A Model for Improving Connectivity and Accessibility of Public Transport via Two-way Car-Sharing Systems

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Abstract

The origins and destinations of users in a transport network are connected by the available Public Transport (PT) means. Therefore, the role of PT of a region in terms of providing a connection from each origin to destination in a PT network is critical which directly affects the efficiency of PT systems. However, even efficient PT systems cannot guarantee the desired performance and service levels as well as equity to users unless they are well interconnected and accessible to the maximum possible population. In this connection, the geographical location of PT stops are also important since the connection to/from PT is provided through PT stops. Such a task is often challenging whenever the considered regions have a sparse geographical structure, such as medium-large sized cities located in mountainous areas.

In such cases, the provision of new PT systems or extension of existing lines is not always a viable solution due to challenging topographical conditions or low budget availability. Alternatively, integrating PT systems with other cost-effective mobility systems (such as car-sharing systems, carpooling, ride-sharing, etc.) can significantly enhance the performance of the existing PT systems in terms of accessibility, connectivity, and flexibility.

In this framework, this thesis develops a methodology for the optimal design of two-way Car Sharing (CS) systems in the least accessible

and the least connected areas of a region by means of PT through the determination of the best locations of CS depots. The specific goal of the proposed approach is to improve the values of suitably defined accessibility and connectivity indexes (CAI) for integrated PT/CS systems. In this context, the operation of CS system should guarantee the efficient distribution of resources such that regions with the lowest values of CAI should be provided with at least one depot to maintain the equity while at the same time maximizing and equalizes the total values of CAI for integrated PT/CS systems. In doing so, the optimization problem has been designed as a Mixed Integer Linear Programming Model (MILP) under a given set of constraints to guarantee efficient resource distribution.

To test the capabilities of the proposed approach over medium to large size cities, real-world case studies of the PT systems of the city of Trento (Italy) and Genova (Italy), representing the case of medium size and large size cities, respectively, are evaluated.

Contents

List of Acronyms

AIS Accessibility Index Score. 19, 21–23, 25, 27

CBD Central Business District. 16, 22

CI connectivity index. 13

CS Car Sharing. iii, iv, 1, 3–9, 11–22, 24, 27–29, 31, 32, 35–56, 59–62, 103–107

ECAI Enhanced Connectivity and Accessibility Index. 29, 32

GIS Geographic Information System. 1, 3–5, 10, 11, 18, 23, 61

MILP Mixed Integer Linear Programming Model. iv, 4, 7, 11, 13, 16, 37–39, 42, 45, 59, 61

PNR Proximity to Nearby Regions. 22, 25, 26, 108

POI Point of Interests. 1–6, 15–17, 31, 37, 38, 52, 53, 104, 105

PPT Proximity to Public Transport Stops. 20, 25, 26, 108

PSC Proximity to Service Centers. 21, 25, 26, 108

PT Public Transport. iii, iv, xii, 0–7, 9–23, 25, 27–40, 42, 43, 45–47, 49–53, 59–62, 103–106

PTAI Public Transport Accessibility Index. 19, 23, 25–28, 108

PTAL Public Transport Accessibility Level. 14

TAI Transport Accessibility Index. 14

TAZ Traffic Analysis Zones. 20, 27, 28, 103, 108

Vot Value of Time. 14

List of Symbols

The following list describes several symbols that will be later used within the main text of this thesis

$\Delta_{n,z}$	area of buffer drawn from node n falling under zone z
Δ_n	total area of the buffer drawn from node n
$\Gamma_{k,z}$	area covered by depot k present in zone z. It is determined in terms of the total aerial coverage from depot k by drawing a buffer around it
$\Im^{t,dis}_{PT,z}$	number of trips distributed within the zone z during time period t
$\Im^{t,inc}_{PT,z}$	number of incoming trips to zone z during time period t
$\Im^{t,out}_{PT,z}$	number of outgoing trips from the zone z during time period t
κ^t_{avg}	arithmetic average of the distribution of activities in all the zones during time period t
κ^t_n	distribution of activities w.r.t each zone z in which the node n is located during time period t
$\Lambda_{k,z}$	weighted number of service centres (POIs) covered within the area $\Gamma_{k,z}$ of depot k in zone z
$\mathbb{P}^t_{k,z,q_{k,z}}$	the probability that a generic user is able to find a vehicle upon request from the nearest depot $k \in \mathcal{C}_z$ during each considered time period t, such that $q_{k,z}$ vehicles are assigned to the same depot k

$\mathcal{C}_z$	set of CS depots in zone z
$\mathcal{D}^t_{k,z}$	demand rate of the depot $k \in \mathcal{C}_z$ during each considered time period t
$\mathcal{L}_{z,n}$	the set of lines passing through generic node $n \in \mathcal{N}_z$
$\mathcal{N}_z$	set of PT stops in generic zone
$\mathcal{Z}$	set of zones (districts for the case study of Trento and Genoa) in the study area
Ω_n	accessibility of node n to population. It is determined in terms of the total aerial coverage from node n by drawing a buffer around it
Π^t	profit for the operator earned during each time slot t
Π_n	proportion of the population of the study area covered within the area Ω_n of node n
$\Theta_{k,z}$	proportion of the population covered within the area $\Gamma_{k,z}$ of depot k in zone z
φ_v	fixed fare charged to the users of car sharing system
Ξ_n	weighted number of service centres also termed as POIs covered within the area Ω_n of node n. It represents the most frequent destinations in the transport network including shopping centres, leisure activities, educational facilities, workplaces, etc.
$a_{k,z}$	accessibility index of depot $k \in \mathcal{C}_z$, if activated
AIS_{PNR}	accessibility index score calculated on the basis of proximity to nearby regions
AIS_{PPT}	accessibility index score calculated on the basis of proximity to public transport
AIS_{PSC}	accessibility index score calculated on the basis of proximity to service centers

B	total budget required for the activation and operation of the CS system in all zones of the study area
$c^{t}_{k,z,q_{k,z}}$	connectivity index in time period t of the depot $k \in \mathcal{C}_z$ if $q_{k,z}$ vehicles are assigned to it
C_V	fixed capacity of CS vehicles
$d^{t,in}_{n,l}$	distance travelled by PT from node n to the destinations in inbound direction during time period t
$d^{t,out}_{n,l}$	distance travelled by PT from node n to the destinations in outbound direction during time period t
Pcs	occupancy of CS vehicles
Pop_z	population of zone z
$PTAI$	public transport accessibility index
Q^{max}	maximum number of vehicles that can be assigned to the considered region
Q^{max}_{z}	maximum number of vehicles that can be assigned to zone z
$q_{k,z}$	number of vehicles assigned to the depot $k \in \mathcal{C}_z$, if activated
R^t	additional net revenues of the operator earned by the operation of car sharing systems during the time slot t
$r^{t,in}_{l}$	total daily capacities of line l in the inbound direction during time period t, obtained by multiplying the number of bus seats by the hourly frequency and number of daily operating hours
$r^{t,out}_{l}$	total daily capacities of line l in the outbound direction during time period t obtained by multiplying the number of bus seats by the hourly frequency and number of daily operating hours
$v^{t,in}_{l}$	average speed of buses on line l in the inbound direction during time period t

$v_l^{t,out}$	average speed of buses on line l in the outbound directions during time period t
$SD_{PT,z}^{t}$	total demand served by the PT systems within a zone z during considered time slot t
$TD_{PT,z}^{t}$	total demand for PT systems in a zone z during considered time slot t
$TD_{PT,z}^{in,t}$	total incoming demand into zone z during considered time slot t
$TD_{PT,z}^{out,t}$	total outgoing demand out of the zone z during considered time slot t
$UD_{PT,z}^{t}$	PT unserved demand in a zone z during each time slot t

Chapter 1

Introduction

Accessibility plays an important role in increasing attractiveness of PT systems to users [1]. The PT system is considered efficient if its goal is not only to move people from their origins to their destinations but also to help mitigate issues related to social exclusion by providing equal opportunities for the entire population. Moreover, an efficient PT system should also focus on providing accessibility to the maximum possible population by offering ease of switching between different modes of PT during a trip while efficiently connecting origins and destinations. Similarly, efficient distribution of PT stops is equally important because most users do not prefer PT options if their distribution is inefficient. A failure to do so makes PT less accessible for the population in a region [2], thus increasing the importance of PT equity. To tackle this problem, an “equity goal” must be pursued with the aim of providing an equal distribution of new resources so that all users have similar access to the PT system [3]. In this context, the concepts of connectivity and accessibility in PT systems are increasingly important [4], which have been studied and evaluated in this thesis, and discussed more in detail in the following section.

1.1 Context of the Study

The increase or decrease in the population of a country is linked directly with its economy and this connection can be seen by its associated impacts on the

PT of the region. If the economy of the region is performing well, it will create additional jobs and increases the migration of people from nearby regions [5]. The basic goal of economic development is the development of sustainable communities that provide a liveable place for people to live and work by adopting a decent lifestyle. Such economic developments not only lead to the up-gradation of individual lifestyles but also encourage people with enough resources, to migrate from rural areas to urban areas, especially towards the city centres. Consequently, urban areas begin to face other challenges related to transport and mobility management especially if the PT systems of the region are not sufficient to satisfy the mobility needs of this incoming population.

In this connection, such a situation leads to the usage of private vehicles and results in congestion and other associated problems. Therefore, it is important for the decision-makers to boost the performance of existing PT by making it accessible to the maximum possible population [6]. In this framework, it is necessary for the PT systems to be operated at certain levels of sustainability while implementing the lessons learned from the past. Over the course of time, the concepts of sustainability and accessibility gain more importance while focusing on equity (which is defined in this framework, in terms of fair distribution of PT network so that the maximum possible population can benefit from PT systems while commuting from their origins to destinations) [7].

In this framework, performance evaluation of PT nodes in terms of their accessibility and connectivity is of utmost importance because access to and from PT is always provided through them [8; 9]. Furthermore, the performance of PT systems is also governed by the management of unsatisfied passenger demand. If PT systems of a region fail to meet the existing passenger demand, possible consequences may be crowdedness at PT stops long waiting times, and/or a general worsening of travel time reliability, along with many other associated impacts [10]. Moreover, major challenges for the researchers and urban mobility planners are the identification and the management of resistances against the efficient operations of PT of a region. In this connection, the availability of alternative travel options offering people to travel freely and flexibly from their origins to destinations is considered as one of the major success factors in increasing the performance of PT systems [11]. In fact, it has been observed that the extension of exiting PT systems or the planning of new services is not always a viable solution to meet the additional passenger demand for PT [12] unless it is supplemented by the integration of other smart mobility solutions, such as CS systems.

In this connection, CS systems have already been successful in major cities around the world towards the reduction of private car usage. Such a mobility service provides flexible, reliable, and cost-effective solutions for commuters to travel freely from their origins to their destinations. In addition, CS systems also eliminate the need for the provision of additional parking places in case of private vehicle usage, thus resulting to be a cost-effective and sustainable solution [13]. In such a context, the integration of PT systems with other sustainable mobility options (CS, bike sharing, ride sharing, etc.) is a viable solution [14] for effectively filling gaps in urban areas with limited street space and congested transport infrastructures [15], particularly when budget limitations do not allow the realisation of new PT infrastructure [16].

Accordingly, CS systems play an important role in shifting users from private mobility to combined mobility because they represent an efficient way to connect users with destinations that are inaccessible by PT for any reason. Accordingly, CS systems also reduce the negative impacts of using private vehicles while providing additional support as a multi-modal transport service along with PT [17]. Nevertheless, CS systems can also attract demand away from PT if not appropriately integrated with PT systems. Therefore, to reduce this effect, transport planners should specifically address the problem of integrating PT with CS. In doing so, the advantages of introducing CS should be jointly investigated with existing PT system performance to maximise the benefits for the population subject to disparities in PT accessibility [18].

1.2 Objectives and Contributions

As already mentioned, in the PT concept, "accessibility" reflects the provision of an opportunity to the maximum possible population of a region/zone to access the PT stops in the same region/zone, whereas "connectivity" indicates the efficiency of PT lines in terms of connecting users from a single line to other lines in a PT network. While the accessibility concept can be directly associated with CS, for such systems, connectivity can be thought of as the capability of CS to provide a connection upon request.

Given this framework, this thesis is focused on defining a unique framework for optimally integrating PT and CS systems to improve the accessibility and connectivity of integrated systems. In doing so, the various factors that define the importance of accessibility and connectivity in PT systems have been considered based on the specific characteristics of the different modes used for both PT and CS systems [8; 9]. More specifically, the proposed approach aims to meet the potential demand of PT arising from the least accessible or inaccessible areas and determine an optimal distribution of new CS resources, particularly new parking slots (depots) and vehicles.

In doing so, a traditional two-way CS system is considered as a possible solution instead of new PT lines and/or the extension of the existing ones. The proposed approach is particularly suitable for areas characterised by relatively small demand or topographic constraints or, in general, whenever the extension of existing lines of PT/planning of new services requires high capital investments [15]. In these cases, CS systems can provide flexible solutions to meet additional demands and efficiently adapt to possible variations in user mobility needs [17; 18].

The proposed approach consists of four main steps:

1. Identification of the least accessible parts of the study area in terms of the suitably defined accessibility and connectivity index (CAI_{PT}) of PT, hereafter indicated as “disparity zones”;

2. Identification of the potential locations for the CS depots using suitable clustering algorithms that take into account the so-called Point of Interests (POI), PT stops, zone centroids, etc.

3. Calculation of the potential contributions that CS resources located in different depots can provide to the total CAI values;

4. Optimisation of the total CAI values in each disparity zone through the introduction of a two-way CS system using the application of a MILP model

aimed at identifying the best location of CS depots as well as determining the optimal number of CS vehicles that can be assigned to them.

The framework presented in this paper is unique in providing a methodology aimed at improving the total values of CAI for PT through optimally designing two-way CS systems in the least accessible areas of PT, considering the structure of the area, PT characteristics, and demand. The same applies to the proposed mathematical programming approach to determine the optimal number of CS depots to be activated and the vehicles to be placed therein. The novelty of the proposed approach is further justified through the literature review of relevant studies summarised in Section 2.5 of Chapter 2. Moreover, the capability of the proposed approach has also been evaluated through the application of the proposed methodology (Chapter 4) to the real-world case studies of Trento, and Genova of Italy, representing the case of medium and large size cities (Chapter 5).

1.3 Overview of the Thesis

The remainder of the thesis will be divided into 5 more chapters, where the explanation of PT performance elements along with main assessment methods, and the solutions will be described briefly in Chapter 2. In this connection, the proposed approach will be justified in the Chapter 2 through the review of relevant studies from the literature, whereas the different methods, and models evaluated towards the formulation of the main methodological framework will be described in detail in Chapter 3 along with appropriate numerical examples. Finally, the main methodological framework will be described in detail in Chapter 4 with its application to real-world case studies in Chapter 5, whereas major conclusions and recommendations will be drawn in Chapter 6.

Chapter 2

State of the Art

Summary

As already discussed, PT is considered as a backbone for mobility in urban areas. Similarly, it plays an important role in shifting people from their private vehicles toward more sustainable PT modes. Although some cities have already been successful in such a modal shift while others are still struggling in attracting the maximum possible users towards the PT modes.

More in details, the stated task is not that simple since the analysis of PT systems includes various elements of human behavior, optimization of the variety of different PT options availability, their accessibility, and connectivity, etc. In this regard, the goal of PT is “evolved” into the achievement of a certain level of sustainability on three basic dimensions: environment, economy, and society [19]. Therefore, it is essential for the PT systems of a region to perform at certain performance levels including temporal and spatial availability, accessibility, connectivity, safety, security, environmental protection, etc. The same will be described more in detail in the following sections.

2.1 Public Transport Performance

As already discussed in the previous chapter that one of the main aims of PT systems are to shift people from their private vehicles to PT. Nevertheless, it is

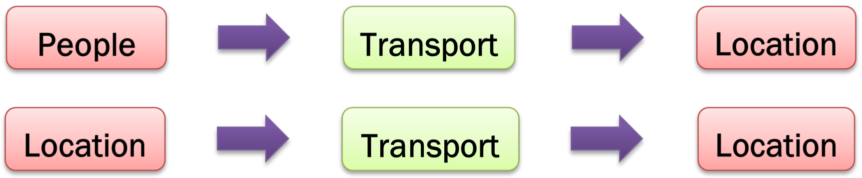

Figure 2.1: Importance of transport systems [21]

almost impossible to attract people to PT, unless it is highly efficient [20]. This efficiency of PT systems gets more importance with the increase in population and its associated impacts on transport infrastructure. So, it is important to design sustainable PT systems that can support the movement of people from one point to another point while minimizing the impacts on the environment [12].

In this connection, the access between the two locations is provided by PT systems in a society that plays an efficient role in moving both the persons and commodities (freight). These origins and destination choices vary from individual to individual; including but not limited to the movements between workplaces, religious places, leisure trips, etc. Thus, it can be suggested that the aim of an efficient PT should not only connect people with the locations but, also connect the locations with other locations as indicated by Figure 2.1 [21].

Furthermore, the performance measurement of a system is usually defined as the evaluation of a company/organization's productivity in terms of the management of its internal resources along with the environment in which they utilize such resources. Similarly, the performance measurement in PT systems is also focused on the measurement of operational efficiency of PT systems to meet the goals and expectations of PT users [22]. In this context, the quality of PT systems should be analysed using various quality features including but not limited to accessibility, availability, connectivity, reliability, environmental emissions, travel times and speed, etc. A combination of all these factors defines the overall system performance [23]. However, the most important among all is the accessibility and connectivity which is important for the concepts of equity as described in the following section.

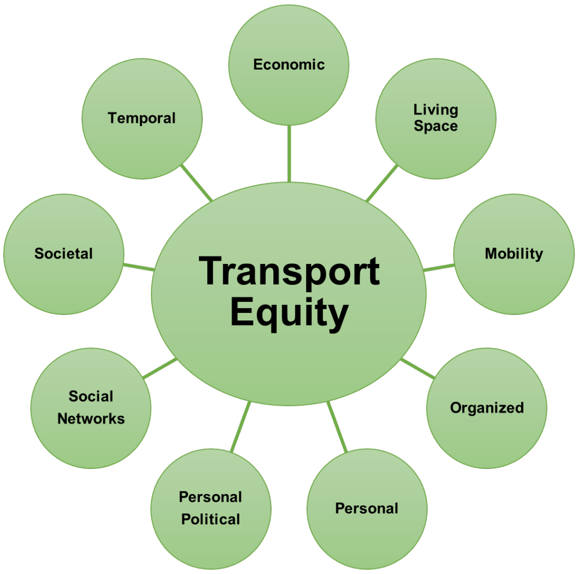

Figure 2.2: Dimensions of transport equity [21]

2.1.1 Equity Concepts in Public Transport Systems

The equity concept is defined by Burchardt in [24] as a process that restricts individuals or groups to participate in the normal activities of life in a society who are geographically the resident of the same society [24]. Equity is not the explanation of the basic terms such as poverty, but it is considered as a more dynamic phenomenon that encircles the sphere of the social life of any individual in any society [24; 25].

In this context, Church in their study of equity and transport in London in [26] identified it as a social exclusion in terms of a broader set of dimensions that are based on the location or on the nature of the facilities themselves including economic exclusion, time-based exclusion, fear-based exclusion, and space exclusion [26]. Furthermore, Kenyon in [27] illustrated a more wide range of dimensions that relate to a number of factors as presented in Figure 2.2.

In the same context, Hilber in [28] stated the different measures of accessibility as

- infrastructure-based accessibility measures: focused on the assessment of the performance of the transport system i.e., travel speed;

- activity-based accessibility measures: developed as the distribution of activities in space and time with in a given region which includes
  - geographical measures: it determines the accessibility of one location to all other locations in an entire transport network i.e. destinations where
    - contour measures indicate the number of activity points accessible within a certain period (e.g. number of jobs within 30 minutes). In this connection, potential accessibility activity points are weighted by the necessary travel time to these points using, e.g. a negative exponential function.
  - space-time measures: representing a participation of an individual in the potential of activities under given time constraints.
- Utility-based accessibility measures: founded based on the benefits for the people driving from access to the spatially distributed activities [28].

Therefore, these dimensions are particularly important when the performance of PT systems is concerned since each of the stated dimensions directly affects the equity of the whole region. In this context, a detailed analysis of such dimensions is important, which is not in the scope of this thesis. However, as already discussed, the most important dimensions are accessibility and connectivity of PT system which will be described in detail in this thesis. In this context, different methods, models, and techniques are available for the evaluation and improvement in accessibility and connectivity of PT systems of a region. Such tools and techniques developed by different researchers will be discussed in Section 2.5 of this thesis, whereas the main methods and models used in this thesis will be described in Chapter 3 and Chapter 4, and a brief summary of two major tools used for the application of such models (as described in Chapter 4) and analysis of results (as discussed in Chapter 5), will be described in the following section.

2.2 GIS as Accessibility Measurement

Geographic Information System (GIS) is considered a key tool for transport planners and policymakers, as also justified by the literature. The tools and theories used in GIS have evolved over the course of time to accommodate the current and future development in the field of transportation. Therefore, it can be said that GIS is a strong tool for spatial planning and transport modeling using a different set of criteria [29]. However, the applicability of GIS in the transport studies is discussed in the following, whereas different methods and techniques developed, will be discussed more in detail in Section 2.5 of this thesis.

In this context, Jong in [21] developed an alternative measure with potential values based on the concept of location profile to avoid problems associated to measure accessibility. Furthermore, Lyborg in [30] considered the number of jobs and opportunities that can be reached within a certain time period from all residential areas in Sweden by comparing car, PT and bike as a mode of transport for accessibility measurement through GIS. Reneland in [31] examined the distances i.e., theoretical and air distance from housing areas to certain destinations for accessibility measurement. More in detail, O'Sullivan measured network level PT accessibility using GIS using aggregated measures and space-time geographic frameworks which are integrated tools of GIS [32].

Furthermore, McCray in his study used GIS as a network planning tool for the analysis of the qualitative data sets collected using the focus group surveys [33]. Similarly, another Spatio-temporal analysis has been conducted by P.Tribby using a model developed using GIS applications. Such a model can measure the travel times of the users traveling between their origins and destinations using PT modes. The model is developed and evaluated entirely using GIS applications [34]. Finally, the impacts of GIS application on PT planning using a case study of London is carried out by Mokashi. In such a study, potential GIS features in terms of PT planning are identified and evaluated towards the practicability of such features in real-world examples. Similarly, the recommendations are drawn towards the importance of GIS features in PT planning [35].

All these studies described the importance of the GIS tool in accessing PT accessibility at a network level. In this context, it can be concluded that GIS is a strong tool in assessing the accessibility of PT stops for any region and can draw the recommendations to the decision-makers through various spatial analysis, especially in terms of highlighting the least accessible areas of PT stops as analysed in Chapter 5 for the stated case studies.

2.3 Role of CPLEX in Public Transport Evaluation

CPLEX is also a powerful tool, used for the implementation of discrete event models toward the determination of optimal solutions. There are different applications of discrete event modeling in different fields of data science, but their application in transport networks towards route optimization, travel time optimization, shortest path calculation, etc., is highly important for transport planners and policymakers. In this connection, CPLEX is one of many tools used for the implementation of these methods and models towards the implementation of real-world examples under a given set of constraints [36].

Furthermore, Shafahi in [37] used the CPLEX to study the transit network scheduling problem aiming at the minimization of travel times of the passengers of transit users using MILP models. Moreover, Gabriel in [38] designed rapid transit systems using optimization models towards the minimization of travel costs. Such a model has been designed and implemented using a CPLEX solver. More in detail, other researchers study different methods and models using CPLEX solver for the optimization of transit system frequencies, route planning of transit lines, and quality assessment of multi-modal PT transport services. The global aim of such studies is the minimization of travel times and cost while at the same time maximizing of overall benefits of transit users in terms of their journey times and their satisfaction from the transit systems [39; 40; 41].

Based on these studies which describe the importance of CPLEX in the evaluation and analysis of PT network, along with the studies described in Section 2.5 of this chapter, suggest the importance of CPLEX towards the determination of optimal solutions especially in case of integrated solutions. Therefore, both GIS and CPLEX proved to be the ideal tools for the analysis of PT network of a region in terms of their accessibility and connectivity as analysed in more detail in Chapter 5 for the stated case studies. However, some solutions to improve the accessibility and connectivity of PT systems of a region are discussed in the following section.

2.4 Solutions for Public Transport Performance Improvement

The performance of PT systems can be improved through the extension of existing PT lines or planning of the new services. However, it is not always possible to extend/plan new PT connections due to the limitations in street space or geographical structure of the area [42]. In this context, the integration of PT systems with the micro-mobility systems are of the utmost importance. Such a connection between PT systems and micro-mobility systems is ideal for the areas characterized by relatively low demand [43] as well as low accessibility and connectivity of PT systems.

There are many micro-mobility solutions which are already existing in the world including but not limited to bike and scooter-sharing, ride-sharing, car-sharing, carpooling, etc. However, such solutions are only discussed as first and last-mile solutions towards the improvements in the overall performance of PT systems (Section 2.5 of this chapter). It is proved from the relevant literature (Section 2.5 of this chapter) that such solutions are limited in their coverage through the provision of availability to the limited population. In this connection, not all micro-mobility solutions are able to provide the stated benefits, but CS is proved to be the ideal solution in satisfying the mobility needs of the population [44; 45; 46; 47; 48; 49]. The same will be studied and implemented in this thesis to improve the accessibility and connectivity of PT systems using the optimization model as described in Chapter 4 and its application to real-world case studies in Chapter 5.

Moreover, all of these solutions are evaluated by different researchers through the development of different models and methods for the determination of ideal solutions as described more in detail in the following section.

2.5 Literature Review

Various studies were developed and different methodologies were applied to different regions for the evaluation of accessibility and connectivity of PT systems separately. All these methodologies were focused on the evaluation of either connectivity or accessibility using different methods and approaches, however, no model is available in the literature for studying the combined effect of connectivity and accessibility together. In this regard, the methodology presented in this thesis defines the new indicators for the determination of accessibility and connectivity index for PT and optimises such values through the operation of CS systems. Similarly, the relevant studies from the literature will be summarized in the following subsection.

2.5.1 Accessibility and Connectivity

The critical points in a PT network were identified by Psaltoglou in [50] using the concepts of graph theory. In this connection, the connectivity index (CI) was calculated based on system performance without emphasizing the concepts of accessibility, using the land use and the variation of its activities over time [50]. Moreover, a survey-based perception of accessibility, connectivity, and mobility was developed in [51], which determines that accessibility was the biggest issue faced by the riders of PT system. In the same context, the relationship between PT connectivity and well-being of the commuters using a multi-variant regression model has been determined in [52]. Variable related to socio-economic and income level of individual travelers were analysed towards the conclusion that the higher life satisfaction level was reported by the walkers than the drivers in the areas of better PT connectivity [52], whereas the role of the street network connectivity in the prediction of transit performance was identified in [53]. Similarly, a new definition of CI was defined using the shortest paths between two transit network nodes depending upon the spatial distribution of the transit network and its demand, which concludes that feeder service was the best alternative for the fulfillment of demand in low accessible PT areas [53].

However, other studies are also available related to the development of optimization models, equations, and surveys which are focused on the determination of the accessibility of PT of a region. In this connection, Transport Accessibility Index (TAI)was developed in [54] based on the combined effect of private vehicles operating on roads and PT with different scoring systems. Road accessibility was used as a base layer for analysis along with the population densities of each zone to evaluate their connectivity to the PT network and road network towards the identification of access-deprived areas based on the transport accessibility scores [54]. Similarly, an indexing system for the determination of the accessibility to the PT was also studied in [55] towards the determination of Public Transport Accessibility Level (PTAL). The average walking time to each PT stop was converted into equivalent doorstep frequency using headways and waiting time, which was used for the determination of PTALs. PTALs were useful towards the identification of areas with the lowest access to PT in the entire PT network [55].

2.5.2 Integration of Public Transport with Car Sharing Systems

Although many researchers developed different methods and models for the determination of accessibility and connectivity of PT systems and evaluated their importance in PT concept, other researchers have also developed various models and methods for balancing demand and supply for PT systems through their integration with CS systems. However, only a few considered CS as a supplement to PT, to meet the unserved demand of PT [56; 57]. Similarly, the substitution of buses by bike-sharing and the car sharing systems was studied in [58] which states that the usage of both shared services increased during and after the pandemic time, especially in the areas with high average income levels [58]. Furthermore, the viability of shared mobility services using stated preference surveys was evaluated in [59] using a mixed logit model to estimate the Value of Time (Vot) for a combination of shared mobility services with conventional PT services. It was observed that e-scooters provide the highest value of Vot among other shared mobility services [59]. Moreover, the factors for successful integration of CS and PT, on the commuter's satisfaction, mobility behaviors, and adoption of the service, were analysed in [56]. Other researchers developed a modal framework for the integration of CS with PT in [57] based on various integration elements such as parking, ticketing, and fare as well as information, data, and physical integration were identified via a case study consisting of the Istanbul city.

Finally, the potential benefits for the integration of ride-sharing and PT were investigated in [60; 61]. In such papers, matching algorithms were designed for the determination of potential matches in ride-sharing as well as park-and-ride services. It was concluded that integration of ride-sharing and PT, increases the potential usage of PT. It also solves other mobility problems by reducing various negative outwardness associated with private vehicle travel.

However, in recent decades, researchers have also carried out various studies and developed different models to assess the potential of user-based allocation based on demand rates and evaluate the performance of different configurations of CS systems, including cost-benefit analyses for the implementation of CS systems in different regions through various case studies in [44; 45; 46; 47; 48; 49]. The relocation problems of CS vehicles were addressed in [46; 47; 48]. User-based performance evaluation for the adoption of CS systems was evaluated in [62; 63], and the benefits of integrating CS with PT systems were assessed in [45; 46; 64].

A two-year field study evaluated factors related to costs, market potential, and environmental impacts and the factors related to the usage of CS systems as feeder services in [44]. A stated preference questionnaire survey was used in [45] to assess the public response towards the usage of CS as a mode. The participant's responses were evaluated using multinomial logit choice models, which suggested that income and travel distance have a stronger influence on the value of travel time savings than other parameters [45]. Other studies focused on the evaluation of the choice behavior of the users towards the adoption of CS systems. The choices of users to travel using CS systems or using other modes of transport were evaluated using a stated preference survey technique, and the data sets related to the willingness to pay, choice of mode, and parking availability were analysed using the logit model in [62]. Similarly, the satisfaction of CS system users, their mobility patterns, and the adoption of CS systems for the allocation of users to combined PT and CS systems were studied in two German cities in [63]. Mobility behavior and customer satisfaction have been shown to be beneficial for the integration of CS with PT systems, although the adoption process was a lengthy task that requires changes in mobility behaviors [63].

To cope with observed operational problems, other studies were focused on the design of CS systems in a region and on the balancing of vehicles between CS stations. Accordingly, the performance indicators and preferences of potential customers using CS services were modeled and optimised in [46] using a fuzzy approach for the reduction of maintenance and human resource management costs. In the same context, a multi-objective MILP model for the planning of a one-way CS system based on the optimal relocation of CS vehicles was designed in [47] to maximise net revenues based on demand. As the accessible distance decreases, the demand for a CS system increases; hence, the total revenue and user benefits increase [47]. Another approach for the optimisation of CS depot locations in terms of number, location, and size was studied by [48] using a mixed integer model aimed at increasing operator revenues. Constraints regarding vehicle flow, timing, and number of vehicles in each depot were considered, and it was concluded that maximum operator profit can be reached by providing 10 depots in the Central Business District (CBD) of a city to serve trips with high demand densities [48]. Finally, a genetic algorithm was developed to solve the problem of the location of CS systems in the city of Lanzhou in [49]. The area was divided into a matrix in which each entry represented a demand point and a candidate station. A nonlinear integer programming model was designed to maximise user demand such that the total cost (i.e., the sum of vehicle purchasing costs, charging costs, parking fees, and land rental fees) was within the maximum available budget [49].

