regional/national levels, other environmental aspects are also popular to assess sustainability as it is the case of the greenhouse gases emissions (69 % of the studies analysed) and the fossil fuel energy consumption (65 %), which is similar to the criterion energy efficiency considered in this study. *Noise pollution* is considered in 54 % of the analysed studies, and land consumption (41 %) was adapted into the criterion *land use by transport*. For the identified environmental criteria, a literature review was conducted to identify the most popular indicators. Table 3.3 outlines these results.

3.1.3.1 Air quality

In 2018, air pollution was responsible for 8.7 million deaths globally [38]. According to the handbook on external costs of transport [35], human problems that result from air pollution mainly concern the inhalation of particles (PM) and nitrogen oxide (NO_x). These problems can cause cardiovascular and respiratory diseases and result in premature deaths [4]. In the European Union, road transport was the largest emitter of NO_x in 2016, with a share of 39 % of the total transport emissions. Particles (PM_{10} and $PM_{2.5}$) contributed with around 10 % each, while greenhouse gases represented 71.7 % [4]. Consequently, these are the pollutants typically used in the definition of sustainability indicators for transport assessment, not only at emission level [18, 21, 26], but also at air quality level [21, 23]. Accordingly, in this study PM_{10} and NO_x concentrations are used to characterize the *air quality* criterion (C_{PM10}, C_{NOx}) [23]. The most popular indicator in the literature seems to be a concentration of several pollutants [21].

3.1.3.2 Pollutant emissions

Regarding the *pollutant emissions* criterion, carbon dioxide (CO_2), which is the most popular greenhouse gas included in sustainability indicators [23, 25, 26], and volatile organic compounds (VOC) (E_{VOC}) [18, 26] are gases usually considered. Additionally, Gazis et al. [18] considered particles (E_{PM10}), nitrogen oxide (E_{NOx}), and carbon monoxide (E_{CO}) emissions. A couple of studies identified the “mass of pollutants emitted” [21, 26]. In [21] the pollutants are not identified. De Gruyter et al. [26] considered pollutants such as NOx, VOC, and CO_2. However, with the growing use of vehicle fleets of natural gas, the methane emissions (E_{CH4}) have a greater importance, as CH_4 is a greenhouse gas that has a CO_2 equivalent equal to 84 [39].

3.1.3.3 Energy Efficiency

Energy efficiency gained a high importance in the last decades since the increasingly high energy consumption has resulted in severe environmental problems. To produce energy, most sectors, including transport, use fossil sources that are unrenewable and produce great amounts of greenhouse gases and pollutant emissions [40]. Concerning consequences of global warming and of the greenhouse effect are originated by CO_2, which has a direct relation to the vehicle energy consumption.

Within the *energy efficiency* criterion, energy consumption is a popular sustainability indicator used in different approaches [23, 24, 26–28]. An option to quantify the energy efficiency is by considering the ratio between the energy consumption and the passenger-km travelled [21, 23, 26]. Additionally, for this criterion, the fossil fuel energy consumption was also a used indicator [21, 24], as well as the proportion of clean energy [23, 24].

Table 3.3 – Main indicators associated to the defined criteria of the environmental dimension in the literature.

Reference	**Criteria of the environmental dimension**				
	Air quality	**Pollutant emissions**	**Energy efficiency**	**Noise pollution**	**Land use by transport**
This study	PM_{10} concentration (C_{PM10}), NO_x concentration (C_{NOx})	NOx emissions (E_{NOx}), PM emissions (E_{PM10}), VOC emissions (E_{VOC}), CH4 emissions (E_{CH4})	Energy consumption (*EC*)	Day’s noise level (N_D), Night’s noise level (N_N)	Route’s density (*RD*), Pathway’s circulation (*PC*)
Medina et al. [23]	C_{PM10}, C_{NOx}	CO_2 emissions	Energy consumption per passenger.km, Use of clean energy	Noise level	Road network density, Pathways for pedestrians, Land used by public transport facilities, Proportion of land with mix use
Sdoukopoulos et al. [21]	Concentrations of several air pollutants	Mass of pollutants emitted	Fossil fuel energy consumption, Energy consumption per passenger.km	Noise level, Share of population exposed to noise levels above the statutory threshold	Land used by public transport facilities
Lima et al. [24]	-	-	Fossil fuel energy consumption, Use of clean energy	Share of population exposed to noise levels	-
Tsiropoulos et al. [25]	-	CO_2 emissions	-	-	Road network density, Pathway network density
De Gruyter et al. [26]	-	Mass of pollutants emitted (e.g., NOx, VOC, CO_2)	Energy consumption per passenger.km	-	Land used by public transport facilities
Gazis et al. [18]	-	E_{NOx}, E_{PM}, E_{VOC}, CO emissions	-	-	-

3.1.3.4 Noise pollution

Noise pollution is a broad problem in urban areas as it can decrease people's quality of life and cause cognitive impairment in children, high levels of stress, sleep disturbance, and negative health impacts [4]. Within the *noise pollution* criterion, some common indicators are noise level [21, 23] and the share of population exposed to noise levels [24], or to noise levels above the statutory threshold [21]. Thus, the noise level during the day and night within an affected area used by a specific route is considered essential to the environment and human health.

3.1.3.5 Land use by transport

Transport has also impact on habitat loss, habitat fragmentation, and habitat degradation [35]. Hence, when determining the costs associated to habitat damage, an understanding on the network's land consumption is required. A popular indicator within this criterion is "land consumption by the transport facilities" [21, 23, 26]. This indicator, along with the indicator "pathways for pedestrians" [23], that is based on the protected pedestrian area per inhabitants, motivated the creation of the pathways' pedestrian circulation (*PC*) indicator. This indicator relies on the importance of promoting and allowing people to have an adequate area of pathway to walk safely on.

Following the same perspective of the authors that considered the "road network density" [23, 25], an adaptation to public transport resulted in the route's density (*RD*) indicator. Additionally, Tsiropoulos et al. [25] also used the so-called "pedestrian network density" for the environmental dimension.

3.2 Quantification of indicators

After the selected indicators' identification, it is required to quantify them and reach a comparable value, thus translating the indicator into a number would be helpful. Hence, most of the indicators are based on the average values of the collected data. These indicators may be defined for the stops, passengers, paths (trips) or vehicles of a specific route being assessed (Table 3.4). Since the analysis object is a route, the average or sum values allow to obtain a representative value for each route.

The measurement frequency of each indicator may be quite relevant as some indicators' values depend on time. These values need to be measured and collected with a given frequency, that can be either weekly, monthly, or annually. The indicators that do not depend on time rely mainly on network characteristics, for instance, the stop shelter or the vehicle capacity.

In urban mobility, two distinct periods of the day are usually considered: the peak period (PP) and the off-peak period (OPP). Their distinction highly depends on the country, or even region, where the public transport network is being assessed. A peak period refers to morning or afternoon periods when the number of passengers using a public transportation system is at its highest. An off-peak period indicates the hours of the day with less mobility activities and scheduled services [2]. Thus, public transportation systems must plan their transport service considering both peak and off-peak periods separately. Otherwise, if the system plan is directed only to peak periods, the system barely will be used during off-peak hours. Alternatively, the possibility of joining both periods and consider an average capacity, will likely result in passengers and transit congestion at the peak hours [2].

Accordingly, some indicators proposed in this work can be separately assessed for different periods of the day, as public transportation systems must plan their transport service considering the different realities of each period. From the selected indicators, we can see 72 % are quantitative and 28 % qualitative (Table 3.4). The following subsections describe how each indicator is computed.

3.2.1 Quantitative indicators

While some of the quantitative indicators may be directly determined, if they consist of just one piece of information, other indicators may require different types of data, thus requiring the use of some simple expressions. The next subsections describe such expressions within each sustainability dimensions.

3.2.1.1 Economic dimension

Within *economic productivity*, PR_{CC} and PR_{PC} are determined by expressions (3.1) and (3.2), respectively. As each indicator description evidences, the difference between these two indicators is the type of costs, while maintaining the same value of revenues.

$$PR_{CC} = \frac{Revenues - Material\ Costs}{Material\ Costs} \cdot 100 \tag{3.1}$$

$$PR_{PC} = \frac{Revenues - Personnel\ Costs}{Personnel\ Costs} \cdot 100 \tag{3.2}$$

The occupation rate (OR), from the *transport efficiency* criterion, concerning only one travel (identified by i), requires the vehicle capacity and its actual occupation during that travel. Hence, it can be calculated by expression (3.3).

$$OR_i = \frac{vehicle\ occupation_i}{vehicle\ total\ capacity} \cdot 100 \tag{3.3}$$

3.2.1.2 Social dimension

From the social dimension, the delay (D) and average speed (AS) that contribute for the *travel time cost* criterion are determined by expressions (3.4) and (3.5), respectively. These require information from planned data (the predicted travel time for indicator D and the travel's distance for indicator AS) and from the characteristics of the travel i (the actual travel time for both indicators). Additionally, the *affordability* indicator value (E) results from expression (3.6), as it expects the income and public transport expenses of each passenger that travelled a specific path associated to a route.

Table 3.4 – Description and characteristics of the selected indicators.

Indicator Acronym		**Description**	**Unit**	**Frequency**			
				N	***W***	***M***	***A***
Economic	PE_{PT}	Average monetary value as public expenditures invested on public transport	€				x
	TTP	Average monetary value spent by passengers on links that include the route	€		x		
	PR_{CC}	Ratio of the amount of revenues to the capital costs	%				x
	PR_{PC}	Ratio of the amount of revenues to the personnel costs	%				x
	OR	Average ratio of a link's vehicle occupation to the vehicle capacity	%		x		
	SD	Average of people that start their trip in every route's stop	Passengers		x		
	AM	Total number of public transport alternative stops/stations (i.e. bus, metro, train) in a walking distance of 300 m	Stops	x			
	F	Average frequency	Minutes	x			
Social	A	Total number of accidents that occurred whether it involves pedestrians, other vehicles, “human fault” from the operator, or machine failure	Accidents				x
	A_{IP}	Total number of injured people from the accidents	Injured people				x
	A_{D}	Total number of deaths from the accidents	Deaths				x
	CL	Average congestion level of that links that include the route	-		x		
	D	Average difference between the real travel time and the planned travel time	Minutes		x		
	AS	Average speed of every link that include the route	km.h^{-1}		x		
	E	Average percentage of the public transport expenses to the household income	%			x	
	A_{MP}	Average number of people (from 14 to 64 years old) who live in a walking distance of 900 m from a route's stop	People	x			
	A_{DP}	Average accessibility level of the vehicle conditions for disabled people that operates in the route	-	x			
	A_{EP}	Average number of people over 65 years old that live in a walking distance of 600 m from a route's stop	People	x			
	PS_{S}	Average security level inside the vehicle and on the stops from the passenger's perception	-	x			
	PS_{C}	Average comfort level inside the vehicle and on the stops from the passenger's perception	-	x			
	PS_{R}	Average reliability level inside the vehicle and on the stops from the passenger's perception	-	x			
Environmental	C_{NO2}	Average NO_x concentration level observed along a route	-				x
	C_{PM10}	Average PM_{10} concentration level observed along a route	-				x
	N_{D}	Average noise level throughout the route during the day	-			x	
	N_{N}	Average noise level throughout the route during the night	-			x	
	RD	Ratio between the route's length and the average of every stop's 900 m radius area of a route	km.km^{-2}	x			
	PC	Average free area for pedestrians’ circulation around stops (the pathway length used was 6 m)	km^{2}	x			
	E_{NOx}	Average NO_x bus emissions throughout a route	g.km^{-1}		x		
	E_{PM}	Average PM bus emissions throughout a route	g.km^{-1}		x		
	E_{COV}	Average COV bus emissions throughout a route	g.km^{-1}		x		
	E_{NH4}	Average NH_4 bus emissions throughout a route	g.km^{-1}		x		
	EC	Energy consumption from all the vehicles that travelled the specific route	MJ.km^{-1}		x		

Frequency: N: None; W: Weekly, M: Monthly; A: Annually

$$D_i = travel\ time_i - planned\ time_i \tag{3.4}$$

$$AS_i = \frac{total\ distance_i}{\frac{travel\ time_i}{60}} \tag{3.5}$$

$$E_{per\ passenger} = \frac{\sum expenses}{income} \cdot 100 \tag{3.6}$$

3.2.1.3 Environmental dimension

Both indicators from the *land use by transport* criterion required the data identified in expressions (3.7) and (3.8) to determine the route's density (*RD*) and the pedestrian circulation area (*PC*), respectively. The characteristics required for indicator *RD* are related to a route and the necessary for indicator *PC* are related to each stop. As it was shown in Table 3.4, both indicators do not depend on time.

$$RD = \frac{km\ extension}{number\ of\ stops\ \cdot \pi\ 0.9^2} \tag{3.7}$$

$$PC = (6\ m\ \cdot pathway\ width) - Stop\ Area \tag{3.8}$$

3.2.2 Qualitative indicators

The values of all the indicators from a qualitative source are translated to a "Likert scale" ranging from 1 to 5 (where 5 is the "best" value) presented in Table 3.5.

Table 3.5 - Meaning of the scale levels for the qualitative indicators.

Indicator	**Unit**	**Meaning of the qualitative levels**				
		1	**2**	**3**	**4**	**5**
CL	-	Very low	Low	Moderate	High	Very high
A_{DP}	nº features	0	1	2	3	4
PS_S, PS_C, PS_R	-	Very poor	Poor	Average	Good	Very good
C_{NO2}	µg.m^{-3}	0-40	41-100	101-200	201-400	401-1000
C_{PM10}	µg.m^{-3}	0-20	21-35	36-50	51-100	101-1200
N_D	dB	> 0	> 55	> 60	> 65	> 70
N_N	dB	> 0	> 45	> 50	> 55	> 60

Congestion level

The congestion level is usually translated from time, if a there is very low (correspondent value of 1) congestion level then traffic should pass through without suffering any delays. On the other side of the scale, if the congestion level is very high (correspondent value of 5) then traffic will suffer a major delay. The main source to study congestion and adopt the scale values in Table 8 was the TomTom website which provides worldwide traffic index in urban areas in order to provide necessary information that can help minimize the congestion problem [37]. In the traffic flow page, the present colour scale corresponds to levels 5 and 4 as situations with major delays, 3 and 2 with minor delays and 1 with no delays.

Disabled people conditions

When assessing the access level for disabled people who suffer from less mobility, the routes' vehicles should provide several features that contribute to minimize such difficulties. These features could refer to low floor, kneeling system, an access ramp, or a designated wheelchair space. Accordingly, the scale levels are assigned based on the total number of features integrated in a vehicle.

Passengers' satisfaction

All three passengers' satisfaction indicators consist of opinions and are measured with equivalent scale levels meanings. As shown in Table 3.5, the scale starts with "very poor" (level 1) and finishes with "very good" (level 5).

Air quality concentrations

The air quality concentrations scales for both type of pollutants considered were collected from the "QualAr" Portuguese webpage which has the main purpose of providing information regarding air quality at a national level [41]. For various locations, an air quality index is calculated that, later, is translated into an index classification scale. This is a "Likert scale" that goes from bad (correspondent to the scale value of 1) to very good (correspondent to the scale value of 5). Regarding this classification, the important information is the range of the concentration values ($\mu g.m^{-3}$) that matches each scale level for the different pollutants. The defined index classification intervals are in line with the limit values recommended by the air quality European Union legislation and, most recently (since 2019), references from the World health Organization (WHO) have been considered as well, due to the deeper knowledge of how the pollutants affects health [41]. Accordingly, Table 3.5 presents those intervals for both NO_x and PM_{10}.

Noise pollution

The European Union Environmental Noise Directive (END) established that for noise levels above 55 dB during the day and evening and above 50 dB during the night, the society is facing noise pollution [42]. The European Environmental Agency provides noise maps for the different main noise sources: road, railways, airports, and industrial. The noise maps show the number of people exposed to different noise intervals that were adapted to the created scale. Depending on the time, whether during the day or night, scale level's intervals present a 5 dB difference.

3.3 Scale normalization

To be able to weight the selected sustainability indicators, these must be normalized first [21]. Several normalization methods such as ranking, standardization or z-scores, re-scaling, distance to a reference, and categorical scales are usually used in the literature [43]. In this study each indicator was re-scaled in an interval from 0 (lowest performance) to 1 (highest performance), whether the desirable value is higher or lower, using expressions (3.9) and (3.10) respectively. I is the indicators value to be normalized, I_{min} is the minimum value of that indicator, and I_{max} is the maximum value.

$$\frac{I - I_{min}}{I_{max} - I_{min}} \tag{3.9}$$

$$\frac{I_{max} - I}{I_{max} - I_{min}} \tag{3.10}$$

Both I_{min} and I_{max} are referenced values for every route. These pose a more relevant role for quantitative indicators, as the qualitative ones are already assigned to a scale of 1 to 5, where depending on the desirable value, both tips of the scale (1 and 5) represent the maximum and minimum values. Given the lack of resources, these references were not determined according to extensive studies, and so they are adapted to the illustrative case, that was also created. Accordingly, the references are presented and explained in section 4.4.

3.4 Assignment of weights

Transport network design problems are complex due to the number of objectives that a solution may consider. When developing this methodology to obtain a level of sustainability performance, trade-offs must be defined as several indicators are considered. This is done through the assignment of weights for each hierarchical level of the model in Figure 3.3. Due to the lack of resources, the adopted weights were based on extensive literature review, mainly focused on the literature used previously to determine the selection of indicators.

To assign weights to different “components”, statistical models can be used or, in alternative, many works have adopted some kind of participatory methods such as the Analytic Hierarchy Process (AHP), multi-criteria analysis methods, Delphi surveys, or principal components analysis [21]. Camargo Pérez et al. [3] concluded that the AHP method is the most used method, followed by the Technique for Order Performance by Similarity to Ideal Solutions (TOPSIS).

Many authors opt to assign equal weights to the different sustainability dimensions, criteria, and indicators e.g. [26, 27]. As Gan et al. [43] focused on selecting the adequate weighting method for sustainability indicators given different contexts, they found 47 % of the literature work using equal weighting. This implies that the indicators are equally important, which is a controversy assumption. Even though it is a generally used method, it would not meet the goals and context of this dissertation as the weights represent the trade-offs that contribute to the overall sustainability performance [43].

As the proposed model is hierarchical, the different levels of the weighting process can be analysed separately. The following sections describe and explain the weighting process for each level.

3.4.1 Dimensions level

At this level, equal weights' studies were not included, as it is not realistic to assign the same importance to the different dimensions and disregard trade-offs [25–27]. Due to a significant number of studies that considered equal weights for the sustainability dimensions, studies with unequal dimensions weights were selected from the Sdoukopoulos et al. [21] literature review [44, 45]. Table 3.6. presents the respective dimensions' weights determined in those sustainability studies [44–46]. To each set of weights, a weight scenario (*WS*) is associated as it will be applied in the illustrative case.

Table 3.6 – Weights' scenarios included in this study.

Reference	**Weight Scenario**	**Dimensions**		
		Economic	Social	Environmental
Lopez-Carreiro et al. [44]	*WS1*	0.289	0.357	0.354
Danielis et al. [45]	*WS2*	0.564	0.023	0.413
Ngossaha et al. [46]	*WS3*	0.11	0.66	0.23

Lopez-Carreiro et al. [44] focus on combining sustainability dimensions and technological innovation to assess the "smartness" level of a city. The used weights were determined by other authors with a similar scope as theirs. These were based on the opinion of 84 transport and urban planning experts and resulted on the first line of Table 3.6. With a balanced range of values, the highest priority was assigned to the social dimension followed by the environmental and economic.

Danielis et al. [45] aims to determine a sustainability index and uses a set of 16 indicators with a hierarchical structure. They used multiple combinations of normalization, weighting, and aggregation techniques. The weights techniques used were equal weighting, literature-based, and principal components (PC/FA). For the second scenario introduced in Table 3.6, the most interesting set was one that resulted from the principal components (PC/FA). The priority order of this differs from the other scenarios by assigning the lowest value to the social dimensions and the highest to the economic one.

Ngossaha et al. [46] follows the concept of designing transportation systems in accordance to sustainable requirements. Thus, considering various indicators, they used the fuzzy AHP multi-criteria method to obtain the weights. The obtained values correspond to the Lopez-Carreiro et al. [44] priority order of the sustainability dimensions. However, the differences between the dimension's weights are bigger as shown in *WS3* in Table 3.6.

3.4.2 Criteria level

The weights assigned to each criterion were based on Medina's et al. [23] study. This study was selected due to its extensive validation methods that included interviews answered by 19 experts in sustainability topics. Additionally, since this study strongly influenced the selection of indicators, these were used to define the weights of the different criteria created in my study. The first steps of this application consisted of gathering the 42 indicators defined by Medina et al. [23] and determining their global priorities (presented in Table 3.7).

Table 3.7 – Association of Medina et al. [23] indicators to each criterion of this study.