Based on the relevant literature, it is evident that CS systems can efficiently provide flexibility, cost management, a shift from private to shared vehicles among the public, and many other advantages. A few researchers have studied CS as a supplement to PT systems, e.g., [45; 46; 64], but there is still insufficient literature addressing an integrated model to assess the effects of CS and PT together, especially in terms of activating CS depots to improve the accessibility and connectivity of PT systems using a linear programming approach. To address this gap, this thesis is focused on developing an integrated model of CS/PT systems using the MILP approach to analyse potential improvements to the total CAI values through the optimal design of CS systems in the least accessible areas of

PT, as explained in detail in the following chapters.

Chapter 3

Conceptualization of Proposed Methodological Framework

Summary

The accessibility and connectivity of PT are the elements related to spatial distribution of PT resources. Moreover, such elements serve as an indirect measure for the evaluation of the number of different PT options available to commuters for traveling from their origins to destinations. Furthermore, the accessibility and connectivity can be improved either by the extension of existing PT lines/integration of PT systems with some micro-mobility solutions as described in Section 2.4 of Chapter 2 of this thesis.

The approach defined in this paper is unique as justified by the review of the relevant studies from the literature in Section 2.5 of Chapter 2 of this thesis. Similarly, the defined methodology is focused on identifying the least accessible areas of PT stops through the utilization of appropriate proximity analysis tools/algorithms in Arc GIS application. Then at the same time improves the so-called CAI values of PT through the design and operation of a traditional two-way CS system. More in detail, the framework for the identification of the least accessible areas of PT, the formulation of the model for the determination of CAI values of PT in integration with proposed CS system, are developed in steps.

Each development step of the main methodological framework (described more in detail in Section 4.2 of Chapter 4) is supported using appropriate literature studies (Section 2.5 of Chapter 2) for the justification of their novelty/uniqueness. Similarly, the mathematical and optimization models used for their development are justified using numerical examples as described more in detail in the following sections.

3.1 Public Transport Accessibility Index Scores

As already discussed in Chapter 2 that rapid urbanization along with population growth increases the pressure on existing transportation systems which boosts the need for the provision of well-connected and efficient PT Systems, to meet the mobility needs of the people. In this framework, it is important for the PT system of a region to perform at certain quality levels including availability (both spatial and temporal), accessibility, affordability, environmental protection, etc. Among all these features, the most important is the accessibility to PT stops. In this connection, a methodology has been developed to evaluate the accessibility of PT at different levels of measurements of a region/city using Public Transport Accessibility Index (PTAI) scores, calculated based on the accessibility of PT stops to the population, service centers and connectivity to nearby regions. The proposed approach is also effective in terms of highlighting the least accessible areas for the improvement of existing PT connections or planning of new services [9]. The methodological framework developed will be briefly discussed in the following section.

3.1.1 Methodology Adopted

The methodological framework in this approach has been developed for the combination of three regional levels using data sets as presented in Table 3.1.

The desired methodology calculates the Accessibility Index Score (AIS) a combination of two levels of measurements and it is necessary to define the same or similar level of measurement for the region under consideration, as follows:

- intra-regional and inter-regional level combination: the smallest unit of

Table 3.1: Required Data Sets and their Definitions

Data	**Attribute**	**Description**
Spatial Data	Administrative Boundaries	Regional boundaries, City boundaries, or Intra-city smaller units (Traffic Analysis Zones (TAZ), census blocks, etc.)
Demographic Data	Population	Population data for each level (if population data is not available for smaller units, population density is calculated and applied to smaller units to estimate the population)
	Service Centres	This represents the major origins and destinations of a trip including workplaces, education, leisure facilities, religious facilities, etc.
Transport Data	PT Network	Containing all the lines/links of all the modes of PT operating in all three levels of the regions
	PT Stops	Includes stops of metros, buses, railways including the local connections as well international connections

measure are the TAZ, census blocks or any other smaller unit available and the biggest unit of measure are the city boundaries;

- regional and inter-regional level combination: the smallest unit of measure is city boundaries, and the biggest unit of measure is the regional boundaries.

Similarly, the combination of these levels can be extended based on the availability of data sets in accordance with the smallest unit of measurement. Moreover, the Proximity to Public Transport Stops (PPT) using the PT network is calculated for each mode of transport and relevant scores are calculated. The following scores are defined based on the literature review in [65; 66; 67], which explains the effect of walking distances on the performance of PT. They define the recommended walking distance to access the bus stops based on the type of stops (regional stops, inter-regional stops, intra-regional stops) and the type of service accessible through the stops (bus, trams, metro, etc.). In this connection, walking distance buffers are drawn to determine

- $\wp_{bus}^{PPT}$: A walking distance buffer of 400 meters is generated around each bus stop;

- $\wp^{PPT}_{metro}$: A walking distance buffer of 800 meters is generated around each metro stop as well as railway station (in case of local connections);
- $\wp^{PPT}_{railway}$: A walking distance buffer of 1000 meters is generated around the railway station, bus stop, and metro stop (in case of regional connections).

whereas, relevant scoring brackets are recommended as

- Score 0 – 0% of the population;
- Score 1 – 0 to 30% of the population;
- Score 2 – 30% to 60% of the population;
- Score 3 – 60% to 90% of the population;
- Score 4 – More than 90% of the population;

falling under each of $\wp^{PPT}_{bus}$, $\wp^{PPT}_{metro}$, and $\wp^{PPT}_{railway}$, which defines AIS scores. The set of criteria can be extended in a similar pattern based on the availability of other PT options within the cities/regions. By combining this criterion, it is possible to calculate AIS for each smaller unit of measure, and the maximum of AIS for each criterion is taken into consideration as

$$AIS_{PPT} = \max\left(\wp^{PPT}_{bus}, \wp^{PPT}_{metro}, \wp^{PPT}_{railway}\right) \tag{3.1}$$

Furthermore, Proximity to Service Centers (PSC) is calculated in a similar way, whereas these service centres represent destinations in a network of PT and it is important to connect the population with these destinations. The following scores are defined based on the literature studies as defined in [68; 69], which explains the effect of walking distances (to access these destinations from PT stops) on the performance of PT. Similarly, walking distance buffers are drawn to determine

- $\wp^{PSC}_{bus}$: A walking distance buffer of 400 meters is generated around each bus stop;

- $\wp^{PSC}_{metro}$: A walking distance buffer of 800 meters is generated around each metro stop as well as railway station (in case of local connections);
- $\wp^{PSC}_{railway}$: A walking distance buffer of 1000 meters is generated around each railway station, bus stop, and metro stop (in case of regional connections).

whereas, relevant scoring brackets are recommended as

- Score 0 – 0% of the service centers;
- Score 1 – 0 to 45% of the service centers;
- Score 2 – 45% to 90% of the service centers;
- Score 3 – More than 90% of the service centers;

falling under each of $\wp^{PSC}_{bus}$, $\wp^{PSC}_{metro}$, and $\wp^{PSC}_{railway}$, which defines AIS scores. By combining this criterion, it is possible to calculate AIS for each smaller unit of measure and the maximum of AIS for each criterion is taken into consideration as

$$AIS_{PSC} = \max\left(\wp^{PSC}_{bus}, \wp^{PSC}_{metro}, \wp^{PSC}_{railway}\right) \tag{3.2}$$

Finally, the proximity of the smallest unit of measure to the largest unit of measure (Proximity to Nearby Regions (PNR)) is calculated from the centroids (based on business activities within the towns) of the smallest unit of measure to the nearby PT stops. Since the activities are distributed around the CBD of a region, therefore it is important to see the PT connections around CBD of each zone [70]. This can be done by drawing a walking distance buffer of 1000 meters around each centroid of the smallest unit of measure and capturing the PT stops falling under this buffer by using the following criteria

- Score 0 – 0% of the PT stops;
- Score 1 – 0 to 45% of the PT stops;
- Score 2 – 45% to 90% of the PT stops;
- Score 3 – More than 90% of the PT stops;

falling under the buffer. The PTAI on a scale of $0-10$ is simply the summation of the AIS for all three criterion as follow

$$PTAI = AIS_{PPT} + AIS_{PSC} + AIS_{PNR} \tag{3.3}$$

3.1.2 Numerical Example

The method designed for the evaluation of PT AIS is evaluated using a numerical example in the following section. It is assumed that regional boundaries are considered the largest unit of measure while city boundaries are considered the smallest unit of measure. In the considered example, analysis is done at the city level while AIS scores are determined for each city within the region. In this connection, a region with the following characteristics is considered

- 4000 inhabitants is assumed which contain five cities A, B, C, D, and E with a population of 500, 1500, 800, 300, and 900 respectively as presented in Figure 3.1;
- total area of the region and of each city is known, and populations of each city are converted into the respective population densities;
- the geographical centroids (located using a tool in Arc GIS) of each city are represented by the yellow dots while locations of the service centres are shown by small black dots as presented in Figure 3.1;
- PT network in the cities is shown in the Figure 3.1 with the following characteristic
  - two bus lines: green line (where nodes 1, 6, and 10 serve as regional connections; nodes 4 and 8 serve as local connections while nodes 2, 7, and 18 serve both as regional as well as local connections); blue line (where nodes 5, 7, 9, and 11 serve as regional connections; nodes 3 serve as a local connection while node 18 serve both as regional as well as local connections);

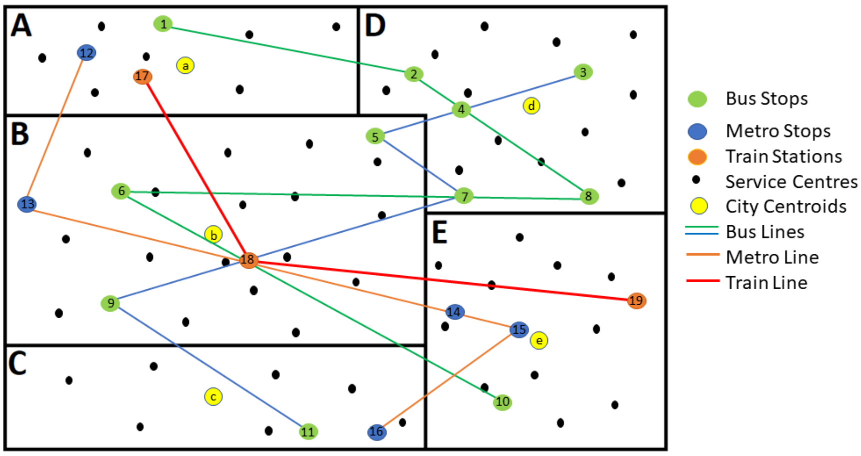

Figure 3.1: Characteristics of region and city for analysis at city-wide level

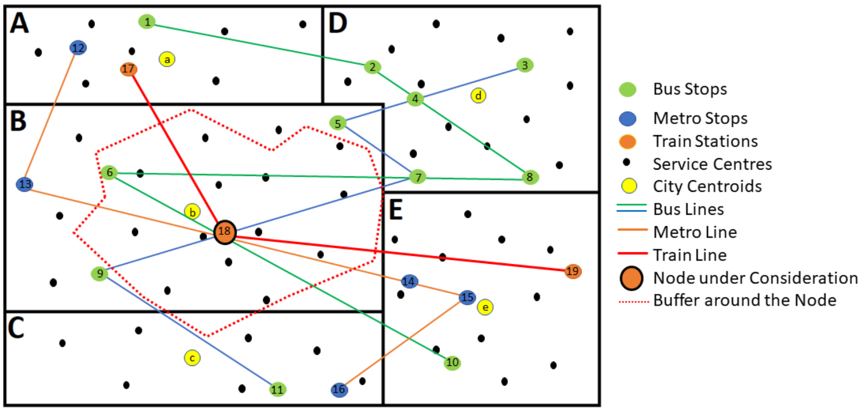

Figure 3.2: Walking distance buffer drawn around node 18

- one metro line shown by orange colour (where nodes 12, 13, and 16 serve as regional connections while nodes 14, 15, and 18 serve both as regional as well as local connections);
- one regional train connection (shown by red colour) operating between the cities A, B, and E (meaning that all the nodes 17, 18, and 19 serve as regional connections, whereas node 18 serves as a multi-modal node).

Furthermore, to illustrate the application of the methodology, calculations at node 18 are represented by Figure 3.2. Node 18 is selected because it serves as

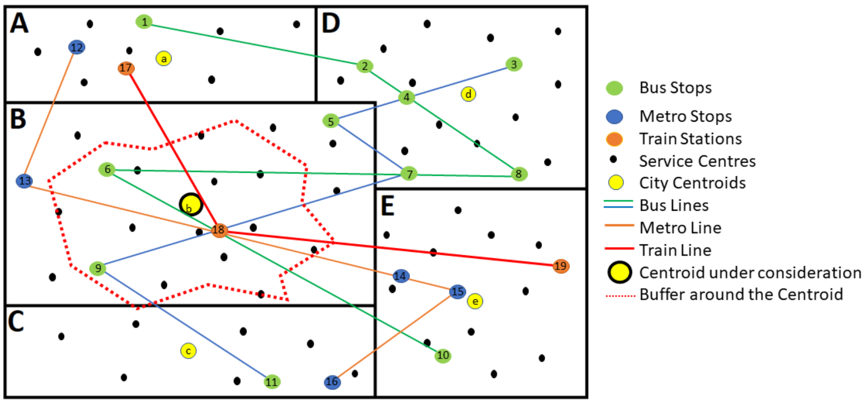

Figure 3.3: Walking distance buffer of 1000 meters drawn around the centroid of city B

a multi-modal node and is crossed by all the modes of transport in the city B. This node serves both as regional and local connections while crossed by bus lines and metro lines but it serves only as a regional connection while crossed by railway line. So, each criterion explained in Section 3.1.1, is applied separately and the maximum value for each criterion is considered for the calculation of PTAI according to (3.3). Similarly, buffers are generated across each node by taking into consideration the type of connection that a node provides. An example of the buffer around the centroid of city B is shown in Figure 3.3.

In this connection, the values of AIS are determined based on the PPT, PSC, and PNR. The results are summarized in Table 3.2. The total value of PTAI is calculated using (3.3), as summarized in Table 3.3. Since nodes 2, 7, 15, and 18 are serving both as regional as well as local connections, the AIS is calculated separately based on the type of connection that each node provides as shown in Table 3.2. The highest value of AIS is given by city B because more options of PT are available within this city along with a multi-modal node 18. In addition to this, the number of connections is less in city A but the value of PTAI is still high because of two reasons:

- existing PT options in the city A are enough to distribute the demand for the PT by connecting the maximum possible population to the service centers;

Table 3.2: Accessibility index scores based on PPT, PSC and PNR (^{a} = regional connection; ^{b} = local connection)

Cities	**Nodes**	**Mode**	$\wp^{PPT}$	AIS_{PPT}	$\wp^{PSC}$	AIS_{PSC}	AIS_{PNR}
A	1	Bus^a	1	2	2	2	3
	12	Metro^a	2		1		
	17	Train^a	1		1		
B	5	Bus^a	1	4	1	2	2
	13	Metro^a	1		1		
	6	Bus^a	1		1		
	18	Train^a	4		2		
		Bus^b	1		1		
		Bus^a	2		2		
		Metro^a	2		2		
		Metro^b	3		2		
	9	Bus^a	1		1		
C	11	Bus^a	1	2	2	2	3
	16	Metro^a	2		2		
D	2	Bus^a	1	3	1	2	1
		Bus^b	1		1		
	3	Bus^b	2		1		
	4	Bus^b	3		2		
	7	Bus^a	1		2		
		Bus^b	1		2		
	8	Bus^b	1		2		
E	14	Metro^a	1	2	1	2	1
		Metro^b	1		1		
	15	Metro^a	2		1		
		Metro^b	1		1		
	10	Bus^a	2		2		
	19	Train^a	2		2		

- all nodes in city A act as regional nodes and they are distributed around the centroid of city A so, it has high proximity of connecting city A to the nearby cities.

The other cities C, D, and E show low values of PTAI (as represented by high-

Table 3.3: Total values of PTAI based on all considered criterion

City	AIS_{PPT}	AIS_{PSC}	AIS_{PNR}	$PTAI$
A	2	2	3	7
B	4	2	2	8
C	**2**	**2**	**2**	**6**
D	**3**	**2**	**1**	**6**
E	**2**	**2**	**1**	**5**

lighted rows in the Table 3.3) meaning that PT systems in these cities are not serving the minimum possible population and the spatial distribution of nodes within these cities are not efficient to connect the commuters with the service centres as well as to the nearby regions. Therefore, these cities require new connections to improve the accessibility of PT stops. Since the analysis is carried out at a city-wide level, the PTAI scores represent the accessibility of each city. Since city boundaries are quite large and contain different kinds of PT options, it is suggested that the formulated methodology is applied to the lowest possible unit of measurement, according to the availability of data sets. The applicability of this concept is further explained by taking the city B (Figure 3.1) and sub-dividing it into the TAZ as shown in Figure 3.4.

In this connection, each criterion defined in Section 3.1.1 is applied for subdivisions of city B in TAZ as represented by Figure 3.4. PTAI scores are calculated for each TAZ and the results are summarized in the Table 3.4. It can be clearly seen from Table 3.4 that traffic analysis zone I gives lower values of AIS than traffic analysis zone II. If just the first case (Figure 3.1) is considered then entire city B appears to be accessible by PT; but, after the sub-division of the city into smaller regions, traffic analysis zone II is accessible to the PT in the city B while traffic analysis zone I needs improvements in terms of new connections or improvements in the spatial distribution of nodes. This represents the importance of splitting the areas into the smallest possible zones and carrying out analysis at the smallest possible level.

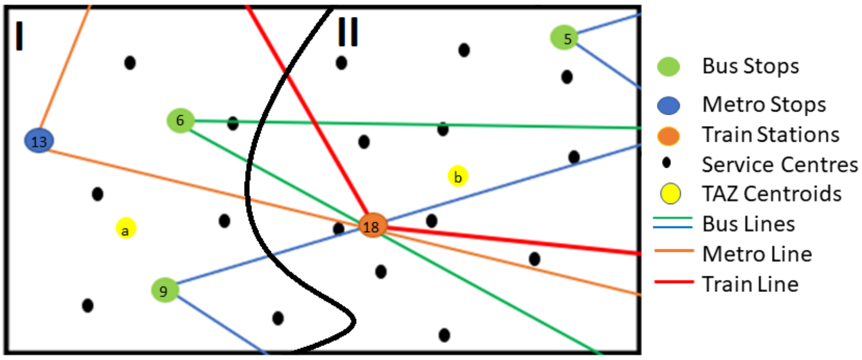

Figure 3.4: Sub-divisions of city B according to the TAZ

Table 3.4: Total values of PTAI for each TAZ within city B

City	AIS_{PPT}	AIS_{PSC}	AIS_{PNR}	$PTAI$
I	2	2	2	6
II	4	2	2	8

3.1.3 Pros and Cons of the Approach

In this approach, since only the attributes of PT have been taken into consideration and the travel times (used for drawing buffers) are solely based on the network of PT, the scoring system directly provides the performance of PT of a given region. However, the identification of areas in terms of the lower's values of PTAI requires large data sets, especially when the analysis needs to be performed at the microscopic level. Furthermore, the accessibility index alone is not enough to purpose improvements in PT performance in terms of extending the existing lines/proposing the new connections. In this connection, it is important to study the connectivity of individual PT lines along with the accessibility of PT stops to draw recommendations towards the improvements in the performance of PT of a region.

Therefore, it is recommended to develop analytical methods for the determination of accessibility and connectivity index together using a single model, since the proposed approach is more subjective than objective. In this connection, the accessibility index (based on the importance of PT stops accessibility as described by the considered approach) will be reformulated using the analytical model with the combined effect of the connectivity index of PT, in the following section.

3.2 Identification of Critical Nodes

As already described in Chapter 2 that the PT of a region is extremely important for connecting the commuters from their origins to destinations, such that PT with large fleets cannot be guaranteed to perform efficiently unless it is well connected and accessible to the maximum possible population. In this regard, the localization of PT stops (nodes) are highly important, since access to public transit systems is only possible through these nodes [8].

In this framework, the next step towards the development of the main methodological framework (Chapter 4), a general methodology for the evaluation of PT nodes of a region based on transit system characteristics, including but not limited to the spatial coverage and characteristics of zones considering the concepts of connectivity and accessibility, will be evaluated in this section. An initial framework for the determination of CAI of PT is established, which is enhanced based on the distribution of PT trips in zones, for the identification of critical nodes in PT network [8].

3.2.1 Methodology

As already discussed, the major aim of this approach is the assessment of the performance of PT of a region based on its accessibility and connectivity characteristics. These parameters are specifically evaluated for the PT stops (nodes) which act as points of access/egress from PT network. In doing so, values of CAI as well as Enhanced Connectivity and Accessibility Index (ECAI) are calculated for all nodes of PT based on the following characteristics of transit lines:

- transit line capacities;
- speed of the transit lines;
- network distance covered by transit lines;

- availability of PT during different time periods (comparing the number of lines available during the morning vs number of lines available during the evening) [71];
- spatial coverage;
- population availability in terms of accessibility;
- accessibility to the service centres (service centres refer to the origins and destinations for a PT trips e.g. shopping, education, workplaces, religious places, etc.) [72].

All of these factors are combined to form a single equation for the calculation of connecting powers of PT lines at a specific time period. Since the demand for the PT is not constant and it varies over different time periods, e.g., during peak and off-peak time periods, during some emergency events (representing the closure of few PT lines due to strikes, etc.), it is important to evaluate the value of connecting power during different time periods to represent the availability of service among each considered time periods. Furthermore, for each PT line, there are two possible directions (inbound and outbound), therefore connecting power of a PT line p_l^t, is calculated for the inbound direction as incoming connecting power $p_l^{t,in}$, expressed as

$$p_l^{t,in} = \rho^{t,in} r_l^{t,in} \cdot \varphi^{t,in} v_l^{t,in} \cdot \mu^{t,in} d_{n,l}^{t,in}, \quad \forall l \in \mathcal{L}_{z,n}, \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{3.4}$$

the product of total capacities $r_l^{t,in}$, speeds $v_l^{t,in}$, and distance travelled $d_{n,l}^{t,in}$ by the PT line l in the incoming direction from node n till its destination during each considered time period t [73], whereas connecting power of a PT line p_l^t, is also calculated in the outbound direction as outgoing connecting power $p_l^{t,out}$, which is expressed as

$$p_l^{t,out} = \rho^{t,out} r_l^{t,out} \cdot \varphi^{t,out} v_l^{t,out} \cdot \mu^{t,out} d_{n,l}^{t,out}, \quad \forall l \in \mathcal{L}_{z,n}, \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{3.5}$$

the product of total capacities $r_l^{t,out}$, speeds $v_l^{t,out}$, and distance travelled $d_{n,l}^{t,out}$ travelled from node n till the termination of the PT line l, in outgoing direction during each considered time period t [73]. Moreover, the values of coefficients $\rho^{t,in}$, $\varphi^{t,in}$, and $\mu^{t,in}$ in (4.1) and of coefficients $\rho^{t,out}$, $\varphi^{t,out}$, and $\mu^{t,out}$ in (4.2) are determined as the reciprocals of the average bus capacities, speeds, and route lengths computed over all PT lines operating during the time period t.

Moreover, the total connecting power of a PT line at PT node n is

$$p^t_{l,n} = \frac{p^{t,in}_l + p^{t,out}_l}{2}, \quad \forall l \in \mathcal{L}_{z,n}, \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{3.6}$$

the arithmetic average of incoming connecting power (calculated using (4.1)), and the outgoing connecting power (calculated using (4.2)) during each considered time period t. In this connection, the value of CAI of each node is calculated based on the summation of the connecting powers of all PT lines (since one node can be crossed by several lines) passing through the node and the accessibility parameters of the node during each time period t, expressed as

$$CAI^t_{PT,n} = p^t_{l,n} + \omega^t \Omega^t_n + \pi^t \Pi^t_n + \xi^t \Xi^t_n, \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{3.7}$$

consisting of the summation of

- the total connecting power of node n (calculated using (3.6));
- the accessibility parameters, expressed by the area within the walking distance Ω^t_n from node n
- population Π^t_n and the number of POI Ξ^t_n, both within area Ω^t_n, for node n during time period t.

The coefficients ω^t, π^t, and ξ^t in (3.7) are scaling parameters, determined as the reciprocals of the average areas within the walking distance, populations and numbers of POI falling within these areas, computed over all the nodes of the entire PT network. Note that since the number of active PT lines (and consequently the number of reachable nodes) vary with time, as well as the number of POI, the scaling parameters ω^t, π^t, and ξ^T also depend on time.

Furthermore, the demand for PT also varies according to the distribution of trips carried out by PT within the zones during different time periods. So, it is important to enhance the calculated value of CAI (calculated using (3.7)) based on the fluctuation in demand resulting from the trip distributions [73]. The best method to evaluate the variation in PT demand is the characterization of the region into a number of zones and studying the factors which affect the demand for PT, which includes

- PT trip distribution within each zone;
- population of each zone;
- socio-economic characteristics of each zone (income level, car ownership, household sizes, etc.).

All these factors affect the demand for PT directly/indirectly. The effect of these factors on the value of CAI is studied under different time periods with the help of a network distance buffer (proportional to the standard walking distance for each mode of PT), drawn around each node Δ_n, and the number of zones falling under this network distance buffer $\Delta_{n.z} \forall z \in \mathcal{Z}$ are highlighted, such that the equation for the CAI (calculated using (3.7)), is modified to represent the value of ECAI for each node n during each considered time period t, as

$$ECAI_n^t = CAI_{PT,n}^t \cdot \left(\frac{\kappa_n^t}{\kappa_{avg}^t} \right), \quad \forall n \in \mathcal{N}_z, \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.8}$$

the multiplication of $CAI_{PT,n}$ with division of the distribution of activities κ_n^t with respect to each zone z in which the node n is located during time period t and arithmetic average of the distribution of activities $\kappa_{avg,z}^t$, in all the zones during same time period t. More in detail, the value of activities distribution is calculated zone-wise as

$$\kappa_n^t = \sum_{z \in \mathcal{Z}} \frac{\kappa_{n,z}^t \cdot \Delta_{n,z}}{\Delta_n}, \quad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{3.9}$$

the product of activity distribution $\kappa_{n,z}^t$ for a zone z during time period t in which the node n is located and the area of buffer $\Delta_{n.z}$, drawn from node n falling under zone z, which is divided by the total area of the buffer Δ_n drawn from node n.

In this connection, the value of activity distribution κ_z^t, for a zone z is calculated as

$$\kappa_z^t = \frac{\Im_{PT,z}^{t,inc} + \Im_{PT,z}^{t,out} + \Im_{PT,z}^{t,dis}}{Pop_z}, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.10}$$

a function of the number of incoming trips $\Im_{PT,z}^{t,inc}$ and outgoing trips $\Im_{PT,z}^{t,out}$, to/from the zone, respectively as well as the trips distributed, $\Im_{PT,z}^{t,dis}$, within the zone z, all during time period t. (3.10) is divided by the population Pop_z of zone z, to evaluate the distribution of trips per population of each zone. The feasibility of this approach is tested using the numerical example as described in the following section.

3.2.2 Numerical Example

The efficiency of the model defined in Section 3.2.1 is justified with the help of a numerical example in this section. It is assumed that the region is divided into 4 zones with 2 bus lines and a metro line, connecting 8 nodes in all the zones as shown in Figure 3.5 and Figure 3.6, where the bigger dots represent nodes and smaller dots represents the locations of the service centers. It is assumed that PT trip distribution within the same zone and between two different zones are known (for the calculation of activities distribution using (3.9) and (3.10)). The whole region comprises 6000 people and headways of buses and metros are 10 min and 5 min, respectively with the following characteristics:

- green line starts from node 2 and end at node 6 passing through nodes 1, 3, and 5 (covering zone 1, 2, and 3);
- purple line starts from node 3 and ends at node 8 passing through nodes 7 and 8 (covering zone 2, 1, and 4);
- blue line starts from node 2 and ends at node 7 passing through nodes 4, 3, and 6 (covering zone 2, 1, 3, and 4);
- capacity, frequency, and total daily operations by each PT line are known along with the total distance covered on the route by each PT line. Trip distribution according to population density as well as population distribution of each zone is known;

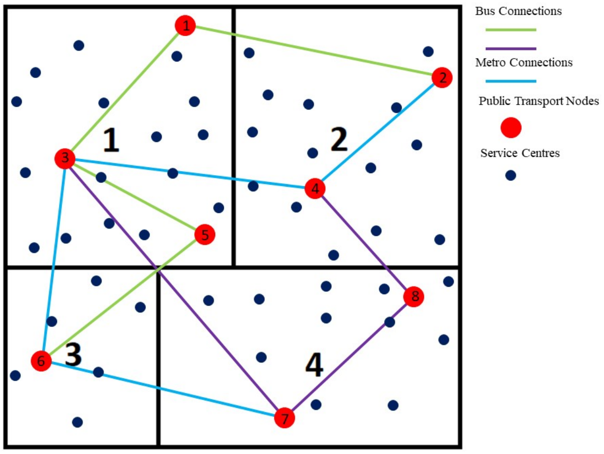

Figure 3.5: Division of region in zones and PT nodes and line availability during the day

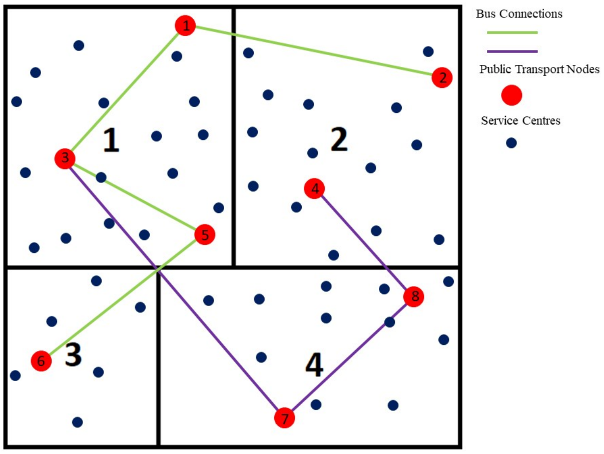

Figure 3.6: Division of region in zones and PT nodes and line availability during the night

- during the day, all three services are available (Figure 3.5) while at night, the metro service is not available as well as there is no alternative service is operated at night to meet the demand (Figure 3.6).

Based on given data sets, the values of CAI and $ECAI$, are calculated using (3.7)) and (3.8), respectively, and reported in Table 3.5 and Table 3.6 along with the comparison of these values in the last column during day and night,

Table 3.5: Values of CAI and $ECAI$ during the day

Zone	**Node**	CAI	$ECAI$	**Difference(%)**
1	1	1.70	1.73	1.38
2	2	4.74	4.03	-14.99
1	3	6.60	7.23	9.57
2	4	4.63	4.36	-5.78
1	5	2.21	3.01	36.39
3	6	4.05	1.43	-64.78
4	7	4.12	5.76	39.81
4	8	1.98	1.95	-1.60

Table 3.6: Values of CAI and $ECAI$ during the night

Zone	**Node**	CAI	$ECAI$	**Difference(%)**
1	1	1.7	1.73	1.38
2	2	2.14	1.82	-14.99
1	3	4.34	4.76	9.57
2	4	2.42	2.28	-5.78
1	5	2.21	3.01	36.39
3	6	2.11	0.74	-64.78
4	7	1.64	2.3	39.81
4	8	1.98	1.95	-1.6

respectively such that the positive values in the column of difference show the increase in $ECAI$ value from CAI and vice versa.

The entries of Table 3.5 reveal that the value of CAI for node 6 is quite high as compared to other nodes, representing that connectivity of PT is relatively good, but this value is reduced by about 64% after the calculation of $ECAI$, representing that PT connectivity is not performing well in terms of PT trip distribution. Nodes 2, 4, and 8 show a similar behavior since the values of percentage difference are <0. If the performance assessment of node 6 is limited to the values of CAI, node 6 is not a critical node, but the values of $ECAI$ indicate it as a critical one. Similar results are seen for all the nodes during the night (Table 3.6) and the same nodes represent the reduction in the values of $ECAI$ as those evident through Table 3.5.

Furthermore, the values of CAI and $ECAI$ are constant for some nodes (including node 1, node 5, and node 8). Such behavior is explained since these nodes are passed by only one PT mode (Figure 3.5 and Figure 3.6), and there are no connections available to transfer to other modes of PT. In practice, these nodes represent the areas of PT with low demand, nevertheless, in the considered example these nodes are introduced to put into evidence the fluctuation of the connectivity and accessibility indexes. On contrary, for some nodes (nodes 2, 3, 4, and node 6), there exists a big difference between the values of CAI and $ECAI$ during both time periods due to the fact that the metro lines are closed during the night (Figure 3.6) and therefore there is the unavailability of alternative PT services to satisfy this demand.

To conclude, it is possible to state that a node that is shared between different modes of PT shows better values of CAI and $ECAI$ than the nodes passed by the smaller number of PT options. It is also observed that the value of CAI is not enough for the identification of critical nodes unless the effect of the distribution of actual PT demands (in terms of PT trips within each zone) is seen through the value of $ECAI$.

3.2.2.1 Pros and Cons of the Approach

The proposed methodology evaluates the importance of connectivity and accessibility at the PT nodes showing the importance of the calculation of values of $ECAI$ to identify actual critical nodes since critical nodes are identified based on the value of CAI is misleading. The numerical example showed that the proposed approach is effective for the determination of the performance of PT in terms of connectivity and accessibility. Although the values of $ECAI$ give the actual representation of the criticality of nodes in a region, the data sets required for these values' determination are huge which makes it difficult to implement this model to a larger network with hundreds of PT nodes. Moreover, given the complexity of PT networks of big cities, the calculation of $ECAI$ values (even if the entire data set is available) is not easy and computationally challenging.

In this context, it is necessary to develop an integrated model using optimization methods to evaluate the efficiency of PT network based on the values of CAI

using analytical models, whereas values of CAI should be optimized through the extension of existing PT lines or design and operation of other micro-mobility solutions. In this context, the impacts of PT demand on the values of CAI can be investigated directly inside the optimization models and, computational effort can also be minimized, whereas linear programming models guarantee the optimum solutions under a given set of constraints. Similarly, the effects of designing a CS system towards the management of PT demand in the least accessible areas, will be investigated in the following section.

3.3 Design of Car Sharing System to meet Public Transport Demand

As described in Section 3.1 and Section 3.2 of this chapter that PT systems of a region serve as key players in satisfying the mobility needs of people. Nevertheless, the rapid urbanization and population growth increase the pressure on existing PT infrastructure in terms of effectively meeting additional passenger demand, and a failure in this goal will result in users' shift to their private vehicles with consequent worsening of the congestion problems along with other environmental impacts. In this framework, it has been observed that providing more and more PT options, is not always a viable solution due to limited street space and large investments required for their operations. To tackle this issue, shared mobility services such as car sharing, ride-sharing, and other micro-mobility services proved to be a feasible solution. Considering these facts, the proposed model under this section is aimed at the design of CS systems as a supplement to PT to attract the additional demand for PT systems of a region. To do so, an optimization model is stated as MILP model, aiming at minimizing the unserved demand for PT in each zone but maximizing, at the same time, the operator's revenues [43], as discussed more in details in the following section.

3.3.1 Methodology Adopted

The methodological framework is developed based on the assumption that the total PT trips within a zone are distributed equally between each PT node, present in the same zone. Furthermore, PT operator's revenues are assumed to be constant during the optimization process because neither the changes in the existing PT lines nor the planning of new lines is suggested. Therefore, the increase of the Additional Net Revenue (R), that is deriving from the additional met demand, is calculated and optimized through the activation and operation of CS systems.

In this context, let $\mathcal{T}$ be the set of considered time slots and $\mathcal{Z}$ be the set of zones in the considered study area. Given these definitions, the total demand for PT systems $TD^{t}_{PT,z}$ in a zone z, during each time slot t is computed as

$$TD^{t}_{PT,z} = TD^{in,t}_{PT,z} + TD^{out,t}_{PT,z}, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.11}$$

the summation of total incoming demand $TD^{in,t}_{PT,z}$, and total outgoing demand $TD^{out,t}_{pub,z}$ into and out of the zone z, respectively during each considered time slot t. Similarly, total demand served by the PT systems $SD^{t}_{PT,z}$ within a zone z during each time slot t, is calculated as

$$SD^{t}_{PT,z} = \sum_{l \in \mathcal{L}_{z,n}} f^{t}_{l} \cdot C_{l}, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.12}$$

the summation of the product of frequency f_l and capacity C_l of each PT line l, during each considered time slot t, whereas $\mathcal{L}_{z,n}$ represents the set of lines l passing through node n, located in the zone z. Finally, the PT unserved demand in a zone z during each time slot t, is expressed as

$$UD^{t}_{PT,z} = TD^{t}_{PT,z} - SD^{t}_{PT,z}, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.13}$$

the difference between total demand $TD^{t}_{PT,z}$, and total demand served $SD^{t}_{PT,z}$ by PT in zone z during each considered time slot t. Based on the initial formulations as described from (3.11)-(3.13), the optimization model is designed as a MILP problem aimed at the minimization of maximum values of unserved passenger demand in each zone z, summed over all the time slots, and the maximization of the operator's revenue R earned through the activation and operation of CS systems. To this aim, let

- $\mathcal{V}$ is the set of potential vehicles located into the considered depots (it is assumed that CS depots are located at parking facilities already existing in each zone z and the locations of these CS depots remain fixed during the optimization period);
- R^t are the additional net revenues of the operator earned by the operation of CS systems, that need to be maximized during the time slot t;
- $g^t_{v,z}$ is the binary variable set to 1 if the vehicle v is placed in the zone z during the time slot t, and 0 vice-versa;
- h^t_z is the binary variable set to 1 if the CS system is activated in the zone z during the time slot t, and 0 vice-versa.

Based on these assumptions, the MILP problem is given as

$$[\boldsymbol{g}^\star, \boldsymbol{h}^\star] = \left| arg \max_{g,h} \sum_{\forall t \in \mathcal{T}} R^t - \beta \max_{\forall z \in \mathcal{Z}} \left\{ \sum_{\forall t \in \mathcal{T}} UD^t_{PT,z} \right\} \right| \tag{3.14}$$

the maximization of operator revenues R^t, while at the same time minimization of maximum values of unserved passenger demands for each zone z, both during considered time slot t. The absolute function is used to make the two terms comparable. In other words, the reduction of the unserved demand must provide an equivalent revenue. In doing so, β is introduced as a normalization factor, to numerically compare both functions, R^t and $UD^t_{tot,z}$ with each other and avoid any bias in the optimal solution. The value of β is calibrated based on the theoretical possible best values of R^t and $UD^t_{tot,z}$ for each value of p_{CS} under each time period scenario (discussed in Section 3.3.2). The MILP model as stated in (2.2) is subject to the following set of constraints.

Firstly the total operational cost for CS systems is calculated

$$\Phi^t = \sum_{\forall v \in \mathcal{V}} \sum_{\forall z \in \mathcal{Z}} 0.5 \cdot \gamma_3 \cdot \left| x^{t+1}_{v,z} - x^t_{v,z} \right| + \gamma_4 \cdot x^t_{v,z}, \quad \forall t = 1 \dots |\mathcal{T} - 1| \tag{3.15a}$$

$$\Phi^{|\mathcal{T}|} = \sum_{\forall v \in \mathcal{V}} \sum_{\forall z \in \mathcal{Z}} 0.5 \cdot \gamma_3 \cdot \left| x_{v,z}^{1} - x_{v,z}^{|\mathcal{T}|} \right| + \gamma_4 \cdot x_{v,z}^{|\mathcal{T}|} \tag{3.15b}$$

as a function of vehicle relocation cost (represented by γ_3), and fixed operational cost of vehicles (represented by γ_4). In fact, the cost γ_3 is accounted for if the vehicle v is in different zones in the periods t and $t+1$, whereas the cost γ_4 is accounted for if the vehicle v must be in at least a zone z during t. Note that factor 0.5 prevents the relocation costs to be considered twice for the same time slot. Relocation costs account for the salaries of staff doing the relocation jobs as well as the extra fuel expenses incurred during the operation of relocation, whereas the fixed operational costs account for the regular fuel charges, routine maintenance charges, and other unexpected charges incurred during daily operations of CS vehicles. Since the relocation of CS vehicles is done at the end of the current time slot t, so (3.15a) calculates the γ_3 for all time periods from $1 \ldots |\mathcal{T} - 1|$, except the last time slot $\mathcal{T}$. The relocation costs at the end of the last time slot $\mathcal{T}$ are calculated using (3.15b). In this connection total revenue, earned through the operation of the CS system during each time slot t is expressed by

$$R^t = \sum_{\forall v \in \mathcal{V}} \sum_{\forall z \in Z} \varphi_v \cdot g_{v,z}^{t}, \quad \forall t \in \mathcal{T}, \tag{3.16}$$

multiplying the number of vehicles placed in each zone by the fixed fare of the vehicles φ_v. The value of φ_v is dependent on the type of CS vehicles used, whereas the profit for the operator Π^t, earned through the operation of CS system as a supplement to PT during each time slot t is expressed as

$$\Pi^t = R^t - \Gamma^t, \quad \forall t \in \mathcal{T}, \tag{3.17}$$

difference between (3.16) and (3.15b). Furthermore, the values of unserved demand from (3.13) is updated in each zone z during each time slot t, as

$$UD_{tot,z}^{t} = UD_{PT,z}^{t} - p_{CS} \sum_{\forall v \in \mathcal{V}} g_{v,z}^{t} \cdot C_v, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.18}$$

a difference between the unserved demand and the sum of the demand served by each CS vehicle v, here expressed as the multiplication of the average vehicle's occupancy factor p_{CS} and the capacity of each CS vehicle C_v. In this context, if a CS vehicle is placed in a zone z during a time slot t, then it cannot be placed in another zone during the same time slot t, as ensured using

$$\sum_{\forall z \in \mathcal{Z}} g_{v,z}^{t} \leq 1, \quad \forall v \in \mathcal{V}, \forall t \in \mathcal{T} \tag{3.19}$$

whereas the capacity of each zone with a maximum number of vehicles Q_z^{max}, that can be placed in it is correlated using

$$\sum_{\forall v \in \mathcal{V}} g_{v,z}^{t} \leq Q_z^{max}, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.20}$$

which states that during each time slot t, the number of vehicles in a zone z should not exceed Q_z^{max}. Moreover, the values of binary variables g and h are related to each other.

$$\max_{\forall v \in \mathcal{V}} \left\{ g_{v,z}^{t} \right\} \leq h_z^t \leq \sum_{\forall v \in \mathcal{V}} g_{v,z}^{t}, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{3.21}$$

which states that vehicles cannot be placed in a zone z during a time slot t, if the CS service is not activated in that zone (value of $h_z^t = 0$). Conversely, at least one vehicle must be placed (value of $g_{v,z}^t = 1$) in a zone in which the CS service is already activated (value of $h_z^t = 1$). The auxiliary variables that clarify the statement of the following constraints are expressed as

$$g_v^{aux} = \min \left\{ 1, \sum_{\forall t \in \mathcal{T}} \sum_{\forall z \in \mathcal{Z}} g_{v,z}^{t} \right\}, \quad \forall v \in \mathcal{V} \tag{3.22}$$

which ensure that the value of the binary variable x_v^{aux} in (3.22) is set to 1 if the vehicle v is activated in at least one zone z during at least one time slot t (value of $g_{v,z}^t = 1$); if $g_{v,z}^t = 0$, $\forall z \in \mathcal{Z}$, $\forall t \in \mathcal{T}$, then $x_v^{aux} = 0$. Concerning the meaning of x_v^{aux}, whenever it is associated with a cost parameter, it must be accounted for once even if such a vehicle is placed in different zones during different time slots. For instance, if multiplied by γ_2 it guarantees that the buying and maintenance cost of v is considered once. In analogy to (3.22), constraint

(3.23) defines auxiliary variable for the CS activation in any generic zone z, as

$$h_z^{aux} = \min\left\{1, \sum_{t \in \mathcal{T}} h_z^t\right\}, \quad \forall z \in \mathcal{Z} \tag{3.23}$$

h_z^{aux} is equal to 1 if the service is activated in zone z, in at least a one-time slot t. If the service is never activated, then $h_z^{aux} = 0$. Concerning their use, if multiplied by γ_1, such a variable guarantee that the activation cost in z is considered once. Finally, total costs for the buying and maintaining of vehicles (γ_2) as well as the activation of CS service (γ_1), should be

$$\sum_{\forall z \in \mathcal{Z}} \gamma_1 \cdot h_z^{aux} + \sum_{\forall v \in \mathcal{V}} \gamma_2 \cdot g_v^{aux} \leq B \tag{3.24}$$

under the total available budget B.

3.3.2 Numerical Example

The capability of the proposed model will analyzed through a numerical example in this section. To this aim, a reference region is divided into 15 zones (administrative zones) with a population of 60,000 inhabitants. It is further assumed that the PT network of the region comprises 9 bus lines passing through a total of 53 stops as represented by Figure 3.7. All 9 bus lines operate during the day from (06:00 till 20:00), but after 20:00 only 5 bus lines operate till 24:00. There is neither any PT option nor any replacement service to serve PT demand from 00:00 till 06:00. Similarly, the optimization problem is solved for these two time period scenarios; 18hr (06:00-24:00, when PT is operational) and 24hr (24:00-6:00, when PT is non-operational) time periods.

Furthermore, the O/D matrix in terms of PT passenger flows between different zones during different time slots is known, and corresponding unserved demands for PT are calculated using (3.13). The CS depots are assumed to be located at the parking places already existing in each zone, as depicted by Figure 3.7. Finally, the proposed MILP problem is solved using the input data sets as described in Table 3.7.

Given the O/D matrix, the total demand for PT is calculated using passenger

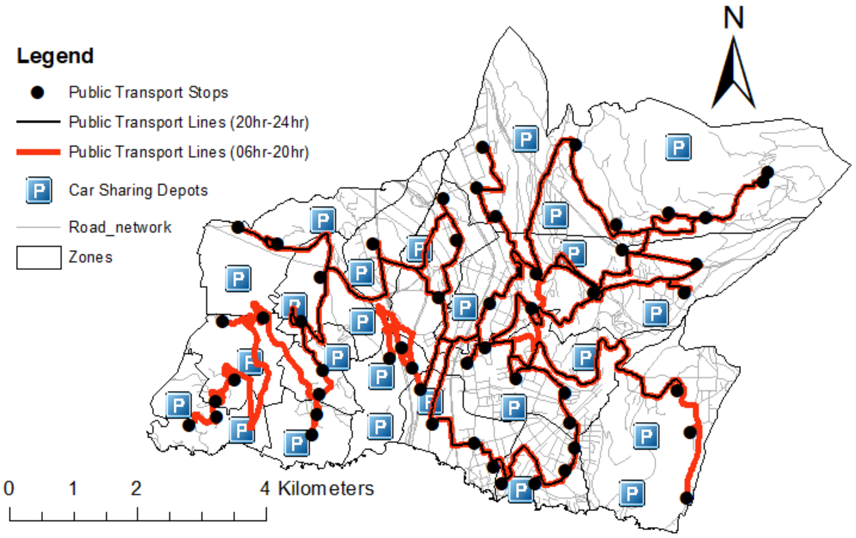

Figure 3.7: PT lines and stops along with the location of CS depots in study area

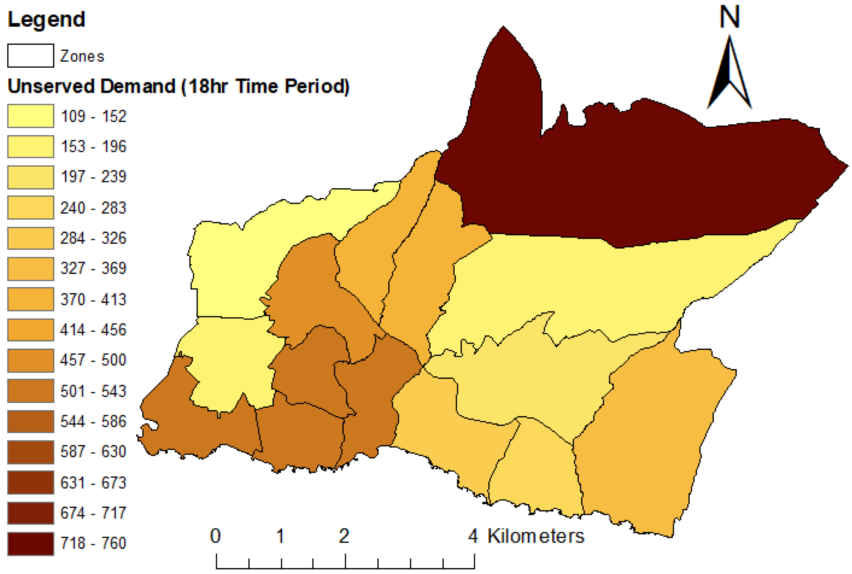

Figure 3.8: Distribution of unserved demand of PT considering 18hr time period

flow O/D matrix using (3.11), whereas the total demand served by PT during each time slot is calculated using (3.12). Similarly, the total unserved demand for PT during both 18hr and 24hr time period scenarios is calculated using (3.13) and represented by Figure 3.8 and Figure 3.9, respectively. Moreover, the calibrated

Table 3.7: Modelling parameters

Parameter	**Definition**	**Meanings and Values**
$\mathcal{V}$	number of CS vehicles to be used at the start of optimization	50
$\mathcal{T}$	time period during which the optimization is performed	$\mathcal{T} = 1 \ldots 18$ for 18 hr time period scenario
		$\mathcal{T} = 1 \ldots 24$ for 24 hr time period scenario
p_{CS}	occupancy of CS vehicles, p_{CS} which is based on sharing of CS vehicles between users [74]	$p_{CS} = 0.25$ – poor sharing
		$p_{CS} = 0.50$ – intermediate sharing
		$p_{CS} = 0.75$ – good sharing
		$p_{CS} = 1$ – excellent sharing
β	Weighing coefficient	for 24 hr time period scenario = 0.42 for $P = 1$, 0.75; 0.40 for $P = 0.5$; 0.41 for $P = 0.25$
		for 18 hr time period scenario = 0.41 for $P = 1$; 0.45 for $P = 0.75$; 0.42 for $P = 0.5$; 0.44 for $P = 0.25$
γ_1	CS vehicle activation cost	3000 €
γ_2	CS acquisition and maintenance cost	14000 €
γ_3	CS vehicle relocation cost	3 € per vehicle
γ_4	fare charged to the user for using CS vehicles	2 € per vehicle
Q_z^{max}	maximum number of CS vehicles that can be placed in each zone	10
B	total available budget for the activation and operation of CS	500000 €

values of β, as defined in Table 3.7, give the optimal objective values of 0 for all considered time period scenarios under different values of p_{CS}. This assures

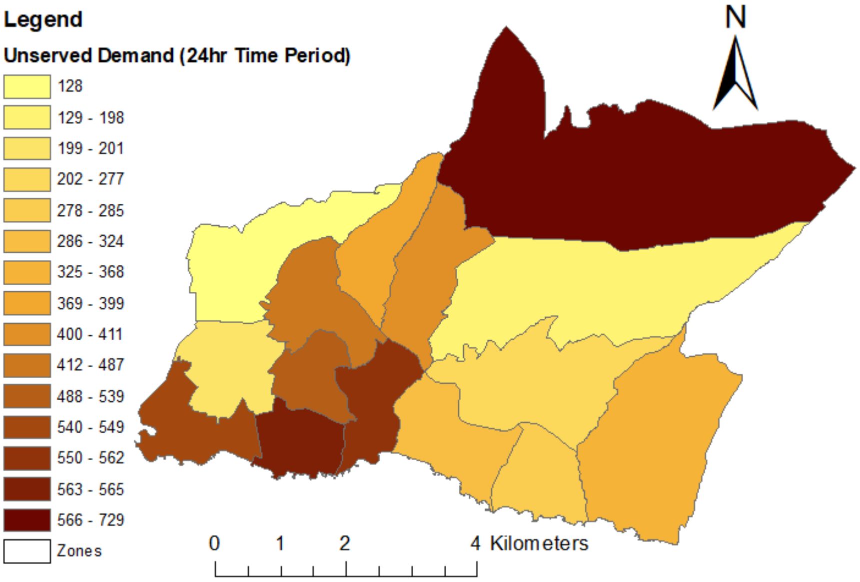

Figure 3.9: Distribution of unserved demand of PT considering 24hr time period

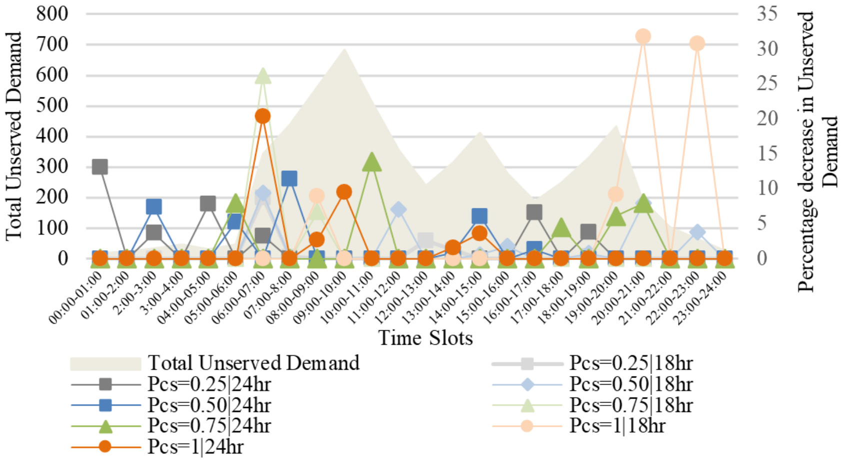

Figure 3.10: Variation in unserved demand of PT during different time slots (at different values of p_{CS} and time period scenarios)

that there is no biasness in the solution and the MILP model should give equal weight-age to both functions, R^t and $UD^t_{tot,z}$ towards the computation of the best optimal results. The results in terms of changes in the unserved demand of PT, for all zones during both time period scenarios (18hr and 24hr) under different values of occupancy factors are represented by Figure 3.10.

It is evident from Figure 3.10 that the values of the unserved demands are reduced in the zones which are characterized by the maximum values of unserved demand. The variations in the unserved demand are observed, for the time slots 06:00-09:00, 11:00-16:00, 18:00-21:00, 22:00-23:00 under an 18hr time period scenario and, for time slots 00:00-01:00, 02:00-03:00, 04:00-11:00, 13:00-15:00, 16:00-21:00 under 24hr time period scenario, as represented by Figure 3.10. The unserved demand in other time slots remains the same because they are characterized by lower values as compared to other time slots, therefore the optimization model neither activates any CS service nor places any vehicle in them according to the cost function defined in (3.14). Moreover, the time slot from 06:00-07:00 is characterized by the time of the day during which a rapid increase in PT demand was observed (according to the O/D matrix), therefore the optimization model places the maximum number of vehicles in such a time slot. As expected, the highest variation in the values of unserved demand is observed during the same time slot (i.e., 06:00-07:00) for the most of occupancy factors under both time period scenarios.

Concerning the effect of the occupancy factor, as expected, if it increases then the maximum value of unserved demand for each time slot decreases. Although more vehicles are placed in different time slots during a day under 24hr time period scenario, an overall higher decrease in the unserved demands is observed for the 18hr time period scenario, as represented by Figure 3.10. This effect is due to the number of time slots considered in the optimization model. In fact, in the 24hr time period scenario, the optimization model also considers the PT demand during the time slots 00:00-6:00 as unserved demand (totally due to the non-availability of PT) and places vehicles during those time slots as well. As a result, fewer vehicles are placed in other time slots and a low decrease in the unserved demand is observed as compared to the 18hr time period scenario.

Furthermore, the cost function defined in (3.14) also maximizes the operator's revenues in minimizing the unserved demand of PT. In fact, CS systems are only activated in such zones in different time slots if they contribute towards the minimization of unserved demand and maximization of operator revenues, simultaneously. The same effect can be seen during time slot 09:00-10:00 from Figure 3.10. Although this time slot is represented by the highest values of

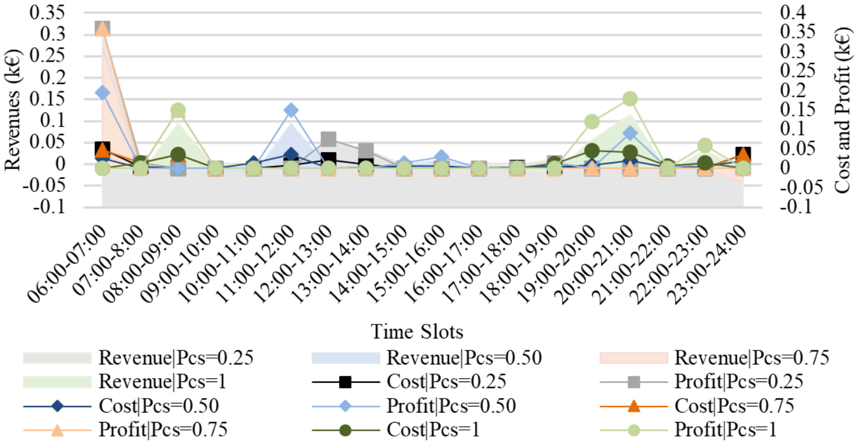

Figure 3.11: Variation in costs, profits, and revenues during different time slots considering different values of occupancy factor under 18hr time period scenario

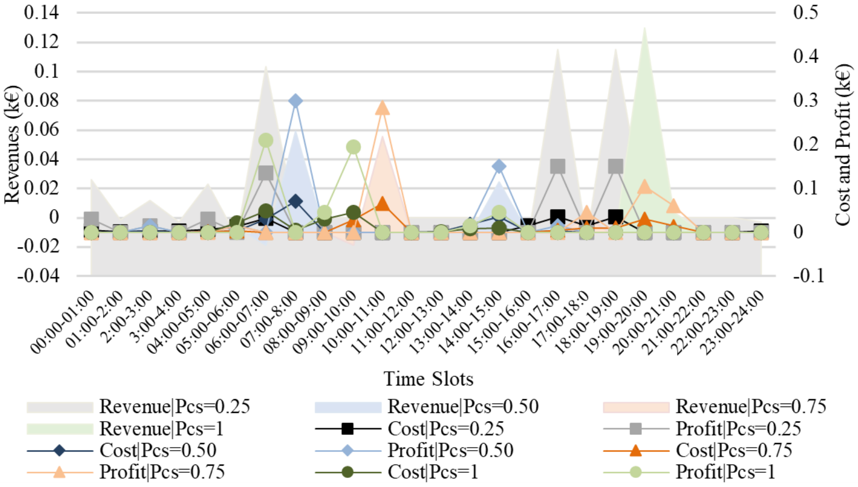

Figure 3.12: Variation in costs, profits, and revenues during different time slots considering different values of occupancy factor under 24hr time period scenario

unserved demand, the optimisation model neither activates CS service nor places any vehicles during this time slot (except for 24hr time period scenarios under an occupancy factor of 1) because it does not contribute to maximizing the operator's revenues due to budget constraint (3.24). Such variations in costs, profits, and revenues are represented in Figure 3.11 and Figure 3.12. For what concerns costs, profits, and revenues, they are strongly correlated to the unserved demand

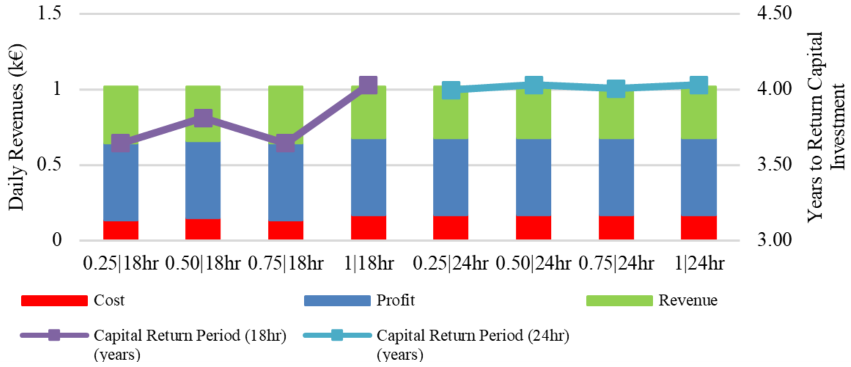

Figure 3.13: Total costs, profits, and revenues in one day for different values of occupancy factor under different time period scenarios

because they can only be incurred if the CS systems are activated for a particular scenario. At the end of a global assessment, costs, profits, and revenues are summed up for all time slots to calculate the gain in terms of the total number of years required to return the capital investment, calculated as

$$G = 365n \sum_{\forall t \in \mathcal{T}} R^t - \sum_{\forall v \in \mathcal{V}} \gamma_2 \cdot g_v - \sum_{\forall z \in \mathcal{Z}} \gamma_1 \cdot h_z \tag{3.25}$$

and represented by Figure 3.13, where n is the number of years, which are varied from $1 \ldots n$, until a positive value of G is obtained. It is evident from Figure 3.13 that total costs, profits, and revenues remain almost the same for one day, but under an 18hr time period scenario, daily revenues of 376€, 359€, 376€ and 340€ at p_{CS} values of 0.25, 0.50, 0.75 and 1, respectively are earned by utilizing a budget of 500€. In the case of 24hr time period scenario, daily revenue of 340€ is earned at all p_{CS} values; by utilizing a budget of 497€, at p_{CS} values of 0.75 and 500€ at all other p_{CS} values. Since costs and profits are dependent upon individual vehicle usage, less demand is served while using a lower value of occupancy factor. As a consequence, the daily operator revenues are higher as expected, and the capital return period slightly increases with the increase in the value of the occupancy factor under both time period scenarios, as observed by Figure 3.13. The highest capital return periods of 4.03 years are observed, under both 18hr and 24hr time period scenarios at p_{CS} value of 1. The best results in terms of daily operator's revenues, capital return period, and more realistic minimization of unserved demand of PT have been achieved using an 18hr time period scenario at p_{CS} value of 1. It has also been observed that increasing the budget beyond 500k€ and relaxing the constraint (3.24), further decreases the unserved demand of PT, through the placement of additional vehicles in the zones during high-demand time slots, thus further increasing the operator revenues.

3.3.3 Pros and Cons of the Approach

The proposed approach proves to be effective for minimization of maximum unserved demand in different zones of a region during different time slots for different values of occupancy factors under different time period scenarios. The optimization model proves to be effective in the minimisation of unserved demand for PT and maximization of the operator's revenues, through the activation of CS systems in different zones and the consequent placement of a sufficient number of vehicles.

However, since the CS systems are limited in their capacities and based on the occupancy of CS vehicles, they cannot be used for meeting the demand of PT in the areas with very high PT demand. But, given the flexibility of CS systems, they are efficient in improving the accessibility and connectivity indexes of PT, through their operation in the areas with low PT demand. In this connection, CS system proves to be the best solution in providing the access to the commuter in the least accessible areas of PT, thus improving the overall accessibility and connectivity of PT systems. The same will be discussed more in detail in Section 4.2 of Chapter 4 using the real-world case study as described in Chapter 5.

Chapter 4

Methodology

Summary

The models described under Section 3.1 of Chapter 2 of this thesis were limited in terms of the provisions of optimal solutions. The same lacked in providing enough recommendations towards the improvements in the performance of PT systems in terms of their accessibility and connectivity index values. In this framework, the benefits of designing a CS system were evaluated based on different values of occupancy of CS vehicles to serve the additional demand for PT systems under Section 3.1 of Chapter 2 of this thesis. Such an approach proves to be efficient in managing the additional demand for PT systems. Similarly, it provides recommendations for the utilisation of CS systems for connecting areas of low PT access to the city centers. In this context, a unified methodological framework is designed under this chapter for the optimal design of two-way CS systems in the least accessible and the least connected areas of PT systems of a region. This is done through the determination of the best locations of CS depots. The specific goal of the proposed approach is to improve the values of suitably defined accessibility and connectivity indexes (CAI) for integrated PT/CS systems.

The capabilities of the proposed approach will also be tested using real-world case studies of the PT systems for the cities of Trento (Italy), and Genova (Italy) which will be described more in detail in Chapter 5.

4.1 Introduction to Approach

Based on the initial conceptualizations described and evaluated using numerical examples in Chapter 3 of this thesis, this section is focused on defining a unique framework for optimally integrating PT and CS systems with the aim of improving the accessibility and connectivity of integrated systems. In doing so, the various factors that define the importance of accessibility (as described in Section 3.1 of Chapter 3 based on the study described in [9]) and connectivity in PT systems are considered based on the specific characteristics of the different modes used for PT (as described in Section 3.2 of Chapter 3 based on the study described in [8]) and CS systems (as described in Section 3.3 of Chapter 3 based on the study described in [43]).