Dimensions	**Medina et al. [23] Indicators**	**P**	**GP**	**Correspondent criterion**
Environment and human health	Traffic related fatalities	32.29	15.45	Safety
	Air quality PM_{10}	31.65	15.14	Air quality
	Transport related CO_2 emissions	20.59	9.85	Pollutant emissions
	NO_x concentration	10.79	5.16	Air quality
	Traffic noise pollution	4.68	2.24	Noise pollution
Economy and social	Access PT service	21.24	10.16	Accessibility
	PT affordability	17.92	8.57	Affordability
	Variation of non-motorized in the model split	10.98	2.61	-
	Variation of PT in the modal split	10.48	2.50	-
	Transport security	9.29	2.21	Passengers' satisfaction
	Indirect trip cost for user (minutes)	8.36	1.99	Travel time costs
	Share of PT vehicles which are wheelchair accessible	8.13	1.94	Accessibility
	Population density	7.81	1.86	-
	Variation of the female users in the PT	5.8	1.38	-
Operational	Multimodality integration	16.68	1.39	Transport efficiency
	Efficiency of public transportation (MJ/passenger.km)	16.68	1.39	Energy efficiency
	PT frequency	15.88	1.33	Transport efficiency
	Financial attractiveness of PT	13.03	1.09	-
	Proportion of clean energy in PT fleet	11.61	0.97	Energy efficiency
	Bike sharing performance	10.24	0.86	-
	Average age of PT fleet	7.25	0.61	Emissions / Energy efficiency
	Road network density	4.03	0.34	Land use by transport
	Parking cost	2.48	0.21	-
	Parking capacity	2.14	0.18	-
Fiscal and governance	Public expenditures and investment in transport system	21.89	1.28	Transport costs and finance
	Master plan	20.86	1.22	-
	Operational cost PT system	17.77	1.04	Economic productivity
	Expertise of technicians and managers	13.48	0.79	-
	Financial autonomy	9.84	0.58	Transport costs and finance
	Stakeholder engagement	7.34	0.43	-
	Participation of the multilateral banks	5.33	0.31	-
	Variation of the informal transport modal split	3.5	0.21	-
Mobility system effectiveness and land use	Pathways for pedestrians	21.66	3.06	Land use by transport
	Satisfaction with mobility services	20.2	2.86	Passengers' satisfaction
	Cycle path network density	17.79	2.52	-
	Proportion of land with mix use	9.55	1.35	Land use by transport
	PT fleet size	8.3	1.17	-
	Average occupancy rate of passenger vehicles	6.57	0.93	Transport efficiency
	Traffic congestion delay	5.5	0.78	Travel time costs
	Land consumption by transport facilities	4.91	0.69	Land use by transport
	Motorization rate	2.97	0.42	-
	Motorcycle rate	2.55	0.36	-

PT: public transport, P: priority. GP: global priority

Each indicator has a correspondent criterion that has been also evidenced in the selection of indicators section (Table 3.1, Table 3.2, and Table 3.3). Some Medina et al. [23] indicators were not included in this study, nor are related to the defined criteria. For these there is no criteria association in the fifth column in Table 3.7. Distinctively, the "average age of the public transport fleet" indicator is associated to two criteria, even though it was mentioned in the selection of indicators. Since this indicator influences both energy consumption and pollutant emissions values, as it will be further explained, it is correspondent to both criteria.

By aggregating every indicator correspondent to a specific criterion (from Table 3.7), the total priority per criterion was displayed in Table 3.8. These values were re-scaled, combined into the respective dimension, and used to determine the priority in percentage of the criterion within each dimension (shown in the fifth column of Table 3.8).

Table 3.8 – Obtained weights for the criteria of this study.

Dimension	**Criteria**	**Total priority**	**Re-scaled total priority**	**Dimensions' priority**	**Criteria weights (%)**
Economic	Transport costs and finance	1.859	2.064	7.271	28.4
	Economic productivity	1.041	1.156		15.9
	Transport efficiency	3.648	4.050		55.7
Social	Safety	15.451	17.155	48.810	35.1
	Travel time costs	2.768	3.074		6.3
	Affordability	8.575	9.520		19.5
	Accessibility	12.099	13.434		27.5
	Passengers' satisfaction	5.068	5.627		11.5
Environmental	Air quality	20.308	22.547	45.984	49.0
	Noise pollution	2.239	2.486		5.4
	Land use by transport	5.444	6.044		13.1
	Pollutant emissions	10.458	11.611		25.3
	Energy efficiency	2.968	3.295		7.2

3.4.3 Indicators level

Even though assigning equal weights states that the indicators are equally important, which is controversy assumption, almost 50 % of the studies apply that [43]. However, given the incoherence of the literature and the lack of resources to opt for a participatory method, at this level, an equal weight was assigned to each indicator with the respective criterion. Nonetheless, the tool is configurable and allows the assignment of unequal weights at the indicators level.

Chapter 4

Illustrative case

A simple bus transit network was designed with the purpose of testing and validating the proposed model. For this purpose, an illustrative case based on the STCP company, that provides a public transport service in Porto's metropolitan area was used. Therefore, a brief introduction of the illustrative case is described in section 4.1. Section 4.2 identifies and justifies the software used to implement the tool and respective application. Then, section 4.3 presents and explains how the illustrative case was completed and organized with the necessary data to the indicators' quantification process. This section is followed by the determination and description of the references used to re-scale the indicators, that allow the weights' assignment , in section 4.4.

4.1 Network

A simple bus transit network was designed with the purpose of validating the proposed tool. This is composed by three fixed routes (A, B, C), 24 stops, and three zones (NZ, WZ, EZ). The routes are distinguished by colors and associated to a letter: route A associated to green with 8 stops, route B associated to purple with 9 stops, and route C associated to blue with 7 stops. The stops are represented by dashed lines and identified by numbers from 1 to 24. Similarly to real networks, this presents intersection stops represented by double lines. These are common to two routes with two identifiers, one for each route, as it is the case of stops 5 and 22. Given the dimension of the illustrative network, it was opted to create only three zones designated by North Zone (NZ), West Zone (WZ), and East Zone (EZ). Figure 4.1 shows the network presented.

Generally, stops are distributed for both sides of the street due to the direction of the route. However, for simplification purposes, a stop in this network represents both directions, and consequently, whether a path travelled by a passenger goes from stop 1 to 8 (in route A) or from 8 to 1, the path will be the same according to distance and time.

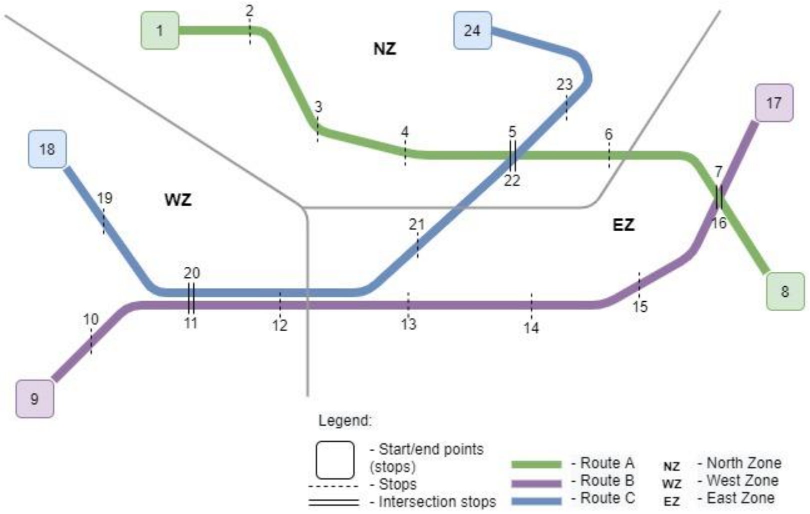


Figure 4.1 – Bus network used to assess the tool proposed.

Beyond the network drawing, more information is required to feed the sustainability indicators and complete the demonstration. Thus, section 4.2 presents the software used to implement the tool and section 4.3 how the dataset of the illustrative case was generated.

4.2 Used software applications

To implement the developed tool and allow its application, different software applications were used throughout this work. To gather the information required to quantify the indicators (described in section 4.3), multiple sources were consulted and most of the information was treated in Excel, as it is a very useful program for data analysis. Additionally, for geographical aspects both Google Maps and a Geographic Information System (GIS) were used due to their practicality and accuracy.

The data was inserted and saved in a PostgreSQL database provided by FEUP and managed through “PhpPgAdmin” page (http://db.fe.up.pt/phppgadmin/). To collect the information from the database, a program in Python was implemented. The library “psycopg2” is the most used to establish a connection with a PostgreSQL and implement functions to select, insert, delete, and update the information of the database. Hence, this was used in the quantification functions created in the Python program. Regarding the implementation of the type of period, that is considered to assess the sustainability, a function was also implemented. Since the definition of these type of periods depends on the type of region and other circumstances, the function defines two intervals per day (delineated by hours) for each type of period and has the flexibility to alter its values whenever being used. PostgreSQL and Python were adopted for this work due to the previous experience with both technologies.

Additionally, to obtain the sustainability index, functions to normalize, assign weights and aggregate the indicators, criteria, and dimensions, were implemented. In order to demonstrate the results, the “matplotlib” library of Python was used (Chapter 5).

4.3 Dataset

The selected sustainability indicators demand data to determine their respective values. Accordingly, it is necessary to identify the required data that will enable the quantification process of the adopted methodology explained in section 3.2. The defined transport network was supported with data from one of the main public transport providers in Porto's metropolitan area, the STCP company. Data such as the frequency, accessibility, and demand of a route was directly deduced from real routes. For this purpose, three routes from a set of five from STCP were assessed. However, many required estimations were performed since data such as the number of injured people in accidents, or the vehicle occupation is not publicly available from STCP. Hence, besides STCP [47], the services of public transport companies such as TUB from Braga district [48] and Carris from the Metropolitan Area of Lisbon (AML) [49] were analysed. Focusing on the bus mode, Appendix A outlines the general information related to the bus services provided by these three companies.

As Table 3.4 describes each indicator, it is understandable how the illustrative case requires information related to different topics. Thus, an organizational approach to include all the required information was developed. Through the PostgreSQL database, a structural data model was implemented to dynamically collect the information for each indicator depending on the time of the day and route. As previously explained, some indicators values are obtained directly, while others must be estimated. Yet, to determine them, all the required data is part of the data model shown in Figure 4.2, and the following subsection discuss each table.

4.3.1 Routes

A public transport company provides a service with routes that together complete its designed network. Each route is represented by a tuple of the *routes* table. For mainly economic indicators, the necessary attributes that define a route are its average frequency in both type of periods (OPP and PP), kilometer extension, accessibility to disabled people, revenues, capital and personnel costs, and public expenditures.

Since a route is the object of analysis, the *routes* table is the one with most relations to other tables (Figure 4.2). Two of its relations consist of "composition aggregation" relationships, which are defined by the filled diamond shape on the parent side of that relation. This means that there can only be environmental measures and accidents registries associated to only one route, as it simplifies the model. Additionally, the relation to the *vehicles* table represents which vehicles operate in a specific route and, as routes are composed by stops, the *routes* table is referenced in the *stops* table.

Frequency

To characterize the routes of the illustrative case, an extensive analysis of five STCP routes operated in Porto city (200, 204, 504, 603, and 208) was pursued. These routes were selected to perform an exploratory analysis in order to further select distinct routes among each other. The first section of these routes, always considering the same direction, was analysed.

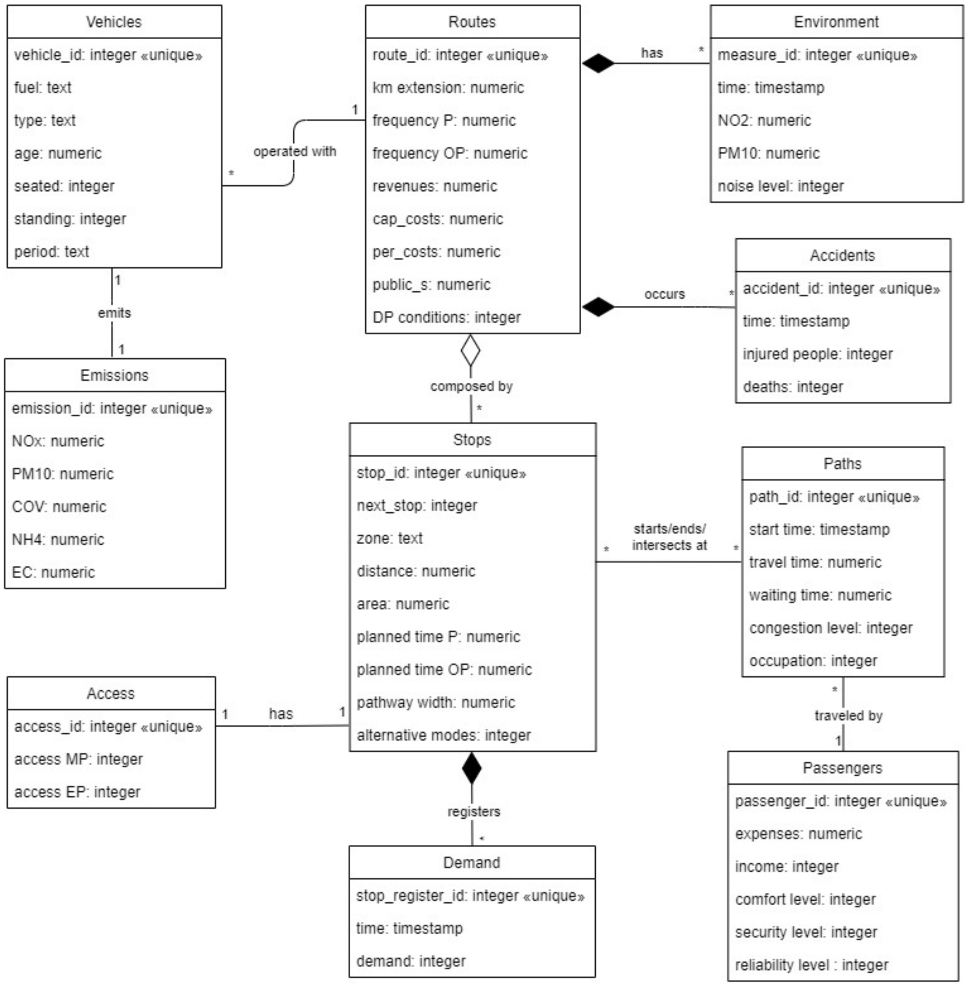


Figure 4.2 - Data model using UML.

To compute the frequency of the analysed routes, the inverse of the difference between a departure time and the next departure, along the day, was calculated considering the first stop of each route. For instance, the first bus of route 200 leaves “Bolhão” (the first stop) at 06h00 and the next one at 06h20, which results in a bus frequency of 0.05 (1/difference in minutes).

The main idea was to determine a frequency for each route during peak (PP) and off-peak (OPP) periods, however these periods still had to be defined. Accordingly, a frequency average value was determined considering the highest and lowest frequency of each route along a weekday. Values above that average were part of the peak period and bellow the average were part of the off-peak period. Figure 4.3 shows the variation of the frequency of the analysed route during the day.

Route 200 has, in its peak periods, the higher frequency. Most route’s lines show how the frequency increases at the beginning of the day around 07h00. Both routes 200 and 204 emphasize another rapid increase before 08h00. Around 09h00, routes 200, 204 and 504 decrease the frequency. For route 208 this decrease happens closer to 10h00. Differently, route 603 has a very stable frequency during the day.

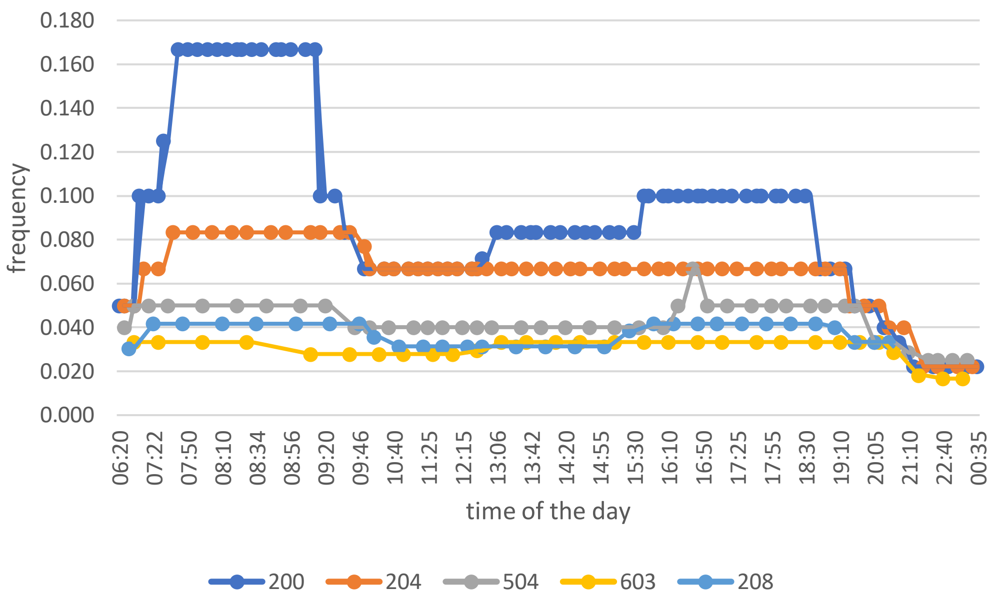


Figure 4.3 – Variation of the frequency of the routes during a day.

Unlike the others, routes 204 and 603 evidence only one peak period, that can be better understood in Table 4.1, that presents the time periods for each OPP (light blue) and PP (grey blue). The table's colour pattern indicates the standard relation between OPP and PP, which consists in peak periods interlocked by off-peak periods. This approach is the most coherent with the definition of each type of period, as the ridership rate in public transport (and transit in general) is higher at commuting periods, which are evidenced by the peak periods in Table 4.1. Once the periods were distinguished, the average frequency value for each type of period was introduced in the respective attribute in the *routes* table.

Table 4.1 – Route's peak (grey blue) and off-peak (light blue) periods.

Route	**Periods**				
200	06h00-07h00	07h10-09h28	09h40-15h30	15h40-18h30	18h45-00h35
204	06h20-07h00	07h15-19h10			19h30-00h00
504	06h15-06h40	07h00-09h20	09h45-16h00	16h20-19h35	20h05-23h50
603	06h30-20h45				21h40-23h40
208	06h25-06h58	07h22-09h46	10h14-15h02	15h28-19h05	19h35-20h35

The time it takes to travel from the start of the route until the end of the first section, that corresponds to an average of 11 stops, during the day, was determined for each route using the weekday schedules from STCP website and Excel. The distances between the first and last stops of the analysed sections were measured through Google Maps. The available information allowed to determine the average speed throughout the day. For each type of period and route, the average speed was determined (Table 4.2). For every route, the average speed is higher during OPP than during PP. This is coherent with the concept of both type of periods.

Table 4.2 – Route's average speeds for peak and off-peak periods.

Route	Average speed (km.h^{-1})	
	Peak	Off-peak
200	9.42	10.65
204	14.93	18.19
504	11.95	16.63
603	23.44	29.7
208	11.83	12.71

Based on the above preliminary analysis, routes 200, 204, and 504 were selected to try to emulate their different characteristics. Route 200 has a very defined distinction of the OPP and PP (Table 4.1) as well as the highest frequencies (Figure 4.3). While route 200 demonstrates a very small difference between both speeds, less than 2 km.h^{-1}, route 504 shows a difference of 4.68 km.h^{-1} (Table 4.2). Route 504 also has the standard five periods throughout the day, however it has lower frequencies. Route 204 is the example of a one peak period with a relatively overall high frequency.

The association was based on the number of stops in each first section of the selected routes. Route C has the same number of stops as the first section from route 504 and route B has the same number of stops as the first section from route 200. Route 204 has 17 stops in its first section and, so, 8 of them were handpicked to match the 8 stops in route A.

Extension

To determine the distances between stops, a few sets of stops (stop 1 and stop 2) were selected from STCP routes 204 and 208 to measure their distance in kilometers, that are presented in Table 4.3. Every chosen section is part of an urban center, and an average distance of 0.355 km was obtained.

Table 4.3 - Distances between a few stops from STCP's 204 and 208 routes.

Route	Stop 1	Stop 2	Distance (km)
204	H. S. João	Esc. Sup. Educação	0.406
204	Esc. Sup. Educação	Faculdade de Engenharia	0.273
204	Faculdade de Economia	Manuel Laranjeira	0.274
204	Manuel Laranjeira	Outeiro	0.239
208	Carmo	H. S. António	0.57
208	Av. Do Bessa	S. João Bosco	0.408
208	Casa de Ramalde	BR. Ramalde	0.432
208	Martim Freitas	Vila Nova	0.235
		Average:	**0.355**

The distances between the stops in the drawing of the created network (shown in Figure 4.1) were also measured in centimeters. After analysing those and concluding that most of the distances were around 2 cm, the correspondent distance considered was 0.3 km. Therefore, a proportional distance in kilometers was determined with expression (4.1), where d is the distance measured in centimeters in the illustrative case draw.

$$distance\ in\ km = \frac{0.3\ d}{2} \tag{4.1}$$

Finally, by incrementing each distance, the kilometer extension of each route was determined. It should be noted that while the illustrative case has routes with 7 to 9 stops and a kilometer extension of 2.3 to 2.6 km, a real route is 9.14 km long and has 30 stops (route 200). Therefore, the illustrative case represents, size wise, sections of real routes.

Accessibility to disabled people

The disabled people conditions directly represent the A_{DP} indicator from the accessibility criterion. STCP has strongly invested in an accessible vehicle fleet to help people with reduced mobility, whether physical, cognitive, or sensorial. Even though the improvements are directly related to the vehicles, the STCP company associates each route to one of three accessibility scenarios. The best scenario consists of four conditions in vehicles with ramp: wheelchair accessible, baby carriage accessible, guide dogs allowed and with low floor. The second-best scenario consists of the last two mentioned conditions. Alternatively, a route can have no accessibility conditions to reduce mobility. Consequently, compared to the five level “Likert scale” defined (subsection 3.2.2), this study case based on STCP only shares levels 1, 3, and 5. Specifically for the selected routes, both routes A and B contribute with level 5 and route C with level 3.

Monetary attributes

The last attributes in the *routes* table reference monetary values required to determine profit rates and public expenditures. A global profit rate is not enough to compute the economic productivity indicators since these are related to different type of costs. Thus, additional information was collected from the STCP report [47] and presented in Table 4.4.