More specifically, the proposed approach aims to meet the potential demand of PT arising from the least accessible or inaccessible areas and determine an optimal distribution of new CS resources, particularly new parking slots (depots) and vehicles. In doing so, a traditional two-way CS system is considered as a possible solution instead of new PT lines and/or the extension of the existing ones. The proposed approach is particularly suitable for areas characterised by relatively small demand or topographic constraints or, in general, whenever the extension of existing lines of PT/planning of new services requires high capital investments [15]. In these cases, CS systems can provide flexible solutions to meet additional demands and efficiently adapt to possible variations in user mobility needs [17; 18].

The framework presented in this thesis is unique in providing a methodology aimed at improving the total values of CAI for PT through optimally designing two-way CS systems in the least accessible areas of PT, considering the structure of the area, PT characteristics, and demand. The same applies to the proposed mathematical programming approach to determine the optimal number of CS depots to be activated and the vehicles to be placed therein. The novelty of the proposed approach was also justified through the literature review of relevant studies as summarised in Section 2.5 of Chapter 2 of this thesis.

Prior to the introduction and explanation of the various factors and modeling constraints used in the methodological framework, a description of the different terminologies used will be offered briefly in Section 4.1.1.

4.1.1 Definitions and Assumptions

The following definitions and assumptions are considered:

- A zone z consists of the area within the given administrative boundaries of the considered region (e.g., districts or traffic analysis zones). Zones are assumed to be fixed and gathered in the set $\mathcal{Z}$.
- POIs represents specific activities within a zone. These activities are the origins (usually households) and destination points in the considered region (e.g., workplaces, educational institutes, leisure activity points, religious places, etc.) resulting in an implicit motivation for users to carry out PT trips. POIs are weighted through the selection of appropriate coefficients determined based on their relative importance by means of the Theil index [75].
- A served area consists of the gathering of all the locations around PT stops that can be reached by walking within a maximum distance threshold [76].
- An unserved area consists of the gathering of all locations that cannot access any PT stop [76].
- A time period t is defined as a specific time interval during a day, week, or month and is specifically selected for analytical purposes (e.g., peak hour periods and off-peak periods). Time periods are assumed to be fixed and gathered in the set $\mathcal{T}$.
- All existing PT lines have fixed, two-way routes with a conventionally defined "origin". In this connection, the term "outbound" indicates the trip from the origin to the destination, whereas the term "inbound" indicates the trip from the destination back to the origin.
- The considered CS system scheme consists of a so-called two-way CS system that requires the users to drop the vehicles off in the same depot from

where they were originally picked up. Moreover, since the system under investigation is an integrated CS/PT system, users are expected to pay approximately the same fare as the PT system of the region to use the CS service.

- The non-satisfactory demand arising from the least accessible areas of PT can be managed by the activation of the CS system.

The detailed framework and optimization model developed will be discussed in detail in the following sections.

4.2 Methodological Framework

The proposed methodological framework is developed with the aim of providing a general model that can be applied to any region by means of limited inputs. A sketch of the proposed methodological approach is illustrated by the flowchart presented in Figure 4.1, where the steps for the application of the proposed methodological framework are presented along with the input data sets required. According to Figure 4.1, the required data sets are classified into three major categories as follows

- Public Transport Network: the PT network includes temporal and spatial features of the PT systems of the study area under consideration i.e., PT lines, locations of stops, hours of service, frequencies, speeds, and distances;
- Administrative Boundaries: it gathers the boundaries of the different zones of the study area under consideration i.e., regional boundaries, city boundaries, or any other smaller available zoning systems;
- Spatial Data Set: these data sets include the XY points in a 2D space which represents the locations of different facilities required for the application of the proposed methodological framework. Such spatial points include the locations of POI (e.g., households, shopping centres, schools, offices, etc.) and of the CS depot candidates in each zone, along with their population distributions and PT mobility demands, all classified according to the selected zoning system of the study area under consideration.

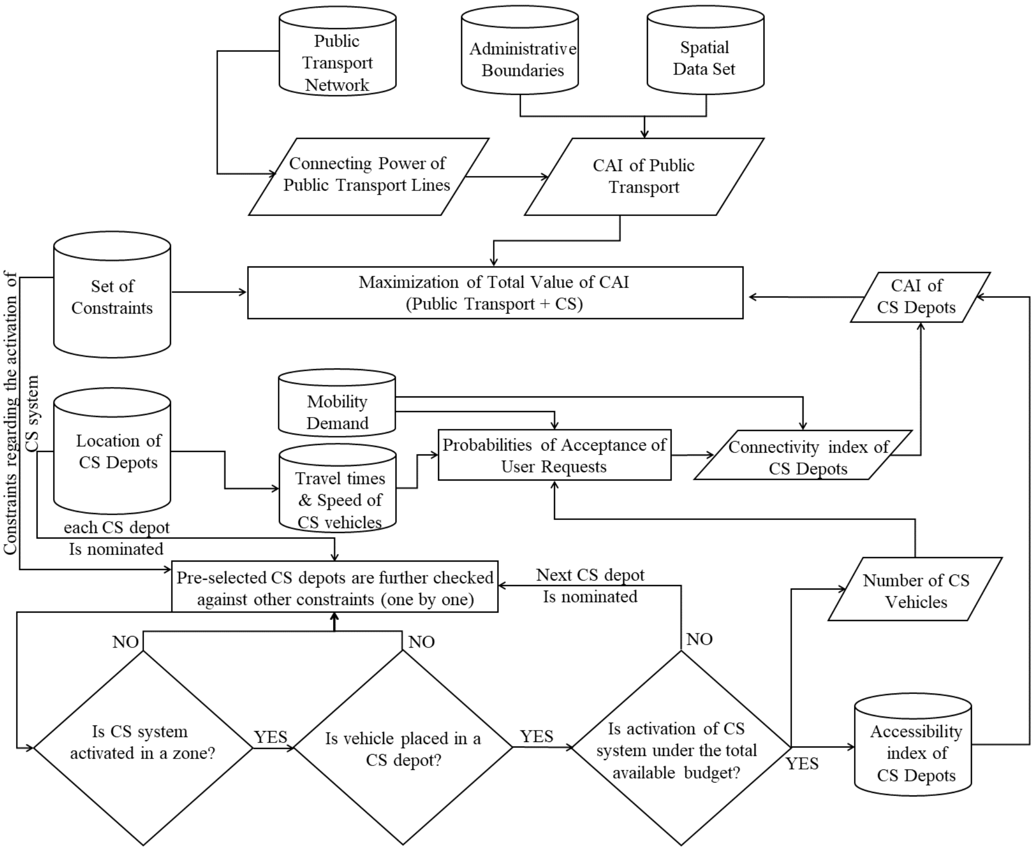

Figure 4.1: Conceptualisation of the methodological framework.

More in details, all these data sets are necessary to calculate the CAI_{PT} values of PT and are used as inputs for various constraints in the proposed mathematical programming model that will be described more in details in Section 4.2.3 of this Chapter.

Once the desired data sets are collected, the data related to PT lines are utilized for the determination of connecting power of each PT line as represented by Figure 4.1 and will be discussed more in details in Section 4.2.1 of this chapter. The connecting power values are utilized along with the spatial data sets and administrative boundaries for the determination of CAI_{PT} values for PT systems of the study area under consideration (Figure 4.1) and will be discussed more in details in Section 4.2.1 of this chapter. These CAI_{PT} values serve as a major input for the maximization and equalization of the total CAI of the entire region under consideration (as discussed more in detail in Section 4.2.3 of this chapter).

-Furthermore, according to Figure 4.1 the data sets related to the location of POIs and PT stops as well as the centroids of PT served areas are also important for the determination of the locations of CS depot candidates using an adequate clustering algorithm in Arc GIS as represented by Figure 4.2. In this context, the value of the accessibility index for each CS depots candidate location is calculated using the criteria discussed in Section 4.2.2 of this chapter and checked against the activation of CS service in the zone along with the placement of vehicles using the optimization model, such that operation of CS system should be under the total available budget (according to Figure). Once a CS candidate satisfies all the constraints, it is selected by the optimization model as a potential location of CS depot and a number of vehicles to be placed in that CS depot candidates are calculated by the model as represented in Figure 4.2.

These locations of CS depot candidates are further utilized along with the travel times and speed of CS vehicles, and mobility demand of the passengers, for the determination of acceptance probabilities of user requests for each CS depot candidate (based on the actual number of the vehicle placed therein) as represented in Figure 4.1 and will be discussed more in details in Section 4.2.2.1 of this chapter. Finally, connectivity and accessibility index of the CS depot candidates satisfying all given constraints, are determined based on an actual number of CS vehicles placed therein, such that activation of these depots should maximize and equalize the total CAI values of all the zones as represented by Figure 4.1.

4.2.1 Connectivity and Accessibility Index of Public Transport

In this section, the model for determining the CAI_{PT} index of PT in each zone of the considered region is presented. Accessibility and connectivity represent the performance indicators used to evaluate the effectiveness of the resource distribution and the equity level of PT systems. To compute these parameters, the equations of “connecting power” as described in Section 3.2.1 of Chapter 3 of this thesis in (3.4)-(3.5), is reformulated for a generic PT line l passing through node n of zone z as the average of the incoming and outgoing connecting powers during different time periods t and for both inbound and outbound directions, that is,

$$p_{z,n,l}^{t,in} = \rho^{t,in} r_l^{t,in} \cdot \varphi^{t,in} v_l^{t,in} \cdot \mu^{t,in} d_{n,l}^{t,in}, \quad \forall l \in \mathcal{L}_{z,n}, \forall n \in \mathcal{N}_z, \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \quad (4.1)$$

$$p_{z,n,l}^{t,out} = \rho^{t,out} r_l^{t,out} \cdot \varphi^{t,out} v_l^{t,out} \cdot \mu^{t,out} d_{n,l}^{t,out}, \forall l \in \mathcal{L}_{z,n}, \forall n \in \mathcal{N}_z, \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \quad (4.2)$$

where $r_l^{t,in}$ and $r_l^{t,out}$ are the total capacities of the line $l \in \mathcal{L}_{z,n}$ passing through node n [73]. The values of coefficients $\rho^{t,in}$, $\varphi^{t,in}$, and $\mu^{t,in}$ in (4.1) and of coefficients $\rho^{t,out}$, $\varphi^{t,out}$, and $\mu^{t,out}$ in (4.2) are determined as the reciprocals of the average bus capacities, speeds, and route lengths computed over all lines operating during the time period t.

Therefore, the CAI of each node $n \in \mathcal{N}_z$ during each time period t can be expressed as

$$CAI_{PT,z,n}^{t} = \sum_{l \in \mathcal{L}_{z,n}} \frac{1}{2} \left(p_{z,n,l}^{t,in} + p_{z,n,l}^{t,out}\right) + \omega^t \Omega_n^t + \pi^t \Pi_n^t + \xi^t \Xi_n^t, \quad \forall n \in \mathcal{N}_z, \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \quad (4.3)$$

consisting of the summation of

- the average inbound/outbound connecting power of node n;
- the accessibility parameters, expressed by the area within the walking distance Ω_n^t from node n
- population Π_n^t and the number of POI Ξ_n^t, both within area Ω_n^t, for node n during time period t.

The coefficients ω^t, π^t, and ξ^t in (4.3) are scaling parameters, determined as the reciprocals of the average areas within the walking distance, populations, and numbers of POI falling within these areas, computed over all the nodes of the entire PT network. Note that since the number of active PT lines (and consequently the number of reachable nodes) vary with time, as well as the number of POI, the scaling parameters ω^t, π^t, and ξ^T also depend on time.

Finally, the total value of CAI_{PT} for PT of each zone z during each time period t is determined as the average value of the $CAI^t_{PT,z,n}$ indexes of all nodes $n \in \mathcal{N}_z$, that is,

$$CAI^t_{PT,z} = \frac{1}{|\mathcal{N}_z|} \sum_{n \in \mathcal{N}_z} CAI^t_{PT,z,n}, \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{4.4}$$

where $|\mathcal{N}_z|$ is the number of nodes in zone z. Note that, thanks to the scaling parameters, the CAI indexes of PT are unitless.

4.2.2 Connectivity and Accessibility Index of Car Sharing Depots

In this section, the model for determining the CS depot candidates and the relevant CAI_{CS} index will be presented.

In this connection, to determine the optimal geographical positions of CS depot candidates in each zone of the study area under consideration, any standard clustering algorithm satisfying the following major specifications can be applied as presented using Figure 4.2 and will be explained in details in the following. More specifically, the clustering algorithm must be able to

- be applied independently to each zone $z \in \mathcal{Z}$;
- consider the walking distance along the existing road network in $z \in \mathcal{Z}$;
- finds the best number of clusters and locates the relevant barycentres, which will coincide with the CS depot locations, in feasible geographical locations.

Given such specifications, as described using Figure 4.1, the data sets required for the application of clustering algorithm in GIS are as follows

- the locations of POI (e.g., households, shopping centres, schools, offices, etc.) and PT stops;
- the areas served by PT stops by drawing a network distance buffer around each PT stop;

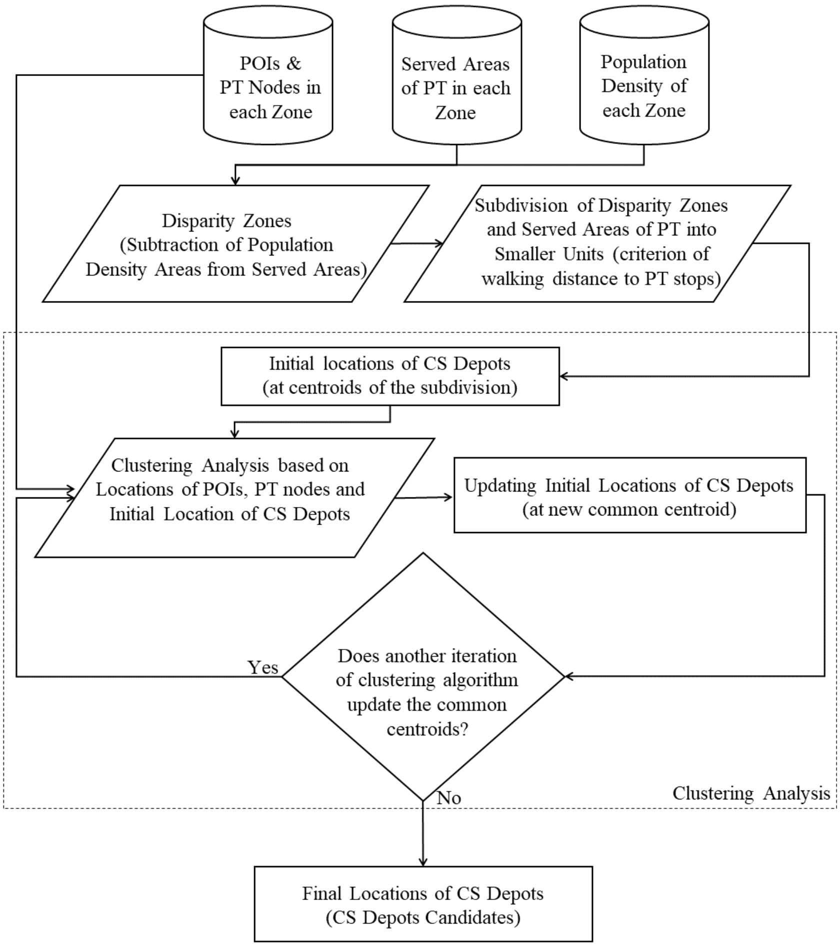

Figure 4.2: Conceptualization of clustering algorithm utilized

- the population densities of each smallest area of the study region under consideration.

After the collection of stated data sets, according to Figure 4.2, the served areas of PT stop along with the population densities of the study area are utilized for the determination of disparity zones. These disparity zones represent the access-deprived areas of a region where the residents either have low or zero access to PT service. Furthermore, both the disparity zones and served areas are sub-divided into smaller units using an appropriate tool of GIS application as represented using Figure 4.2.

These sub-divisions of disparity zones and served areas of PT stops represent the initial locations of CS depots candidates according to Figure 4.2. These initial locations are then subjected to a clustering algorithm using GIS application to find the common centroids (barycentres) within a walking distance threshold between PT stops, POI and initial locations of CS depots. As presented in Figure 4.2, after each iteration the common centroids are updated with new ones and the algorithm is repeated until the geographic locations of these common centroids do not change, which represents the final locations of CS depot candidates to be used in the optimization model (as described in Section 4.2.3 of this chapter).

Regarding the CAI values of CS depots, it is necessary to determine the contribution that each depot could provide, if activated, by explicitly considering all possible conditions under which it will operate. Such values must be calculated considering all possible demand scenarios.

Let us first consider the connectivity index of a generic CS depot $k \in \mathcal{C}_z$. This index is defined as the connection power of a depot in terms of the capability of "providing a connection" to any generic user that needs a ride. In this respect, it is possible to define the connectivity index in period t as the number of requests that are expected to be satisfied. Formally, it is expressed as the product of the demand and the probability that a request is accepted, that is,

$$c^t_{k,z,q_{k,z}} = \mathcal{D}^t_{k,z} \cdot \mathbb{P}^t_{k,z,q_{k,z}}, \quad \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{4.5}$$

where the total demand rate $\mathcal{D}^t_{k,z}$ of depot k present in zone z during time period t is assumed to be known in advance and the acceptance probability $\mathbb{P}_{k,z,q_{k,z}}$ will be estimated as described in Section 4.2.2.1.

Accessibility is expressed as

$$a_{k,z} = \gamma\Gamma_{k,z} + \theta\Theta_{k,z} + \lambda\Lambda_{k,z}, \quad \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z} \tag{4.6}$$

where $\Gamma_{k,z}$ is the area within the walking distance Δ from depot $k \in \mathcal{C}_z$, whereas $\Theta_{k,z}$ and $\Lambda_{k,z}$ are the population and number of POI within $\Gamma_{k,z}$. The coefficients γ, θ, and λ are suitable scaling factors, determined as the reciprocals of the average areas within walking distance from all depots in all zones of the whole region under consideration, of the average proportion of the population, and of

POI falling within these areas, respectively.

Finally, the total value of CAI_{CS} for a zone z with $|\mathcal{C}_z|$ activated depots is

$$CAI^t_{CS,z} = \sum_{k \in \mathcal{C}_z} \left(a_{k,z} + c^t_{k,z,q_{k,z}} \right), \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{4.7}$$

which considers the accessibility provided by each depot and the connectivity expressed by the expected satisfied demand.

Note that, thanks to the scaling parameters, the CAI indexes for CS depots are unitless.

To conclude, it is worth remarking that $CAI^t_{CS,z}$ is an indicator subject to optimisation; therefore, the definitions in (4.5) and (4.6) represent "potential" connectivity and accessibility values that become "real" if the relevant depot is activated in the optimal CS system as described in Section 4.2.3. (4.7) will next be reformulated according to its explicit dependence on the optimisation variables.

4.2.2.1 Acceptance probability estimation

As mentioned, to evaluate the connectivity parameter of the CS depots activated in zone z, it is necessary to estimate the probability that the requests occurring during a generic time period t in zone z can be satisfied.

Therefore, the aim of this section is to describe a simple Monte Carlo-based approach that can be applied to estimate the probability that a request occurring in a generic time instant τ can be fulfilled if $q_{k,z}$ vehicles are assigned to depot $k \in \mathcal{C}_z$ and knowing that, whenever picked up, a vehicle remains "busy" for a random time Δ_T.

In doing so, it is assumed that the users are independent of each other. As a consequence, the occurring times of their requests can be modeled for any depot $k \in \mathcal{C}_z$ and during the time period t by means of a Poissonian distribution with demand rate $\mathcal{D}^t_{k,z}$. Finally, it is assumed that in the random busy time Δ_T, which follows a Gaussian distribution, the expectation and variance depend on the considered zone z.

More specifically, given the demand rate $\mathcal{D}^t_{k,z}$ and assuming a fixed number of CS vehicles $q_{k,z}$ assigned to depot $k \in \mathcal{C}_z$, a generic i-th instance of the Monte

Carlo simulation is performed by means of the following algorithm:

1. A request is generated at a random instant τ. In such an instant, the availability of a vehicle in the depots $k \in \mathcal{C}_z$ is checked. Then,
   - if there is at least one vehicle, the request is accepted, and the counter $\sharp^i_{a,k,z}$ of the accepted requests in the i-th simulation instance is increased by one. Then, the vehicle is removed from k for a random time period Δ_T;
   - if there is not an available vehicle, the request is rejected, and the counter $\sharp^i_{r,k,z}$ of rejected requests in the i-th simulation instance is increased by one;
2. a new request is generated in $\tau + \delta_\tau$ time units, with δ_τ being a random interarrival time according to the Poissonian requests and considering the demand rate $\mathcal{D}^t_{k,z}$.

The above steps are repeated until τ is less than 10 hours to consider time-averaged outputs.

After I independent simulations, the acceptance probability for a depot characterised by $q_{k,z}$ vehicles and demand is estimated as

$$\mathbb{P}^t_{k,z,q_{k,z}} \simeq \frac{1}{I} \sum_{i=1}^{I} \frac{\sharp^i_{a,k,z}}{\sharp^i_{a,k,z} + \sharp^i_{r,k,z}}, \quad \forall t \in \mathcal{T}, \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z} \tag{4.8}$$

By applying the above algorithm for different values of $q_{k,z}$ and for different values of the demand, it is possible to fill a table of probabilities that provides the connectivity indexes of all depots $k \in \mathcal{C}_z$ for each zone z under different setups.

4.2.3 Optimisation Model

Based on the indexes defined in this chapter, the proposed MILP model will be stated and discussed in detail in this section. Such a model aims at the determination of the best locations for CS depots to be activated in each zone z such that the minimum total CAI value of each zone z is maximised.

Then, to state the optimisation problem, let

- $\mathcal{V}$ be the set of potential vehicles to be in the CS depots;
- $x_{k,z,v}$ be a binary variable that assumes a value of 1 if vehicle $v \in \mathcal{V}$ is placed in depot $k \in \mathcal{C}_z$ and 0 otherwise;
- $y_{k,z}$ be a binary variable that assumes a value of 1 if CS depot $k \in \mathcal{C}_z$ is activated and 0 otherwise;
- $\boldsymbol{x}$ and $\boldsymbol{y}$ be vectors gathering the variables $x_{k,z,v}$ and $y_{k,z}$, $\forall k \in \mathcal{C}_z$, $z \in \mathcal{Z}$, $v \in \mathcal{V}$, whereas $\boldsymbol{x}^\star$ and $\boldsymbol{y}^\star$ indicate their optimal values.

Since the system under investigation is a traditional two-way CS system without any relocation of vehicles between two subsequent time periods, the relevant optimisation variables (the activation of a depot and the number of vehicles assigned to it) do not explicitly depend on the time period t.

Given such definitions, the considered optimisation problem can be stated as

$$[\boldsymbol{x}^\star, \boldsymbol{y}^\star] = \arg\max_{\boldsymbol{x},\boldsymbol{y}} J(\boldsymbol{x}, \boldsymbol{y}) \tag{4.9}$$

whose specific cost function will be discussed in Section 4.2.3.1 and will be subjected to the constraints described in the following section 4.2.3.2 of this chapter, which defines the characteristics of the considered CS system.

4.2.3.1 Cost Function

In the proposed approach, the cost function is formulated as

$$J(\boldsymbol{x}, \boldsymbol{y}) = \frac{1}{|\mathcal{Z}|} \sum_{z \in \mathcal{Z}} \frac{1}{|\mathcal{T}|} \sum_{t \in \mathcal{T}} \beta_z^t \cdot \left(CAI_{PT,z}^t + CAI_{CS,z}^t(\boldsymbol{x}, \boldsymbol{y}) \right) \tag{4.10}$$

which calculates the total CAI index averaged over all zones and time periods. To privilege the disparity zones in the distribution of the CS resources, the weighing coefficient β_z^t is determined:

$$\beta_z^t = \left(\beta_0 + \frac{CAI_{PT}^{\max} - CAI_{PT,z}^t}{CAI_{PT}^{\max}} \right)^\ell, \quad \forall t \in \mathcal{T}, \forall z \in \mathcal{Z} \tag{4.11}$$

where $CAI_{PT}^{\max} = \max_{z \in \mathcal{Z}} CAI_{PT,z}^{t}$ indicates the maximum value of the PT CAI index among all considered zones in the time period t, whereas ℓ is a parameter to be chosen and β_0 is a small positive value that guarantees that β_z^t is always positive. Such coefficients guarantee that the zones with a null $CAI_{PT,z}$ have maximum weight equal to β_0+1, whereas the zones characterised by the maximum $CAI_{PT}^{\max}$ have value β_0. More specifically, the higher the value of ℓ, the more weight is given to the zones with the smallest $CAI_{PT,z}$.

Let us consider the term $CAI_{CS,z}^{t}(\boldsymbol{x}, \boldsymbol{y})$ in (4.10), which expresses the CAI index of CS by explicitly indicating its dependence on optimisation variables. In this connection, to state the optimisation problem, the index (4.7) must be written as

$$CAI_{CS,z}^{t} = \sum_{k \in \mathcal{C}_z} \left(a_{k,z} \cdot y_{k,z} + f_{k,z}^{t}(\boldsymbol{x}) \right), \quad \forall z \in \mathcal{Z}, \forall t \in \mathcal{T} \tag{4.12}$$

where

$$f_{k,z}^{t}(\boldsymbol{x}) = \begin{cases} c_{k,z,q_{k,z}}^{t} & \text{if } q_{k,z} \text{ vehicles are assigned to the depot } k \in \mathcal{C}_z \\ 0 & \text{otherwise} \end{cases} \tag{4.13}$$

is a function of the optimisation variables $\boldsymbol{x}$. Note that even though the number of vehicles assigned to depot k does not depend on the time, the value of $CAI_{CS,z}^{t}$ is due to the time dependence of the demand, which is included in the connectivity index in (4.5).

Thanks to the definition in (4.13), constraint (4.12) guarantees that if CS depot $k \in \mathcal{C}_z$ is activated and $q_{k,z}$ are assigned to it ($y_{k,z} = 1$ and $\sum_{\forall v \in \mathcal{V}} x_{k,z,v} = q_{k,z}$), then the value of CAI_{CS} is increased by the values $a_{k,z}$ and $c_{k,z,q_{k,z}}^{t}$ of the accessibility and connectivity indexes, respectively. In addition, it guarantees that if no CS depots are activated in zone z, no vehicles can be assigned to them ($y_{k,z} = 0, \forall k \in \mathcal{C}_z$ and $\sum_{\forall v \in \mathcal{V}} x_{k,z,v} = 0, \forall k \in \mathcal{C}_z$); consequently, the contribution of the CS systems in zone z is null.

For the sake of simplicity, the linear formulation of the function $f_{k,z}^{t}(\boldsymbol{x})$ is reported with a proof that (4.13) can be formulated as a linear constraint as follows. To this aim, consider the equality

$$f^t_{k,z}(\boldsymbol{x}) = \sum_{m=1}^{Q^{\max}} c^t_{k,z,m} \cdot \left(1 - \min\left\{\left|m - \sum_{\forall v \in \mathcal{V}} x_{k,z,v}\right|, 1\right\}\right), \qquad \forall t \in \mathcal{T}, \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z} \quad (4.14)$$

where $Q^{\max}$ is the total number of vehicles that can be assigned to zones and, hence, to any generic depot $k \in \mathcal{C}_z$, $\forall z \in \mathcal{Z}$.

Let us consider a generic entry of the summation over m: if $\sum_{\forall v \in \mathcal{V}} x_{k,z,v} = m$ (that is, if a number m are assigned to depot $k \in \mathcal{C}_z$), then it assumes the value $c^t_{k,z,m}$, since

$$c^t_{k,z,m} \cdot \left(1 - \min\left\{\left|m - \sum_{\forall v \in \mathcal{V}} x_{k,z,v}\right|, 1\right\}\right) = c^t_{k,z,m} \cdot (1 - \min\{0, 1\}) = c^t_{k,z,m}, \qquad \forall t \in \mathcal{T}, \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z}$$

In contrast, if $\sum_{\forall v \in \mathcal{V}} x_{k,z,v} \neq m$, then the argument of the absolute value assumes a generic non-null value a. Consequently,

$$c^t_{k,z,m} \cdot \left(1 - \min\left\{\left|m - \sum_{\forall v \in \mathcal{V}} x_{k,z,v}\right|, 1\right\}\right) = c^t_{k,z,m} \cdot (1 - \min\{|a|, 1\}) = c^t_{k,z,m} \cdot 0 = 0, \qquad \forall t \in \mathcal{T}, \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z}$$

That is, the generic m-th entry of the summation is null.

Consequently, all terms in the external summation of (4.14) are null but the one corresponding to the number of actual vehicles assigned to the depot $k \in \mathcal{C}_z$, given by the summation of the variables $\boldsymbol{x}$. In particular, if $q_{k,z}$ vehicles are assigned to depot $k \in \mathcal{C}_z$, then function $f^t_{k,z}(\boldsymbol{x})$ assumes the value

$$f^t_{k,z}(\boldsymbol{x}) = c^t_{k,z,0} \cdot 0 + \ldots + c^t_{k,z,q_{k,z}} \cdot 1 + \ldots + c^t_{k,z,Q^{\max}_z} \cdot 0 = c_{k,z,q_{k,z}}, \qquad \forall t \in \mathcal{T}, \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z}$$

To conclude, it is worth recalling that both the function's "absolute value" and “minimum among problem variables” can be easily rewritten by means of a few auxiliary variables and a suitable set of linear inequalities.

4.2.3.2 Constraints

In this section, the set of constraints defining the characteristics of the considered CS system will be described, with reference to the capacity of depots, the maximum budget, and some consistency relations between the optimisation variables.

First, to guarantee a minimum level of accessibility and connectivity of all zones in the considered area, at least one depot must be activated in all the zones characterised by $CAI^t_{PT,z} = 0$ in all the time periods. Such a requirement is formalised as

$$\sum_{\forall k \in \mathcal{C}_z} y_{k,z} \geq 1, \quad \forall CAI^t_{PT,z} = 0, \forall t \in \mathcal{T}, \forall z \in \mathcal{Z} \tag{4.15}$$

Note that constraints (4.15), also referred to as “null CAI_{PT} constraints” in the following, do not fix the numbers of vehicles in the activated depots but only state that at least one depot must be activated in the zone with null CAI in at least one time period.

Furthermore, a vehicle cannot be assigned to more than one depot at a time but can be unassigned. To these ends, the inequity

$$\sum_{\forall z \in \mathcal{Z}} \sum_{\forall k \in \mathcal{C}_z} x_{k,z,v} \leq 1, \quad \forall v \in \mathcal{V} \tag{4.16}$$

must hold.

Then, considering the characteristics of zones, their size, and their population, it is possible to determine the maximum number of vehicles $Q^{\max}_z$ that each zone can accommodate [77]. Formally, such a constraint can be expressed as

$$\sum_{\forall k \in \mathcal{C}_z} \sum_{\forall v \in \mathcal{V}} x_{k,z,v} \leq Q^{\max}_z, \quad \forall z \in \mathcal{Z} \tag{4.17}$$

where the number of vehicles in the zones is characterised by the highest and lowest population densities of $Q^{\max}$ and 2, respectively. Given the extreme values, the maximum number of vehicles for all other zones can be set proportionally according to their population density.

In addition, the total number of vehicles that can be allocated in the whole considered region is limited to $Q^{\max}$. Therefore, the inequality

$$\sum_{\forall z \in \mathcal{Z}} \sum_{\forall k \in \mathcal{C}_z} \sum_{\forall v \in \mathcal{V}} x_{k,z,v} \leq Q^{\max}, \tag{4.18}$$

in which the left-hand side counts the total number of vehicles assigned to the CS service that must be fulfilled.