A dull proportional approximation was performed to determine the correspondent annual revenues and expenses values for a network with three routes. The equal distribution of the total values obtained per route was not implemented, since each route cannot generate or expend the same amount of money. Hence, random percentages of the total values of revenues and expenses (also presented in Table 4.4) were assigned to each route in order to reflect a more realistic case. The values in bold of each route’s column in Table 4.4 were inserted in the respective attributes of the *routes* table.

To determine the share of financing devoted to public transport, a similar method was applied. From the STCP public report, a total investment throughout the year reached 16.3 million € [47]. Most of the investment was used to improve the bus fleet and, therefore, to maintain a certain coherence and simplicity, the total monetary value of investment per three routes was distributed with the same expenses’ percentages. This resulted in the values in bold presented in the last line of Table

4.4, which were also introduced in the database and directly selected to obtain the public expenditures indicator (PE_{PT}).

Table 4.4 – Adaptation of the STCP road service monetary results to the illustrative case.

Economic elements/variables		**Complete STCP road service 2019**		**Illustrative case**			
		Values (10^3 €)	Percentage of the total	Per 3 routes (10^3 €)	Route A	Route B	Route C
					R: 20%, **E**: 30%	**R**: 40%, **E**: 45%	**R**: 40%, **E**: 25%
R	Earnings	47 497	86.50%	1951.9	390.39	780.77	780.77
	Rental of vehicles	4	0.01%	0.2	0.03	0.07	0.07
	Others	2 862	5.21%	117.6	23.52	47.05	47.05
	FCPSO*	4 546	8.28%	186.8	37.36	74.73	74.73
	Total	54 909	-	2256.5	**451.31**	**902.61**	**902.61**
E	CSCM+SES	20 946	40.11%	860.8	**258.24**	**387.36**	**215.20**
	Personnel	30 602	58.60%	1257.6	**377.28**	**565.93**	**314.40**
	Other	672	1.29%	27.6	8.28	12.43	6.90
	Total	52 220	-	2146.0	643.81	965.71	536.51
I	Total	16 300		669.9	**200.96**	**301.44**	**167.47**

R: revenues, E: expenses, I: investments, FCPSO: financial compensation of public service obligations, CSCM: costs of sold and consumed materials, SES: supplies to external services.

4.3.2 Environment

The aim of the *environment* table is to provide traffic noise, PM_{10} and NO_x air concentration measurements in order to determine the respective indicators (C_{PM10}, C_{NOx}, N_D, N_N). Hence, there is an attribute for each type of pollutant and one for the noise level. Since air quality can be assessed in the different type of periods (PP and OPP), as well as noise traffic must be assessed during the day and night, there is a timestamp data type attribute to register the time of the measurement.

The air quality data was collected from "QualAr" [41]. Given "QualAr" objective, previously mentioned in subsection 3.2.2, they obtain air quality data from monitoring stations located in different areas of Portugal. The collection of data consisted of selecting a north station per route and collecting a sample of measurements from the total from 2019. The measurements were registered every half an hour during a year. The selected stations were "Francisco Sá Carneiro – Campanhã", "João Gomes Laranjo – S. Hora", and "Pe Moreira Neves – Castelões de Cepeda". Even though they provide real measurements, the association between a route and a single station is not real. Given the purposes of this dissertation, a few monitoring stations along each route would be required and that level of detail is not available.

The European Environment Agency provides a reliable traffic noise map with the different Lden intervals (created by the European Union noise policy indicator), and the respective number of people exposed to them [42]. Table 4.5 outlines the values found for some Portuguese counties. A brief analysis highlights that Lisbon has the highest percentage of population exposed to noise pollution. Contrarily, the city of Porto shares the lowest value. However, comparing the highest Lden interval, Porto has the highest number of people exposed. Every county shows a decrease of the number of people exposed with the increase of the Lden intervals. Since this source does not provide noise values for the distinct periods of the day, for demonstration purposes, values of noise levels between 50 dB and 76 dB were randomly assigned to each air measurement date and hour.

Table 4.5 – Number of people exposed to noise per Lden intervals in Portuguese counties [42].

County	**Population**	**Total number of people exposed per each noise band for roads - Lden**					**Total nº of people exposed**	**Proportion of the population (%)**
		Lden 55-59	Lden 60-64	Lden 65-69	Lden 70-74	Lden >75		
Matosinhos	174 382	25 600	10 900	9 400	8 900	2 400	57 200	32.80%
Porto	215 284	10 600	8 800	7 900	6 200	4 000	37 500	17.42%
Odivelas	159 602	18 400	22 800	16 600	2 600	-	60 400	37.84%
Amadora	181 724	25 600	24 100	19 800	8 900	1 300	79 700	43.86%
Oeiras	176 218	27 800	15 700	9 400	800	-	53 700	30.47%
Lisboa	507 220	86 900	79 200	53 300	18 200	1 900	239 500	47.22%

4.3.3 Accidents

A tuple in the *accidents* table is always associated to a route. Each line of the table corresponds to an accident and its attributes state when it occurred (timestamp), the number of injured people, and the number of deaths. Other than the number of accidents from the STCP report [47], further information about the accidents is not available. Thus, it was opted to determine the number of annually accidents with a dull approximation considering the network's kilometer extension (492 km) using expression (4.2), that resulted in nearly 20 accidents per 7.4 km (total network extension). These were randomly associated to the three routes of the illustrative case and inserted in the *accidents* table.

$$total\ number\ of\ accidents = \frac{1290\ \cdot 7.3598}{492} \cong 20 \tag{4.2}$$

According to the road security annual report from ANSR ("Autoridade Nacional de Segurança Rodoviária") published in 2019 [50], only 3 % of the vehicles involved in accidents with victims are heavy vehicles. Since the document did not focus on public transport vehicles, these are included in the heavy vehicle category. Regarding this category, 99 % of the accidents' passengers victims are mild injured [50].

Out of the 20 accidents above estimated, no deaths should be suffered related to urban public transport. However, with the purpose of distinguishing the three routes, one accident resulted in one death. On the other hand, certain occurrences such as hard braking when preventing an accident or certain operator's driving characteristics can originate mild injured passengers. As it seems more common, a number of injured people between 0 and 3 was randomly assigned to 80 % of the accidents.

4.3.4 Vehicles

For simplification purposes, each tuple in the *vehicles* table represents one vehicle that operates only in one of the network routes. Each vehicle is characterized by the type of fuel, type of segment, and age, that all influence the associated pollutant emissions in the *emissions* table. The vehicles' standing and seated capacity are used to determine the occupation rate (*OR*). Additionally, since the *vehicles* table is directly associated to the *routes* table, rather than the *paths* table, a column was added to identify in which type of period (OPP and PP) that particular vehicle operates in.

To determine the number of vehicles, and respective characteristics, required to operate the three routes, data was collected from the STCP report and used to estimate the equivalent proportion of each type of vehicles for the illustrative case. Table 4.6 shows the data used and the results obtained.

Table 4.6 – Number of each type of vehicles for the illustrative case.

Type of fuel	**Type of segment**	**Average age (years)**	**Number of vehicles used by STCP (73 routes)**	**Number of vehicles for the illustrative case (3 routes)**
Natural gas	Standard	10	239	10
Natural gas	Articulated	13	29	1
Electric	Standard	1	15	1
Diesel	Standard	20	99	4
Diesel	Articulated	9	20	1
Diesel	Minis	8	8	0
		Total	**410**	**17**

The STCP report did not share the vehicles capacity, and therefore, this information was searched in Carris webpage and reports. Within their vehicle fleet characteristics, Carris shares the seated and standing capacity of 9 standard and 3 articulated models. From the analysis of this information, it was noted that each type of segment matches similar capacity sets, yet it depends on the specific model of the vehicle. Thus, 5 different sets were randomly distributed to the 15 standard illustrative vehicles and a set was chosen for each remaining articulated vehicle.

From the 17 vehicles estimated, six vehicles were assigned to route A and another six to route B, as these have the higher frequencies. The remaining five were assigned to route C. It should be noted that the detail of existing additional fleet in case of technical failures or accidents was not included in this illustrative case.

Different distributions of the vehicles per period were applied to obtain a variety of situations. Hence, route A has four vehicles associated to the PP and two associated to the OPP. For Route B it was split equally resulting in three vehicles per each type of period. For route C, three vehicles operate during peak periods (PP) and two operate during off-peak periods (OPP).

4.3.5 Emissions

As it is required by the created indicators, the *emissions* table associates a value of each pollutant emission and energy consumption to each vehicle. Ideally, as the description of these indicators and respective monthly frequency are defined, the *vehicles* table should be connected to the *paths* table. Since measurements were not provided, an alternative method was required and it was opted to associate each estimated emission to a vehicle, otherwise the demonstration would become much more complex.

The air pollutant emission inventory guidebook published by the European Environment Agency defines how emissions from various vehicle categories can be quantified [51]. For the vehicle category of urban buses, the guidebook provided an appendix (an Excel document) with the emissions and energy consumption values. To obtain those, the collected characteristics from the STCP vehicles were filtered. Both the type of fuel and segment were used straight forward unlike the vehicle's age. For each vehicle's age the correspondent Euro norm was determined [52]. To simplify, it was always considered a road slope of zero (flat roads) and a vehicle load of 50 %. The obtained values were introduced in the respective attributes of the *emissions* table of the database.

4.3.6 Stops

Every route is composed by stops, and so every stop from the *stops* table is associated to a route. Thus, each tuple focusses on each stop that has is characterized by its zone, distance and planned time regarding the next stop (per type of period), shelter area, pathway width, and number of alternative stops of bus or different modes. These match the table's attributes. The *stops* table has some relations as well since many indicators require information at the stop's level. Hence, it is connected to the *access*, *demand*, and *paths* tables.

The zones delineated in the illustrative network (Figure 4.1) define the fee of each path travelled. In Porto's metropolitan area, a zone system was implemented to determine each fee based on the number of included zones. For instance, if the passenger travels in four distinct zones its fee is 2 € per trip. Hence, in this work a similar system was implemented. If the passenger's path crosses one or two zones its fee is 1.2 €, and if it crosses three zones its fee is 1.6 €. This was used to determine the travel ticket price indicator (*TTP*).

Previously, the distances between two stops were determined. As the used referenced distance between stops was 0.3 km, this was also used to determine the planned time considering the obtained average speeds presented in Table 4.2 (in subsection 4.3.1). By applying expression (4.3), the respective planned time per 0.3 km was determined, and then used to determine each stop planned time for each type of period (Table 4.7).

$$Planned\ time = \frac{0.3\ km}{Average\ Speed\ km.h^{-1}} \cdot 60\ min. \tag{4.3}$$

Table 4.7 – Selected routes and respective duration and frequencies.

Study route	**STCP route**	**Average Speed (km.h^{-1})**		**Planned time per 0.3 km (min)**		**Frequency (min^{-1})**	
		PP	OPP	PP	OPP	PP	OPP
B	200	9.42	10.65	1.911	1.690	0.126	0.064
A	204	14.93	18.19	1.206	0.990	0.07	0.038
C	504	11.95	16.63	1.506	1.082	0.051	0.036

The pathway width, shelter area, and number of alternative stops were deduced and collected from an analysis based on stops of routes 603, 208, and 504. These characteristics are presented in Table 4.8. Lengths and widths were measured using the "measure distance" tool from Google Maps, which can only be used with satellite view and, consequently, interfered negatively in some cases.

For example, when the shelter was covered by trees or when the colour distinction between the shelter's rooftop and the pathway was not clear enough, the measurements could not be clearly determined. Additionally, it should be noted that the used method is not very precise and that an error in the measurements should be considered. Therefore, while the pathway width and the number of alternative stops estimations include data from 24 stops, the shelter area estimation considers 19 stops given the explained difficulties.

Table 4.8 – Collection of stop's pathway widths, shelter's dimensions, and number of alternative stops distinguished by colour groups using conditional formatting.

STCP route	**Stop's name**	**Pathway width**	**Shelter's Area**			**Number of alternative stops**
			Length	**Width**	**Area**	
603	Marquês	1.32	-	-	-	9
	Constituição	2.07	no shelter			4
	Covelo	2.29	3.71	1.25	4.64	7
	Igreja de Paranhos	10.36	3.71	1.3	4.82	3
	ISEP/AGRA	2.36	-	-	-	3
	I.S.E.P	2.58	-	-	-	1
	Ilha Brava	2.73	3.52	1.19	4.19	3
	S. Tomé	2.75	no shelter			5
	IPO (Circunval.)	1.62	-	-	-	8
	Hosp. S. João (Urgência)	11.56	16.33	2.43	39.68	13
208	Av. Aliados	6.91	no shelter			14
	Trindade	5.15	3.67	1.37	5.03	5
	Pr. Filipa de Lencastre	4.29	3.67	1.27	4.66	12
	Gui. G. Fernandes	3.16	8.2	1.29	10.58	8
	Carmo	1.2				8
	Hosp. S. António	4.21	7.69	1.17	9.00	5
	Palácio	3.75	10.07	1.3	13.09	3
	Pr. da Galiza	3.44	4.3	1.84	7.91	4
	Boavista - B. Sucesso	4	no shelter			8
504	Boavista - Casa da Música	3.53	7.82	1.4	10.95	8
	Agramonte	4.23	3.67	1.15	4.22	1
	António Patrício	7.95	2.61	1.3	3.39	3
	Casa das Artes	3.65	2.61	1.3	3.39	2
	Jardim Botânico	3.17	3.67	1.77	6.50	2

For the third, sixth, and seventh columns a conditional formatting based on a colour scale was performed to distribute the different values into groups. The ascendent colour scale was divided into shades of green (lowest values), yellow, orange, and red (highest values), each colour matched a group. Regarding the shelters area, two additional groups were created.

Firstly, Table 4.8 shows how, in urban centres, it is usual to find stops without shelters, and so, the "no shelter" group was included. Given the discrepancy between the bigger area (39.68 m^2) and the second bigger area after that one (13.09 m^2), the stop Hosp. S. João (Urgência) was not included in the conditional formatting, and it was highlighted in blue. This is the second additional group, since it is a particular case justified by its surroundings. That stop is located on the ring road that delimits the municipality of Porto, next to a hospital and in a university area. Even though it is not very common, it would be a reasonable representation of an area with a lot of access and demand.

After separating the groups, its average value and proportional number of stops out of all stops considered were determined. Table 4.9 presents the obtained results for the different attributes. When translating these results into the illustrative case, the percentage of the total number of stops should be applied considering the number of stops created. To exemplify, out of the 24 stops, 38 % of the pathways' width should be 2.10 m. A special attention was given to the network connectivity points as they share the same location and, consequently, the same stop's characteristics.

Table 4.9 – Proportions of this and that for the illustrative case

Groups	**Pathway width**			**Shelters' area**			**Alternative modes**		
	Width (m)	Nº stops	Total nº of stops (%)	Area (m)	Nº stops	Total nº of stops (%)	Alternative stops	Nº stops	Total nº of stops (%)
green	2.10	9	38	3.80	4	21	3	11	46
yellow	3.74	10	42	4.79	4	21	5	3	13
orange	6.67	3	13	7.80	3	16	9	7	29
red	10.96	2	8	11.54	3	16	13	3	13
blue	-	-	-	39.68	1	5	-	-	-
no shelter	-	-	-	-	4	21	-	-	-

4.3.7 Access

The *access* table allows to compute the accessibility indicators (A_{MP} and A_{EP}) as it provides, for each stop, the number of people that live in a 900 m and 600 m radius, respectively. To correspond exactly to the indicators' definition, both mentioned distances should coincide to the walking distance. However, given the available tools, considering the radius was the best option to emulate reality. Accordingly, the first step was to identify the stops from the sections, already considered, of STCP routes 200 (route A), 204 (route B), and 504 (route C). The *access* table and the *stops* table share a "one to one" relationship since for each stop there is a correspondent tuple in the *access* table.

The access data was defined based on the 2011 census, to collect the population data, and on a Geographical Information System (GIS) software, to identify the areas around each station (buffers). Figure 4.4 shows the 600 m scenario on the left and the 900 m scenario on the right. For each area, the respective resident population was quantified per age group. For the 900 m scenario, it corresponded to ages from 14 to 64 years old, and for the 600 m scenario, it corresponds to ages above 64 years old, as each indicator describes. Each resident population was multiplied by the proportion of the blocks' area. Finally, each proportion of resident population was incremented according to its stop, resulting in the values introduced in the database *access* table.

For the stops that are identified as connectivity points in the designed network an adjustment was made: stops 5 and 22, stops 11 and 20, and stops 7 and 16 (Figure 4.1). These should share the same number of people as they represent the same location in the illustrative case. Therefore, the average between both real stops values was the one included in the database for each set of stops. These sets of stops are not resumed to only one stop due to simplifications and to the demand aspect, that is explained in the following subsection.

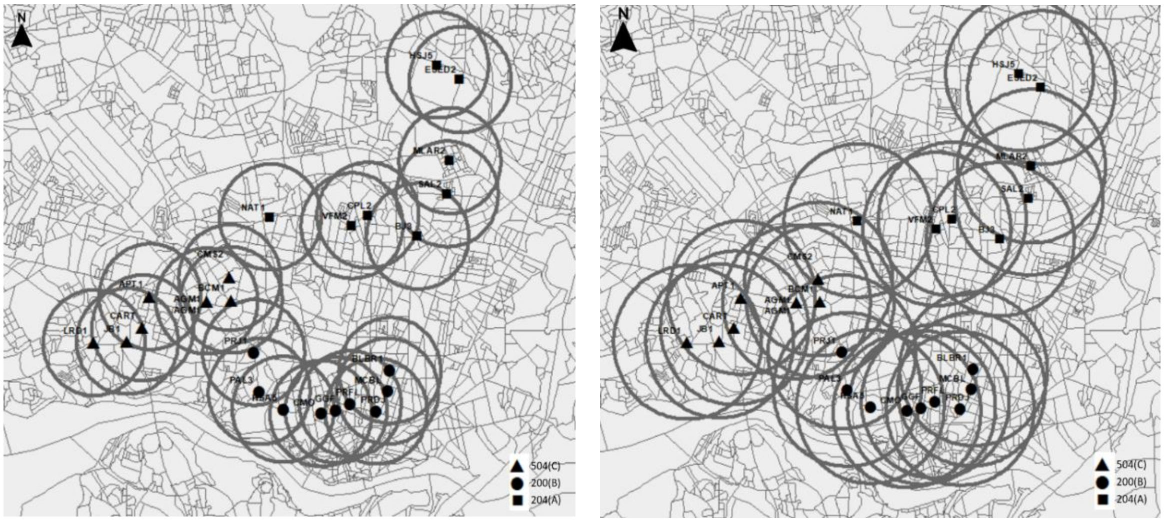


Figure 4.4 – Delimited Porto's subsection and respective stops buffers (on the left for 600 m and on the right for 900 m).

4.3.8 Demand

The *demand* table was created to support the transport efficiency *SD* indicator. As demand depends on time, the registered time (timestamp data type) and the respective demand were considered to characterize it. Therefore, for each stop there is more than one demand registry.

The stops used for the *access* table data collection were also used here. The data was collected from a transport validation set from 2013, that registered the number of validations every half an hour during 24h for every STCP stop [53]. To complete this dataset, five weekdays were collected, resulting in 240 registries for each stop of the illustrative case.

4.3.9 Paths

The *paths* table represents the passengers' travels and provides information to determine a few indicators such as the congestion level (*CL*), the travel delay (*D*), the average speed (*AS*), the occupation rate (*OR*), and the travel tickets price (*TTP*). Each tuple corresponds to a path and is characterized by the start time of the path, its duration (while travelling), its waiting time (only applied to indirect trips), its congestion level, its occupation (average number of people in that travel), and its passenger. A stop is associated to more than one path and a path is associated to more than one stop. Its attributes are the path identification, its start stop, end stop, and intersection stop (when it concerns an indirect trip).

To represent the use of the defined routes, 120 paths were associated to a total of 14 passengers. Each set of start and end stops was used more than once with different start times to emulate the reality of commuting, the most common use of a public transport service. To allow some consistency among data, both the travel's average occupation and its congestion level were randomly assigned in accordance with the start time, whether it was a peak period or an off-peak period.

Regarding time, the travel's duration was determined depending on the type of period, as an arbitrary delay was created based on the planned time of that travel. For the waiting time, that represents the time a passenger spends waiting for the bus of the second part of their travel, the values were randomly assigned with close attention to not register them above the defined route's frequency.

4.3.10 Passengers

The *passengers* table was used to collect information directly related to the passengers such as their perceptions of comfort, security, and reliability, while travelling or waiting for a bus, as well as their household income and public transport expenses. Such data is used to estimate the *passengers' satisfaction* indicators and the *affordability* indicator, respectively.

The attributes related to the passengers' satisfaction were randomly assigned using a qualitative scale ranging from 1 to 5. For the passenger's income, the considered value range was from 700 €, the minimum legal income registered in 2019, and 2500 €, the threshold income value considered for most people preferencing and using private transport. Regarding the *affordability* indicator, additionally to the income, passengers' expenses are also required. These were determined based on the *paths* table, and respective number of zones crossed by each passenger travel.

The choice between using occasional tickets or purchasing the monthly signature usually depends on number of trips the passenger plans to travel per month. Thus, in the STCP service, there are occasional tickets (1.20 € for two zones and 1.60 € for three zones) and monthly signatures available. The monthly signature standard fee is 30 €, excluding social group discounts. This fee includes a maximum of three zones, that matches the number of zones in the illustrative case. Hence, these values were used for this work.

If the passenger's commuting includes one or two zones, the monthly signature was applied, as it compensates when the number of travelled trips equalled seven or above per week. When it includes three zones, the monthly signature was applied if the number of travelled trips equalled five or above per week.

4.4 Reference values for normalization process

This section presents the defined references to use for the re-scale normalization (explained in section 3.3) of the quantified indicators of the illustrative case. Due to the extension of the designed network and the multiple data sources and estimations used, the references must be determined in accordance with those values in order to obtain valid normalized results. Hence, the following subsections introduce brief explanations on how the quantitative indicators from the economic dimension (4.4.1), social dimension (4.4.2), and environmental dimension (4.4.3) were determined. Accordingly, Table 4.10 presents the determined references of every dimension.

Table 4.10 – Reference values for the re-scaling process for every indicator.

Dimension	Criterion	Indicator	Unit	Reference values	
				Worst	Best
Economic	Economic productivity	PR_{CC}	%	80	332
		PR_{PC}	%	23	196
	Transport costs and finance	PE_{PT}	€	6.6	223.3
		TTP	€	0	2
	Transport efficiency	OR	%	30	100
		SD	passengers	0	53
		AM	modes	1	14
		F	1/minutes	0.167	0.017
Social	Safety	A	accidents	7	0
		A_{IP}	injured people	7	
		A_{D}	deaths	1	
	Accessibility	A_{MP}	people	2543	15083
		A_{EP}	people	329	2253
		A_{DP}	-	1	5
	Affordability	E	%	4	0
	Travel time cost	CL	-	5	1
		D	minutes	2	0
		AS	km.h^{-1}	6	30
	Passengers' satisfaction	PS_{C}	-	1	5
		PS_{S}	-		
		PS_{R}	-		
Environmental	Air quality	C_{NOx}	-	5	1
		C_{PM10}	-		
	Pollutant emissions	E_{NOx}	g.km^{-1}	26.3529	0
		E_{PM}	g.km^{-1}	1.4556	
		E_{COV}	g.km^{-1}	7	
		E_{NH4}	g.km^{-1}	6.8	
	Energy efficiency	EC	MJ.km^{-1}	29.9885	0
	Traffic noise	ND	-	5	1
		NN	-		
	Land use by transport	RD	km.km^{-2}	0	0.125
		PC	km^{2}	7.2	57.3

4.4.1 Economic dimension

Economic productivity

The STCP report used to deduce part of the dataset presents a comparison between their goals for 2019 and the actual values obtained for some indicators [47]. The EBITDA (earnings before interest, taxes, depreciation, and amortization) obtained value was 2 690 (10^3 €) and the goal was 4 328 (10^3 €). As this value can be determined by the difference between the total revenues and expenses, calculations were proceeded to determine the correspondent values of revenues, personnel costs (58.60 % of the total expenses) and capital costs (40.11 % of the total expenses).

The difference between the two EBITDA values was determined, and half of that difference was added to the 2019 total revenues and the other half was subtracted to the 2019 total expenses. This assumption allowed to obtain a set of revenues and expenses values coherent with the aimed EBITDA value. The same percentages assigned to each route (Table 4.4) were used, and both indicators were determined for each route. The worst and best percentage for the capital costs profit rate (PR_{CC}) were 80 % and 332 %, respectively. Regarding the personnel costs (PR_{PC}) the worst and best percentage determined were 23 % and 196 %, respectively.

Transport costs and finance

The investment received by STCP in 2019 was the highest (16 300 (10^3 €)) compared to the previous years (2018 and 2017) [47]. In 2017, the total applied investment was 428 (10^3 €), the lowest value. When making the same proportion for the three route network and dividing it equally, a total of 6 600 € would be associated to each route, that is considered as the worst reference for the PE_{PT} indicator. For the best reference, the highest value was applied with an equal distribution resulting in 223.3 (10^3 €) per route.

Regarding the average transport ticket price (*TTP*) indicator, a best reference of 2 € and worst reference of 0 € were considered. Since the total number of zones delimited in the created network is three, it is not possible to obtain a value higher than 2 €. The worst reference translates no travels on the specific route during a particular period.

Transport efficiency

If the occupation rate (*OR*) is 100 % then the operator is transporting the vehicle's full capacity, which represents the optimal value from the company's perspective. Therefore, this value was considered as the best reference. However, the STCP annual average occupation in 2019 rate was 14.3 % [47]. This value may not represent their losses. Hence, the worst reference considered for this indicator was 30 %.

To determine the stops' demand (*SD*), a sample of the stops of the illustrative case were assessed. The highest average value found was 53 passengers, which was, therefore, associated to the best reference. The worst case possible is no demand at all, and since some values were close to zero, this was considered as the worst reference.

For both the frequency (*F*) and alternative modes (*AM*) indicators, the references were chosen based on the previous analysis when selecting the STCP routes and stops characteristics (subsections 4.3.1 and 4.3.6). Thus, for every frequency (including the 5 initial routes) and for the alternative modes registered, the minimum and maximum values were chosen to represent the worst and best references, respectively. These are presented in Table 4.10.

4.4.2 Social dimension

Safety

In the *safety* criterion, the optimal situation is always to not suffer an accident and, consequently, no injured people or deaths. These were considered the best references for all the safety indicators (A, A_{IP}, A_D). Additionally, the lost of a single life is the worst reference for indicator A_D. For the remaining indicators and respective worst references, the created data of the illustrative case was used. A total of 20 accidents and 20 injured passengers distributed for the 3 routes at the different type of periods. The total divided by the 3 network routes corresponds to approximately 7 accidents and injured people per route. Since the developed tool evaluates the peak periods and the off-peak separately, 7 was adopted as the worst reference for both A and A_{IP} indicators as presented in Table 4.10.

Accessibility

For both *accessibility* indicators that consist of the resident population in a certain area, the best and worse chosen values were determined out of all obtained values for the networks stops (subsection 4.3.7). Accordingly, for the accessibility of the majority of people (A_{MP}), 15 083 was the highest value found and 2 543 the lowest. For the accessibility of elderly people (A_{EP}), the highest value is 2 253 and 329 is the lowest. These are displayed in Table 4.10.

Affordability

By comparing the expenses with the income per passenger, it is noted that it takes a very low percentage of the income to afford public transport. Nonetheless, the worst reference for the affordability indicator (E) was based on the minimum income (700 €) and the monthly signature (30 €), which resulted in 4 %. Considering that this indicator is related to social concerns and less expenses is the greatest situation for people, the best reference considered was 0 %, that means free public transport.

Travel time cost

The smaller the delay of a travel, the more reliable the route is. Ideally, a travel will suffer no delay making it the best reference. On the other hand, a delay of 5 minutes can negatively affect the passenger, for instance, in case of an indirect travel. However, the delays generated in the dataset were small, and consequently, the worst reference considered for delay (D) was 2 minutes.

Regarding the average speed indicator (AS), the same approach adopted for the frequency (subsection 4.4.1) was used. From the STCP route analysis, the lowest and the highest speed values were selected. Still, as the waiting time is considered in the average speed indicator, this decreases the speed value a lot comparing to the minimum value of 9 km.h^{-1}. The maximum waiting time is approximately 30 minutes (determined with the inverse of the frequency data). During this time there is no progress regarding the travelled distance, and so, when added to 9 km.h^{-1}, the speed decreases to 6 km.h^{-1}. Accordingly, for the AS indicator, this is the worst reference considered and the best is 30 km.h^{-1} (approximately the average speed of route 603 during the off-peak period).

4.4.3 Environmental dimension

Pollutant emissions and energy efficiency

Regarding vehicles' pollutant emissions, it is known that electric vehicles do not emit emissions and, therefore, the best reference is zero as well as for the energy consumption indicator. For the worst reference of each *pollutant emissions* indicators and energy consumption (EC), the same Excel document provided by the European Environment Agency and used to determine the emissions values was consulted (subsection 4.3.5). For this purpose, the vehicles fleet characteristics previously defined were used.

Land use by transport

For the routes' density indicator (*RD*), the data used to determine such indicator was analysed. The area defined in the description of the indicator (Table 3.4), that is later multiplied by the number of stops, corresponds to approximately 2.54 km^2 and the average kilometer extension of a route is 2.45 km, thus resulting in a very close proportion of 1 $km.km^{-2}$. Since the average number of stops is 8, the proportion of 0.125 (= 1/8) was considered as the best reference in order to create a suitable scale for the particular route densities.

The references for the indicator related to the pathway circulation (*PC*) were determined with the same approach used to estimate the references of the number of alternative stops (subsection 4.4.1). Hence, according to the collected data, the lowest pathway area available for pedestrian circulation was 7.2 m^2 (worst reference) and the highest area value determined was 57.3 m^2 (best reference).

Chapter 5

Preliminary results and discussion

Once the indicators were determined and re-scaled, the assignment of weights was the next step towards a sustainability index. This was determined for both peak periods and off-peak periods. For this illustrative case, the intervals were based on the analysis of the STCP routes' frequencies and respective type of periods. Accordingly, the peak periods are represented from 08h00 to 09h59 and from 16h00 to 18h59, and the off-peak periods are defined from 10h00 to 15h59 and from 19h00 to 23h59.

Firstly, the re-scaled indicators were aggregated into their respective criterion based on equal weights. To obtain the dimensions aggregated value, a similar procedure was applied to each criterion value with its respective weight (subsection 3.4.2). For the overall sustainability index the different weight scenarios (defined in subsection 3.4.1) were applied and compared. In every bar chart presented, each colour bar corresponds to a route. For a simpler visualization, the colours used match the ones on the network design (in Figure 4.1). These results are displayed and discussed from section 5.1 to section 5.3.

A further analysis was performed to understand and evidence the tool response to indicators value's variation within the defined references, by changing the indicators value for a specific route (subsection 5.3.1). Another completed analysis involved unequal weights at the indicators hierarchical level (subsection 5.3.2) and partial criteria with missing indicators (subsection 5.3.3) to understand its influence in the overall sustainability index.

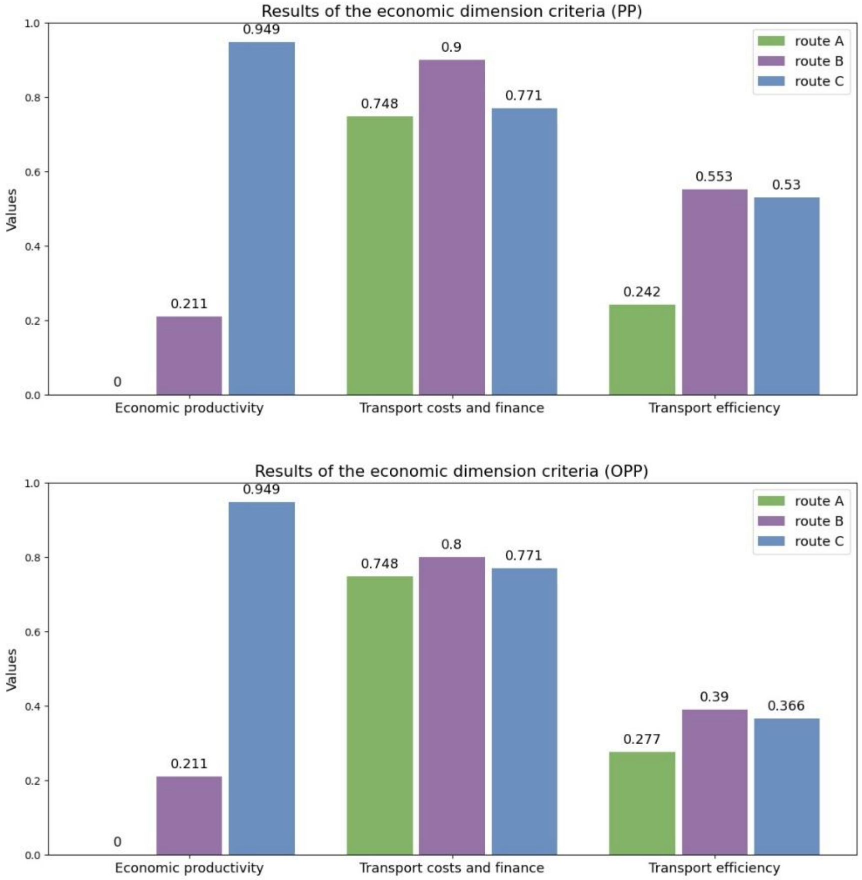
5.1 Sustainability criteria

As previously explained in section 3.2, some indicators and, consequently, criteria do not depend on time resulting in the same route's value for both type of periods. Thus, this is the case of the *economic productivity* criterion from the economic dimension, *accessibility*, *affordability* and *passenger satisfaction* from the social dimension, and *traffic noise* and *land use by transport* criteria from the environmental dimension. However, they were all included in each graphic.

5.1.1 Economic dimension

Figure 5.1 compares the obtained results of criteria from the economic dimension during peak periods (PP) and off-peak periods (OPP) for the three routes of the defined illustrative case.

As the *economic productivity* indicators are not influenced by time, the overall results show how there is a big discrepancy between the network routes. Route A performs so poorly, that it does not contribute to the sustainability level at all, as its indicators' values are lower than the estimated worst reference. Route C barely needs improvements regarding its *economic productivity* since it has a high value of 0.949. These results are consistent with the distributed percentages of the total values of revenues and expenses (Table 4.4 in subsection Routes). While route C outcome relies on a higher revenues' value compared to its expenses, both routes A and B have more expenses than revenues. Evidently, both revenues and expenses percentages of route A are lower than the ones associated to route B.


Results of the economic dimension criteria (PP)

Results of the economic dimension criteria (OPP)

Figure 5.1 – Results of the economic dimension criteria for peak periods (the top graphic) and off-peak periods (the bottom graphic).

One of the indicators from the *transport costs and finance* criterion (*TTP*) depends on time, and it is responsible for route B having a higher value during peak periods (0.900) compared to the off-peak periods (0.800). Hence, the travelled paths include more zones, making their average price higher during PP. Such difference was not observed for routes A and C. Within this criterion, the overall result shows that route B has a better performance, followed by routes C (0.771) and A (0.748), with very close values.

For each route, *transport effectiveness* results vary depending on its type of period, as three out of the four indicators depend on time. While route A has a better value during off-peak periods, both routes B and C share a better performance, around 50 %, during peak periods. The contextualization acquired from the development of this study allows to state that aspects such as occupation rate, stops demand, and frequency should be higher during peak periods. Consequently, route A becomes a focal point, as it is necessary to understand the sources of a considerable distinct and lower value compared to the other routes.

5.1.2 Social dimension

Figure 5.2 presents the results of the social dimension criteria. In the dataset used, more accidents occur at peak-periods rather than off-peak periods. Such circumstance is translated into the obtained results, as *safety* contributes better for the sustainability index during the off-peak periods. Even though the analysis priority is focused on route B, that has the lowest value during PP (0.381), this route has the highest *safety* index during OPP (0.856). Additionally, route C has the best overall performance of preventing accidents compared to the other routes.

For both *accessibility* and *affordability* criteria, route B has the highest values. Comparing both criteria and every route, *accessibility* results are considerably acceptable, while *affordability* requires more attention, as no route reaches half of the maximum value. Furthermore, route A has a comparable lower affordability result in relation to the other routes, that share approximate values.

Once again, the illustrative case is coherent with reality as the *travel time cost* criterion presents a better outcome for off-peak periods regarding both routes A and B. Naturally, as previously stated, the congestion level and delay are higher during PP and the average speed is higher during OPP. Accordingly, the main concern to interpret and solve would be discovering the reasons behind route's C lower index during the off-peak periods, that is also very close to the value determined for peak periods.

In the dataset, *passenger satisfaction* information was randomly generated and resulted in the index values displayed in Figure 5.2. These are noticeably good, yet when focusing on increasing passengers' satisfaction, one of the purposes of the tool can be evidenced. For each route, a more extensive analysis can be performed, due to its hierarchical structure and flexible implementation. Therefore, it would be possible to understand what aspect represented by the chosen indicators, such as security, comfort, and reliability, needs to be worked on more urgently.

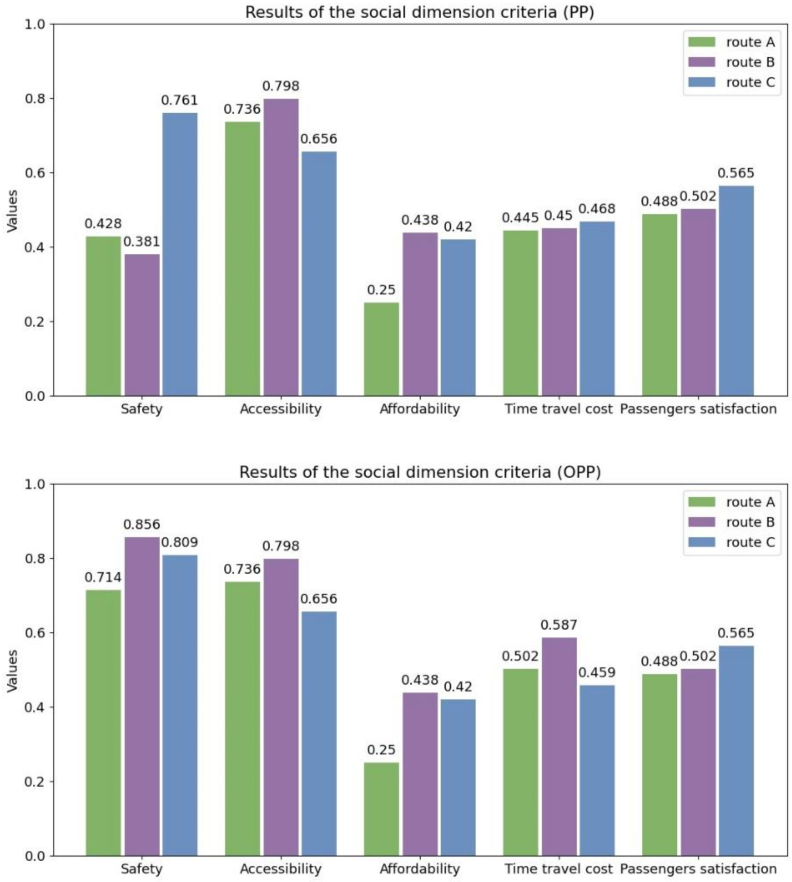


Figure 5.2 – Results of the social dimension criteria for peak periods (the top graphic) and off-peak periods (the bottom graphic).

5.1.3 Environmental dimension

The environmental criteria results are presented in Figure 5.3. The *air quality* results seem a bit odd as routes B and C present the exact index value for both type of periods. Thus, an additional code verification was performed to be sure that the respective function correctly collected and treated the dataset defined in subsection 4.3.2. Notably, it is not very suspicious to obtain similar values since the *air quality* assessment consists of qualitative intervals as well as air concentration depend on weather-related conditions, that could justify a small variation during the day. Route A has a variation of 0.125 between both type of periods and allows a higher contribution for the sustainability index during peak periods.

Regarding *pollutant emissions*, every route presents a better index level during the peak periods. Additionally, in both cases, there is a small variation between the routes' results. Despite the differences between both type of periods analysed, the obtained values are quite high, which may be related to the references used. As previously explained (in subsection 4.3.5), within the bus category, the worst value found for the type of pollutant emissions matched the defined worst reference. Hence, it could by argued that the vehicles considered for the illustrative case are fairly sustainable, compared with the worst scenarios determined by the guidebook published by the European Environment

Agency [51]. Thereby, an adjustment to these references through other criteria could be implemented and it would result on other indexes values.

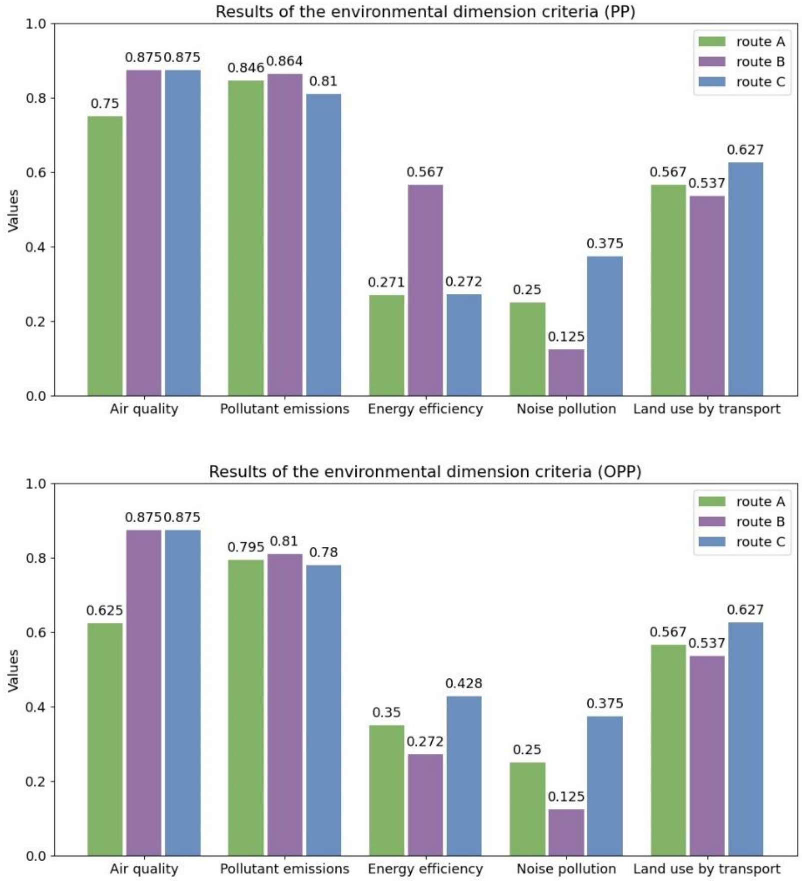


Figure 5.3 – Results of the environmental dimension criteria for peak periods (the top graphic) and off-peak periods (the bottom graphic).