Furthermore, it is necessary to state that CS vehicles can only be placed in depot $k \in \mathcal{C}_z$ if the CS service is activated in this zone; conversely, no vehicles can be placed in non-activated depots. This can be expressed by means of the following inequalities:

$$\begin{cases} x_{k,z,v} \leq y_{k,z}, & \forall v \in \mathcal{V}, \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z} \\ y_{k,z} \leq \sum\limits_{\forall v \in \mathcal{V}} x_{k,z,v}, & \forall k \in \mathcal{C}_z, \forall z \in \mathcal{Z} \end{cases} \tag{4.19}$$

which relates the values of the variables $y_{k,z}$, and $x_{k,z,v}$. In particular, the first inequality in (4.19) states that no vehicles can be assigned to depot $k \in \mathcal{C}_z$ if the service is not activated (i.e., $y_{k,z} = 0 \Rightarrow x_{k,z,v} = 0, \forall v \in \mathcal{V}$). In contrast, the second inequality in (4.19) states that if the service is activated, at least one vehicle must be assigned to it (i.e., $y_{k,z} = 1 \Rightarrow \exists v \in \mathcal{V}$ such that $x_{k,z,v} = 1$).

Finally, CS service activation, vehicle placement, and depot activation can only occur if all the relevant costs fulfill a budget constraint. To this aim, the inequality

$$\sum_{\forall z \in \mathcal{Z}} \sum_{\forall k \in \mathcal{C}_z} \alpha_1 \cdot y_{k,z} + \sum_{\forall v \in \mathcal{V}} \sum_{\forall k \in \mathcal{C}_z} \sum_{\forall z \in \mathcal{Z}} \alpha_2 \cdot x_{k,z,v} \leq B \tag{4.20}$$

guarantees that the total expenses for CS service activation and management are less than a given budget B. In such a constraint, the coefficient α_1 represents the cost associated with the realisation and maintenance of the CS depots, whereas α_2 is the cost associated with buying and maintaining the assigned CS vehicles.

Note that in (4.20), the costs α_1 and α_2 are assumed to be constant, although it is easy to relax this assumption by making them dependent on the type of depots or on the zones.

The optimization model along with the various constraint, as described in this chapter will be applied to real-world case studies of Trento and Genova (cities of Italy), for the purpose of the justification of MILP model. Moreover, the results achieved will be described and evaluated in the next chapter.

Chapter 5

Experimental Results

Summary

The goal of the proposed methodology as described in Chapter 4 is the improvement in the values of CAI for PT systems in the areas which are the least accessible to PT systems. In doing so, CS system is designed and implemented to see the impacts on overall values of CAI for the integrated CS/PT systems.

The goal of such an integration is aimed at the maximization and equalization of CAI of the whole considered region. In this context, this Chapter will be focused on the application of the proposed methodology, to a real-world case study with the aim of discussing its capabilities. The selected case studies consist of the cities of Trento and Genova Italy. Similarly, their PT systems whose relevant data sources are available online, will be evaluated using the stated methodology in the following sections.

5.1 Case Study I: Trento

Trento is a city of approximately $120,000$ residents[1] located in a mountain area of approximately 158 km^2. The city is divided into 48 districts[2].

The Trento PT network comprises 22 bus lines operating within the city,

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[1] Population and households as of 2022, Istat - in Italian, accessed in September 2022

[2] Administrative Boundaries, Istat - in Italian, accessed in September 2022

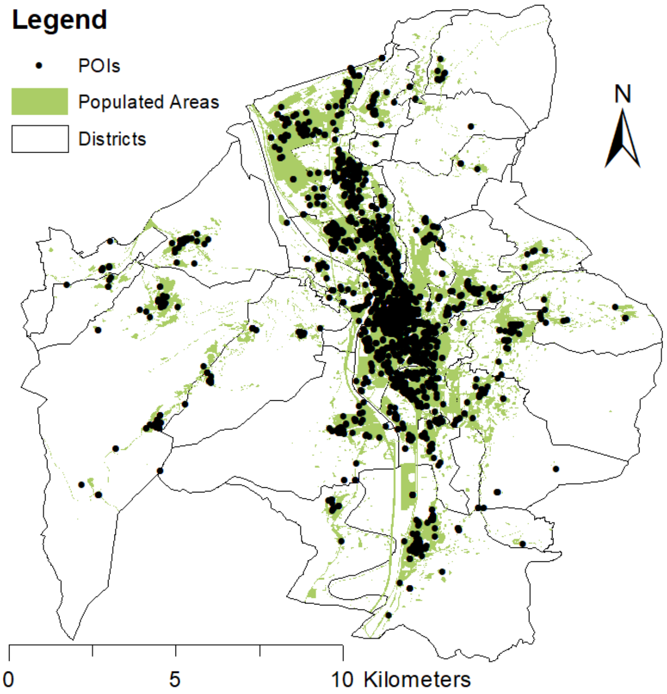

Figure 5.1: Distribution of POI in the populated areas of different districts of Trento

regional trains, and touristic cable cars operating during the peak tourist seasons[1]. Nevertheless, since the scope of the defined methodology is the evaluation of the PT system within the same region, only the city bus lines are taken into consideration in the calculation of CAI_{PT} values for PT in each district of Trento. The city's PT system consists of 22 lines in two directions (outbound and inbound trips) with a network of 570 nodes distributed within the above-mentioned 48 districts, as presented in Figure 5.2[2]. All lines operate from 5:00 a.m. until 10:00 p.m. on workdays, whereas only 11 bus lines operate during weekend days and holidays[3].

Regarding the distribution of the households in the considered area, a sketch of the population density in Trento[4] is depicted together with the POI[5] in Figure 5.1

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[1] Trento bus and trains data - in Italian, accessed in September 2022

[2] Trento bus and trains data

[3] Public transport data (GTFS format) - in Italian, accessed in September 2022

[4] Neighbours and PoI's data in Trento - in Italian, accessed in September 2022

[5] Location of the Service centres, Trentino Open Data - in Italian, accessed in September

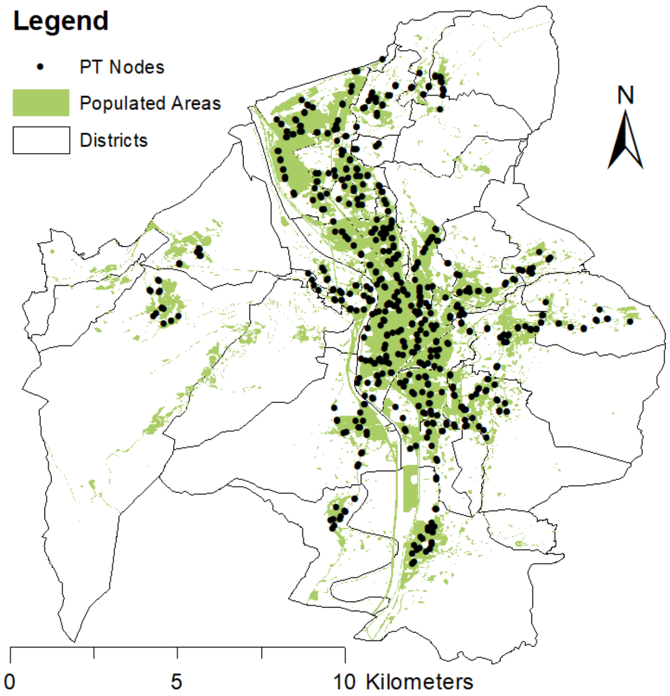

Figure 5.2: Distribution of PT nodes in the populated areas of different districts of Trento

and the bus nodes in Figure 5.2. Comparing these figures shows that there are populated areas characterised by the presence of POIs that are not connected with the PT network.

The main input data are summarised in Table 5.1[1,2].

5.1.1 Mobility demand and CAI Values of Public Transport and Car Sharing depot candidates

The mobility demand of PT considered in the case study was estimated based on the distribution of the population within each zone of Trento, as presented in Figure 5.3 during weekdays and Figure 5.4 during weekend days. This demand represents a potentiality for the different zones for the activation of CS service

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2022

[1] Average costs of parking area in Italy - in Italian, accessed in September 2022

[2] Average CS costs in Italy- in Italian, accessed in September 2022

Table 5.1: Main input data for the Trento case study.

Parameter	**Value**
Type of CS service	two-way CS
$\lvert\mathcal{Z}\rvert$	48
$Q^{\max}$	20 and 50 in scenarios A and B, respectively
$\mathcal{T}$	an entire week (5 weekdays and 2 weekend days)
Type of vehicles	Fiat Panda
T	Gaussian random variable with an expectation of 6 hours and a standard deviation of 2 hours (based on estimates for similar cities [78; 79; 80])
B	500k€
β_0	0.01
ℓ	1
α_1	6.9k€
α_2	14k€

in the same zones. The relevant values are reported in Table 5.2 and Table 5.3, which are visualised in Figure 5.3 and Figure 5.4, for weekdays and weekend days, respectively.

The CAI indexes of PT were calculated for all zones by means of the model proposed in Section 4.2.1 of Chapter 4. The resulting values are visualised for both weekdays and weekend days in the maps in Figure 5.5 and Figure 5.6, whereas the detailed values are reported in Table 5.2 and Table 5.3, respectively. By inspecting the two maps, it is possible to note that the city centre is characterised by the highest values in both considered time periods. On weekdays, good levels of CAI_{PT} (i.e., values between 2.5 and 5) are available in a wide area around the city centre, but the performance worsens significantly on weekend days. In both cases, the peripheral zones are characterised by low null values regardless of the presence of POI. More specifically, examining the entries in the tables shows that some zones are characterised by small CAI_{PT} values (i.e., zones 14, 29, 31, 37, 44, and 48 on weekdays and zones 6, 14, 29, 31, 37, 41, 44, and 48 on weekend days). In addition, some zones have null PT CAI values (i.e., zones 14, 31, 37, 44, and 48 on weekdays and zones 6, 14, 29, 31, 37, 41, 44, and 48 on weekend days). Consequently, such districts serve as major hot spots where the population could be better connected through the provision of a CS system.

Table 5.2: Results with $Q^{max} = 20$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.73	–	4.73	0.87	0	2
2	**Campotrentino**	**3.38**	**20.11**	**23.48**	**3.30**	**2**	**2**
3	**San Bartolomeo**	**2.80**	**13.43**	**16.22**	**1.51**	**1**	**2**
4	Villazzano	2.53	–	2.53	4.03	0	3
5	**Clarina**	**4.11**	**12.94**	**17.05**	**4.65**	**1**	**3**
6	**Melta**	**2.51**	**4.36**	**6.87**	**0.73**	**1**	**2**
7	Canova	3.42	–	3.42	1.31	0	2
8	Solteri-Centochiavi	4.82	–	4.82	3.69	0	2
9	San Dona'-Laste	1.83	–	1.83	0.32	0	2
10	**Spini-Ghiaie**	**2.89**	**20.55**	**23.45**	**6.32**	**2**	**4**
11	Cristo Re	6.17	–	6.17	1.99	0	2
12	Centro Storico	11.43	–	11.43	2.30	0	2
13	San Bernardino	7.93	–	7.93	0.98	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.04**	**0.04**	**0.03**	**1**	**2**
15	San Lazzaro	1.66	–	1.66	0.13	0	2
16	Povo	3.00	–	3.00	3.66	0	2
17	Ravina	2.84	–	2.84	4.44	0	3
18	Santissimo	7.87	–	7.87	1.50	0	2
19	Sopramonte	2.50	–	2.50	4.98	0	3
20	Mattarello	3.30	–	3.30	7.65	0	5
21	**Roncafort**	**2.18**	**10.90**	**13.08**	**5.46**	**1**	**4**
22	Madonna Bianca	2.65	–	2.65	1.81	0	2
23	Villazzano 3	2.98	–	2.98	1.00	0	2
24	**Gardolo**	**3.72**	**12.43**	**16.15**	**4.49**	**1**	**3**
25	Gazzadina	3.49	–	3.49	0.81	0	2
26	Meano	2.66	–	2.66	1.89	0	2
27	Cortesano	3.98	–	3.98	0.43	0	2
28	Martignano	2.49	–	2.49	3.98	0	3
29	**Gardolo Di Mezzo**	**0.61**	**0.87**	**1.48**	**0.23**	**1**	**2**
30	San Martino	8.19	–	8.19	1.78	0	2
31	**Sardagna**	**0.00**	**3.41**	**3.41**	**1.99**	**1**	**2**
32	Lamar	2.52	–	2.52	1.38	0	2
33	La Vela	3.25	–	3.25	1.61	0	2
34	Piedicastello	3.48	–	3.48	1.85	0	2
35	**San Giuseppe**	**4.86**	**36.29**	**41.15**	**4.30**	**2**	**3**
36	Vigo Meano	2.96	–	2.96	0.90	0	2
37	**Valsorda**	**0.00**	**0.70**	**0.70**	**0.20**	**1**	**2**
38	Oltrecastello	1.59	–	1.59	1.80	0	2
39	Cadine	2.27	–	2.27	2.22	0	2
40	Romagnano	2.57	–	2.57	2.10	0	2
41	**Villamontagna**	**1.82**	**2.76**	**4.58**	**1.39**	**1**	**2**
42	Cognola	2.84	–	2.84	3.18	0	2
43	Cappuccini	2.91	–	2.91	1.16	0	2
44	**Baselga Del Bondone**	**0.00**	**2.50**	**2.50**	**0.57**	**1**	**2**
45	San Dona di Cagnola	2.32	–	2.32	1.28	0	2
46	Belvedere-San Francesco	8.56	–	8.56	0.27	0	2
47	**Bolghera**	**6.13**	**29.52**	**35.66**	**3.07**	**2**	**2**
48	**Vigolo Baselga**	**0.00**	**2.33**	**2.33**	**0.59**	**1**	**2**
	Minimum CAI value	–	***0.04***	***0.04***			
	Average CAI value	***3.35***	***3.61***	***6.96***			

Regarding the CS depot candidates, a proximity clustering algorithm[1] was

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[1] ArcGIS Documentation: Proximity analysis - accessed in September 2022

Table 5.3: Results with $Q^{max} = 20$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	D_z^{t2}	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	**Campotrentino**	**2.55**	**19.23**	**21.78**	**2.20**	**2**	**2**
3	**San Bartolomeo**	**2.24**	**13.20**	**15.44**	**1.00**	**1**	**2**
4	Villazzano	1.95	–	1.95	2.69	0	3
5	**Clarina**	**2.55**	**12.82**	**15.36**	**3.10**	**1**	**3**
6	**Melta**	**0.00**	**4.16**	**4.16**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	**Spini-Ghiaie**	**1.70**	**20.13**	**21.84**	**4.21**	**2**	**4**
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**1**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	Santissimo	5.91	–	5.91	1.00	0	2
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	**Roncafort**	**2.18**	**10.52**	**12.69**	**3.64**	**1**	**4**
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**12.20**	**15.08**	**2.99**	**1**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.80**	**0.80**	**0.16**	**1**	**2**
30	San Martino	5.47	–	5.47	1.19	0	2
31	**Sardagna**	**0.00**	**3.02**	**3.02**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**36.00**	**39.97**	**2.87**	**2**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.63**	**0.63**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**2.46**	**2.46**	**0.93**	**1**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**2.35**	**2.35**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	**Bolghera**	**3.95**	**29.07**	**33.02**	**2.05**	**2**	**2**
48	**Vigolo Baselga**	**0.00**	**2.19**	**2.19**	**0.39**	**1**	**2**
	Minimum CAI value	***–***	***0.03***	***0.03***			
	Average CAI value	***2.43***	***3.52***	***5.95***			

applied to determine their locations by means of the ArcGIS tool. The CS depot candidates are visualised in Figure 5.7. In addition, the accessibility and connec-

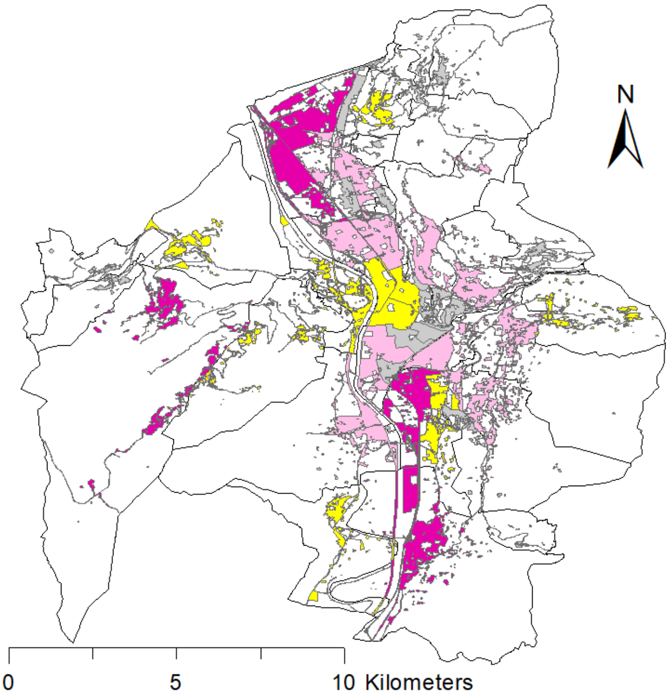

Figure 5.3: Distribution of the values of mobility demand during weekdays for all zones of Trento. Colour legend: ■ $(0-1.5)$; ■ $(1.5-3.0)$; ■ $(3.0-4.5)$; ■ (> 4.5)

tivity values for all the candidate depots were calculated by means of the model proposed in Section 4.2.2 considering all possible different operating conditions in the optimisation problem, i.e., for all possible numbers of vehicles assigned to them. For the sake of compactness, only the accessibility values of the depots are reported in Table (5.4) and Table (5.5).

5.1.2 Results and discussion

In this section, the results provided by the proposed approach will be presented and discussed for two different scenarios:

A – the total number of CS vehicles is limited to $Q^{\max} = 20$: this case study is designed to test the distribution of limited resources. This value is estimated based on size of Trento[1];

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[1] Population and households as of 2022, Istat

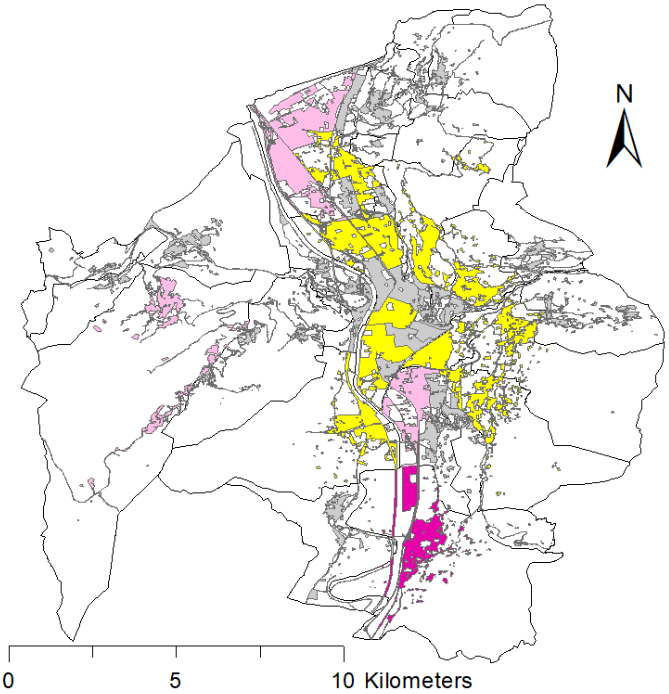

Figure 5.4: Distribution of the values of mobility demand during weekend days for all zones of Trento. Colour legend: ■ $(0-1.5)$; ■ $(1.5-3.0)$; ■ $(3.0-4.5)$; ■ (> 4.5)

B – total number of CS vehicles is limited to $Q^{\max} = 50$, which is a reasonable approximation of a scenario in which $Q^{\max}$ is unlimited: this case study is designed to test the effect of budget limitations.

Concerning the time frame reference, the optimisation problem in Section 4.2.3 of Chapter 4 of this thesis is considered a whole generic week. Therefore, weekdays have greater weight than weekend days, as there are 5 of the former and 2 of the latter.

Finally, the problem solution was implemented via the IBM CPLEX solver, and the optimisation run was performed by means of a PC with an Intel i7 - 1.80 GHz processor and 8 GB RAM. Given this setup, the solution time was always less than 2 minutes for all tested configurations.

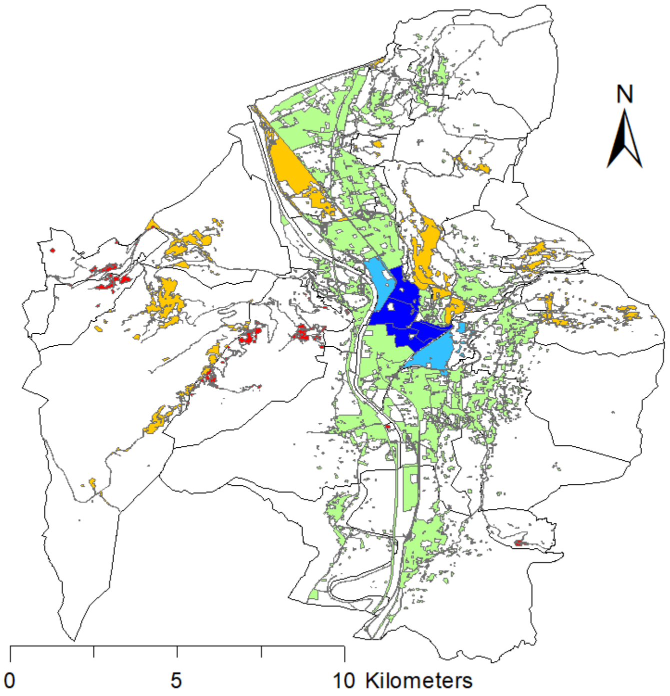

Figure 5.5: Distribution of the values of CAI indexes of PT during weekdays for all zones of Trento. Colour legend: 🟥 0; 🟨 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

5.1.2.1 Scenario A

Let us first consider the results reported in Table 5.2 and Table 5.3, during weekdays and weekend days, respectively, both are relevant to a case study setup characterised by a maximum number of CS vehicles $Q^{\max} = 20$. This table provides, in the last two rows, the minimum and the average values of the CAI before optimisation (i.e., CAI_{PT}) and after optimisation (i.e., CAI_{TOT}) and of the contribution provided by CS (i.e., CAI_{CS}). It is possible to note that the minima vary on weekdays (Table 5.2) and weekend days (Table 5.2) from 0 to 0.04 and 0.03, respectively, whereas the averages vary from 3.35 to 6.96 (+108%) and from 2.43 to 5.95 (+145%), respectively. The small change in the minima is due to the characteristics of zone 14, i.e., the zone with the worst performance, which is explained in more detail in the following. The improvements in the average values are the result of a compromise between assigning resources to

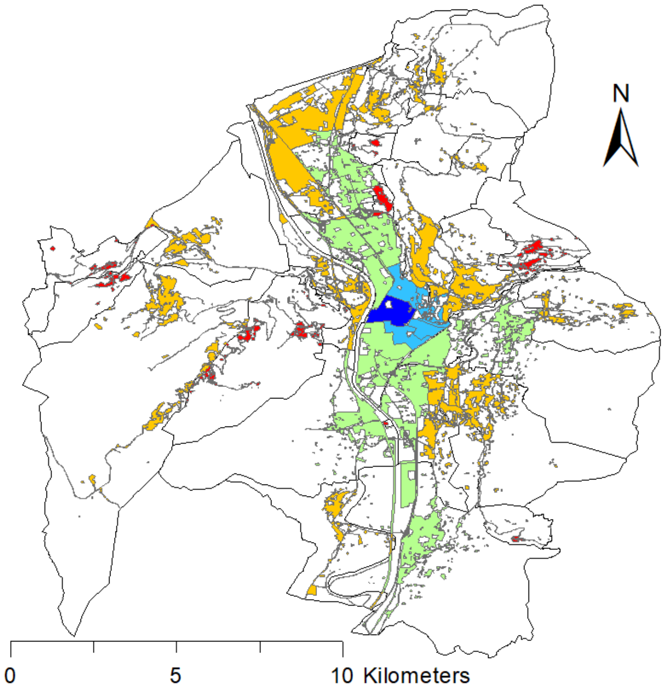

Figure 5.6: Distribution of the values of CAI indexes of PT during weekend days for all zones of Trento. Colour legend: 🟥 0; 🟨 (0−2.5); 🟩 (2.5−5.0); 🟦 (5.0−7.5); 🟦 (> 7.5)

zones with low/null CAI_{PT} and assigning resources to zones characterised by high accessibility and connectivity potentialities (i.e., resulting in $CAI_{CS,z} > 5$ in Table 5.2 and Table 5.3, during weekdays and weekend days, respectively). The zones with low/null CAI_{PT} are privileged, in the resource assignment, by the considered definition of the weighting coefficients (4.11) and by constraints (4.15) (as described in Section 4.2.3.2 in Chapter 4 of this thesis) even if they are characterised by limited accessibility and connectivity potentialities (i.e., resulting in $CAI_{CS,z} < 5$ in Table 5.2 and Table 5.3, during weekdays and weekend days, respectively).

If the performance assessment is restricted to zones characterised by $CAI^{t}_{PT,z} < 5$, the improvement are +137% and +211% on weekdays and weekends, respectively. Such a result shows the effectiveness of the proposed approach in terms of balancing equitable resource distribution and the global aim of improving the whole connectivity and accessibility of PT in the considered case study. In fact,

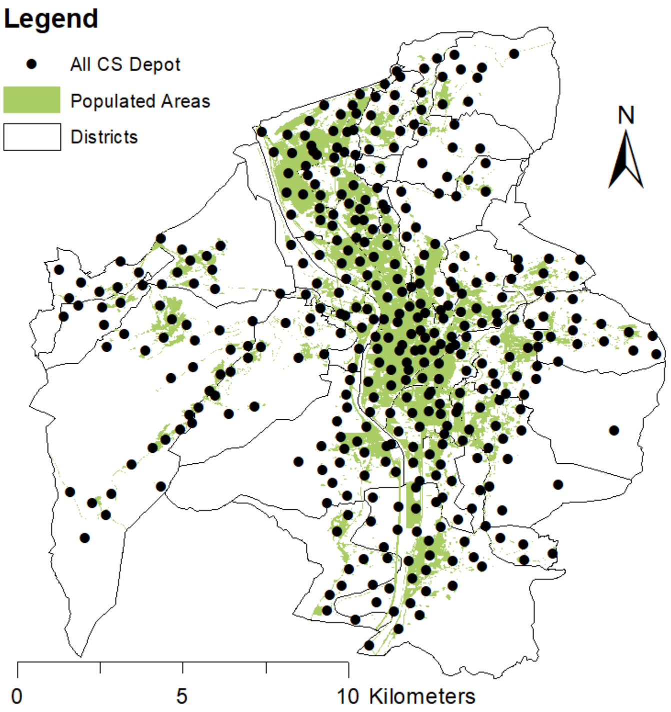

Figure 5.7: Distribution of candidate CS depots with respect to the populated areas of Trento

the solution provides a significant improvement for the whole region and a very large improvement for disadvantaged zones.

As depicted in Figure 5.12 and Figure 5.13 during weekdays and weekend days, respectively, the CS depots activated in this scenario are distributed in the most districts of the city. Most of the activated depots (indicated by the black dots) are located in the zones with $CAI_{PT} < 5$ in both time periods. In contrast, only one depot is located in a zone with $CAI_{PT} > 5$ (zone 47), which is characterised by high demand in both time periods (see Table 5.2 and Table 5.3, during weekdays and weekend days, respectively) and very high values of the accessibility index (see Table 5.4 and Table 5.5).

To evaluate the effects of the proposed approach in the whole considered area, consider again the CAI maps reported in Figure 5.8 and Figure 5.10 for the two considered time periods. In such maps, which provide contributions to CAI_{TOT} values provided by CS, it is possible to note that not all activated CS

Table 5.4: Values of the accessibility index for all candidate depots $k \in \mathcal{C}_z$, $\forall z = 1 \ldots 23$ for Trento. Highlights: Grey refers to both scenarios A and B; blue refers to scenario B; yellow refers to scenario A with additional vehicles in scenario B

(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$
(1,1)	8.32	**(10,5)**	**11.27**	(2,15)	0.59	(4,18)	18.77	(12,20)	0.73
(2,1)	10.90	**(1,6)**	**3.74**	(1,16)	2.74	(1,19)	0.03	(13,20)	4.88
(1,2)	1.36	(2,6)	3.71	(2,16)	0.80	(2,19)	0.09	(14,20)	0.05
(2,2)	0.14	(1,7)	1.37	(3,16)	1.18	(3,19)	0.22	(15,20)	0.18
(3,2)	4.67	(2,7)	7.03	(4,16)	3.41	(4,19)	0.61	(16,20)	0.24
(4,2)	0.25	(3,7)	6.69	(5,16)	1.58	(5,19)	0.00	(17,20)	0.34
(5,2)	**8.41**	(4,7)	8.00	(6,16)	2.01	(6,19)	0.09	(18,20)	6.38
(6,2)	6.55	(1,8)	8.09	(7,16)	6.63	(7,19)	0.00	(19,20)	0.13
(7,2)	**8.40**	(2,8)	8.95	(8,16)	1.38	(8,19)	0.08	(20,20)	6.88
(1,3)	**12.48**	(3,8)	10.11	(9,16)	2.09	(9,19)	0.06	(21,20)	6.23
(2,3)	5.14	(4,8)	5.81	(10,16)	0.20	(10,19)	3.18	(22,20)	0.14
(3,3)	4.03	(5,8)	9.58	(11,16)	6.94	(11,19)	1.15	(23,20)	2.68
(4,3)	1.63	(1,9)	0.66	(12,16)	0.05	(12,19)	0.07	(24,20)	0.08
(5,3)	4.09	(2,9)	3.89	(13,16)	0.78	(13,19)	4.32	(25,20)	0.89
(1,4)	3.16	(1,10)	3.38	(14,16)	2.53	(14,19)	3.84	(26,20)	0.82
(2,4)	1.38	**(2,10)**	**8.12**	(15,16)	0.41	(15,19)	0.06	(27,20)	0.67
(3,4)	3.93	(3,10)	5.74	(1,17)	0.05	(16,19)	5.79	(28,20)	0.04
(4,4)	4.90	(4,10)	2.81	(2,17)	0.03	(17,19)	0.23	(1,21)	0.26
(5,4)	2.81	(5,10)	2.31	(3,17)	0.00	(18,19)	1.90	(2,21)	1.85
(6,4)	0.12	**(6,10)**	**8.65**	(4,17)	0.03	(19,19)	0.56	(3,21)	3.78
(7,4)	2.93	(7,10)	4.82	(5,17)	0.01	(20,19)	0.10	(4,21)	4.47
(8,4)	0.07	(8,10)	0.64	(6,17)	0.30	(21,19)	0.25	(5,21)	2.39
(9,4)	2.69	(9,10)	2.23	(7,17)	0.02	(22,19)	1.36	(6,21)	3.10
(10,4)	3.82	(10,10)	6.21	(8,17)	2.45	(23,19)	0.09	(7,21)	3.04
(11,4)	0.02	(11,10)	1.20	(9,17)	6.34	(24,19)	1.05	(8,21)	3.55
(12,4)	1.47	(12,10)	0.82	(10,17)	0.72	(25,19)	0.47	(9,21)	3.44
(13,4)	0.87	(1,11)	9.11	(11,17)	0.28	(26,19)	1.89	**(10,21)**	**8.99**
(14,4)	0.49	(2,11)	7.33	(12,17)	0.00	(27,19)	0.13	(1,22)	3.54
(15,4)	0.74	(3,11)	11.01	(13,17)	0.37	(1,20)	0.17	(2,22)	2.27
(16,4)	0.17	(1,12)	6.29	(14,17)	5.94	(2,20)	0.06	(3,22)	3.12
(1,5)	0.12	(2,12)	32.42	(15,17)	1.44	(3,20)	0.12	(4,22)	0.17
(2,5)	0.97	(3,12)	27.97	(16,17)	6.46	(4,20)	0.05	(5,22)	1.85
(3,5)	8.46	(4,12)	15.49	(17,17)	3.38	(5,20)	0.56	(6,22)	0.44
(4,5)	6.85	(5,12)	31.59	(18,17)	2.69	(6,20)	0.08	(7,22)	0.00
(5,5)	2.91	(1,13)	15.10	(19,17)	1.96	(7,20)	0.04	(1,23)	0.93
(6,5)	4.03	(2,13)	13.82	(20,17)	1.61	(8,20)	0.12	(2,23)	2.55
(7,5)	0.41	(3,13)	8.33	(1,18)	17.52	(9,20)	0.04	(3,23)	0.00
(8,5)	2.80	**(1,14)**	**0.01**	**(2,18)**	**20.85**	(10,20)	0.26	(4,23)	0.55
(9,5)	7.26	(1,15)	0.94	(3,18)	10.12	(11,20)	3.10	(5,23)	0.08

depots provide the highest possible values of CAI_{CS} (indicated in blue) due to differences not only in the number of assigned vehicles but also in the accessibility indexes. In particular, as it is possible to note in Table 5.4 and Table 5.5, that the zones with $CAI_{CS,z} < 5$ are characterised by accessibility values smaller than those with $CAI_{CS,z} > 5$.