Concerning *energy efficiency*, route B has the best performance during peak periods, while route A and C share a practically identical result. Yet, route B presents the lowest index value during off-peak periods. The obtained results depend only on the vehicles' association process (explained in subsection 4.3.4). However, if these index values resulted from a real network case, given the multiple factors in which *energy efficiency* depends on, it would be more difficult to analyse and determine the causes for the discrepancy between route B and routes A and C. Thus, the application of this tool would allow to find the focal start point on locating a sustainability issue and aid the discovery of alternative decisions to decrease routes' A and C energy consumption.

When ranking the routes for both *traffic noise* and *land use by transport* criteria, route C has the best contribution for the sustainability index, followed by routes A and B. While *land use by transport* outcomes are considerably good, an average above 50 %, *traffic noise* results are low with an average of 25 %.

5.2 Sustainability dimensions

After computing the criteria values, it was possible to aggregate each group of criteria to determine the dimensions indexes. Identically, Figure 5.4 presents these results for the three route and during each type of period. The results show that route A has the lowest values for every dimension in both type of periods analysed, evidencing its lack of sustainable performance, and suggesting that more attention for improvements is required when compared to the other routes.

Regarding the economic dimension, the ranking of the performances of the network routes follows the same order for both type of periods with route C at the top. The best route performance, considering the social dimension, depends on the type of period. During peak periods, route C is better than route B, and during off-peak periods, route B is better than route C. This results from route’s B better values of the *safety* and *travel time cost* criteria compared to route C, during off-peak periods. Within the environmental dimension, routes B and C have very similar results. While route B is better than route C during the peak periods, the contrary happens during off-peak periods. Additionally, this dimension has the best results.

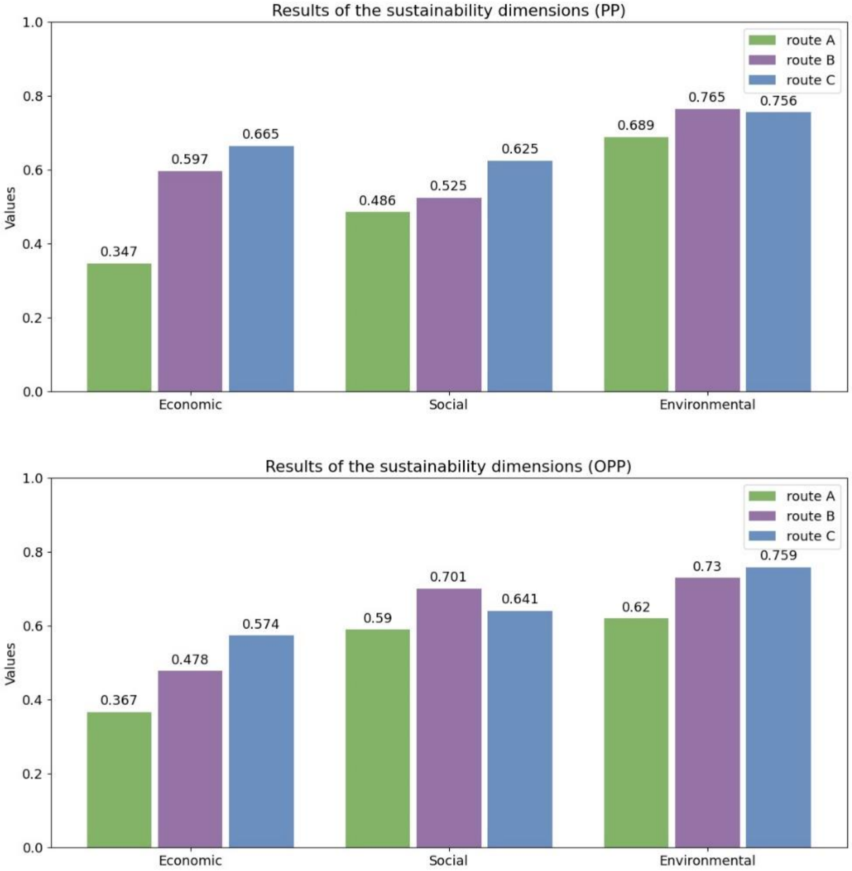


Figure 5.4 – Results of the sustainability dimensions for peak periods (the top graphic) and off-peak periods (the bottom graphic).

5.3 Sustainability index

The aggregation of the dimensions' values allows to determine the sustainability index by assigning a weight to each dimension. As the assignment of these weights can be defined according to the stakeholders' perspectives and interests, could change the results of the sustainability index significantly. Figure 5.5 represents the sustainability indexes of the routes using different weight scenarios, defined in the literature studies, previously identified in subsection 3.4.1.

Comparing both type of periods, the results demonstrate a small variation of the sustainability indexes for weight scenarios 1 and 2, while keeping the same ranking order. Distinctively, weight scenario 3 results in a higher sustainability index for route B during the OPP and a higher index for route C during the PP. The third weight scenario assigns a considerably high weight to the social dimension (0.66) and route B has the highest result of the social index during the off-peak periods, the sustainability index becomes slightly higher than route C. Unlike the other results that, even with different indexes, present the same ranking order, this situation demonstrates the influence of a different weight set.

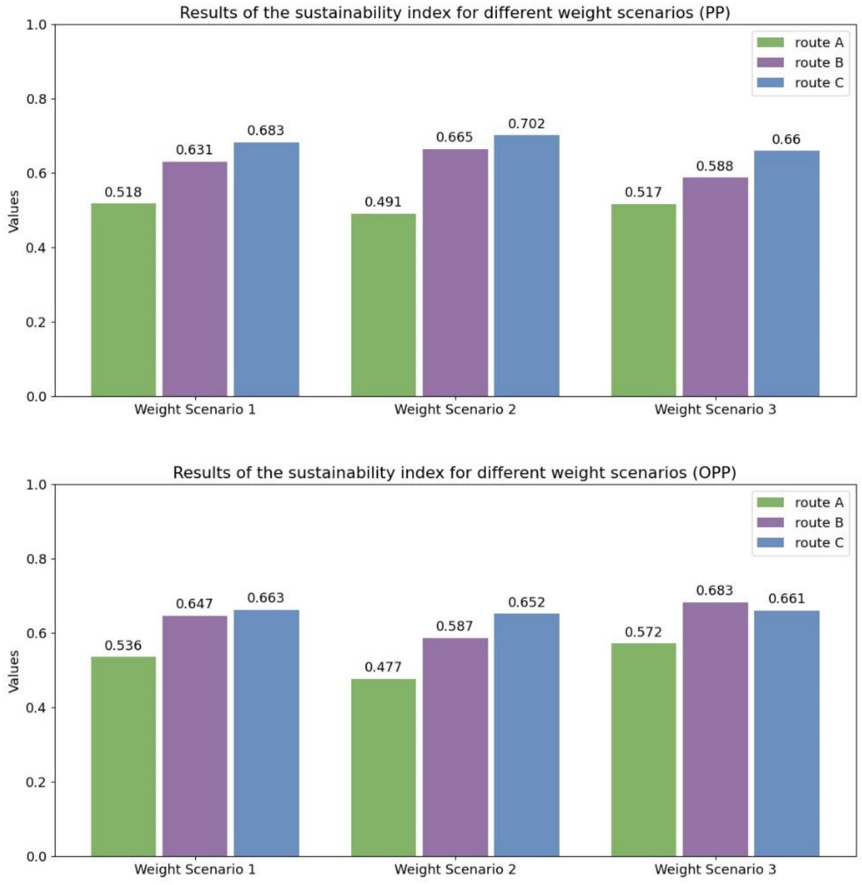


Figure 5.5 – Results of the sustainability index for different weight scenarios and for peak periods (the top graphic) and off-peak periods (the bottom graphic).

5.3.1 Variation of the indicators value

To demonstrate the indicator influence on the final sustainability index, an additional analysis was performed. This consisted of varying a certain indicator's value, or piece of information necessary to determine that indicator, and study the sustainability index response. Hence, this was applied to a specific route, type of period, and weight set for the dimension level. With the purpose of exemplifying, route A during the PP with the weight scenario 1 was considered.

The chosen indicators were public transport expenses (E) and the PM_{10} concentrations (C_{PM10}) from the *affordability* and the *air quality* criteria, respectively. Apart from belonging to different dimensions, these also contribute for their criteria with different priorities. While *affordability* is considered the third most important criterion of the social dimension, *air quality* has the highest weight assigned in the environmental dimension. The results are presented in Figure 5.6, the plot line on the left refers to the E indicator and the plot line on the right refers to the C_{PM10} indicator.

The public transport expenses indicator is quantitative and depends on both the passengers' income and expenses. Instead of varying the indicators value, while maintaining the same passengers' income of the created dataset, a variation of the monthly signature was applied. The variation range was from zero to 50 €, with 5 € as the interval between the values.

The plot line on the left in Figure 5.6 shows that the higher the monthly signature value is, which also increases the E indicator value, the lower the sustainability index will be. Once again, proving that the developed tool responds accurately to the dataset values and respective manipulation. Above 40 € as the monthly signature value, the sustainability index decreases with a less acute slope until 45 €, and from this value to 50 € there is no variation of the index result.

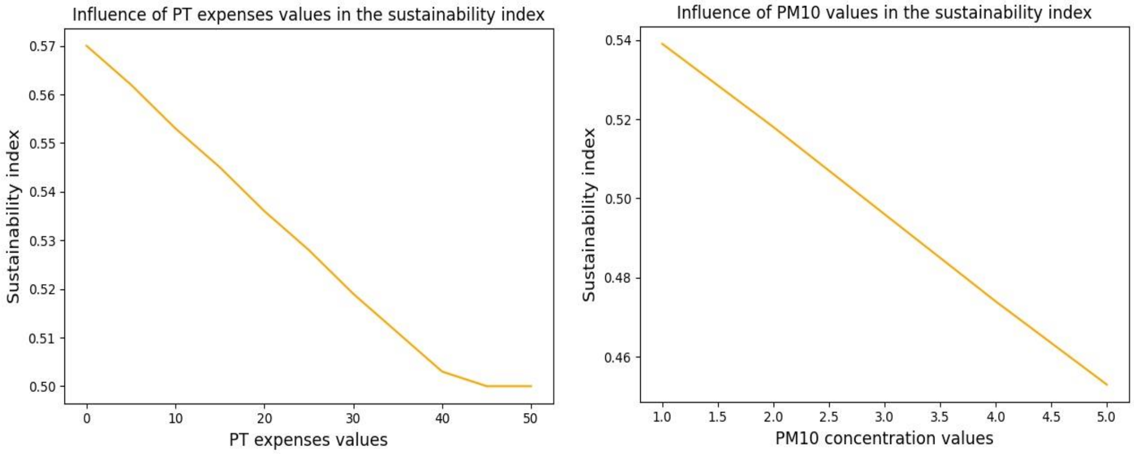


Figure 5.6 – Plot line that shows the influence of PT expenses values in the sustainability index (on the left) and plot line that shows the influence of PM10 values in the sustainability index (on the right) of route A during the peak period and considering the weight scenario 1.

As expected, the plot line on the right in Figure 5.6 shows how the higher the PM10 concentration level is, the lower the sustainability index becomes. This indicator is qualitative and, therefore, the analysis included every level of the scale. Since higher C_{PM10} indicator values negatively influence the sustainability performance of a route, this plot line proofs that the developed tool responds as it should.

5.3.2 Unequal weights at the indicators level

To perform a sensibility analysis of the model, an assessment of how unequal weights at the indicators level affect the sustainability index was conducted. Following the same perspective used in the previous analysis, different dimensions and criteria with different priorities were selected. For their respective indicators, unequal weights were assigned.

The analysis was performed to every route in the network to understand the variations according to the dataset. Each case is identified by UW_i where i corresponds to the numbers in the vertical axis in Figure 5.7. Every case considered the peak periods and the weight scenario 1. The following topics define the changed weights distribution for each case. The criteria not mentioned have the equal weights distribution at the indicators level.

- UW_0: equal weights in the indicators level (original result)
- UW_1: unequal weights for the *transport efficiency* criterion: a weight of 0.3 was assigned to the occupation rate (*OR*), 0.4 to the stops demand (*SD*), 0.2 to the alternative modes (*AM*), and 0.1 to the frequency (*F*).
- UW_2: unequal weights for the *safety* criterion: a weight of 0.2 to the number of accidents (*A*), 0.3 to the number of injured people (A_{IP}), and 0.5 to the number of related deaths (A_D).
- UW_3: combination of the unequal weights defined in cases UW_1 and UW_2.
- UW_4: combination of the case UW_3 and unequal weights for the *pollutant emissions* criterion: a weight of 0.3 for NO_x emissions (E_{NOx}), 0.3 for PM_{10} emissions (E_{PM10}), 0.15 for VOC emissions (E_{VOC}), and, suffering no change, 0.25 for CH_4 emissions (E_{CH4}).

In the case UW_1 only the *transport efficiency* criterion was affected by unequal weights, and when comparing to UW_0, its results suffer a small decrease for routes A and C. Yet, the sustainability index of route B does not change. Thus, these results suggest that the chosen distribution of weights applied to the least important criterion of the economic dimension does not significantly affect the sustainability index.

Regarding the social dimension, UW_2 consists of altering the weights of the *safety* criterion. For this case, the sustainability index of routes A (0.534) and C (0.691) increased. The preliminary cause for the registered increases is that there are no deaths related to the accidents that occurred in these routes and, consequently, half of the safety criterion is contributing its maximum value for the overall sustainability index. Hence, since there is a death resulted from an accident in route B, its index decreases from 0.631 to 0.619. Additionally, *safety* is the criterion with the highest priority in the social dimension.

As expected, by combining UW_1 and UW_2, the sustainability indexes slightly changed for case UW_3. While this consisted of an increase for routes A and C, for route B it consisted of a decrease. Overall, the values are quite similar, and it appears that unequal weights at the indicators level do not significantly influence the sustainability index.

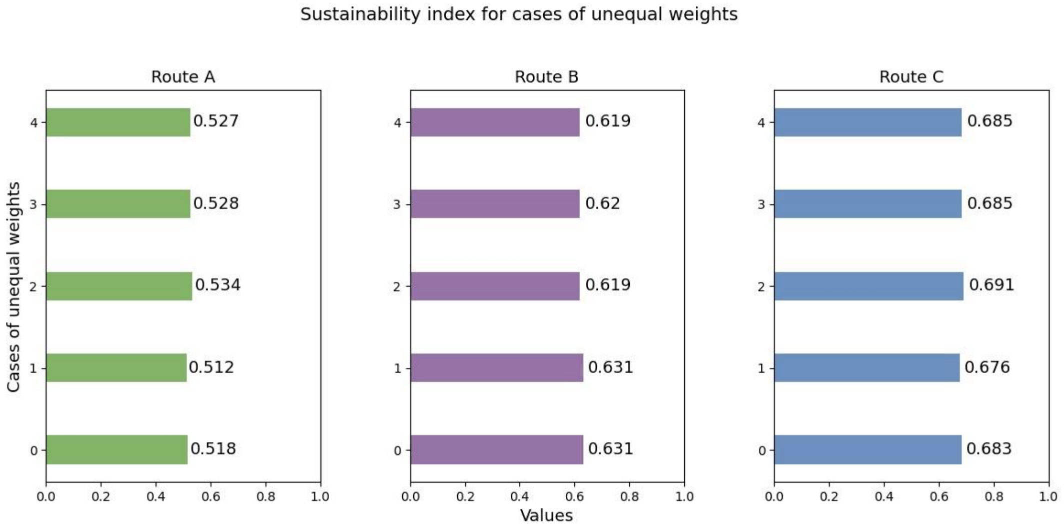


Figure 5.7 – results of the sustainability index for the described cases of unequal weights (UW_0 to UW_4).

By maintaining UW_3 and changing the assignment of weights of the indicators from the *pollutant emissions* criterion, UW_4 was created and tested. Even though this is the second most important criterion with a priority of 25.3 %, for every route there is barely a difference between the third and fourth cases (0.001 and 0), evidencing the small impact of the weights generated to exemplify this analysis. Nonetheless, multi-criteria problems imply trade-offs, and, in this context, the assignment of weights allows a more accurate assessment of the sustainability index.

5.3.3 Partial criteria

This analysis consists of understanding how the tool behaves when the criteria are incomplete. Thus, the sustainability index was analysed for different cases, that are described further. Even though the tool provides the flexibility to include only the desired indicators, this test aims to demonstrate how the tool should be used in a complete way.

This was performed to every network route considering the peak period and the weight scenario 1. At the indicators level, the initial equal weights were used, as the main results of the tool were also analysed under this condition. Figure 5.8 presents the obtained sustainability index for each case of partial criteria, identified by PC_i where i is the number of the vertical axis of this figure. The following topics define the excluded indicators for each case.

- PC_0: includes every indicator (original result).
- PC_1: in the *safety* criterion only the number of accidents (A) is included.
- PC_2: in the *economic productivity* criterion only the profit rate related to capital costs (PR_{CC}) is included.
- PC_3: combination of the cases PC_1 and PC_2.
- PC_4: in the pollutant emissions criterion only the emissions of NO_x (E_{NOx}) and emissions of PM_{10} (E_{PM10}) are included.

For the first case (PC_1), both routes A and C, the sustainability index decreased compared to the original value (PC_0). An initial analysis concludes that the increase of route's B index is due to not including its worst/minimum value of indicator A_D.

The change defined by PC_2 has no impact on the sustainability index of route A, as it equals the one obtained for PC_0. The achieved result was expected given the poor performance of route A considering the *economic productivity* criterion, that resulted on a null value. However, when performing a more complete analysis, the user would not identify the problem regarding the personnel expenses, as both indicators are not used in the *economic productivity* criterion. Distinctively, the sustainability index of both routes B and C decreased comparing to the original value. Particularly, route's C index for both PC_1 and PC_2 is the same (0.659).

The combination of PC_1 and PC_2 describes PC_3. As predicted, for route A the obtained value corresponds to the one that resulted from the second case. Comparing to the original value (PC_0), while the sustainability index of route B increased (from 0.631 to 0.645), route's C index decreased (from 0.683 to 0.635). This proves how every indicator influences the final result, and even though the tool under these conditions still provides the sustainability index, information that was found to be quite important towards the sustainability perspective is omitted.

To include the environmental dimension, an additional case, PC_4, was defined. This alteration resulted in a very small variation of the sustainability index for every route. Accordingly, when combined with PC_3, that defines PC_5, the obtained results are close to the third case sustainability index values.

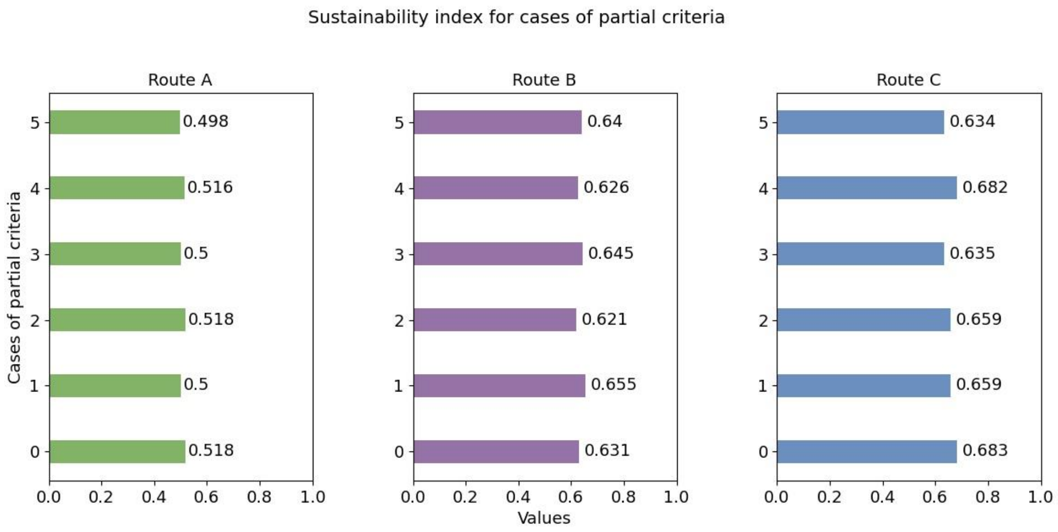


Figure 5.8 – Results of the sustainability index for cases of partial criteria (PC_0 to PC_5).

Chapter 6

Conclusions and future work

In this work, a tool was developed to support the design of public transport networks by assessing their sustainability performance. Overall, the preliminary results show the potential of this tool to address more realistic situations, therefore contributing to improving urban sustainability.

The tool allows a comprehensive, multi-criteria, and multi-level analysis of routes, that produces a single global sustainability index. Moreover, it is applied to both peak and off-peak periods in order to distinguish the different conditions related to each type of period, and to compare their respective sustainability indices.

The developed tool was structured hierarchically around three levels: dimensions, criteria, and indicators. For each sustainability dimension, criteria were defined as well as their respective indicators, that were selected from a literature review analysis. Given the different perspectives in this literature and the importance of the selection of the indicators, as they are the foundation of the sustainability index, this process was the most complex in the adopted methodology. Specifically, for both the dimensions and criteria levels, a more consensual perspective identified in the literature was followed.

The sustainability index was computed considering a total of 3 dimensions, 13 criteria, and 32 indicators. After the quantification of the indicators, that highly depended on their description, the re-scale of their values allowed the assignment of weights. Unequal weights were collected from the literature for the dimensions and criteria levels, while equal weights were assigned to the indicators level.

For validation and demonstration goals, the tool was applied to a simple illustrative case designed based on real data from a real public transport company, STCP that operates in the metropolitan area of Porto. The network of the illustrative case consisted of 3 routes, 24 stops, and 3 zones. Due to the extensive number of data sources required to create the dataset, some simplifications and data estimations were considered.

The application of the tool with the illustrative case allowed to obtain comparable sustainability indices for the route of the designed network and the defined type of periods (peak periods and off-peak periods). Due to the hierarchical structure of the tool, and consequently its flexibility, the results of the criteria and dimensions levels were analysed as well. This allows to identify and understand potential problems that negatively affect the sustainability index.

To further validate the developed tool, sensitivity analyses of alternative cases were performed. The assessment of the influence of the indicators values, or of the information used to determine them, on the sustainability index was confirmed by varying the indicators values while studying the sustainability result. Additionally, the contribution of unequal weights at the indicators level was analysed and its preliminary results do not show much influence on the final index. However, as the tool aims to solve a multi-criteria problem, it implies trade-offs, and thus it is always advantageous to assign weights. It was also demonstrated how the tool must be used in a complete way by including every indicator, as the lack of certain indicators may or may not change the sustainability index. Consequently, it may not evidence or identify possible problems.

Alternatively, creating different scenarios from the initial dataset became noteworthy for further analysis. Some preliminary tests were performed, however it was noted that the influence between data from different related aspects in the dataset was not covered. A certain detail and coherence were taken into consideration when creating the data, yet if something, like the number of accidents of a route, significantly changes, then what is the effect on the related information regarding the same route. Therefore, given the complexity to analyse these effects and the lack of time to implement them, this was not further explored in this dissertation.

Nonetheless, the main results from the preliminary tests were described in a research paper (Appendix B). The research paper was submitted to the 7th IEEE International Smart Cities Conference (ISC2 2021), that will be held as a virtual conference from 7-10 September 2021. This paper focus on the methodology adopted in this work, particularly, in the selection of indicators.

As future work, several issues should be explored. Regarding the development of the tool, further work could focus on the improvement of the assignment of weights, as it is always beneficial to properly define the trade-off when solving multi-criteria problems.

It would also be interesting to collect accurate and updated information related to a public transport company in order to apply the tool to a complete real network. This application could require a different data model, probably with less simplifications, and a new set of references for the re-scale normalization process. Nonetheless, this application could allow an extensive sensibility analysis to create and understand the relations and effects between the data, and consequently between the indicators.

Appendix A – Portuguese public transport contextualization

To help emulate a complete, close to reality, and useful example, three Portuguese public transport companies were studied: STCP that operates in the Metropolitan Area of Porto (AMP) [47], TUB from Braga district [48], and Carris that provides public transport in the Metropolitan Area of Lisbon (AML) [49].

To characterize the companies in terms of the operational and financial characteristics of the service provided to the society, the companies' public reports were analysed. These characteristics were selected based on the criteria and indicators previously defined. Table 1 outlines the information related to the three companies and to the year 2019. Even though the public information does not specify the evolution over the year, routes or stops of the network, it was used to deduce data for the illustrative case as it is explained later in chapter 4.

As shown in Table 1, the service area, and the kilometer extension, from the network characteristics subject, have an ascendent proportional relation. Differently, the same type of relation is not found regarding the number of routes since STCP has practically the same number (73 routes) as TUB (74 routes), while this company operates in a smaller area.

Also following an ascendent proportional relation, the bigger the served population is, the larger the number of passengers will be. Thus, Carris has the larger number of passengers and TUB the smaller. Both STCP and Carris share a very high passenger-km value. Specifically, passenger-km is the total number of kilometers travelled by passengers on vehicles, which is determined by multiplying the number of unlinked passenger trips times the average length of their trips [2] Therefore, through expression (1), it is possible to determine the average number of km travelled per passenger in Carris, that resulted in 3.51 km. Curiously, STCP determined an average of 3.75 km travelled per passenger, determining that STCP passengers travel a longer distance, when compared to Carris.

$$km\ travelled\ per\ passenger = \frac{passenger\ km}{number\ of\ passengers} = \frac{490\ 117}{139\ 496} = 3.51\ km \qquad (1)$$

Table 1 - Collection of specific data from STCP, Carris and TUB.

Subject	**Aspects**	**Companies**		
		STCP	Carris	TUB
Service Area	District	Porto	Lisbon	Braga
	Area (km2)	2 395	2 800	2 673
	Population (mil)	1 817 117	2 250 533	848 185
Network Characteristics	Km Extension	492	720	301
	Number of stops	2 484	-	1 861
	Number of defined routes	73	87	74
Passengers	Number of passengers	75 985 000	139 496 000	12 413 299
	Average km travelled per passenger	3.75	-	-
	Passengers.km (mil.)	285 269	490 117	-
Service Offer	Vehicles km of service (mil.)	22 065	30 924	-
	Occupancy rate (%)	14.3	21.33	10.82
	Average service velocity (km.h^{-1})	15.6	14.23	19.3
	Service completion rate (%)	96.2	98.14	99.91
Operational Activity	Passenger per vehicle km service	3.4	-	2.2
	Revenue per vehicle km service (€)	2.2	-	-
	Total tickets revenue (€)	47 497 000	106 792 000	7 071 499
	Revenue per passenger (€)	**0.625**	**0.766**	**0.570**
Fleet Size and typology	Standard	348	463	-
	Mini	8	33	-
	Medium	-	21	-
	Articulated	49	91	-
	2 floors	15	-	-
	Total	**425**	**608**	**136**
Fleets' Fuel	Natural gas	268	-	-
	Diesel	142	-	-
	Electricity	15	5	-
Energy Consumption	Natural gas (TOE)	9 633	-	-
	Diesel (TOE)	3 638	-	-
	Electricity (TOE)	53	-	-
Consumption Cost	Natural gas (€)	-	1 688 253	73 143
	Diesel (€)	-	15 878 032	2 646 332
	Electricity (€)	-	-	83 266
	Total (€)	-	**17 566 285**	**2 802 741**
Accidents	**Total**	**1290**	**1476**	**158**
	Accidents per million passengers	**16.98**	**10.58**	**12.73**
Complains	Driver	-	-	109
	Network	-	-	113
	Deficient Information	-	1 076	11
	Fleet	-	-	50
	Sales Outlets	-	169	13
	Irregularities	-	2 819	155
	Deficient Offer	-	120	-
	Maintenance	-	190	-
	Total	**2 378**	**4 754**	**451**
	Complains per million passengers	**31.30**	**34.08**	**36.33**
Financial Costs	EBITDA[2] (€)	2 690 000	14 835 000	724 071
	Bus mode maintenance costs (€)	-	12 683 233	-
	Total Expenses (€)	52 220 000	125 363 000	12 608 446
	Revenues (€)	54 909 000	127 658 000	12 339 831
	Profit rate (%)	**5.15%**	**1.83%**	**-2.13%**

---

[2] Earnings before interest, taxes, depreciations, and amortization.

Related to the service offer, the three companies admit a relatively low occupation rate. A proportional relation between the occupation rate and the population of each service area is highlighted, as the smaller the population is, the lower the occupation rate will be. The service average speed is approximately 20 km.h^{-1} for TUB, while for STCP and Carris is lower. Accordingly, it is possible to observe how the higher the number of passengers, the lower the service average speed is. Both the occupation rate and the service average speed are directly two of the considered sustainability indicators, which values cannot be used due to its macro level. They consist of an average annual value that includes every route and considers both peak and off-peak periods.

Fortunately, all three companies share a high completion rate. Carris determined two types of service completion rates, one referred to vehicle kilometer (the one included in Table , 98.14%) and the other to vehicle hour, that resulted in 99.72 % [49].

Within the operational activity subject, it is possible to compare the companies' total tickets revenues, where the difference between TUB and STCP is around 40 million € and between STCP and Carris is approximately 60 million €. To be able to understand better these disparities, the tickets revenues per passenger were determined by expression (2). As expected, its results (last line in the operational activity criterion of Table 1) evidence the same increased differences.

$$Revenues\ per\ passenger = \frac{Total\ tickets\ revenues\ (€)}{Total\ number\ of\ passengers} \tag{2}$$

The vehicle fleet that a company uses to provide the transport service plays an important roll in it. Hence, Table 1 exposes the fleet size and the respective number of vehicles according to their type. These were gathered from the STCP and Carris reports. Additionally, STCP provided the number of vehicles within the total fleet that are fueled with diesel, electricity, and natural gas. Out of the 425 vehicles, STCP has 268 fueled with natural gas.

For the respective types of fuel, the energy consumption was also included in Table 1. However, only STCP shared that data with the energy unit TOE (Ton of Oil Equivalent). Reasonably, the highest energy consumption value is associated to the vehicles fueled with natural gas, as these constitute more than 50 % of their vehicle fleet. However, to understand the average energy consumption per vehicle with different fuels, the total energy consumption was divided by the number of vehicles with a specific type of fuel. Annually, a natural gas bus consumes an average of 35.94 TOE and a diesel bus consumes an average of 25.62 TOE. Distinctively, an electric bus consumes 3.53 TOE. STCP also shares that a route's energy consumption per total passenger-km is 47 TOE [47].

Even though Carris and TUB did not provide energy consumption data, their reports shared their fuel consumption costs. As expected, due to each company service area, it can be noted a large discrepancy between Carris and TUB values. Regarding the types of fuel, diesel makes up approximately 90 % of Carris' total energy costs and 94 % of TUB's total energy costs. For Carris, both natural gas and diesel consumption costs were determined by the number of liters and the volume (Nm^3) consumed, respectively, multiplied by the defined average cost. While per liter the average cost was 1.053 €, per Nm^3 it was 0.407 €, which emphasises some economic leverage in investing on natural gas [49].

Related to accidents, the analysed reports do not expose the number of injured people or deaths suffered in each accident. While STCP and Carris only present the total number of accidents, TUB opted to distinguish them into collisions, falls, and occurrences resulting in 99 collisions, 5 falls, and 54 occurrences [48]. Even though, Carris has the highest number of accidents, STCP has the highest number of accidents per million passengers, making it the company with the worse situation (in 2019) regarding the safety criterion.

A way to gather some information about the passengers' satisfaction is to analyse the number and topics of the claims made about the transport service. Unlike STCP, that only shared the total number of complains, Carris and TUB divided them into different topics. To compare the three companies, the number of complains per million passengers was determined, and it was concluded that TUB has the highest number of complains.

Practically half of Carris' complains are related to irregularities and the report states that these are directly associated to congestion [49]. Regarding TUB, its irregularities' complains refer to inspections, titles of transport, strikes, disorders, cleaning, internet, and information [48]. In Carris, another popular type of complain was deficient information, mainly related to providing false information, for instance, on the new Carris mobile application [49]. Additionally, Carris obtained a passengers' satisfaction index of 6.86 points in a scale of 1 to 10.

Finally, some financial data was collected from the reports. The focus was on the required values for the determination of the public transport profit rate. Thus, with the total monetary value of revenues and expenses, it was possible to determine the annual network's profit rate, which is shown in the last line of Table 1. STCP has the highest profit rate with 5.15 % and TUB is accentuated by its negative profit rate.

Appendix B – Research paper

A multicriteria evaluation tool for designing sustainable public transport routes

Joana Santos
Faculty of Engineering,
University of Porto
Porto, Portugal
up201606208@edu.fe.up.pt

Tânia Fontes
INESC TEC
Porto, Portugal
https://orcid.org/0000-0001-5183-5321

Jorge Pinho de Sousa
INESC TEC / Faculty of Enginneering,
University of Porto
Porto, Portugal
https://orcid.org/0000-0002-9292-0386

***Abstract*—Public transport negative externalities have been increasing over the past years with a growing concern on their elimination and minimization. One way to address this problem is to design public transport networks based on an integrated assessment of its sustainability performance. Thus, the main goal of this work is to develop a tool to accomplish a multicriteria evaluation of public transport routes regarding the three main sustainability domains: economic, social, and environmental. An analysis structure has been developed based on a hierarchical relation between domains, themes, and indicators. Accordingly, for each domain, a selection of indicators within different chosen themes was performed. Each indicator was quantified before the assignment of the themes and domains' weights. This assignment was based on the literature, and subject to a sensitivity analysis. The tool was applied to a demonstration case with three routes, based on a bus company operating in Porto's area (Portugal).**

Keywords—public transport, sustainability, indicators, routes' design

I. INTRODUCTION

According to the United Nations, 68% of the world population will live in urban areas by 2050 [1]. The increase of urban population will, rise the mobility levels of people.

Although public transport is essential to society for many decades, it has several important negative externalities [2]. Such externalities include pollutant emission, energy dependency, accidents, noise, and traffic congestion [3]. Thus, a sustainable transport infrastructure that targets economic development, environment protection and social equity should have the ambition of optimizing the use of transport systems to accomplish economic, social, and environmental goals, without preventing the ability of future generations to do the same [3].

To manage resources efficiently, cities need tools that can estimate, sustainability indicators, particularly concerning the design of routes for public transport. This development requires a multicriteria approach to balance the sustainability domains. For this end, decision-makers must have access to all possible information related to the city's environment, the public transport system and its social usage and costs, as well as to their direct and indirect impacts [2]. This information will contribute and justify selecting certain criteria, as a basis for a successful creation of a tool to support decision-making.

Unlike other researchers, Sdoukopoulos et al. [4] extensively studied sustainability indicators, themes, and their application, with a literature review covering 2644 indicators included in 78 studies. Out of these, only three studies are related to the road axis/corridor level. The average number of indicators proposed by these three studies is 13 [4].

The Texas Transportation Department proposed similar indicators for measuring the sustainability performance of a road corridor [6, 7]. Zietsman et al. [5] focused on freeways, while Ramani et al. [6] applied their methodology highway corridors. In addition, Svensson et al. [7] argue that multi-functional arterial streets, as people use those streets for different activities, should be designed and managed as such. Therefore, a group of indicators for street sustainability performance was included in their methodology. Gazis et al [8] also assessed the sustainability of a route. However, the indicators they propose are only focused on pollutant emissions and is only applied for private road transport.

Most studies regarding sustainability indicators include a lot of aspects related to urban mobility [4, 9–11]. Given the public transport context, these studies consider, in general, a much more extensive range of aspects. Focusing only on the sustainability level of public transport, a couple studies have been analysed [12, 13]. A common characteristic of these studies is their macro perspective.

This work proposes an assessment method for public transport routes (micro approach) based on a multicriteria evaluation of different sustainability domains. This approach combines several indicators relevant for each sustainability domain and considers the respective trade-offs and constraints. To demonstrate the applicability of the global indicator proposed, three public transport routes were used.

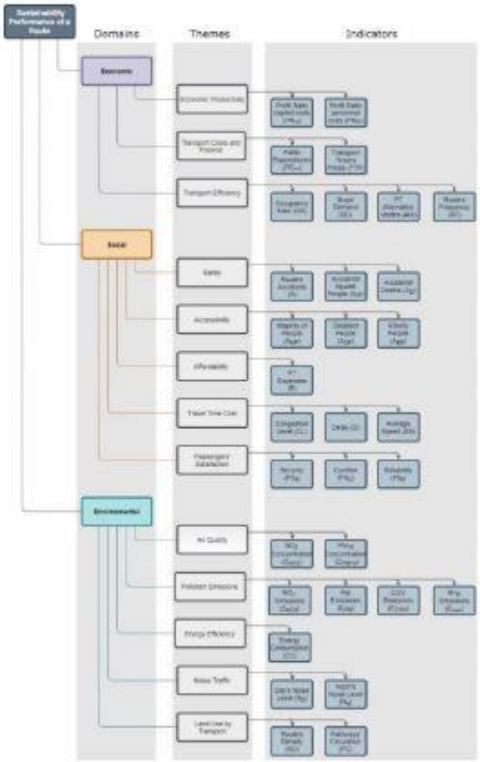


Fig. 1. Indicators model.

II. ADOPTED METHODOLOGY

In this work four steps were pursued: (a) selection of indicators; (b) quantification of indicators; (c) scale normalization; and (d) assignment of weights. The selection of indicators was based on an extensive literature review (II.A). Then, data from different sources was collected and treated (II.B), and scales normalised (II.C). Last, as transport network design problems are of a multicriteria nature, weights have been assigned to the each hierachical level (II.D).

A. Selection of indicators

The studies analysed have considerably different perspectives on the type of elements to use in a hierarchical structure to define a sustainability indicator. Some authors consider domains that contain themes/elements, which will accommodate one or more indicators [4, 10]. Others relate the indicators directly to the chosen domains [9, 11–14].

Most of the studies consider the economic, social, and environmental sustainability dimensions as their domains [4], [11–14]. However, a group of studies opted to broaden their domains to include other aspects, for instance, fiscal and political aspects [9, 10] or system effectiveness [12].

In our study, we propose a hierarchical structure including "domains" (1st level), "themes" (2nd level), and "indicators" (3rd level). As the fundamental idea behind the model proposed is the sustainability concept, the three sustainability domains defined in the Brundtland Protocol were used. Even though each theme is connected to only one sustainability domain of the model, every theme can influence, directly or indirectly, all the domains. To allow a simpler visualization and understanding of the model, only the strongest and most evident connections were represented, (Fig. 1).

The selection of the themes and indicators was based on a recent literature review study conducted by Sdoukopoulos et al. [4] and other studies [8–12]. Next subsections present the selection of indicators and themes used in each domain.

Economic indicators

Within the road axis/corridor level, no economic themes were identified by the literature review conducted by Sdoukopoulos et al. [4]. However, considering the urban and regional/national level, *economic productivity* is considered in 31 % of the studies and *public expenditures, investments and subsidies* is considered in 45 %. Additionally, themes such as *transport costs and prices* and *transport efficiency* are included in 26 % and 27 % of the proposed studies, respectively [4]. For each economic theme identified, a literature review was conducted to identify the most popular indicators. Table I presents these results.

TABLE I. MAIN ECONOMIC THEMES AND INDICATORS.

Reference	Economic productivity	Transport costs and finance	Transport efficiency
Our study	PR_{CC}, PR_{PC}	PE_{PT}, TTP	OR, SD, AM, RF
[9]	PR	PE_{TS}, FPT	OR_{PV}
[4]	OC_{PTS}	PE_{TS}, FA	OR_{PV}, MM
[10]	-	PE_{TS}, TF	OR_{PV}, MM, F
[11]	-	-	-
[12]	OC_{PTS}, CR	-	OR_{PV}, PTT, MS, FS

Economic Productivity: PR_{CC}: profit rate related to capital costs; PR_{PC}: profit rate related to personnel costs; OC_{PTS}: operational costs of the public transport system; PR: ratio of public transport revenues to the respective maintenance and operation cost; CR: proportion of costs recovered.

Transport costs and finance: PE_{PT}: public expenditures on public transport; TTP: transport ticket prices; PE_{TS}: public expenditures, subsidies, and investment in transport system; FA: financial autonomy (scale 1 to 5); FPT: fuel prices and taxes; TF: transit fares.

Transport Efficiency: OR: occupation rate; SD: stop's demand; AM: number of alternative stops/stations within a 300 m walking distance; RF: route's frequency; OR_{PV}: occupation rate of private passenger vehicles; MM: multimodality integration level; F: transit service frequency; PTT: annual public transport trips per capita; MS: public transport mode split; FS: public transport fleet size.

The "ratio of public transport revenues to the respective maintenance and operation cost" (PR) is the most common indicator related to *economic productivity* [4]. However, operating costs spent on the public transport system (OC_{PTS}) [10, 13] and the proportion of the recovered costs (CR) [12] are also common economic indicators. Hence, within the *economic productivity* theme the main idea for its indicator was the profit rate in a similar way as indicator PR determines it. However, this indicator was divided into two, since two categories of costs stand out [15]. Thus, personnel costs, as the biggest proportion of the total costs, originated the PR_{PC} indicator, and capital costs, as another significant proportion of the total costs, originated the PR_{CC} indicator.

Considering the *public expenditures, investments and subsidies* and the *transport costs and prices* themes identified by Sdoukopoulos et al. [4], we created the transport costs and finance theme. Within these themes, the most popular indicator is the public subsidies invested in a transport system (PE_{TS}) [4, 9, 10]. Due to the high percentage of studies in the literature that use the public expenditure's theme [4], this indicator was adjusted for public transport (PE_{PT}). Related to finance, Medina et al. [9] assessed the financial autonomy (FA). Sdoukopoulos et al. [4] also found the fuel prices and taxes (FPT) to be a common indicator related to *transport costs and prices*. From the passenger's perspective, Lima et al. [10] considered transit fares (TF), that was adapted into the indicator transport travel tickets (TTP).

Transport system efficiency is considered by researchers in different ways. For example, De Gruyter et al. [12], additionally to the sustainability dimensions, have created system effectiveness as a specific domain.

Within the *transport efficiency* theme, the most popular indicator in the literature is the occupation rate of passenger vehicles (private) (OR_{PV}) [4, 9, 10, 12]. This supported the creation of the OR indicator which consists of the occupation rate of the public transport vehicles. If a bus travels a particular route that has a low occupancy rate, it can be shown that, possibly, by adopting an alternative route or adapting certain route characteristics, the route will satisfy more demand and, consequently, be more useful.

The more a person uses the public transport service, the more effective it is. Thus, based on the annual number of public transport trips per capita (PTT), proposed by De Gruyter et al. [12], we also included in our study the stops' demand (SD), as a *transport efficiency* indicator.

Even though transport efficiency is also related to multimodality integration (MM) [9, 10] and mode split (MS) [12], Sdoukopoulos et al. [4] did not find multimodality as a common theme according to their literature review. However, when people use a transport service that cannot reach the wanted destination, it will be advantageous if that service provides connectivity points with other motorized or active modes. That way, the use of combined modes will increase the possibility of people reaching their destinations. Therefore, the number of alternative stops/stations from a stop within 300 m was considered as an indicator (AM).

Finally, Lima et al. [10] considered the transit service frequency (TF) and De Gruyter et al. [12] added the public transport fleet size (FS). As time is rather important in transport services, their system efficiency may be affected by the frequency of a certain route. Therefore, the route frequency (RF) is an indicator related to the occupation rate, time of the day or traffic congestion.