In addition, by comparing such maps with those depicted in Figure 5.5 and

Table 5.5: Values of the accessibility index for all candidate depots $k \in \mathcal{C}_z$, $\forall z = 24 \dots \mathcal{Z}$ for Trento. Highlights: Grey refers to both scenarios A and B under $\ell = 1$; blue refers to scenario B; yellow refers to scenario A with additional vehicles in scenario B

(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$
(1,24)	0.00	(3,28)	0.48	(2,33)	0.14	(8,38)	0.29	(3,42)	3.92
(2,24)	7.78	(4,28)	0.43	(3,33)	2.51	(9,38)	0.03	(4,42)	4.87
(3,24)	0.01	(5,28)	4.21	(4,33)	2.53	(10,38)	0.50	(5,42)	0.28
(4,24)	3.49	(6,28)	4.45	(5,33)	4.64	(11,38)	0.21	(6,42)	6.30
(5,24)	2.93	(7,28)	5.36	(6,33)	5.42	(12,38)	0.00	(7,42)	0.37
(6,24)	3.84	(8,28)	2.31	(1,34)	0.28	(13,38)	0.19	(8,42)	4.14
(7,24)	**8.33**	(9,28)	1.75	(2,34)	0.85	(14,38)	0.00	(9,42)	0.09
(8,24)	5.46	(10,28)	1.18	(3,34)	4.64	(15,38)	0.03	(10,42)	2.03
(9,24)	0.40	(11,28)	2.20	(4,34)	1.09	(16,38)	0.01	(11,42)	1.94
(10,24)	6.47	(12,28)	0.04	(5,34)	2.47	(1,39)	0.03	(12,42)	0.17
(11,24)	3.32	(13,28)	1.43	(6,34)	5.50	(2,39)	0.26	(1,43)	3.83
(12,24)	**10.50**	(14,28)	1.33	(7,34)	6.61	(3,39)	0.84	(2,43)	2.26
(13,24)	**8.07**	(15,28)	0.03	(8,34)	4.29	(4,39)	3.08	(3,43)	4.11
(14,24)	3.07	(1,29)	0.26	(1,35)	8.40	(5,39)	4.62	(1,44)	0.30
(15,24)	3.55	**(2,29)**	**0.65**	(2,35)	2.61	(6,39)	1.23	(2,44)	0.24
(1,25)	2.14	(1,30)	17.66	(3,35)	6.33	(7,39)	3.79	(3,44)	0.69
(2,25)	1.46	(2,30)	3.56	(4,35)	6.41	(8,39)	1.64	(4,44)	0.18
(3,25)	0.14	(3,30)	13.12	(5,35)	7.90	(9,39)	0.04	**(5,44)**	**1.99**
(4,25)	0.11	(4,30)	12.19	**(6,35)**	**15.10**	(10,39)	0.58	(6,44)	0.42
(1,26)	2.55	(5,30)	20.63	**(7,35)**	**18.09**	(11,39)	0.09	(1,45)	1.76
(2,26)	0.36	(1,31)	0.49	(1,36)	2.58	(1,40)	0.77	(2,45)	2.86
(3,26)	1.93	(2,31)	0.51	(2,36)	0.68	(2,40)	0.23	(3,45)	2.92
(4,26)	4.21	(3,31)	1.69	(3,36)	0.10	(3,40)	3.63	(4,45)	1.41
(5,26)	0.30	(4,31)	0.40	(4,36)	0.09	(4,40)	0.07	(1,46)	7.31
(6,26)	1.02	(5,31)	0.84	(5,36)	0.13	(5,40)	2.81	(2,46)	0.81
(7,26)	0.59	(6,31)	1.00	(6,36)	0.08	(6,40)	0.52	(3,46)	3.83
(8,26)	0.55	(7,31)	0.03	(7,36)	0.04	(7,40)	0.03	**(1,47)**	**13.55**
(9,26)	1.25	(8,31)	1.41	(8,36)	0.10	(8,40)	0.19	(2,47)	12.41
(10,26)	0.00	(9,31)	0.03	(1,37)	0.05	(9,40)	0.03	**(3,47)**	**12.90**
(1,27)	0.69	**(10,31)**	**2.16**	(2,37)	0.10	(10,40)	1.46	(4,47)	1.45
(2,27)	0.01	(11,31)	0.32	**(3,37)**	**0.50**	(1,41)	0.38	(5,47)	0.02
(3,27)	0.54	(12,31)	0.29	(4,37)	0.06	(2,41)	0.13	(1,48)	0.05
(4,27)	0.06	(13,31)	1.54	(1,38)	0.78	**(3,41)**	**1.73**	(2,48)	0.16
(5,27)	0.61	(14,31)	0.04	(2,38)	3.87	(4,41)	1.41	(3,48)	0.10
(6,27)	0.04	(1,32)	4.56	(3,38)	1.54	(5,41)	1.18	(4,48)	1.68
(7,27)	0.76	(2,32)	3.12	(4,38)	0.09	(6,41)	0.39	**(5,48)**	**1.81**
(8,27)	0.56	(3,32)	2.33	(5,38)	2.34	(7,41)	0.18	(6,48)	0.12
(1,28)	0.02	(4,32)	3.97	(6,38)	0.92	(1,42)	1.02	(7,48)	0.18
(2,28)	0.26	(1,33)	0.15	(7,38)	0.16	(2,42)	0.75	—	—

Figure 5.6, it is possible to note that in all cases, the resources are assigned to zones characterised by CAI_{PT} values between 0 and 5, with the single exception of central zone 47, which is already characterised by $CAI_{PT,47} > 5$. This is explainable, as better discussed in the following, by the fact that such a zone has

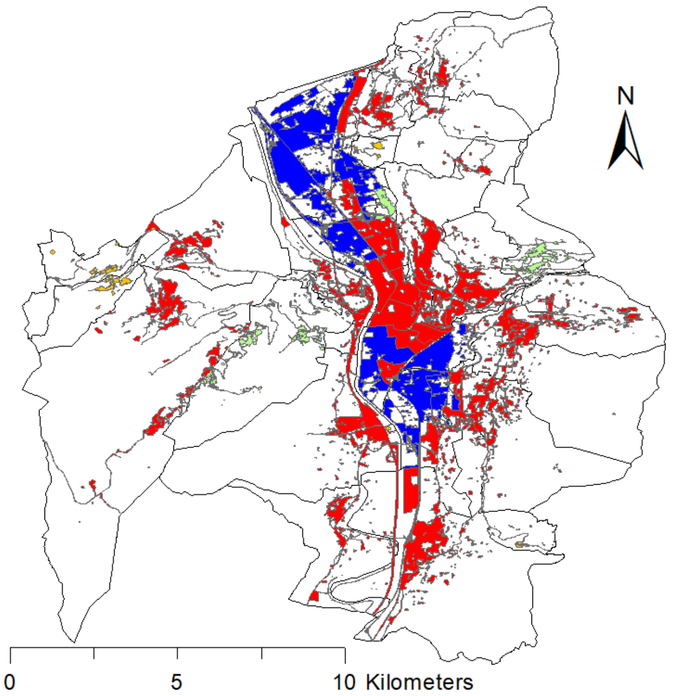

Figure 5.8: Distribution of the values of CAI indexes of CS during weekdays for all zones of Trento under Scenario A. Colour legend: 🟥 0; 🟨 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; ■ (> 7.5)

a relatively high demand rate but very high accessibility.

A more detailed analysis of the results can be performed by considering the figures reported in Table 5.2 and Table 5.3, during weekdays and weekend days, respectively, where the different entries reveal that the optimisation approach places the maximum vehicles and activates the CS service in the zones that are characterised by the lowest values of CAI_{PT} for PT or high demand and accessibility indexes. More specifically, the service is activated in zones 2, 3, 5, 6, 10, 14, 21, 24, 29, 31, 35, 37, 41, 44, 47, and 48 on both weekdays and weekend days.

In addition, according to constraints (4.15) (Section 4.2.3.2 in Chapter 4 of this thesis), at least one vehicle is assigned to all zones characterised by null CAI_{PT} in both time periods (zones 14, 31, 37, 44, and 48) or only on weekend days (zones 6, 29, and 41). Nevertheless, it is interesting to note that, even where possible, no more than one vehicle is assigned to such zones. Such an expected result is due to the low values of demand characterising such zones in both considered

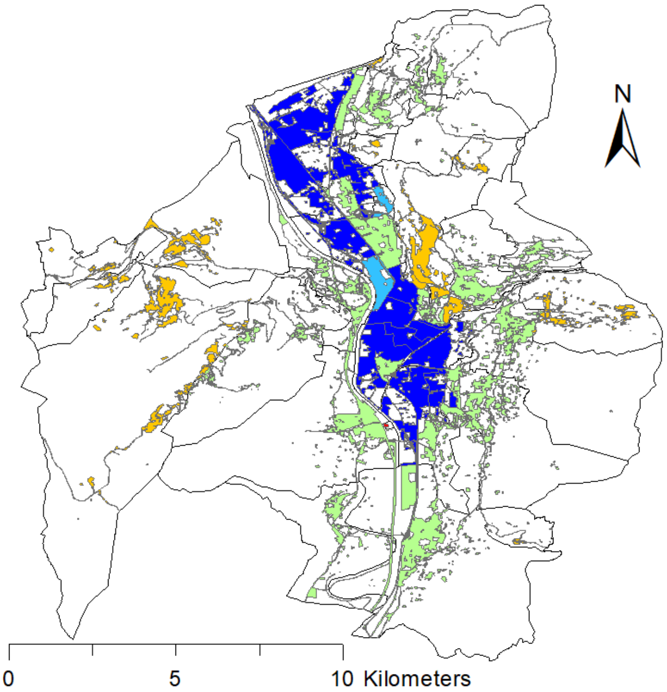

Figure 5.9: Distribution of the total values of CAI indexes during weekdays for all zones of Trento under Scenario A. Colour legend: 🟥 0; 🟧 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

time periods. In fact, according to (4.5) (Chapter 4), the connectivity index, which is the sole contribution that depends on the number of vehicles, is also proportional to the demand. Consequently, it is not convenient to assign more than the minimum number of vehicles to the zones characterised by low demand. In contrast, it is convenient to assign more than one vehicle to the zones with high demand, as occurs for zones 2, 10, 35, and 47. In these cases, it is interesting to note in Table 5.4 and Table 5.5, that vehicles are assigned to different depots.

Regarding the effect of constraints (4.15) (Section 4.2.3.2 in Chapter 4 of this thesis), it is possible to note in Table 5.2 and Table 5.3, during weekdays and weekend days, respectively that the zones characterised by null CAI_{PT} during at least one of the considered time periods (i.e., zones 6, 14, 29, 31, 37, 41, 44, and 48) are assigned with a CS depot with a single vehicle according to the limitation determined by $Q_z^{\max}$, i.e., by the relevant population density. The results of zone 14 determine the minimum CAI_{TOT} of the considered case study. This influence

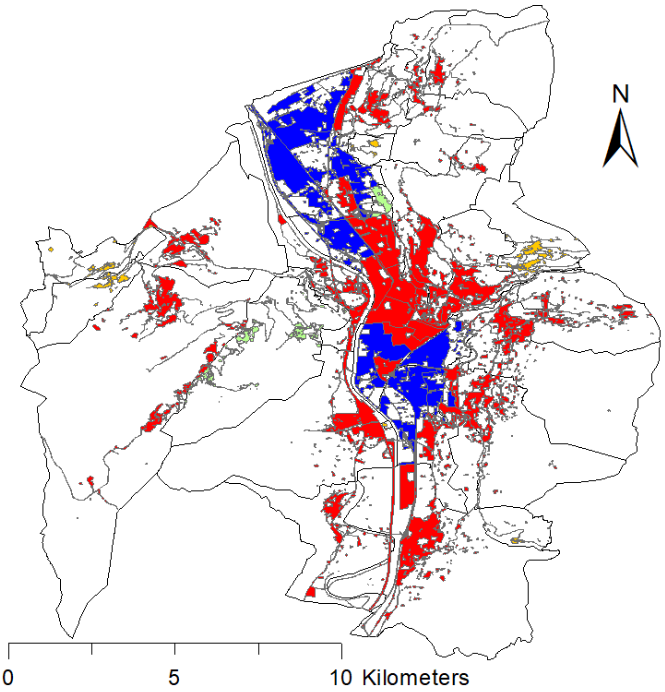

Figure 5.10: Distribution of the values of CAI indexes of CS during weekend days for all zones of Trento under Scenario A. Colour legend: 🟥 0; 🟨 (0 – 2.5); 🟩 (2.5 – 5.0); 🟦 (5.0 – 7.5); 🟦 (> 7.5)

reflects the small value of accessibility (the smallest in Table 5.4 and Table 5.5) and the low demand (the smallest for both time periods, as reported in Table 5.2 and Table 5.3, during weekdays and weekend days, respectively).

The results of this scenario were achieved by utilising a budget of 418k€ to activate a total of 20 depots along with the placement of all 20 vehicles. In other words, the upper bound of the performance is determined by the chosen number of vehicles.

5.1.2.2 Scenario B

As discussed, in scenario A, not all of the budget was invested in resources. Therefore, to investigate the effectiveness of the proposed approach, it is tested with $Q^{max} = 50$ (corresponding, in the considered case study, to the simulation of a scenario in which Q^{max} is unlimited) to check the solution that exploits the

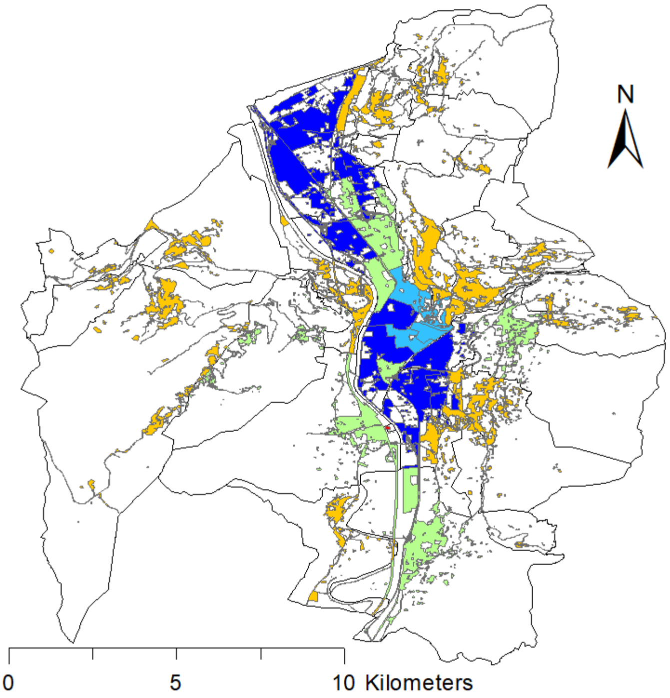

Figure 5.11: Distribution of the total values of CAI indexes during weekend days for all zones of Trento under Scenario A. Colour legend: 🟥 0; 🟨 (0 – 2.5); 🟩 (2.5 – 5.0); 🟦 (5.0 – 7.5); 🟦 (> 7.5)

entire budget.

A general view of the results of this scenario is depicted in Figure 5.12 and Figure 5.13 during weekdays and weekend days, respectively, where the red dots indicate the additionally activated depots with respect to scenario A (in black). In these maps, which depict the two considered time periods, the three additional depot activation are concentrated in the city centre and, as indicated in Table 5.6 and Table 5.7, during weekdays and weekend days, respectively, in the zones characterised by high accessibility and connectivity values resulting in $CAI_{CS,z} > 5$.

Regarding the minimum and average values, the results reported in the last row of Table 5.6 and Table 5.7, during weekdays and weekend days, respectively show the same values of the minima in scenario A, whereas the averages of CAI_{TOT} increased by an additional +13% (from 6.96 to 7.87) and an additional +15% (from 5.95 to 6.84) on weekdays and weekend days, respectively. For the

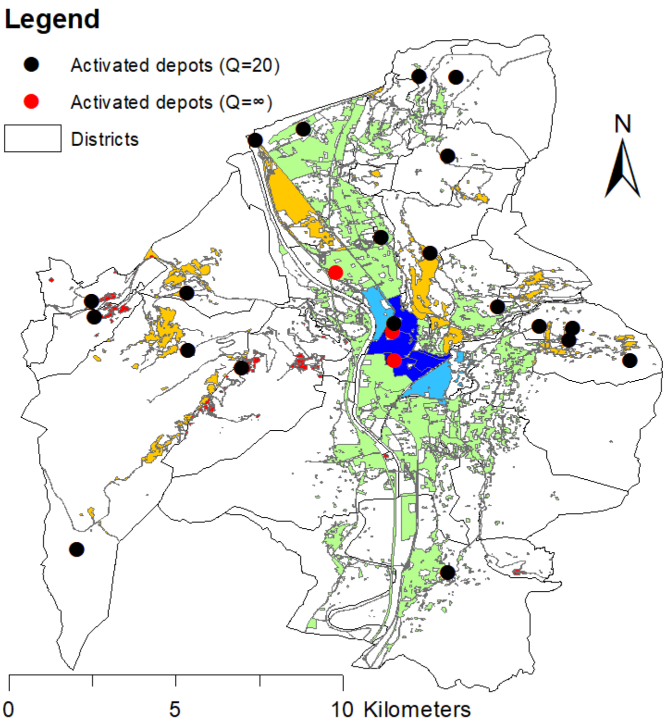

Figure 5.12: Distribution of activated CS depots in scenario A (black dots) and scenario B (black and red dots compared with the CAI_{PT} on weekdays for Trento. Colour legend: 🟥 0; 🟨 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5).

sake of comparison, the increase in budget usage is +19%.

If the performance assessment is restricted to zones that were characterised by $CAI^t_{PT,z} < 5$, the improvement turns out to be +159% and +237%, compared with +137% and +211% in scenario A on weekdays and weekends, respectively. The improvement compared with scenario A is due to the placement of 3 additional vehicles in the depots with medium-low CAI values (i.e., depot 2 in zone 10 and depots 7 and 13 in zone 24), as shown in Table 5.4 and Table 5.5. This result shows the capability of the model to privilege zones with low $CAI_{PT,z}$ if the relevant potentialities in terms of demand and accessibility are high, as it is possible to verify in Table 5.6 and Table 5.7, during weekdays and weekend days, respectively as well as in Table 5.4 and Table 5.5, respectively. In this context, values of CAI indexes for CS and their total values under Scenario B can be visualized using Figure 5.14 and Figure 5.16 during weekdays and using Figure 5.15

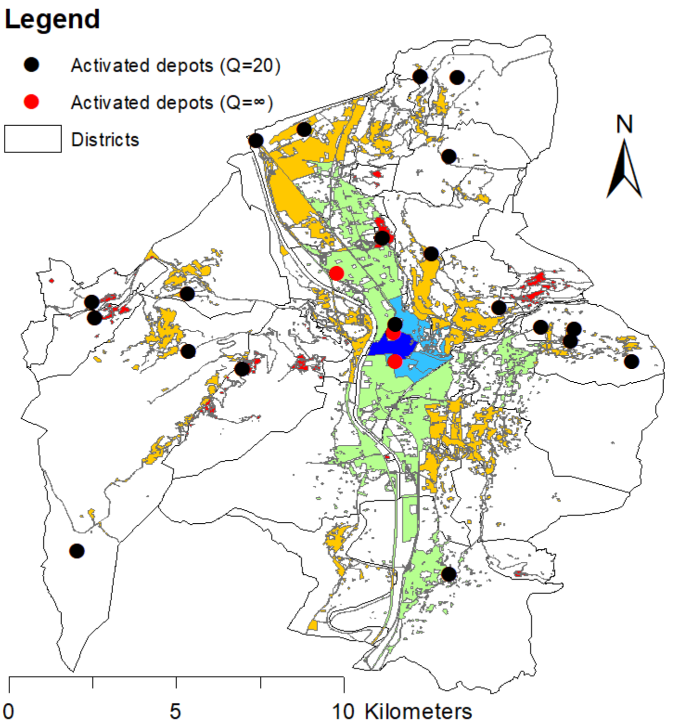

Figure 5.13: Distribution of activated CS depots in scenario A (black dots) and scenario B (black and red dots compared with the CAI_{PT} on weekend days for Trento. Colour legend: 🟥 0; 🟨 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5).

and Figure 5.17 during weekend days, respectively.

As a more detailed analysis, an inspection of the entries in Table 5.6 and Table 5.7, during weekdays and weekend days, respectively reveals that in this scenario, 23 depots along with the placement of 24 vehicles were activated. In addition, a new CS depot is activated in an additional district, 18, with a single vehicle (which is also the maximum for such a zone), whereas the 3 remaining vehicles are assigned to zones 10 (+1 vehicles) and 24 (+2 vehicles). Table 5.4 shows that the additional vehicle in zone 10 is placed in depot number $(k, z) = (2, 10)$, which already has a vehicle in scenario A, whereas the new vehicles in zone 24 are assigned to the new depots (Table 5.5). Such a result is a compromise between activating new depots and then "gaining" their accessibility in CAI_{CS} and the relevant activation costs γ_1. In other words, the proposed methodology determines that, compared with scenario A, it is globally better to have three

Table 5.6: Results with $Q^{max} = 50$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.73	–	4.73	0.87	0	2
2	**Campotrentino**	**3.38**	**20.11**	**23.48**	**3.30**	**2**	**2**
3	**San Bartolomeo**	**2.80**	**13.43**	**16.22**	**1.51**	**1**	**2**
4	Villazzano	2.53	–	2.53	4.03	0	3
5	**Clarina**	**4.11**	**12.94**	**17.05**	**4.65**	**1**	**3**
6	**Melta**	**2.51**	**4.36**	**6.87**	**0.73**	**1**	**2**
7	Canova	3.42	–	3.42	1.31	0	2
8	Solteri-Centochiavi	4.82	–	4.82	3.69	0	2
9	San Dona'-Laste	1.83	–	1.83	0.32	0	2
10	**Spini-Ghiaie**	**2.89**	**22.26**	**25.15**	**6.32**	**3**	**4**
11	Cristo Re	6.17	–	6.17	1.99	0	2
12	Centro Storico	11.43	–	11.43	2.30	0	2
13	San Bernardino	7.93	–	7.93	0.98	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.04**	**0.04**	**0.03**	**1**	**2**
15	San Lazzaro	1.66	–	1.66	0.13	0	2
16	Povo	3.00	–	3.00	3.66	0	2
17	Ravina	2.84	–	2.84	4.44	0	3
18	**Santissimo**	**7.87**	**21.83**	**29.70**	**1.50**	**1**	**2**
19	Sopramonte	2.50	–	2.50	4.98	0	3
20	Mattarello	3.30	–	3.30	7.65	0	5
21	**Roncafort**	**2.18**	**10.90**	**13.08**	**5.46**	**1**	**4**
22	Madonna Bianca	2.65	–	2.65	1.81	0	2
23	Villazzano 3	2.98	–	2.98	1.00	0	2
24	**Gardolo**	**3.72**	**32.69**	**36.42**	**4.49**	**3**	**3**
25	Gazzadina	3.49	–	3.49	0.81	0	2
26	Meano	2.66	–	2.66	1.89	0	2
27	Cortesano	3.98	–	3.98	0.43	0	2
28	Martignano	2.49	–	2.49	3.98	0	3
29	**Gardolo Di Mezzo**	**0.61**	**0.87**	**1.48**	**0.23**	**1**	**2**
30	San Martino	8.19	–	8.19	1.78	0	2
31	**Sardagna**	**0.00**	**3.41**	**3.41**	**1.99**	**1**	**2**
32	Lamar	2.52	–	2.52	1.38	0	2
33	La Vela	3.25	–	3.25	1.61	0	2
34	Piedicastello	3.48	–	3.48	1.85	0	2
35	**San Giuseppe**	**4.86**	**36.29**	**41.15**	**4.30**	**2**	**3**
36	Vigo Meano	2.96	–	2.96	0.90	0	2
37	**Valsorda**	**0.00**	**0.70**	**0.70**	**0.20**	**1**	**2**
38	Oltrecastello	1.59	–	1.59	1.80	0	2
39	Cadine	2.27	–	2.27	2.22	0	2
40	Romagnano	2.57	–	2.57	2.10	0	2
41	**Villamontagna**	**1.82**	**2.76**	**4.58**	**1.39**	**1**	**2**
42	Cognola	2.84	–	2.84	3.18	0	2
43	Cappuccini	2.91	–	2.91	1.16	0	2
44	**Baselga Del Bondone**	**0.00**	**2.50**	**2.50**	**0.57**	**1**	**2**
45	San Dona di Cagnola	2.32	–	2.32	1.28	0	2
46	Belvedere-San Francesco	8.56	–	8.56	0.27	0	2
47	**Bolghera**	**6.13**	**29.52**	**35.66**	**3.95**	**2**	**2**
48	**Vigolo Baselga**	**0.00**	**2.33**	**2.33**	**0.43**	**1**	**2**
	Minimum CAI value	*–*	*0.04*	*0.04*			
	Average CAI value	*3.35*	*4.52*	*7.87*			

additional depots in zones 18 and 24 but only add vehicles to an existing depot in zone 10.

Table 5.7: Results with $Q^{max} = 50$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_2}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	**Campotrentino**	**2.55**	**19.23**	**21.78**	**2.20**	**2**	**2**
3	**San Bartolomeo**	**2.24**	**13.20**	**15.44**	**1.00**	**1**	**2**
4	Villazzano	1.95	–	1.95	2.69	0	3
5	**Clarina**	**2.55**	**12.82**	**15.36**	**3.10**	**1**	**3**
6	**Melta**	**0.00**	**4.16**	**4.16**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	**Spini-Ghiaie**	**1.70**	**21.40**	**23.10**	**4.21**	**3**	**4**
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**1**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	**Santissimo**	**5.91**	**21.63**	**27.54**	**1.00**	**1**	**2**
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	**Roncafort**	**2.18**	**10.52**	**12.69**	**3.64**	**1**	**4**
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**32.02**	**34.90**	**2.99**	**3**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.80**	**0.80**	**0.16**	**1**	**2**
30	San Martino	5.47	–	5.47	1.19	0	2
31	**Sardagna**	**0.00**	**3.02**	**3.02**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**36.00**	**39.97**	**2.87**	**2**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.63**	**0.63**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**2.46**	**2.46**	**0.93**	**1**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**2.35**	**2.35**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	**Bolghera**	**3.95**	**29.07**	**33.02**	**2.05**	**2**	**2**
48	**Vigolo Baselga**	**0.00**	**2.19**	**2.19**	**0.39**	**1**	**2**
	Minimum CAI value	–	***0.03***	***0.03***			
	Average CAI value	***2.43***	***4.41***	***6.84***			

The utilised budget turns out to be 494.7k€, which is very close to the maximum admissible value. In this case, since the remaining 5.3k€ does not allow

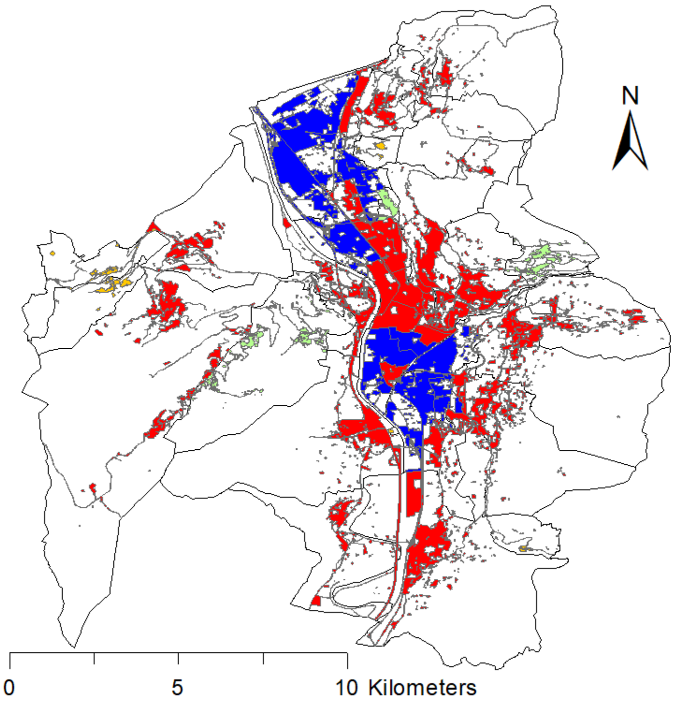

Figure 5.14: Distribution of the values of CAI indexes of CS during weekdays for all zones of Trento under Scenario B. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

the activation of a new depot or the purchase of an additional vehicle, the budget determines the upper bound of the achievable performance.

5.2 Case Study II: Genova

Genova is the sixth largest city of Italy comprising approximately $816,000$ residents[1] located on Ligurian Rivier, covering an area of approximately 243 km^2 [2]. The city is divided into 71 districts[3]. However, only 42 main districts of Genova have been evaluated in this case study for the purpose of simplification and

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[1] Resident Population and households as of 2022, Istat - in Italian, accessed in November 2022

[2] Superficie di Comuni Province e Regioni italiane al 9 ottobre 2011 - in Italian, accessed in November 2022

[3] ADMINISTRATIVE BOUNDARY as of 01 Gennaio 2012 - in Italian, accessed in November 2022

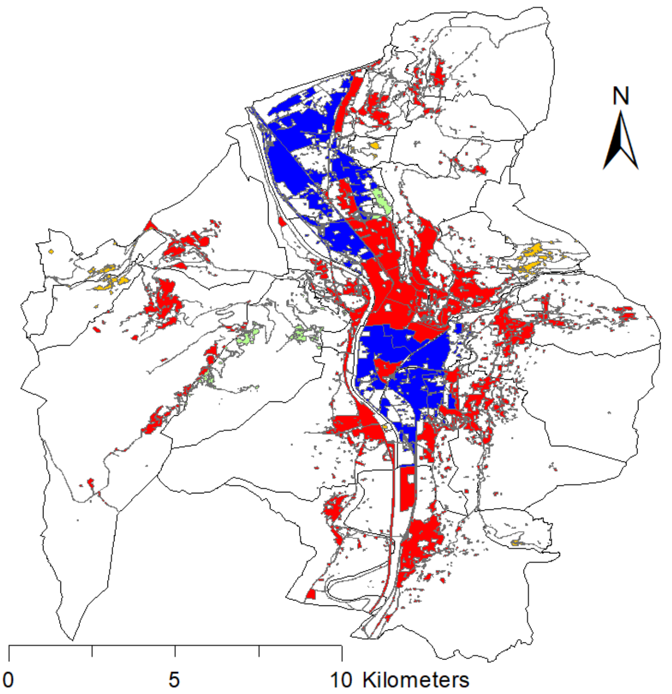

Figure 5.15: Distribution of the values of CAI indexes of CS during weekend days for all zones of Trento under Scenario B. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

saving the computation effort of the proposed optimisation model (Section 4.2.3 in Chapter 4 of this chapter). All other PT characteristics of Genova will be explained according to these reduced 42 districts in the following.