Social indicators

Around 85% of the studies analysed by Sdoukopoulos et al. [4] between 1996 and 2018 consider the *safety* theme, not only at road axis/corridors level, but also for urban as well as regional/national levels. Alongside the *safety* theme, the mobility theme is included in 77% of those studies. *Accessibility* stands out for being considered in around 68 % of those studies, while *affordability* is included in 50%. *Travel time* theme is usually addressed considering commuting travel time, and average time spent travelling under congestion [4]. Even though, *passengers' satisfaction* was not a theme identified by Sdoukopoulos et al. [4], we found several works that highlight the importance to include it [9–11]. Like the economic domain, for each social theme, the most popular indicators are presented in Table II.

TABLE II. MAIN SOCIAL THEMES AND INDICATORS.

Reference	Safety	Accessibility	Affordability	Travel time	Passengers' satisfaction
Our study	A, A_{IP}, A_D	A_{MP}, A_{DP}, A_{EP}	E	CL, D, AS	PS_S, PS_C, PS_R
[9]	RF	A_{DP}, A_{500}	E_{itrip}	D_C, T_{IT}	S_{MS}, UE_{SI}
[4]	RF	$A_{300\text{-}500}$	E_{itrans}	T_C, T_{UCC}	PS_S
[10]	A	A_{DP}, AC	UE_{trans}	CL, AS	S_{MS}
[11]	A	A_{DP}, A_{350}	E	TT	PS_S, PS_C, PS_R
[12]	A_D	SA	E_{itrip}	Td	-

Safety: A: total number of public transport accidents; AD: total number of deaths that resulted from public transport accidents; A_{IP}: total number of injured people that resulted from public transport accidents RF: road fatalities.

Accessibility: A_{MP}: number of people who live in a walking distance of 900 m from a route's stop; A_{DP}: number of vehicle features that contribute for disabled people accessibility; A_{EP}: number of people who live in a walking distance of 600 m from a route's stop; A_{500}: percentage of people that live 500 m from a public transport stop; $A_{300\text{-}500}$: percentage of people that live 300-500 m from a public transport stop; SA: system accessibility (pkm/capita).

Affordability: E: percentage of the income spend monthly on public transport; E_{itrip}: money spent on a trip in relation to income; E_{itrans}: cost of transport in relation to income; UE_{trans}: transport use expenses.

Travel time costs: CL: congestion level; D: total delay; AS: average speed; D_C: delay due to congestion; T_{IT}: time of indirect trips; T_C: time spent commuting; T_{UCC}: time spent under congestion conditions; TT: travel time; Td: average trip distance.

Passengers' satisfaction: PS_S: level of security from the passenger's perspective; PS_C: level of comfort from the passenger's perspective, PS_R: level of reliability from the passenger's perspective; S_{MS}: satisfaction with the mobility service; UE_{SI}: proportion of public transport users exposed to security incidents.

Safety in public transport impacts both economic and social stability. Traffic accidents has different types of costs that include human costs, medical costs, administrative costs, production losses, and material damages [16]. At urban level, the most used indicator related to *safety* is the number of road fatalities per 100,000 inhabitants (RF) [4, 9], followed by the number of road accidents [10, 11]. The number of deaths that result from public transport accidents (A_D) is another indicator used [12]. However, the European Union determined that the human costs are the biggest contributor to the overall accident costs [16]. Thus, to assess *safety*, the number of public transport accidents (A), and the annually number of injured people (A_{IP}) are also of major importance.

Accessibility is directly related to the social dimension and, is often used to quantify the physical ease of passengers' (or possible passengers') access to public transport [4, 9, 11–13]. The most popular indicator, also used in our study, is the share of population living within a certain distance from public transport stations/stops [4, 9, 11]. The most common range of distances found was between 300-500 m [4]. However, the walking distance that a person is willing to walk depends on various factors, namely gender, age, and health [17]. Additionally, an increase of elderly people of 10.5 % from 2017 until 2060 is expected [17]. Thus, the *accessibility* indicator was divided into A_{MP} and A_{EP}, for people from 14 to 64 years old, and on people with 65 or more years old, respectively. Some researchers consider people with special needs and their respective access to public transport [9–11]. The share of public transport vehicles that are wheelchair accessible [9], public transport for users with special needs [10], and the number of public transport accessible by disabled people [11] was used to create the A_{DP} indicator that quantify the average accessibility level of the vehicle conditions for disabled people.

Affordability is presented in various studies as a relevant aspect to assess urban sustainability [4, 9, 11–13]. Beyond having access to public transport services, people must afford them. Practically, most of the affordability indicators relate passengers' income with either the price of a public transport trip (E_{itrip}) [9, 12], the monthly price of transport (E_{itrans}) [4] or the overall price of public transport (E) [11]. Transport use expenses (UE_{trans}) was also used previously [10]. For our study, the proportion of the passenger income with the monthly expenses on public transport was used *(E)*.

Time is, naturally, an aspect that strongly influences studies related to network design, mainly the waiting time and the travel time. In congested urban areas, these times may be substantially larger, affecting transport reliability by increasing delays and consequently the travel time. In 2019, near 4 % of the world cities had a congestion level higher than 50 %, and 28 % of the world cities have a congestion levels ranging from 30 % and 50 % [18]. Accordingly, the theme *travel time cost* was included in our study.

Many authors consider different types of time spent on travels [4, 9–12], the congestion level (CL), and the average speed (AS) [10] when trying to define an indicator. The time spent on indirect trips (T_{IT}) [9], the congestion delay (D_C) [9], the time spent commuting (T_C) [4], the time spent under congestion conditions (T_{UCC}) [4], and the time spent on the travel [11] are time related indicators used in the literature.

Congestion and delays have a very strong relation as congestion appears to be the main cause for travel delays. However, the total travel time may be affected by other occurrences such as vehicle suppression or vehicle failures, that may justify the assessment of both factors separately, by using indicators such as the total delay (D) or the congestion level (CL). Additionally, indirect trips are very common in public transit networks and, consequently, they may create a considerable waiting time when there is a change in transport modes or routes, that can be associated to a time cost. To address this reality, some authors consider the duration of an indirect trip for the user (T_{IT}) [9] and the average user trip distance (Td) [12]. Alternatively, the travel average speed (AS), which relates time and distance, can be used.

The passengers' opinion can be very relevant as it influences directly the economical and the environmental performance of operators. The more satisfied passengers are, the more passengers will rely on transport services, thus using less private transport modes. *Passengers' satisfaction* is therefore considered a theme in the social dimension, and can be assessed in several levels such as security, comfort, satisfied demand, or trip duration. The most popular indicator in the literature is the share of population feeling safe from relevant incidents and violations while travelling (PS_S) [4].

The proportion of public transport users that have been exposed to security related incidents (UE_{SI}) [9], the assessment of security (PS_S) along with comfort (PS_C) and reliability (PS_R) through a scale of 1 to 5 [11], and the mobility (S_{ms}) service [9, 10] were also used in the literature.

Environmental indicators

Sdoukopoulos et al. [4], found that the most popular environmental themes to assess road axis/corridors are related with air *pollutant emissions* and *air quality* (100 % in that type of study). However, at urban and regional/national levels, other themes are also popular to assess sustainability as it is the case of the greenhouse gases emissions (69 % of the studies), the *fossil fuel energy consumption* (65 %), the *traffic noise* (54 % of the studies), and the *land consumption* (41 %). Alike the previous domains, table III presents the most popular indicators.

TABLE III. MAIN ENVIRONMENTAL THEMES AND INDICATORS.

Reference	Air quality	Pollutant emissions	Energy efficiency	Traffic noise	Land use
Our study	C_{PM10}, C_{NOx}	E_{NOx}, E_{PM}, E_{VOC}, E_{CH4}	EC	N_D, N_N	RD, PC
[9]	C_{PM10}, C_{NOx}	E_{CO2}	$EC_{passenger.km}$, U_{CE}	NL	D_{RN}, PFP, L_{PTF}
[4]	C_{APE}	M_{PE}	EC_{FF}, $EC_{passenger.km}$	NL, P_{ENL}	L_{PTF}
[10]	-	-	EC_{FF}, U_{CE}	P_{ENL}	-
[11]	-	E_{CO2}	-	-	D_{RN}, D_{PN}
[12]	-	M_{PE}	$EC_{passenger.km}$	-	L_{PTF}
[8]	-	E_{NOx}, E_{PM}, E_{VOC}, E_{CO}	-	-	-

Air quality: C_{PM10}: particles concentration; C_{NOx}: nitrogen oxide concentration; C_{APE}: concentrations of several air pollutants.

Pollutant emissions: E_{NOx}: nitrogen oxide emissions; E_{PM}: particles emissions; E_{VOC}: volatile organic compound emissions; E_{CH4}: methane emissions; E_{CO2}: Carbon dioxide emissions; M_{PE}: mass of pollutants emitted (e.g., NOx, VOC, CO_2); E_{CO}: Carbon monoxide emissions.

Energy efficiency: EC: energy consumption ($MJkm^{-1}$); $EC_{passenger.km}$: energy consumption per passenger.km; U_{CE}: use of clean energy; EC_{FF}: fossil fuel energy consumption.

Noise traffic: N_D: noise level during the day; N_N: noise level during the night. NL: noise level. P_{ENL}: people exposed to high noise level.

Land use: RD: route's density; PC: pedestrian pathway availability; D_{RN}: road network density; PFP: pathways for pedestrians; L_{PTF}: land used by public transport facilities; D_{PN}: pedestrian network density.

In 2018, air pollution was responsible for 8.7 million deaths globally [19], mostly related premature deaths, and cardiovascular and respiratory diseases [20]. Human problems related with air pollution are mainly concern with the inhalation of particles (PM) and nitrogen oxide (NO_x) [16]. In the European Union, road transport was the largest emitter of NO_x in 2016, with a share of 39 % of the total transport emissions. Particles contributed with around 10 %, while greenhouse gases represent 71.7 % [20]. Consequently, these pollutants are typically used in the definition of sustainability indicators for transport assessment, not only at emission level [4, 8, 12], but also at air quality level [4, 9]. PM and NO_x concentrations are used to characterize the *air quality* theme (C_{PM10}, C_{NOx}) [9].

Regarding the *pollutant emissions* theme, carbon dioxide (CO_2), which is the most popular greenhouse gas included in sustainability indicators (E_{CO2}) [9, 11, 12], and volatile organic compounds (VOC) (M_{PE}, E_{VOC}) [8, 12] are gases usually considered. Other pollutants used are particles (E_{PM}) [8], nitrogen oxide (E_{NOx}) [9, 12], and carbon monoxide (E_{CO}) [8] emissions. A couple of studies identified the mass of pollutants emitted (M_{PE}) [4, 12]. In [4] the pollutants are not identified. However, with the growing use of vehicle fleets of natural gas, the methane emissions (E_{CH4}) have a greater importance, as CH_4 is a greenhouse gas that has a CO_2 equivalent equal to 84 [21].

Energy efficiency gained a high importance in the last decades since the increasingly high energy consumption has resulted in severe environmental problems. To produce energy, most sectors, including transport, use fossil sources that are unrenewable and produce great amounts of greenhouse gases and pollutant emissions [22]. Concerning consequences of global warming and of the greenhouse effect are originated by CO_2, which has a direct relation to the vehicle energy consumption.

Within the *energy efficiency* theme, energy consumption is a popular sustainability indicator used in different approaches [9, 10, 12]. Medina et al. [9] showed that fuel consumption should have the highest priority (16.68 %). An option to quantify the energy efficiency is by considering the ratio between the energy consumption and the passenger-km travelled ($EC_{passenger.km}$) [4, 9, 12]. Additionally, in this theme, the fossil fuel energy consumption (EC_{FF}) was also a used indicator [4, 10], as well as theme the proportion of clean energy (U_{CE}) [9, 10].

Noise pollution can decrease people's quality of life and cause cognitive impairment in children, high levels of stress, sleep disturbance, and negative health impacts [20]. Within the *traffic noise* theme, some common indicators are noise level (NL) [4, 9] and the share of population exposed to noise levels (P_{ENL}) [10], or to noise levels above the statutory threshold (P_{ENL}) [4].

Transport has also impact on habitat loss, habitat fragmentation, and habitat degradation [16]. Hence, when determining the costs associated to habitat damage, an understanding on the network's land consumption is required. A popular indicator within this theme is land consumption by the transport facilities (L_{PTF}) [4, 9, 12]. This indicator, along with PFP, that is based on the protected pedestrian area per inhabitants, motivated the creation of the pathways' pedestrian circulation (PC) indicator. Following the same perspective of the authors that considered the road network density (D_{RN}) [9, 11], an adaptation to public transport resulted in the route's density (RD) indicator. The so-called pedestrian network density (D_{PN}) is also an indicator common used for the environmental domain [11].

B. Quantification of indicators

Most of the indicators are based on the total (sum) or average values of the collected data. These indicators may be defined for the stops, passengers, paths (trips) or vehicles of a specific route being assessed (Table IV).

The measurement frequency of each indicator may be quite relevant as some indicators' values depend on time. These values need to be measured with a given frequency, that can be either weekly, monthly, or annually. The indicators that do not depend on time rely mainly on network characteristics, for instance, the stop shelter or the vehicle capacity. The indicators proposed in this work can be separately assessed for different periods of the day, as public transport systems must plan their transport service considering the different realities of each period. From the selected indicators, as presented previously, 72 % are quantitative and 28 % qualitative (Table IV). The next subsections describe how each type of indicator is computed.

Quantitative indicators

While some of the quantitative indicators may be directly determined if they consist of just one piece of information, other indicators may require different types of data, thus requiring the use of some simple expressions as follows.

Within *economic productivity*, PR_{CC} and PR_{PC} are determined by expressions (1) and (2), respectively. The occupation rate (*OR*), concerning only one travel (identified by *i*), requires the vehicle capacity and its actual travel occupation (see expression (3)). From the social domain, the delay (*D*) and average speed (*AS*), that are part of the *travel time cost* theme, are computed by expressions (4) and (5), respectively. The *affordability* indicator value (*E*) is obtained by expression (6). Additionally, both indicators from the *land use by transport* theme use the data in expressions (7) and (8) to determine the route's density (*RD*) and the pedestrian circulation area (*PC*), respectively.

$$PR_{CC} = \frac{Revenues - Material\ Costs}{Material\ Costs} \cdot 100 \qquad (1)$$

$$PR_{PC} = \frac{Revenues - Personnel\ Costs}{Personnel\ Costs} \cdot 100 \qquad (2)$$

$$OR_i = \frac{vehicle\ occupation_i}{vehicle\ total\ capacity} \cdot 100 \qquad (3)$$

$$D_i = travel\ time_i - planned\ time_i \qquad (4)$$

$$AS_i = \frac{total\ distance_i}{\frac{travel\ time_i}{60}} \qquad (5)$$

$$E_{per\ passenger} = \frac{\sum expenses}{income} \cdot 100 \qquad (6)$$

$$RD = \frac{km\ extension}{number\ of\ stops \cdot \pi\, 0.9^2} \qquad (7)$$

$$PC = (6\,m \cdot pathway\ width) - Stop\ Area \qquad (8)$$

Qualitative indicators

The values of all the indicators from a qualitative source are translated to a "Likert scale" ranging from 1 to 5 (where 5 is the "best" value) – see table V.

C. *Scale normalization*

In order to weight the selected sustainability indicators, these are first normalized [4]. Several normalization methods such as ranking, standardization or z-scores, re-scaling, distance to a reference, and categorical scales are usually used in the literature [23]. In our study each indicator was normalized to an interval from 0 (lowest performance) to 1 (highest performance), whether the desirable value is higher or lower, using expressions (9) and (10) respectively. I is the indicators value to be normalized, I_{min} is the minimum value of that indicator, and I_{max} is the maximum value.

$$\frac{I - I_{min}}{I_{max} - I_{min}} \qquad (9)$$

$$\frac{I_{max} - I}{I_{max} - I_{min}} \qquad (10)$$

TABLE IV. CARACTERISTICS OF INDICATORS.

Indicator		Description	Units	Frequency			
				N	*W*	*M*	*A*
Economic	PE_{PT}	Average monetary value as public expenditures invested on public transport	€				x
	TTP	Average monetary value spent by passengers on links that include the route	€		x		
	PR_{CC}	Ratio of the amount of revenues to the capital costs	%			x	
	PR_{PC}	Ratio of the amount of revenues to the personnel costs	%			x	
	OR	Average ratio of a link's vehicle occupation to the vehicle capacity	%		x		
	SD	Total number of people that start their trip in a every route's stop	passengers		x		
	AM	Total n.º of public transport alternative stops/stations (i.e. bus) in a walking distance of 300 m	alternative stops	x			
	F	Average frequency	minutes	x			
Social	*A*	Total number of accidents that occurred whether it involves pedestrians, other vehicles, "human fault" from the operator, or machine failure	accidents				x
	A_{IP}	Total number of injured people from the accidents	injured people				x
	A_D	Total number of deaths from the accidents	deaths				x
	CL	Average congestion level of that links that include the route	-		x		
	D	Average difference between the real travel time and the planned travel time	minutes		x		
	AS	Average speed of every link that include the route	$km.h^{-1}$		x		
	E	Average percentage of the public transport expenses to the household income	%			x	
	A_{MP}	Total number of people who live in a walking distance of 900 m from a route's stop	potential passengers	x			
	A_{DP}	Average accessibility level of the vehicle conditions for disabled people that operates in the route	-	x			
	A_{EP}	Total n.º of people over 65 years old that live in a walking distance of 600 m from a route's stop	potential passengers	x			
	PS_S	Average security level inside the vehicle and on the stops from the passenger's perception	-	x			
	PS_C	Average comfort level inside the vehicle and on the stops from the passenger's perception	-	x			
	PS_R	Average reliability level inside the vehicle and on the stops from the passenger's perception	-	x			
Environmental	C_{NO2}	Average NO_x concentration level observed along a route	-				x
	C_{PM10}	Average PM_{10} concentration level observed along a route	-				x
	N_D	Average noise level throughout the route during the day	-			x	
	N_N	Average noise level throughout the route during the night	-			x	
	RD	Ratio between the route's length and the sum of every stop's 900 m radius area of a route	$km.km^{-2}$	x			
	PC	Average free area for pedestrians' circulation around stops (the pathway length used was 6 m)	km^2	x			
	E_{NOx}	Average NO_x bus emissions throughout a route	$g.km^{-1}$		x		
	E_{PM}	Average PM bus emissions throughout a route	$g.km^{-1}$		x		
	E_{COV}	Average COV bus emissions throughout a route	$g.km^{-1}$		x		
	E_{NH4}	Average NH_4 bus emissions throughout a route	$g.km^{-1}$		x		
	EC	Energy consumption from all the vehicles that travelled the specific route	$MJ.km^{-1}$		x		

W: N: None; Weekly, M: Monthly; A: Annually.

TABLE V. SCALE DESCRIPTION OF QUALITATIVE INDICATORS.

Indicator	Unit	Meaning of the qualitative levels				
		1	2	3	4	5
CL	-	Very low	Low	Moderate	High	Very high
A_{DP}	nº features	0	1	2	3	4
PS_S, PS_C, PS_R	-	Very poor	Poor	Average	Good	Very good
C_{NO2}	µg.m^{-3}	0-40	41-100	101-200	201-400	401-1000
C_{PM10}	µg.m^{-3}	0-20	21-35	36-50	51-100	101-1200
N_D	dB	> 0	> 55	> 60	> 65	> 70
N_N	dB	> 0	> 45	> 50	> 55	> 60

D. *Assignement of weights*

In order to assign weights to the different "components", statistical models can be used or, in alternative, many works have adopted some kind of participatory methods such as the Analytic Hierarchy Process (AHP), multicriteria analysis methods, Delphi surveys, or principal components analysis [4]. In our study, for the weights we consider different sets of values from the literature. As the proposed model is hierarchical, the different levels of the weighting process can be analysed separately. The following sections describe and explain the weighting process for each level.

Domains level

Table VII presents the weights for the domains, determined in some sustainability studies [24–26]. Some authors used the weights proposed by other study with a similar scope to theirs weights [24], while others used techniques such as principal components (PC/FA) [25] or fuzzy AHP method [26]. To each set of weights outlined on Table VII, a "weight scenario" (*WS*) is associated. These scenarios will be applied in the demonstration case.

TABLE VI. SCENARIOS FOR THE DOMAIN WEIGHTS.

Reference	*WS*	Domains		
		Economic	Social	Environmental
[24]	*WS1*	0.289	0.357	0.354
[25]	*WS2*	0.564	0.023	0.413
[26]	*WS3*	0.11	0.66	0.23

WS: weight scenario.

Themes level

The weights assigned to each theme were based on the study by Medina's et al. [9]. This study was selected due to its extensive validation methods that included interviews with 19 experts in sustainability topics. Accordingly, table VI presents the aggregated weights for each domain, based on their values and our selected indicators.

Indicators level

Almost 50 % of the studies assign equal weights to the indicators, suggesting that they are equally important [23]. This is obviously a weak and arguable assumption. However, given the incoherence of the literature and the difficulties in using a participatory method, at this level, equal weights were assigned to all the indicators within the respective theme.

III. CASE STUDY

For testing and validating the approach proposed in this work, a simple small bus transit network was designed based on real data from STCP, the main company providing public transport service in the metropolitan area of Porto.

TABLE VII. DISTRIBUTION OF THE WEIGHTS FOR THE THEMES.

Domain	Theme	Weights (%)
Economic	Economic productivity	15.9
	Transport costs and finance	28.4
	Transport efficiency	55.7
Social	Safety	35.1
	Accessibility	27.5
	Affordability	19.5
	Travel time cost	6.3
	Passengers' satisfaction	11.5
Environmental	Air quality	49.0
	Pollutant emissions	25.3
	Energy efficiency	7.2
	Noise traffic	5.4
	Land use by transport	13.1

A. *Description*

The test bus network, shown in Fig. 2, is composed by three fixed routes: route A (green), route B (purple), and route C (blue). Each route is composed by a set of stops, which are represented by dashed lines and identified by S_{rj}, where r is the route and j identifies the stop within that specific route. Some stops are common to two routes and can therefore be seen as connectivity points. A dataset was generated based on real information to feed the indicators. Data such as the frequency of the route, access, and demand, was directly deduced from each real route. However, some estimations were performed, since data such as the number of injured people in accidents, or vehicle occupation is not provided by the analysed public transport operator.

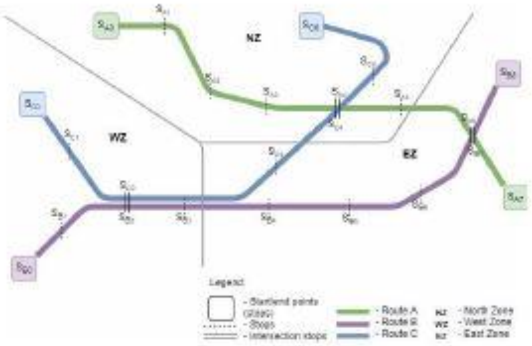


Fig. 2. Demonstration network.

B. *Dataset scenarios definition*

The sustainability model was applied to the described demonstration case. Additionally, to the baseline scenario, two scenarios affecting route 2 were created. The dataset scenario A (DS_A) consists of making the fleet of the second route fully electric, which affects the environmental domain and the *pollutant emissions* and *energy efficiency* directly. The dataset scenario B (DS_B) affects *safety* in the social domain, by having no accidents related to route 2. Both DS_A and DS_B affect the peak and off-peak periods in the same way and, consequently, we opted to only include the results related to each route during peak periods.

C. *Results and discussion*

For the baseline dataset scenario, table VIII presents each sustainability domain value for every route and the sustainability indicator for the three weight scenarios, which shows that WS3 obtains the best average value (highlighted in blue). Additionally, it can be noted that regardless of the weight scenario, route 2 is the most sustainable.

Concerning DSA the overall sustainability indicator increases as the environmental domain increases its value from 0.297 to 0.361 (highlighted in green in table VIII). A similar behaviour is identified in the social domain, when comparing the baseline scenario to the DS_B (highlighted in yellow). However, a bigger increase is obtained since the safety theme has a priority of 35 %, while both pollutant emissions and energy efficiency reach a combined lower priority (~32 %). Accordingly, the sustainability indicator of DS_B is higher than the one of DS_A as the weight scenario is the same. It should be noted that even though the dataset scenarios only change information regarding route 2, the scale normalization process uses all the routes' values, thus influencing the sustainability and domains indicators for the other routes.

TABLE VIII. RESULTS OF EACH WEIGHT AND DATASET SCENARIO.

DS	Level	*WS*	Route 1	Route 2	Route 3
Baseline	Economic	-	0.175	0.633	0.535
	Social	-	0.49	0.697	0.339
	Environmental	-	0.261	0.297	0.27
	Sustainability indicator	WS1	0.318	0.537	0.371
		WS2	0.218	0.496	0.421
		WS3	0.403	0.598	0.345
DS_A	Environmental	-	0.106	0.361	0.19
	Sustainability indicator	WS3	0.367	0.613	0.326
DS_B	Social	-	0.481	0.814	0.264
	Sustainability indicator	WS3	0.397	0.675	0.295

DS: dataset scenario; *WS*: weight scenario; blue: best scenario.

IV. CONCLUSIONS

In this work we have developed a tool to support the design of public transport networks, by assessing their sustainability performance. This tool is based on a comprehensive, multi-criteria, multi-level analysis of routes, with a set of indicators selected from the vast literature in this area. These indicators were structured to produce a single global sustainability index. Although the approach was only tested on a small demonstration case, our preliminary results clearly show its potential to address more realistic situations, therefore contributing to improve urban sustainability.

ACKNOWLEDGMENT

This work is financed by the European Regional Development Fund through the Operational Programme for Competitiveness and Internationalisation - COMPETE 2020 Programme and by National Funds through the Portuguese funding agency, FCT - Fundação para a Ciência e a Tecnologia within project PTDC/ECI-TRA/32053/2017 - POCI-01-0145-FEDER-032053. Tânia Fontes is also funded by FCT through grant SFRH/BPD/109426/2015.

REFERENCES

[1] United Nations and D. of E. and S. Affairs, "World Urbanization Prospects," in *Demographic Research*, 2018, vol. 12, pp. 197–236.

[2] J. Camargo Pérez, M. H. Carrillo, and J. R. Montoya-Torres, "Multi-criteria approaches for urban passenger transport systems: a literature review," *Ann. Oper. Res.*, vol. 226, no. 1, pp. 69–87, 2014.

[3] O. İ. Kolak, O. Feyzioğlu, and N. Noyan, "Bi-level multi-objective traffic network optimisation with sustainability perspective," *Expert Syst. Appl.*, vol. 104, pp. 294–306, 2018.

[4] A. Sdoukopoulos, M. Pitsiava-Latinopoulou, S. Basbas, and P. Papaioannou, "Measuring progress towards transport sustainability through indicators: Analysis and metrics of the main indicator initiatives," *Transp. Res. Part D Transp. Environ.*, vol. 67, no. December 2018, pp. 316–333, 2019.

[5] J. Zietsman, L. R. Rilett, and S. Kim, "Sustainable Transportation Performance Measures for Developing Communities," 2003.

[6] T. Ramani, J. Zietsman, W. Eisele, D. Rosa, D. Spillane, and B. Bochber, "Sustainable Transport System," 2009.

[7] Å. Svensson, S. Marshall, P. Jones, C. Hydén, J. Draskoczy, Magda Papaioannou, Panos Thomsen, and N. Boujenko, "Arterial Streets for people - Guidance for planners and decision makers when reconstructing arterial streets," *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2004.

[8] A. Gazis, T. Fontes, J. Bandeira, S. Pereira, and M. C. Coelho, "Integrated computational methods for traffic emissions route assessment," *IWCTS 2012 - 5th ACM SIGSPATIAL Int. Work. Comput. Transp. Sci.*, pp. 8–13, 2012.

[9] J. C. Medina, J. P. de Sousa, and E. J. Perez, "Defining and Prioritizing Indicators to Assess the Sustainability of Mobility Systems in Emerging Cities," vol. 1, pp. 616–625, 2021.

[10] J. P. Lima, R. da S. Lima, and A. N. R. da Silva, "Evaluation and Selection of Alternatives for the Promotion of Sustainable Urban Mobility," *Procedia - Soc. Behav. Sci.*, vol. 162, no. Panam, pp. 408–418, 2014.

[11] A. Tsiropoulos and D. Papagiannakis, Apostolos Latinopoulos, *Development of an Aggregate Indicator for Evaluating Sustainable Urban Mobility in the City of Xanthi, Greece*. Springer International Publishing, Cham, Switzerland, 2019.

[12] C. De Gruyter, G. Currie, and G. Rose, "Sustainability measures of urban public transport in cities: A world review and focus on the Asia/Middle East Region," *Sustain.*, vol. 9, no. 1, 2017.

[13] R. Kumar, E. Madhu, A. Dahiya, and S. Sinha, "Analytical hierarchy process for assessing sustainability," *World J. Sci. Technol. Sustain. Dev.*, vol. 12, no. 4, pp. 281–293, 2015.

[14] M. Burinskienė, K. Gaučė, and J. Damidavičius, "Successful sustainable mobility measures selection," *10th Int. Conf. Environ. Eng. ICEE 2017*, no. April, pp. 27–28, 2017.

[15] Infras, "COMPETE. Analysis of operating cost in the EU and the US. Annex 1.," p. 74, 2006.

[16] European Commission, *Handbook on the External Costs of Transport*. 2019.

[17] J. Ribeiro, T. Fontes, C. Soares, and J. L. Borges, "Accessibility as an indicator to estimate social exclusion in public transport," *Transp. Res. Procedia*, vol. 52, pp. 740–747, 2021.

[18] "Traffic Index 2020." https://www.tomtom.com/en_gb/traffic-index/ranking/.

[19] K. Vohra, A. Vodonos, J. Schwartz, E. A. Marais, M. P. Sulprizio, and L. J. Mickley, "Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem," *Environ. Res.*, vol. 195, no. January, p. 110754, 2021.

[20] European Enviromental Agency, "The first and last mile — the key to sustainable urban transport," no. 18, p. 84, 2018, [Online]. Available: https://www.eea.europa.eu//publications/the-first-and-last-mile.

[21] "Climate Change Connection, emissions." https://climatechangeconnection.org/emissions/co2-equivalents/.

[22] H. Sasana and A. E. Putri, "The Increase of Energy Consumption and Carbon Dioxide (CO2) Emission in Indonesia," *E3S Web Conf.*, vol. 31, pp. 1–5, 2018.

[23] X. Gan *et al.*, "When to use what: Methods for weighting and aggregating sustainability indicators," *Ecol. Indic.*, vol. 81, no. October, pp. 491–502, 2017.

[24] I. Lopez-Carreiro and A. Monzon, "Evaluating sustainability and innovation of mobility patterns in Spanish cities. Analysis by size and urban typology," *Sustain. Cities Soc.*, vol. 38, no. February, pp. 684–696, 2018.

[25] R. Danielis, L. Rotaris, and A. Monte, "Composite indicators of sustainable urban mobility: Estimating the rankings frequency distribution combining multiple methodologies," *Int. J. Sustain. Transp.*, vol. 12, no. 5, pp. 380–395, 2018.

[26] J. M. Ngossaha, R. H. Ngouna, B. Archimède, and J. M. Nlong, "Sustainability assessment of a transportation system under uncertainty: an integrated multicriteria approach," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 7481–7486, 2017.

References

[1] United Nations and D. of E. and S. Affairs, “World Urbanization Prospects,” in *Demographic Research,* 2018, vol. 12, pp. 197–236, [Online]. Available: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf.

[2] J.-P. Rodrigue, *The Geography of Transport Systems*, Fifth Edit. New York: Routledge.

[3] J. Camargo Pérez, M. H. Carrillo, and J. R. Montoya-Torres, “Multi-criteria approaches for urban passenger transport systems: a literature review,” *Ann. Oper. Res.*, vol. 226, no. 1, pp. 69–87, 2014, doi: 10.1007/s10479-014-1681-8.

[4] European Enviromental Agency, “The first and last mile — the key to sustainable urban transport,” no. 18, p. 84, 2018, [Online]. Available: https://www.eea.europa.eu//publications/the-first-and-last-mile.

[5] EMEP/EEA, “EMEP/EEA air pollutant emission inventory guidebook 2016: Technical guidance to prepare national emission inventories. European Environment Agency.,” no. 21, p. 124, 2016.

[6] European Commission, “White Paper: Roadmap to a Single European Transport Area - Towards a competetive and resource efficient transport system,” 2011.

[7] O. İ. Kolak, O. Feyzioğlu, and N. Noyan, “Bi-level multi-objective traffic network optimisation with sustainability perspective,” *Expert Syst. Appl.*, vol. 104, pp. 294–306, 2018, doi: 10.1016/j.eswa.2018.03.034.

[8] E. Amrina and L. Berti, “A multi-criteria model for evaluating sustainable transportation system in West Sumatra,” *Recent Prog. Mech. Infrastruct. Ind. Eng. Proc. Int. Symp. Adv. Mech. Eng. Qual. Res. 2019*, vol. 2227, no. May, p. 040022, 2020, doi: 10.1063/5.0000881.

[9] S. Duleba and S. Moslem, “Sustainable urban transport development with stakeholder participation, an AHP-Kendall model: A case study for Mersin,” *Sustain.*, vol. 10, no. 10, 2018, doi: 10.3390/su10103647.

[10] E. Cipriani, G. Fusco, S. M. Patella, M. Petrelli, and L. Quadrifoglio, “Transit network design for small-medium size cities,” *Transp. Plan. Technol.*, vol. 42, no. 1, 2019, doi: 10.1080/03081060.2018.1541284.

[11] Xuesong Feng, Xiaojing Zhu, Xuepeng Qian, Yuanpeng Jie, Fei Ma, and Xuejun Niu, “A

new transit network design study in consideration of transfer time composition," *Transp. Res. Part D Transp. Environ.*, vol. 66, Jan. 2019, doi: 10.1016/j.trd.2018.03.019.

[12] R. Camporeale, L. Caggiani, and M. Ottomanelli, "Modeling horizontal and vertical equity in the public transport design problem: a case study," *Transp. Res. Part A Policy Pract.*, vol. 125, Jul. 2019, doi: 10.1016/j.tra.2018.04.006.

[13] M. A. Nayeem, M. M. Islam, and Xin Yao, "Solving Transit Network Design Problem Using Many-Objective Evolutionary Approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 10, Oct. 2019, doi: 10.1109/TITS.2018.2883511.

[14] J. Duran-Micco, E. Vermeir, and P. Vansteenwegen, "Considering emissions in the transit network design and frequency setting problem with a heterogeneous fleet," *Eur. J. Oper. Res.*, vol. 282, no. 2, Apr. 2019, doi: 10.1016/j.ejor.2019.09.050.

[15] M. Owais and M. K. Osman, "Complete hierarchical multi-objective genetic algorithm for transit network design problem," *Expert Syst. Appl.*, vol. 114, Dec. 2018, doi: 10.1016/j.eswa.2018.07.033.

[16] Chao Wang, Zhirui Ye, and Wei Wang, "A multi-objective optimization and hybrid heuristic approach for urban bus route network design," *IEEE Access*, vol. 8, 2020, doi: 10.1109/ACCESS.2020.2966008.

[17] S. M. M. Amiripour, A. Ceder, and A. S. Mohaymany, "Hybrid Method for Bus Network Design with High Seasonal Demand Variation," *J. Transp. Eng.*, vol. 140, no. 6, Jun. 2014, doi: 10.1061/(ASCE)TE.1943-5436.0000669.

[18] A. Gazis, T. Fontes, J. Bandeira, S. Pereira, and M. C. Coelho, "Integrated computational methods for traffic emissions route assessment," *IWCTS 2012 - 5th ACM SIGSPATIAL Int. Work. Comput. Transp. Sci.*, pp. 8–13, 2012, doi: 10.1145/2442942.2442945.

[19] M. V. Corazza and N. Favaretto, "A methodology to evaluate accessibility to bus stops as a contribution to improve sustainability in urban mobility," *Sustain.*, vol. 11, no. 3, 2019, doi: 10.3390/su11030803.

[20] Y. Chen, A. Bouferguene, H. X. Li, H. Liu, Y. Shen, and M. Al-Hussein, "Spatial gaps in urban public transport supply and demand from the perspective of sustainability," *J. Clean. Prod.*, vol. 195, pp. 1237–1248, 2018, doi: 10.1016/j.jclepro.2018.06.021.

[21] A. Sdoukopoulos, M. Pitsiava-Latinopoulou, S. Basbas, and P. Papaioannou, "Measuring progress towards transport sustainability through indicators: Analysis and metrics of the main indicator initiatives," *Transp. Res. Part D Transp. Environ.*, vol. 67, no. December 2018, pp. 316–333, 2019, doi: 10.1016/j.trd.2018.11.020.

[22] M. Burinskienė, K. Gaučė, and J. Damidavičius, "Successful sustainable mobility measures selection," *10th Int. Conf. Environ. Eng. ICEE 2017*, no. April, pp. 27–28, 2017, doi: 10.3846/enviro.2017.102.

[23] J. C. Medina, J. P. de Sousa, and E. J. Perez, "Defining and Prioritizing Indicators to Assess the Sustainability of Mobility Systems in Emerging Cities," vol. 1, pp. 616–625, 2021.

[24] J. P. Lima, R. da S. Lima, and A. N. R. da Silva, “Evaluation and Selection of Alternatives for the Promotion of Sustainable Urban Mobility,” *Procedia - Soc. Behav. Sci.*, vol. 162, no. Panam, pp. 408–418, 2014, doi: 10.1016/j.sbspro.2014.12.222.

[25] A. Tsiropoulos and D. Papagiannakis, Apostolos Latinopoulos, *Development of an Aggregate Indicator for Evaluating Sustainable Urban Mobility in the City of Xanthi, Greece*. Springer International Publishing, Cham, Switzerland, 2019.

[26] C. De Gruyter, G. Currie, and G. Rose, “Sustainability measures of urban public transport in cities: A world review and focus on the Asia/Middle East Region,” *Sustain.*, vol. 9, no. 1, 2017, doi: 10.3390/su9010043.

[27] R. Kumar, E. Madhu, A. Dahiya, and S. Sinha, “Analytical hierarchy process for assessing sustainability,” *World J. Sci. Technol. Sustain. Dev.*, vol. 12, no. 4, pp. 281–293, 2015, doi: 10.1108/wjstsd-05-2015-0027.

[28] J. Zheng, N. W. Garrick, C. Atkinson-Palombo, C. McCahill, and W. Marshall, “Guidelines on developing performance metrics for evaluating transportation sustainability,” *Res. Transp. Bus. Manag.*, vol. 7, pp. 4–13, 2013, doi: 10.1016/j.rtbm.2013.02.001.

[29] J. Zietsman, L. R. Rilett, and S. Kim, “Sustainable Transportation Performance Measures for Developing Communities,” 2003.

[30] T. Ramani, J. Zietsman, W. Eisele, D. Rosa, D. Spillane, and B. Bochber, “Sustainable Transport System,” 2009. doi: 10.18000/ijodam.70016.

[31] Å. Svensson, S. Marshall, P. Jones, C. Hydén, J. Draskoczy, Magda Papaioannou, Panos Thomsen, and N. Boujenko, “Arterial Streets for people - Guidance for planners and decision makers when reconstructing arterial streets,” *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2004.

[32] P. Fernandes *et al.*, “Integrating road traffic externalities through a sustainability indicator,” *Sci. Total Environ.*, vol. 691, pp. 483–498, 2019, doi: 10.1016/j.scitotenv.2019.07.124.

[33] Infras, “COMPETE. Analysis of operating cost in the EU and the US. Annex 1.,” p. 74, 2006, [Online]. Available: http://publica.fraunhofer.de/documents/N-114390.html.

[34] Rodrigue, “The Geograpgy of Transport Systems, The spatial organization of transportation and mobility: glossary.” https://transportgeography.org/glossary/.

[35] European Commission, *Handbook on the External Costs of Transport*. 2019.

[36] J. Ribeiro, T. Fontes, C. Soares, and J. L. Borges, “Accessibility as an indicator to estimate social exclusion in public transport,” *Transp. Res. Procedia*, vol. 52, pp. 740–747, 2021, doi: 10.1016/j.trpro.2021.01.019.

[37] TomTom, “Traffic Index 2020.” [Online]. Available: https://www.tomtom.com/en_gb/traffic-index/ranking/.

[38] K. Vohra, A. Vodonos, J. Schwartz, E. A. Marais, M. P. Sulprizio, and L. J. Mickley, “Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results

from GEOS-Chem," *Environ. Res.*, vol. 195, no. January, p. 110754, 2021, doi: 10.1016/j.envres.2021.110754.

[39] C. C. Connection, "CO2 equivalents." [Online]. Available: https://climatechangeconnection.org/emissions/co2-equivalents/.

[40] H. Sasana and A. E. Putri, "The Increase of Energy Consumption and Carbon Dioxide (CO2) Emission in Indonesia," *E3S Web Conf.*, vol. 31, pp. 1–5, 2018, doi: 10.1051/e3sconf/20183101008.

[41] QUALAR, "QUALAR informação sobre qualidade do ar." [Online]. Available: https://qualar.apambiente.pt/.

[42] European Enviromental Agency, "The Noise Observation & Information Service for Europe." [Online]. Available: https://noise.eea.europa.eu/.

[43] X. Gan *et al.*, "When to use what: Methods for weighting and aggregating sustainability indicators," *Ecol. Indic.*, vol. 81, no. October, pp. 491–502, 2017, doi: 10.1016/j.ecolind.2017.05.068.

[44] I. Lopez-Carreiro and A. Monzon, "Evaluating sustainability and innovation of mobility patterns in Spanish cities. Analysis by size and urban typology," *Sustain. Cities Soc.*, vol. 38, no. February, pp. 684–696, 2018, doi: 10.1016/j.scs.2018.01.029.

[45] R. Danielis, L. Rotaris, and A. Monte, "Composite indicators of sustainable urban mobility: Estimating the rankings frequency distribution combining multiple methodologies," *Int. J. Sustain. Transp.*, vol. 12, no. 5, pp. 380–395, 2018, doi: 10.1080/15568318.2017.1377789.

[46] J. M. Ngossaha, R. H. Ngouna, B. Archimède, and J. M. Nlong, "Sustainability assessment of a transportation system under uncertainty: an integrated multicriteria approach," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 7481–7486, 2017, doi: 10.1016/j.ifacol.2017.08.1064.

[47] STCP, "Relatório e contas 2019," Porto, 2019.

[48] TUB, "Relatório e Contas 2019," Braga, 2019.

[49] Carris, "Relatório e Contas 2019," Lisboa, 2019.

[50] A. N. S. Rodoviária, "Relatório Anual de Segurança Rodoviária 2019," 2019.

[51] L. Ntziachristos and Z. Samaras, "EMEP/EEA air pollutant emission inventory guidebook 2019," *Eur. Environ. Agency*, vol. 53, no. 9, pp. 1689–1699, 2019.

[52] The AA, "Limits to improve air quality and health - Euro emissions standards." [Online]. Available: https://www.theaa.com/driving-advice/fuels-environment/euro-emissions-standards.

[53] M. Torgal, "Exploring the Potential of DRT for Elderly Urban Mobility using Big Data," 2020.