The Genova PT network comprises 45 bus lines operating within the city, 1 metro line, regional trains, and funiculars operating on the hilly areas[1]. Nevertheless, since the scope of the defined methodology is the evaluation of the PT system within the same region, only the city bus lines, and metro lines, are taken into consideration for the calculation of CAI_{PT} values of PT in each district of Genova. As stated earlier, the city's PT system consists of 46 lines (including metro lines) in two directions (outbound and inbound trips) with a network of 620 nodes distributed within the above mentioned 42 districts, as presented in Figure 5.19[2]. All lines operate from 5:00 a.m. until 10:00 p.m. during the day

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[1] trasporto multimodale - in Italian, accessed in November 2022

[2] trasporto multimodale - in Italian, accessed in November 2022

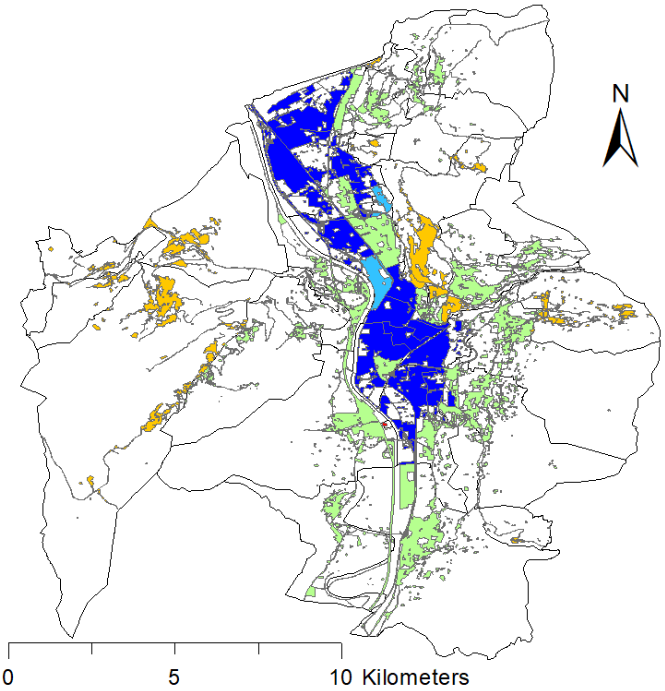

Figure 5.16: Distribution of the total values of *CAI* indexes during weekdays for all zones of Trento under Scenario B. Colour legend: 🟥 0; 🟨 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

time, whereas only 20 bus lines operate during night time[1].

Regarding the distribution of the households in the considered area, a sketch of the population density in Genova[2] is depicted together with the POI[3] in Figure 5.18 and the PT nodes in Figure 5.19. Comparing these figures shows that there are populated areas characterised by the presence of POI that are not connected with the PT network.

The main input data are summarised in Table 5.8[4,5].

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[1] trasporto multimodale - in Italian, accessed in November 2022

[2] Neighbours and PoI's data in Genova - in Italian, accessed in September 2022

[3] Open Data Genova-Liguria Region - in Italian, accessed in November 2022

[4] Average costs of parking area in Italy - in Italian, accessed in September 2022

[5] Average CS costs in Italy- in Italian, accessed in September 2022

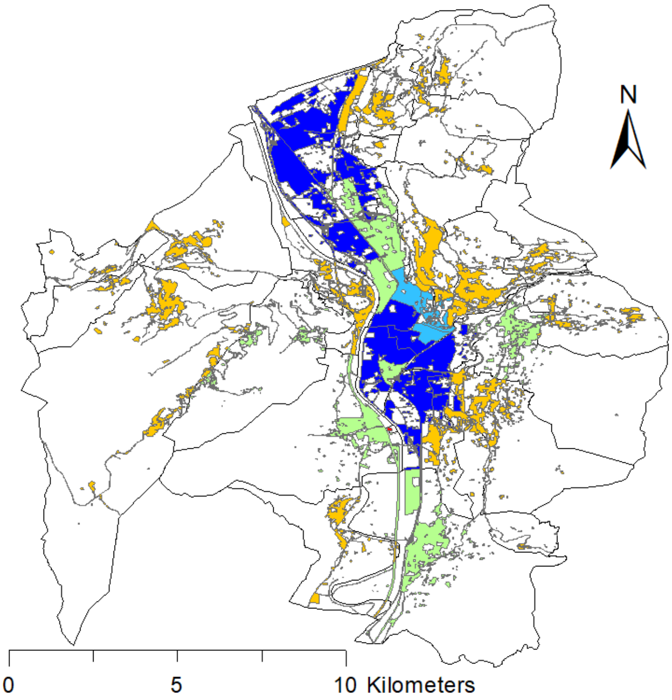

Figure 5.17: Distribution of the total values of CAI indexes during weekend days for all zones of Trento under Scenario B. Colour legend: 🟥 0; 🟧 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

Figure 5.18: Distribution of POI in the populated areas of different districts of Genova

Figure 5.19: Distribution of PT nodes in the populated areas of different districts of Genova

Table 5.8: Main input data for the Genova case study.

Parameter	**Value**
Type of CS service	two-way CS
$\lvert\mathcal{Z}\rvert$	42
$Q^{\max}$	40 and 60 in scenarios A and B, respectively
$\mathcal{T}$	21 hours of PT service during an entire day (17 hours during day time and 4 hours during night time)
Type of vehicles	Fiat Panda
T	Gaussian random variable with an expectation of 6 hours and a standard deviation of 2 hours (based on estimates for similar cities [78; 79; 80])
B	1000k€
β_0	0.01
ℓ	1
α_1	6.9k€
α_2	14k€

5.2.1 Mobility demand and CAI Values of Public Transport and Car Sharing depot candidates

The mobility demand of PT in this case study was estimated based on the distribution of the motorized trips within each zone of Genova as calculated from the Origin Destination matrix published by the municipality of Genonva[1]. In this context, mobility demand was estimated for peak and off-peak periods from the demand matrix such that the former is used during daytime and the latter

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[1] Open Data Genova-Liguria Region - in Italian, accessed in November 2022

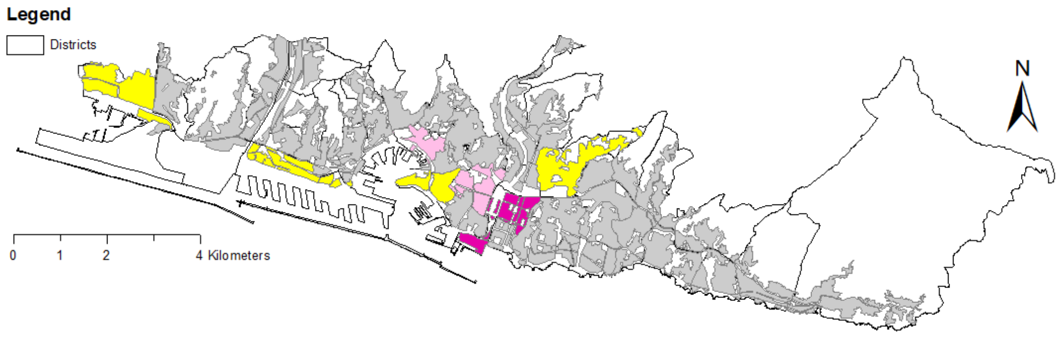

Figure 5.20: Distribution of the values of mobility demand during day time for all zones of Genova. Colour legend: ⬜ (0 – 1.5); 🟪 (1.5 – 3.0); 🟨 (3.0 – 4.5); 🟥 (> 4.5)

Figure 5.21: Distribution of the values of mobility demand during night time for all zones of Genova. Colour legend: ⬜ (0 – 1.5); 🟪 (1.5 – 3.0); 🟨 (3.0 – 4.5); 🟥 (> 4.5)

is used during night time, in the optimization model as presented in Figure 5.20 during day time and Figure 5.21 during night time. More in detail, this demand represents a potentiality of the different zones of Genova for the activation of CS service in the same zones. The relevant values are reported in Table 5.9 and Table 5.10, which are visualised in Figure 5.20 and Figure 5.21, for day times and night times, respectively.

The CAI indexes of PT were calculated for all zones by means of the model proposed in Section 4.2.1 of Chapter 4 of this thesis. The resulting values are visualized for both daytime and nighttime in the maps in Figure 5.22 and Figure 5.23, whereas the detailed values are reported in Table 5.9 and Table 5.10, respectively. By inspecting the two maps, it is possible to note that the city centre

Table 5.9: Results with $Q^{max} = 40$ during day time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.79	0.00	5.79	2.76	0	6
2	**CALCINARA**	**3.00**	**7.04**	**10.04**	**0.78**	**1**	**4**
3	**CERTOSA**	**12.35**	**5.87**	**18.22**	**1.32**	**1**	**3**
4	**CORNIGLIANO**	**3.31**	**26.78**	**30.09**	**0.99**	**4**	**4**
5	**CAMPI**	**1.75**	**16.79**	**18.54**	**0.30**	**3**	**4**
6	**CAMPASSO**	**0.89**	**16.56**	**17.45**	**0.71**	**2**	**2**
7	**S.GAETANO**	**3.09**	**14.47**	**17.55**	**0.39**	**2**	**2**
8	SAMPIERDARENA	5.91	0.00	5.91	1.93	0	3
9	**BELVEDERE**	**1.31**	**12.83**	**14.14**	**0.62**	**2**	**2**
10	**S.BARTOLOMEO**	**2.61**	**15.68**	**18.30**	**0.64**	**2**	**2**
11	**ANGELI**	**2.12**	**25.54**	**27.66**	**0.64**	**3**	**3**
12	**S.TEODORO**	**2.55**	**5.94**	**8.50**	**0.66**	**1**	**3**
13	LAGACCIO	2.18	0.00	2.18	0.90	0	2
14	PRE'	6.40	0.00	6.40	3.24	0	2
15	MADDALENA	5.84	0.00	5.84	1.27	0	2
16	MOLO	12.98	0.00	12.98	1.97	0	3
17	S.NICOLA	2.75	0.00	2.75	0.96	0	3
18	CASTELLETTO	2.38	0.00	2.38	1.26	0	4
19	MANIN	4.09	0.00	4.09	0.70	0	2
20	S.VINCENZO	9.32	0.00	9.32	3.13	0	3
21	**CARIGNANO**	**5.03**	**7.43**	**12.47**	**0.46**	**1**	**3**
22	FOCE	5.55	0.00	5.55	0.21	0	2
23	BRIGNOLE	8.61	0.00	8.61	4.86	0	3
24	**S.AGATA**	**4.05**	**15.05**	**19.11**	**1.25**	**2**	**2**
25	**S.FRUTTUOSO**	**2.09**	**6.15**	**8.24**	**1.81**	**1**	**6**
26	FEREGGIANO	2.47	0.00	2.47	0.50	0	2
27	**MARASSI**	**4.68**	**7.29**	**11.97**	**0.82**	**1**	**2**
28	FORTE QUEZZI	2.09	0.00	2.09	0.40	0	2
29	PARENZO	3.21	0.00	3.21	0.84	0	3
30	**BORGORATTI**	**2.64**	**7.00**	**9.64**	**0.35**	**1**	**3**
31	**CHIAPPETO**	**1.94**	**5.90**	**7.84**	**0.70**	**1**	**2**
32	S.MARTINO	5.36	0.00	5.36	1.07	0	5
33	**ALBARO**	**4.27**	**32.79**	**37.06**	**1.09**	**4**	**4**
34	S.GIULIANO	4.14	0.00	4.14	0.38	0	3
35	**LIDO**	**5.04**	**7.76**	**12.79**	**0.24**	**1**	**3**
36	**PUGGIA**	**3.57**	**19.66**	**23.23**	**0.29**	**3**	**3**
37	**STURLA**	**4.53**	**7.19**	**11.72**	**0.58**	**1**	**4**
38	QUARTO	4.25	0.00	4.25	0.29	0	4
39	QUARTARA	4.61	0.00	4.61	0.90	0	3
40	**CASTAGNA**	**0.34**	**19.49**	**19.83**	**0.52**	**3**	**3**
41	QUINTO	3.26	0.00	3.26	0.24	0	3
42	NERVI	7.02	0.00	7.02	0.32	0	6
	Minimum CAI value	–	***5.87***	***7.84***			
	Average CAI value	***4.27***	***6.74***	***11.01***			

and some zones on the east side of the city are characterised by the highest values in both considered time periods. During the daytime, good levels of CAI_{PT} (i.e., values between 2.5 and 5) are available in a wide area around the city, but the performance worsens significantly during night time. More in detail, the zones with the availability of metro service are characterised by the highest values of

Table 5.10: Results with $Q^{max} = 40$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	D_z^{t2}	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.64	0.00	5.64	1.88	0	6
2	**CALCINARA**	**3.75**	**5.15**	**8.90**	**0.22**	**1**	**4**
3	**CERTOSA**	**0.00**	**3.94**	**3.94**	**0.30**	**1**	**3**
4	**CORNIGLIANO**	**3.78**	**18.81**	**22.59**	**0.34**	**4**	**4**
5	**CAMPI**	**2.35**	**11.87**	**14.22**	**0.05**	**3**	**4**
6	**CAMPASSO**	**0.00**	**12.59**	**12.59**	**0.21**	**2**	**2**
7	**S.GAETANO**	**0.00**	**11.48**	**11.48**	**0.34**	**2**	**2**
8	SAMPIERDARENA	5.33	0.00	5.33	1.03	0	3
9	**BELVEDERE**	**1.17**	**9.31**	**10.48**	**0.21**	**2**	**2**
10	**S.BARTOLOMEO**	**1.40**	**12.37**	**13.77**	**0.32**	**2**	**2**
11	**ANGELI**	**1.52**	**19.87**	**21.39**	**0.24**	**3**	**3**
12	**S.TEODORO**	**2.57**	**4.19**	**6.76**	**0.46**	**1**	**3**
13	LAGACCIO	1.35	0.00	1.35	0.24	0	2
14	PRE’	4.27	0.00	4.27	1.36	0	2
15	MADDALENA	8.42	0.00	8.42	0.91	0	2
16	MOLO	3.62	0.00	3.62	1.35	0	3
17	S.NICOLA	2.10	0.00	2.10	0.09	0	3
18	CASTELLETTO	2.77	0.00	2.77	0.40	0	4
19	MANIN	3.14	0.00	3.14	0.43	0	2
20	S.VINCENZO	5.71	0.00	5.71	3.40	0	3
21	**CARIGNANO**	**3.67**	**5.76**	**9.43**	**0.65**	**1**	**3**
22	FOCE	4.38	0.00	4.38	0.18	0	2
23	BRIGNOLE	7.21	0.00	7.21	1.21	0	3
24	**S.AGATA**	**3.01**	**11.28**	**14.30**	**0.34**	**2**	**2**
25	**S.FRUTTUOSO**	**1.47**	**4.17**	**5.64**	**0.49**	**1**	**6**
26	FEREGGIANO	1.84	0.00	1.84	0.07	0	2
27	**MARASSI**	**3.25**	**5.33**	**8.58**	**0.35**	**1**	**2**
28	FORTE QUEZZI	1.57	0.00	1.57	0.08	0	2
29	PARENZO	2.89	0.00	2.89	0.21	0	3
30	**BORGORATTI**	**2.56**	**5.46**	**8.02**	**0.19**	**1**	**3**
31	**CHIAPPETO**	**3.24**	**3.66**	**6.90**	**0.02**	**1**	**2**
32	S.MARTINO	5.16	0.00	5.16	1.23	0	5
33	**ALBARO**	**3.74**	**24.99**	**28.73**	**0.40**	**4**	**4**
34	S.GIULIANO	3.97	0.00	3.97	0.12	0	3
35	**LIDO**	**5.62**	**6.44**	**12.06**	**0.10**	**1**	**3**
36	**PUGGIA**	**2.19**	**14.76**	**16.95**	**0.02**	**3**	**3**
37	**STURLA**	**4.85**	**5.47**	**10.32**	**0.30**	**1**	**4**
38	QUARTO	7.41	0.00	7.41	0.37	0	4
39	QUARTARA	6.43	0.00	6.43	0.00	0	3
40	**CASTAGNA**	**0.41**	**14.65**	**15.06**	**0.26**	**3**	**3**
41	QUINTO	8.29	0.00	8.29	0.18	0	3
42	NERVI	5.23	0.00	5.23	0.20	0	6
	Minimum CAI value	–	***3.66***	***3.94***			
	Average CAI value	***3.51***	***5.04***	***8.54***			

CAI due to the high connecting powers offered by the metro (since the capacity of the metro is very high as compared to bus lines) service as evident from Table 5.9 and Table 5.10, during daytime and night time, respectively. More specifically, examining the entries in the tables shows that some zones are characterised by small CAI_{PT} values (i.e., zones 5, 6, 9, 31, and 40 during daytime and zones 3,

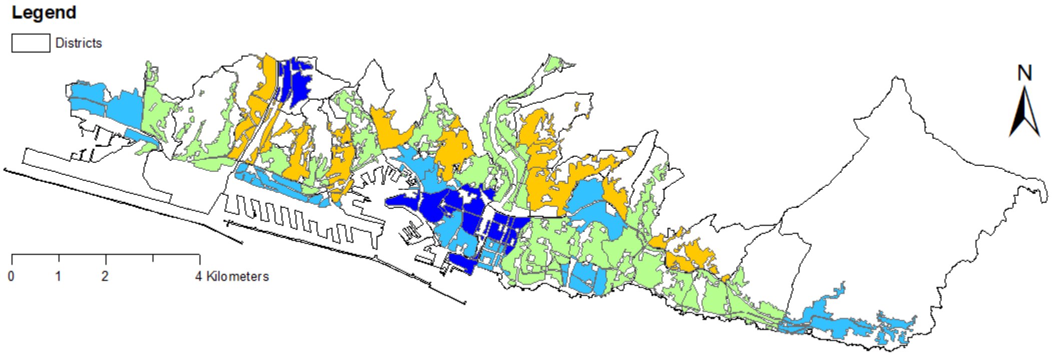

Figure 5.22: Distribution of the values of CAI indexes of PT during day time for all zones of Genova. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

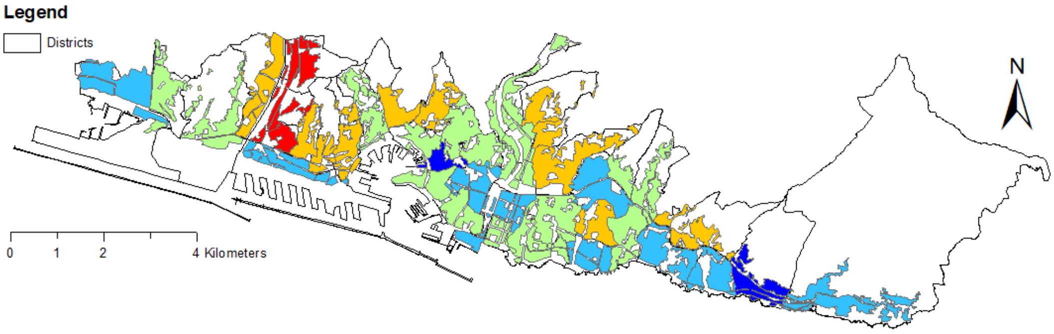

Figure 5.23: Distribution of the values of CAI indexes of PT during night time for all zones of Genova. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

6, 7, 9, 10, 11, 13, 25, 26, 28, and 40 during night time). In addition, some zones have null PT CAI values (i.e., zones 3, 6, 7 during nighttime). It is interesting to note that, CAI values for zone 3 are the highest among all the zones during the daytime because of the availability of metro service, but CAI during night time is the lowest due to the unavailability of metro service as represented by Table 5.10. Consequently, such zones serve as major hot spots where the population could be better connected through the provision of a CS system during each considered time period.

Regarding the CS depot candidates, a proximity clustering algorithm[1] was

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[1] ArcGIS Documentation: Proximity analysis - accessed in September 2022

Figure 5.24: Distribution of candidate CS depots with respect to the populated areas of Genova

applied to determine their locations by means of the ArcGIS tool. The CS depot candidates are visualised in Figure 5.24. In addition, similar to the Trento case the accessibility and connectivity values for all the candidate depots were calculated by means of the model proposed in Section 4.2.2 of Chapter 4 of this thesis, considering all possible different operating conditions in the optimisation problem, i.e., for all possible numbers of vehicles assigned to them. For the sake of compactness, only the accessibility values of the depots are reported in Table (5.11) and Table (5.12).

5.2.2 Results and discussion

In this section, the results provided by the proposed approach are presented and discussed for two different scenarios in a similar way as compared to the case study of Trento:

A – the total number of CS vehicles is limited to $Q^{\max} = 40$: this case study is designed to test the distribution of limited resources. This value is estimated based on the size of Genvoa[1][2] (similar to the case study of Trento);

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[1] Resident Population and households as of 2022, Istat - in Italian, accessed in November 2022

[2] Superficie di Comuni Province e Regioni italiane al 9 ottobre 2011 - in Italian, accessed in November 2022

Table 5.11: Values of the accessibility index for all candidate depots $k \in \mathcal{C}_z$, $\forall z = 1 \dots 21$ for Genova. Highlights: Grey refers to both scenarios A and B; orange refers to scenario A only; blue refers to scenario B only; yellow refers to scenario A with additional vehicles in scenario B

(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$
(1,1)	4.324963	(13,4)	2.595093	(7,9)	1.569203	(8,13)	0.822145	(3,18)	2.386592
(2,1)	3.800167	(14,4)	2.33563	(8,9)	3.077573	(9,13)	1.062544	(4,18)	0.465762
(3,1)	4.835996	(15,4)	2.337174	(9,9)	3.268414	(10,13)	0.674595	(5,18)	0.963816
(4,1)	4.34861	(16,4)	2.608219	(1,10)	5.842226	(1,14)	3.872769	(6,18)	1.178656
(5,1)	3.221056	(17,4)	1.122211	(2,10)	5.673832	(2,14)	0.895465	(7,18)	1.535937
(6,1)	2.251879	(18,4)	2.162875	(3,10)	3.286929	(3,14)	2.164553	(8,18)	0.94755
(7,1)	3.7728	(1,5)	3.394618	(4,10)	2.049286	(4,14)	2.474823	(9,18)	0.729551
(8,1)	3.295579	(2,5)	3.289659	(5,10)	1.844287	(5,14)	2.146591	(10,18)	0.658736
(9,1)	4.336931	(3,5)	3.617457	(6,10)	3.199462	(6,14)	2.723148	(11,18)	1.369799
(10,1)	2.678199	(4,5)	4.229777	(1,11)	4.755002	(7,14)	3.105052	(12,18)	1.332126
(11,1)	3.477751	(5,5)	3.547259	(2,11)	4.756013	(1,15)	4.603892	(1,19)	1.547572
(1,2)	2.089427	(6,5)	2.126178	(3,11)	2.996082	(2,15)	4.205897	(2,19)	2.422576
(2,2)	2.951986	(7,5)	2.131596	(4,11)	5.143322	(3,15)	3.438743	(3,19)	1.440384
(3,2)	4.79817	(8,5)	2.545719	(5,11)	3.933859	(4,15)	4.240453	(4,19)	2.405838
(4,2)	1.072059	(9,5)	1.627009	(6,11)	6.05126	(5,15)	1.484319	(5,19)	2.767653
(5,2)	0.93588	(10,5)	1.628183	(7,11)	3.936657	(1,16)	3.990965	(6,19)	2.534281
(6,2)	2.202843	(11,5)	1.103994	(8,11)	3.222794	(2,16)	3.522585	(7,19)	0.205412
(7,2)	1.244976	(1,6)	6.18112	(9,11)	7.392055	(3,16)	3.326838	(8,19)	0.405807
(1,3)	2.924224	(2,6)	5.709978	(10,11)	3.307152	(4,16)	4.608709	(9,19)	0.206662
(2,3)	1.482836	(3,6)	4.950121	(11,11)	2.990075	(5,16)	2.762615	(1,20)	4.89784
(3,3)	3.511726	(4,6)	4.491291	(1,12)	3.711414	(6,16)	0.870363	(2,20)	5.360001
(4,3)	0.732511	(5,6)	5.308362	(2,12)	1.503361	(7,16)	1.974797	(3,20)	3.836573
(5,3)	2.62051	(1,7)	6.564942	(3,12)	3.424899	(8,16)	4.214818	(4,20)	5.139788
(6,3)	1.185001	(2,7)	4.009916	(4,12)	2.965747	(9,16)	5.016483	(5,20)	4.66781
(7,3)	0.548147	(3,7)	3.346047	(5,12)	3.168969	(1,17)	1.847417	(6,20)	4.543698
(8,3)	0.672113	(4,7)	3.841229	(6,12)	1.800343	(2,17)	1.99341	(7,20)	4.490008
(9,3)	0.385635	(1,8)	2.205652	(7,12)	2.219696	(3,17)	1.760249	(8,20)	4.326751
(10,3)	0.341168	(2,8)	4.650417	(8,12)	2.734478	(4,17)	1.048304	(1,21)	1.041937
(1,4)	2.674826	(3,8)	4.139313	(9,12)	2.661056	(5,17)	2.311629	(2,21)	3.301193
(2,4)	4.254726	(4,8)	3.433918	(10,12)	1.98628	(6,17)	1.352479	(3,21)	2.559774
(3,4)	3.620045	(5,8)	4.806465	(11,12)	1.976919	(7,17)	0.927348	(4,21)	3.261263
(4,4)	3.467681	(6,8)	1.745383	(12,12)	1.145827	(8,17)	1.381604	(5,21)	2.211679
(5,4)	2.218779	(7,8)	2.882726	(13,12)	2.817645	(9,17)	1.599172	(6,21)	1.28541
(6,4)	2.724016	(8,8)	3.622824	(1,13)	0.693064	(10,17)	1.282695	(7,21)	4.249317
(7,4)	4.449187	(1,9)	3.791751	(2,13)	1.054263	(11,17)	0.987842	(8,21)	5.222989
(8,4)	4.391164	(2,9)	4.77176	(3,13)	2.078639	(12,17)	1.810491	(9,21)	4.791513
(9,4)	2.343974	(3,9)	2.968362	(4,13)	1.156208	(13,17)	2.116107	—	—
(10,4)	3.947373	(4,9)	2.236924	(5,13)	1.025633	(14,17)	0.829312	—	—
(11,4)	1.838414	(5,9)	1.472814	(6,13)	1.108948	(1,18)	0.750816	—	—
(12,4)	2.228103	(6,9)	2.463702	(7,13)	1.261658	(2,18)	2.744728	—	—

B – the total number of CS vehicles is limited to $Q^{\max} = 60$, which is a reasonable approximation of a scenario in which $Q^{\max}$ is unlimited: this case study is designed to test the effect of budget limitations (similar to the case study of Trento).

Concerning the time frame reference, as opposed to the Trento case study the

Table 5.12: Values of the accessibility index for all candidate depots $k \in \mathcal{C}_z$, $\forall z = 22 \dots 42$ for Genova. Highlights: Grey refers to both scenarios A and B under $\ell = 1$; blue refers to scenario B only; orange refers to scenario A only; yellow refers to scenario A with additional vehicles in scenario B

(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$	(k,z)	$a_{k,z}$
(1,22)	3.126239	(1,26)	1.727546	(9,30)	2.471585	(4,34)	4.703096	(7,38)	3.478976
(2,22)	3.703827	(2,26)	1.766957	(1,31)	2.081823	(5,34)	2.534972	(8,38)	1.944821
(3,22)	4.56643	(3,26)	2.072835	(2,31)	3.04828	(6,34)	4.355268	(9,38)	2.962316
(4,22)	5.203502	(4,26)	3.084453	(3,31)	2.146471	(7,34)	3.670888	(1,39)	2.449883
(1,23)	1.342266	(5,26)	1.428549	(4,31)	3.591794	(8,34)	2.185965	(2,39)	2.27221
(2,23)	1.43401	(1,27)	4.09447	(1,32)	3.541774	(9,34)	3.846953	(3,39)	2.613876
(3,23)	1.14328	(2,27)	2.625317	(2,32)	1.574244	(10,34)	2.593154	(4,39)	3.09645
(4,23)	2.116876	(3,27)	2.746999	(3,32)	4.062321	(1,35)	3.003988	(5,39)	2.179831
(5,23)	5.572757	(4,27)	4.327843	(4,32)	4.134508	(2,35)	3.190984	(6,39)	2.424405
(6,23)	5.535992	(5,27)	4.879069	(5,32)	2.252055	(3,35)	5.179045	(1,40)	3.398418
(7,23)	5.594602	(6,27)	2.550327	(6,32)	5.324074	(4,35)	4.87608	(2,40)	4.495255
(8,23)	4.389588	(7,27)	4.27773	(7,32)	3.238188	(5,35)	5.030144	(3,40)	3.630551
(9,23)	5.102525	(1,28)	1.182763	(8,32)	2.97345	(6,35)	5.542682	(4,40)	3.847864
(10,23)	6.616812	(2,28)	0.932267	(9,32)	3.064097	(7,35)	6.152242	(5,40)	5.110697
(11,23)	5.216237	(3,28)	1.332268	(10,32)	4.178869	(1,36)	5.531503	(6,40)	2.028661
(12,23)	4.425626	(4,28)	0.611367	(11,32)	2.279929	(2,36)	3.237419	(7,40)	1.927488
(1,24)	4.802719	(5,28)	0.432896	(12,32)	2.014756	(3,36)	2.799902	(8,40)	2.295191
(2,24)	4.210445	(6,28)	1.420191	(13,32)	3.057026	(4,36)	4.52688	(9,40)	1.455707
(3,24)	5.555696	(7,28)	0.633118	(1,33)	4.276215	(5,36)	2.401263	(10,40)	2.151743
(4,24)	1.818348	(8,28)	1.447979	(2,33)	5.890252	(6,36)	3.609151	(1,41)	0.697131
(5,24)	2.116472	(9,28)	1.07874	(3,33)	2.376704	(7,36)	3.381795	(2,41)	1.491236
(6,24)	3.215431	(10,28)	0.356594	(4,33)	5.452328	(8,36)	4.429849	(3,41)	0.840912
(1,25)	3.69419	(11,28)	1.447084	(5,33)	5.22791	(9,36)	2.654328	(4,41)	0.569134
(2,25)	2.739355	(1,29)	1.698993	(6,33)	3.774792	(10,36)	3.943767	(5,41)	0.221756
(3,25)	2.329916	(2,29)	3.501682	(7,33)	6.113937	(1,37)	3.996057	(1,42)	4.130897
(4,25)	0.994367	(3,29)	3.295828	(8,33)	4.41881	(2,37)	4.802503	(2,42)	3.920835
(5,25)	1.267405	(4,29)	2.536791	(9,33)	5.166833	(3,37)	5.065616	(3,42)	3.61149
(6,25)	1.475584	(5,29)	2.459298	(10,33)	5.503025	(4,37)	3.950648	(4,42)	2.482049
(7,25)	0.95857	(6,29)	2.319457	(11,33)	5.751583	(5,37)	2.551721	(5,42)	3.76778
(8,25)	0.288526	(7,29)	2.235695	(12,33)	4.154226	(6,37)	2.853537	(6,42)	3.654217
(9,25)	0.434338	(8,29)	1.406821	(13,33)	2.916516	(7,37)	4.778639	(7,42)	5.244152
(10,25)	1.921967	(1,30)	5.094981	(14,33)	5.009784	(8,37)	4.831337	(8,42)	5.248477
(11,25)	0.811969	(2,30)	1.901965	(15,33)	5.368599	(9,37)	4.943704	(9,42)	3.723014
(12,25)	0.630943	(3,30)	3.387154	(16,33)	5.411863	(1,38)	0.832707	(10,42)	3.048852
(13,25)	0.576626	(4,30)	2.387287	(17,33)	4.733232	(2,38)	2.329616	(11,42)	3.943306
(14,25)	0.681157	(5,30)	3.312432	(18,33)	2.95622	(3,38)	1.809452	(12,42)	5.447481
(15,25)	0.221548	(6,30)	2.261049	(1,34)	2.54934	(4,38)	0.11988	(13,42)	4.27754
(16,25)	2.03781	(7,30)	2.811627	(2,34)	4.378725	(5,38)	2.177886	(14,42)	3.12495
(17,25)	0.516906	(8,30)	2.900606	(3,34)	3.70034	(6,38)	2.932363	(15,42)	2.758287

optimisation problem in Section 4.2.3 of Chapter 4 considers a total of 21 hours of PT service during an entire day. Therefore, daytime has greater weight than night times, as the former is comprised of 17 hours and the latter is comprised of 4 hours of PT service.

Finally, the problem solution was implemented via the IBM CPLEX solver, and the optimisation run was performed by means of a PC with an Intel i7 -

1.80 GHz processor and 8 GB RAM. As compared to the Trento case study, the solution time in the case of Genova is around 60-90 minutes for all tested configurations because of the involvement of bigger data sets. However, the optimisation run was seen to be reduced by using a PC with better processing powers.

5.2.2.1 Scenario A

Let us first consider the results reported in Table 5.9 and Table 5.10, during daytime and nighttime, respectively, both are relevant to a case study setup characterised by a maximum number of CS vehicles $Q^{\max} = 40$. This table provides, in the last two rows, the minimum and the average values of the CAI before optimisation (i.e., CAI_{PT}) and after optimisation (i.e., CAI_{TOT}) and of the contribution provided by CS (i.e., CAI_{CS}). It is possible to note that the minima vary during day time (Table 5.9) and nighttime (Table 5.9) from 0.34 to 5.87 and 0 to 3.66, respectively, whereas the averages vary from 4.27 to 11.01 (+158%) and from 3.51 to 8.54 (+144%), respectively. The highest change in the minima values is due to the accessibility and relevant mobility demand values of the zones in which the CS service is being activated. The improvements in the average values are the result of a compromise between assigning resources to zones with low/null CAI_{PT} and assigning resources to zones characterised by high accessibility and connectivity potentialities. The zones with low/null CAI_{PT} are privileged, in the resource assignment, by the considered definition of the weighting coefficients (4.11) and by constraints (4.15) (as described in Section 4.2.3.2 in Chapter 4 of this thesis) even if they are characterised by limited accessibility and connectivity potentialities (i.e., resulting in $CAI_{CS,z} < 5$ only in Table 5.10 during night time).

If the performance assessment is restricted to zones characterised by $CAI^{t}_{PT,z} < 5$, the improvements are +311% and +235% during daytime and nighttime, respectively. Such a result shows the effectiveness of the proposed approach in terms of balancing equitable resource distribution and the global aim of improving the whole connectivity and accessibility of PT in any considered case study (since similar results were obtained in the case study of Trento). By looking at the values of the percentage increase, it is evident that the solution provides a significant improvement for the whole region and a very large improvement for

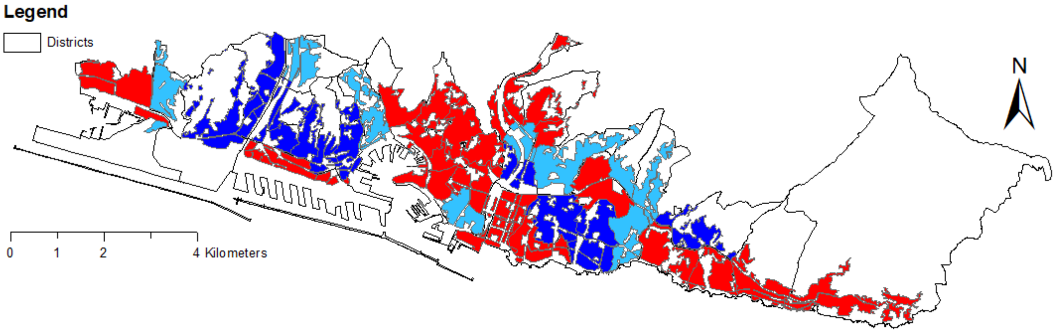

Figure 5.25: Distribution of the values of CAI indexes of CS during day time for all zones of Genova under Scenario A. Colour legend: 🟥 0; 🟧 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

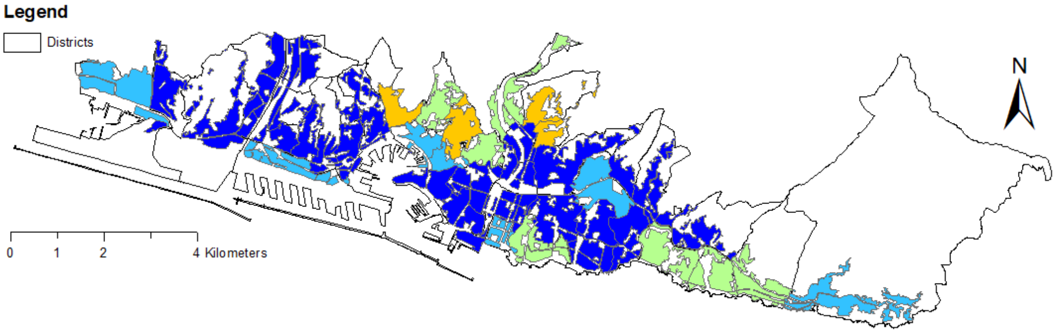

Figure 5.26: Distribution of the total values of CAI indexes during daytime for all zones of Genova under Scenario A. Colour legend: 🟥 0; 🟧 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

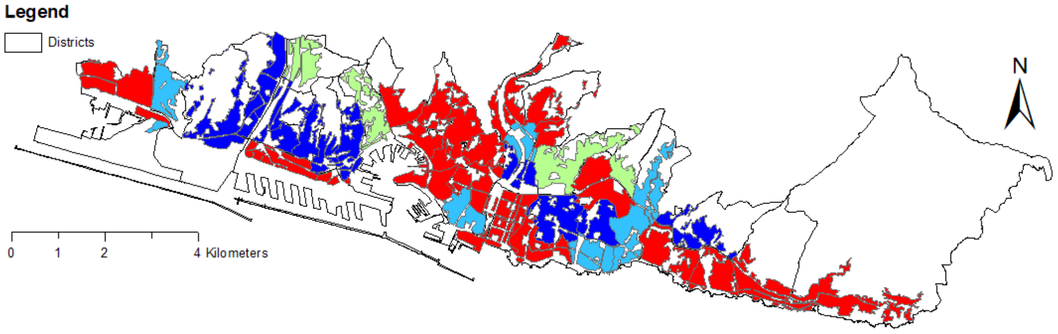

Figure 5.27: Distribution of the values of CAI indexes of CS during night times for all zones of Genova under Scenario A. Colour legend: 🟥 0; 🟧 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

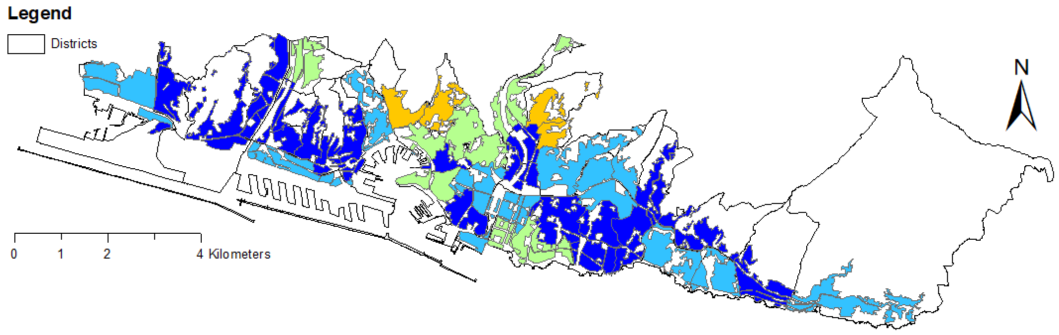

Figure 5.28: Distribution of the total values of CAI indexes during night time for all zones of Genova under Scenario A. Colour legend: 🟥 0; 🟧 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

disadvantaged zones.

As depicted in Figure 5.29 and Figure 5.30 during daytime and night time, respectively, the CS depots activated in this scenario are distributed in the most districts of the city. Like the case of Trento, the majority of the activated depots (indicated by the black dots) are located in the zones with $CAI_{PT} < 5$ in both time periods. In contrast, two depots are located in zones with $CAI_{PT} \geq 5$ (zone 21 and 35), which are characterised by high demand in both time periods (see Table 5.9 and Table 5.10, during day time and night time, respectively) and very high values of the accessibility index (see Table 5.11 and Table 5.12). More in detail, the activation of CS depot in Zone 3 (since the value of $CAI_{PT} > 10$ during day time) is due to the null CAI value of this zone during night time as evident from entries of Table 5.10, therefore optimization models activated CS depots in Zone 3 thanks to constraint (4.15) (as described in Section 4.2.3.2 in Chapter 4).

To evaluate the effects of the proposed approach in the whole considered area, consider again the CAI maps reported in Figure 5.25 and Figure 5.27 for the two considered time periods. In such maps, which provide contributions to CAI_{TOT} values provided by CS, it is possible to note that not all activated CS depots provide the highest possible values of CAI_{CS} (indicated in blue) due to differences not only in the number of assigned vehicles but also in the accessibility indexes.

In addition, by comparing such maps with those depicted in Figure 5.22 and

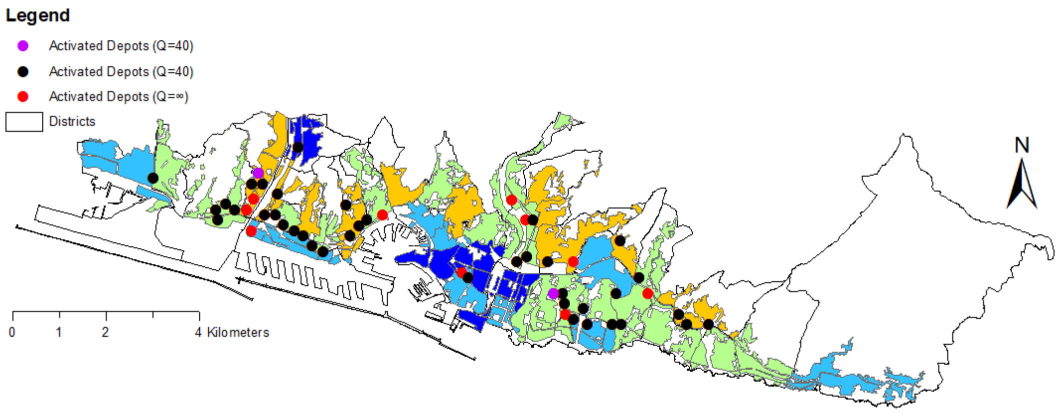

Figure 5.29: Distribution of activated CS depots in only scenario A (black and purple dots) and scenario B (black and red dots) compared with the CAI_{PT} during day time for Genova. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5).

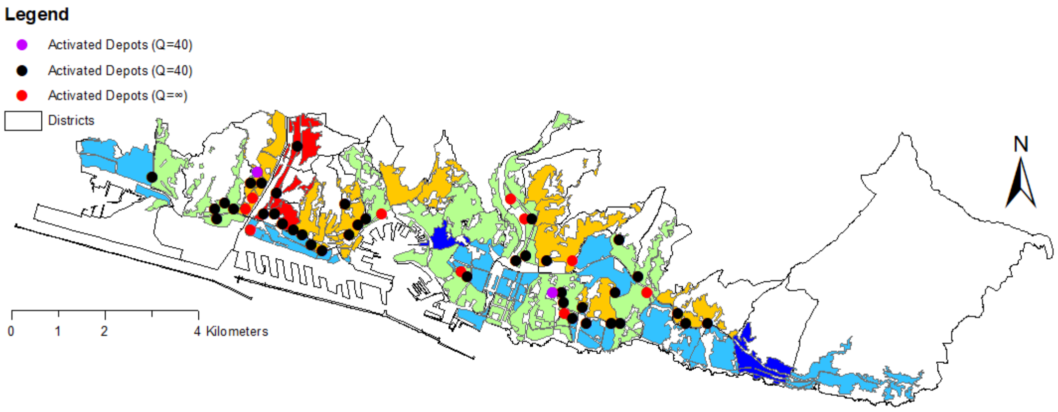

Figure 5.30: Distribution of activated CS depots in only scenario A (black and purple dots) and scenario B (black and red dots) compared with the CAI_{PT} during night time for Genova. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5).

Figure 5.23, it is possible to note that in all cases, the resources are assigned to zones characterised by CAI_{PT} values between 0 and 5, with the exceptions of central zone 21 and 35, which are already characterised by $CAI_{PT} \geq 5$.

A more detailed analysis of the results can be performed by considering the figures reported in Table 5.9 and Table 5.10, during daytime and nighttime, respectively, where the different entries reveal that similar to the case of Trento, the optimisation approach places the maximum vehicles and activates the CS service in the zones that are characterised by the lowest values of CAI_{PT} for PT or high demand and accessibility indexes. More specifically, the service is activated in zones 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 21, 24, 25, 27, 30, 31, 33, 35, 36, 37, and 40 during both daytime and night time.

In addition, according to constraints (4.15) (Section 4.2.3.2 in Chapter 4 of this thesis), at least one vehicle is assigned to all zones characterised by null CAI_{PT} during night time (zones 3, 6 and 7) since no zone is characterized by null CAI_{PT} during day time. Nevertheless, it is interesting to note that, only a single vehicle is assigned to Zone 3, which is due to the low values of demand during night time (Table 5.10) and very high value of CAI_{PT} during the day time for this zone. Consequently, it is not convenient to assign more than one vehicle to Zone 3 since the value of CAI_{PT} is already too high during the daytime. In contrast, it is convenient to assign more than one vehicle to zones 6, and 7 with the null value of CAI_{PT} during nighttime and very low values of CAI_{PT} during the daytime as well when compared with zone 3. In these cases, it is interesting to note in Table 5.11 and Table 5.12, that vehicles are assigned to different depots.

Regarding the effect of constraints (4.15) (Section 4.2.3.2 in Chapter 4), it is possible to note in Table 5.9 and Table 5.10, during day time and night time, respectively that the zones characterised by null CAI_{PT} during night time (i.e., zones 3, 6, and 7) are assigned a CS depot with vehicles according to the limitation determined by $Q_z^{\max}$, i.e., by the relevant population density.

The results of this scenario were achieved by utilising a budget of 836k€ to activate a total of 40 depots along with the placement of all 40 vehicles. In other words, the upper bound of the performance is determined by the chosen number of vehicles.

5.2.2.2 Scenario B

Similar to the case study of Trento, in scenario A, not all of the budget was invested in resources. Therefore, to investigate the effectiveness of the proposed approach, it is tested with $Q^{max} = 60$ (corresponding, in the considered case study, to the simulation of a scenario in which Q^{max} is unlimited) to check the

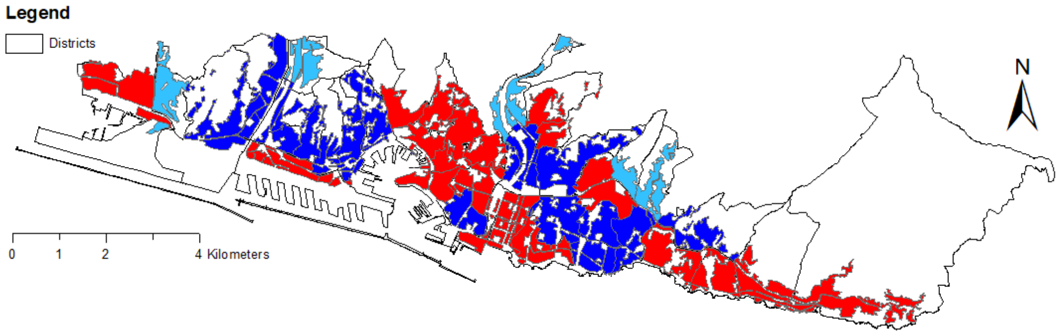

Figure 5.31: Distribution of the values of CAI indexes of CS during day time for all zones of Genova under Scenario B. Colour legend: 🟥 0; 🟧 $(0 - 2.5)$; 🟩 $(2.5 - 5.0)$; 🟦 $(5.0 - 7.5)$; 🟦 (> 7.5)

solution that exploits the entire budget.

A general view of the results of this scenario is depicted in Figure 5.29 and Figure 5.30 during daytime and nighttime, respectively, where the red dots indicate the additionally activated depots with respect to scenario A (in black). In these maps, which depict the two considered time periods, the 9 additional depot activation are concentrated in the city centres in scenario B and, as indicated in Table 5.13 and Table 5.14, during day time and night time, respectively, in the zones characterised by high accessibility and connectivity values resulting in $CAI_{CS,z} > 5$.

Regarding the minimum and average values, the results reported in the last row of Table 5.13 and Table 5.14, during day time and night time, respectively show the same values of the minima in scenario A, whereas the averages of CAI_{TOT} increased by an additional +10% (from 11.01 to 12.09) and an additional +8% (from 8.54 to 9.26) during day time and night time, respectively. By comparison, the increase in budget usage is +19% (like the case of Trento).

If the performance assessment is restricted to zones that were characterised by $CAI^t_{PT,z} < 5$, the improvement turns out to be +357% and +265%, compared with +311% and +235% in scenario A during daytime and nighttime, respectively. The improvement compared with scenario A is due to the placement of 8 additional vehicles in the depots with medium-low CAI values (i.e., depots 1, 2 in zone 5, depot 3 in zone 12, depot 9 in zone 21, depots 1,2 in zone 25, depot

Table 5.13: Results with $Q^{max} = 50$ during daytime for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.79	–	5.79	2.76	0	6
2	**CALCINARA**	**3.00**	**7.04**	**10.04**	**0.78**	**1**	**4**
3	**CERTOSA**	**12.35**	**5.87**	**18.22**	**1.32**	**1**	**3**
4	**CORNIGLIANO**	**3.31**	**26.78**	**30.09**	**0.99**	**4**	**4**
5	**CAMPI**	**1.75**	**21.72**	**23.73**	**0.30**	**4**	**4**
6	**CAMPASSO**	**0.89**	**16.56**	**17.45**	**0.71**	**2**	**2**
7	**S.GAETANO**	**3.09**	**14.47**	**17.55**	**0.39**	**2**	**2**
8	SAMPIERDARENA	5.91	–	5.91	1.93	0	3
9	**BELVEDERE**	**1.31**	**12.83**	**14.14**	**0.62**	**2**	**2**
10	**S.BARTOLOMEO**	**2.61**	**15.68**	**18.30**	**0.64**	**2**	**2**
11	**ANGELI**	**2.12**	**25.54**	**27.66**	**0.64**	**3**	**3**
12	**S.TEODORO**	**2.55**	**11.60**	**14.15**	**0.66**	**2**	**3**
13	LAGACCIO	2.18	–	2.18	0.90	0	2
14	PRE'	6.40	–	6.40	3.24	0	2
15	MADDALENA	5.84	–	5.84	1.27	0	2
16	MOLO	12.98	–	12.98	1.97	0	3
17	S.NICOLA	2.75	–	2.75	0.96	0	3
18	CASTELLETTO	2.38	–	2.38	1.26	0	4
19	MANIN	4.09	–	4.09	0.70	0	2
20	S.VINCENZO	9.32	–	9.32	3.13	0	3
21	**CARIGNANO**	**5.03**	**14.43**	**12.47**	**0.46**	**2**	**3**
22	FOCE	5.55	–	5.55	0.21	0	2
23	BRIGNOLE	8.61	–	8.61	4.86	0	3
24	**S.AGATA**	**4.05**	**15.05**	**19.11**	**1.25**	**2**	**2**
25	**S.FRUTTUOSO**	**2.09**	**13.97**	**10.87**	**1.81**	**3**	**6**
26	FEREGGIANO	2.47	–	2.47	0.50	0	2
27	**MARASSI**	**4.68**	**14.02**	**18.70**	**0.82**	**2**	**2**
28	FORTE QUEZZI	2.09	–	2.09	0.40	0	2
29	**PARENZO**	**3.21**	**5.83**	**3.21**	**0.84**	**1**	**3**
30	**BORGORATTI**	**2.64**	**7.00**	**9.64**	**0.35**	**1**	**3**
31	**CHIAPPETO**	**1.94**	**5.90**	**13.21**	**0.70**	**1**	**2**
32	**S.MARTINO**	**5.36**	**–**	**13.27**	**1.07**	**0**	**5**
33	**ALBARO**	**4.27**	**32.74**	**37.06**	**1.09**	**4**	**4**
34	S.GIULIANO	4.14	–	4.14	0.38	0	3
35	**LIDO**	**5.04**	**7.76**	**12.79**	**0.24**	**1**	**3**
36	**PUGGIA**	**3.57**	**19.65**	**23.23**	**0.29**	**3**	**3**
37	**STURLA**	**4.53**	**14.27**	**25.72**	**0.58**	**2**	**4**
38	QUARTO	4.25	–	4.25	0.29	0	4
39	QUARTARA	4.61	–	4.61	0.90	0	3
40	**CASTAGNA**	**0.34**	**19.49**	**19.83**	**0.52**	**3**	**3**
41	QUINTO	3.26	–	3.26	0.24	0	3
42	NERVI	7.02	–	7.02	0.32	0	6
	Minimum CAI value	*–*	***5.87***	***7.84***			
	Average CAI value	***4.27***	***7.82***	***12.09***			

4 in zone 27, depot 2 in zone 29, depot 4 in zone 33 and depots 9 in zone 37), as shown in Table 5.11 and Table 5.12. This result shows the capability of the model to privilege zones with low $CAI_{PT,z}$ if the relevant potentialities in terms of demand and accessibility are high, as it is possible to verify in Table 5.13 and Table 5.14, during day time and night time, respectively as well as in Table 5.11

Table 5.14: Results with $Q^{max} = 50$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	D_z^{t2}	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.64	–	5.64	1.88	0	6
2	**CALCINARA**	**3.75**	**5.15**	**8.90**	**0.22**	**1**	**4**
3	**CERTOSA**	**0.00**	**3.94**	**3.94**	**0.30**	**1**	**3**
4	**CORNIGLIANO**	**3.78**	**18.80**	**22.59**	**0.34**	**4**	**4**
5	**CAMPI**	**2.35**	**15.17**	**17.78**	**0.05**	**4**	**4**
6	**CAMPASSO**	**0.00**	**12.59**	**12.59**	**0.21**	**2**	**2**
7	**S.GAETANO**	**0.00**	**11.48**	**11.48**	**0.34**	**2**	**2**
8	SAMPIERDARENA	5.33	–	5.33	1.03	0	3
9	**BELVEDERE**	**1.17**	**9.31**	**10.48**	**0.21**	**2**	**2**
10	**S.BARTOLOMEO**	**1.40**	**12.37**	**13.77**	**0.32**	**2**	**2**
11	**ANGELI**	**1.52**	**19.87**	**21.38**	**0.24**	**3**	**3**
12	**S.TEODORO**	**2.57**	**8.09**	**10.66**	**0.46**	**2**	**3**
13	LAGACCIO	1.35	–	1.35	0.24	0	2
14	PRE’	4.27	–	4.27	1.36	0	2
15	MADDALENA	8.42	–	8.42	0.91	0	2
16	MOLO	3.62	–	3.62	1.35	0	3
17	S.NICOLA	2.10	–	2.10	0.09	0	3
18	CASTELLETTO	2.77	–	2.77	0.40	0	4
19	MANIN	3.14	–	3.14	0.43	0	2
20	S.VINCENZO	5.71	–	5.71	3.40	0	3
21	**CARIGNANO**	**3.67**	**11.09**	**9.43**	**0.65**	**2**	**3**
22	FOCE	4.38	–	4.38	0.18	0	2
23	BRIGNOLE	7.21	–	7.21	1.21	0	3
24	**S.AGATA**	**3.01**	**11.28**	**14.30**	**0.34**	**2**	**2**
25	**S.FRUTTUOSO**	**1.47**	**7.83**	**6.08**	**0.49**	**3**	**6**
26	FEREGGIANO	1.84	–	1.84	0.07	0	2
27	**MARASSI**	**3.25**	**10.11**	**13.36**	**0.35**	**2**	**2**
28	FORTE QUEZZI	1.57	–	1.57	0.08	0	2
29	**PARENZO**	**2.89**	**3.87**	**2.89**	**0.21**	**1**	**3**
30	**BORGORATTI**	**2.56**	**5.46**	**8.02**	**0.19**	**1**	**3**
31	**CHIAPPETO**	**3.24**	**3.66**	**10.02**	**0.02**	**1**	**2**
32	**S.MARTINO**	**5.16**	**–**	**11.07**	**1.23**	**0**	**5**
33	**ALBARO**	**3.74**	**24.94**	**28.73**	**0.40**	**4**	**4**
34	S.GIULIANO	3.97	–	3.97	0.12	0	3
35	**LIDO**	**5.62**	**6.44**	**12.06**	**0.10**	**1**	**3**
36	**PUGGIA**	**2.19**	**14.76**	**16.95**	**0.02**	**3**	**3**
37	**STURLA**	**4.85**	**10.82**	**20.88**	**0.30**	**2**	**4**
38	QUARTO	7.41	–	7.41	0.37	0	4
39	QUARTARA	6.43	–	6.43	0.00	0	3
40	**CASTAGNA**	**0.41**	**14.65**	**15.06**	**0.26**	**3**	**3**
41	QUINTO	8.29	–	8.29	0.18	0	3
42	NERVI	5.23	–	5.23	0.20	0	6
	Minimum CAI value	***–***	***3.66***	***3.94***			
	Average CAI value	***3.51***	***5.75***	***9.26***			

and Table 5.12, respectively. In this context, values of CAI indexes for CS and their total values under Scenario B can be visualized using Figure 5.31 and Figure 5.32 during day time and using Figure 5.33 and Figure 5.34 during night time, respectively.

As a more detailed analysis, an inspection of the entries in Table 5.13 and Ta-

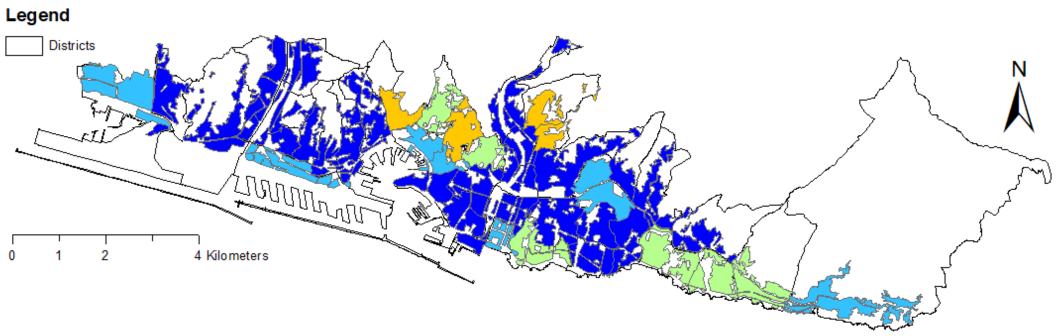

Figure 5.32: Distribution of the total values of CAI indexes during daytime for all zones of Genova under Scenario B. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

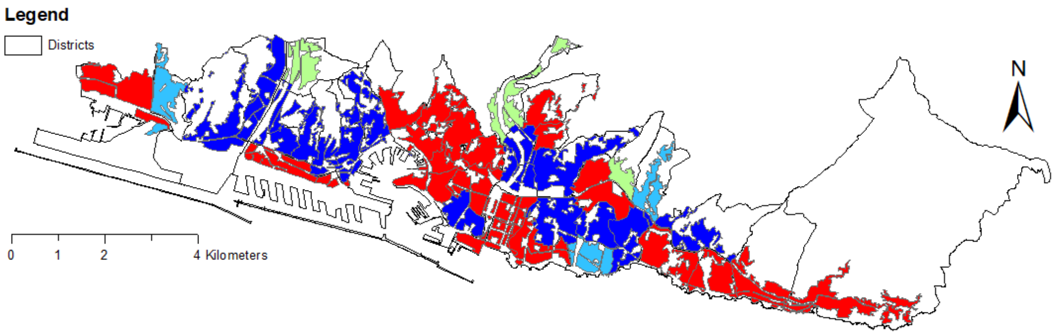

Figure 5.33: Distribution of the values of CAI indexes of CS during night time for all zones of Genova under Scenario B. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

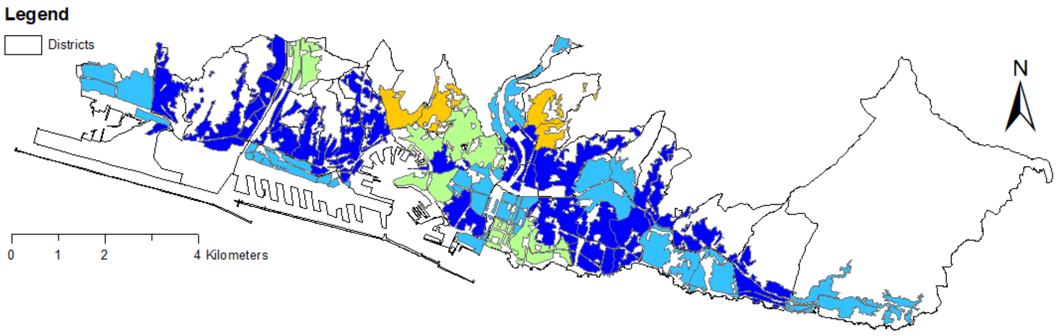

Figure 5.34: Distribution of the total values of CAI indexes during night time for all zones of Genova under Scenario B. Colour legend: 🟥 0; 🟨 $(0-2.5)$; 🟩 $(2.5-5.0)$; 🟦 $(5.0-7.5)$; 🟦 (>7.5)

ble 5.14, during daytime and nighttime, respectively reveals that in this scenario, 48 depots along with the placement of 48 vehicles are activated. In addition, two activated depots i.e., depot 5 of zone 5 and depot 10 of zone 33 (Purple dots in Figure 5.29 and Figure 5.30) in scenario A have been replaced by depot 1 of zone 5 and depot 4 of zone 33 in scenario B (red dots in Figure 5.29 and Figure 5.30), due to the better distribution of CS resources under this scenario. Moreover, a new CS depot is activated in an additional district, 29, with a single vehicle, whereas the 9 remaining vehicles are assigned to zones 5 (+2 vehicles), zones 7 (+1 vehicles), zones 12 (+1 vehicles), zones 21, zones 25 (+2 vehicles), zones 27 (+1 vehicles), zones 33 (+1 vehicles) and 37 (+1 vehicles). Table 5.12 shows that the additional vehicle in zone 25 is placed in depot number $(k, z) = (1, 25)$, which already has a vehicle in scenario A. Such a result is a compromise between activating new depots and then "gaining" their accessibility in CAI_{CS} and the relevant activation costs γ_1. In other words, the proposed methodology determines that, compared with scenario A, it is globally better to have 9 additional depots in zones 5, 7, 12, 21, 25, 27, 33, and 37 but only add vehicles to an existing depot in zone 25.

The utilised budget turns out to be 996k€, which is very close to the maximum admissible value. In this case, since the remaining 4k€ does not allow the activation of a new depot or the purchase of an additional vehicle, the budget determines the upper bound of the achievable performance.

5.3 Discussion

In general, the application of the proposed methodology shows good results for both case studies, in terms of both average performance and resource assignment equity. Nevertheless, this behaviour is driven by the introduction of specific factors and constraints. In particular, the achievement of good average performance is guaranteed by the cost function (4.10) (Chapter 4), which considers all zones and time periods, whereas the equity in resource assignment is partially due to the weighting factors β_z^t and partially due to the so-called "null CAI_{PT}" constraints in (4.15) (Section 4.2.3.2 in Chapter 4 of this thesis). Additional experimental results that are reported in Appendix B and Appendix C, show that if considered alone, neither the weighting factors nor the null CAI_{PT} guarantee a proper distribution. In fact:

- if only (4.15) are considered (Table B.1 and Table B.2, during weekdays and weekend days, respectively for a case study of Trento, and Table B.3 and Table B.4, during day time and night time, respectively for the case study of Genova, both in Appendix B), once they satisfy the minimum assignment, the remaining resources are assigned to depots with high potential accessibility and connectivity, even if the relevant CAI_{PT} is already large;
- if only the weighting parameters β_z^t are considered (Table C.1 and Table C.2, during weekdays and weekend days, for the case study of Trento, and Table C.3 and Table C.4, during day time and night time, respectively for the case study of Genova, both in Appendix C), there is no guarantee that at least a minimum level of CAI_{TOT} is provided to all zones.

A further general comment derives from the comparison between scenarios A and B. In scenario B, the more resources are made available, the more resources are concentrated in zones with high potentialities. Table 5.2-5.3 under Scenario A and Table 5.6-5.7 under Scenario B, during weekdays and weekend days, respectively for Trento case study show that if the performance assessment is restricted to zones characterised by $CAI_{PT,z}^t < 2.5$, the average CAI improvement result is +140% under both scenarios A and B during weekdays, while it is +146% and +150% during weekend days under scenarios A and B, respectively. Similarly, Table 5.9-5.10 under Scenario A and Table 5.13-5.14 under Scenario B, during day time and night time, respectively, for Genova case study shows that if the performance assessment is restricted to zones characterised by $CAI_{PT,z}^t < 2.5$, the average CAI improvement result is +530% and +590% during day time, while it is +430% and +470% during night time, under scenarios A and B, respectively. These results, when considered together with those calculated for the zones $CAI_{PT,z}^t < 5$ for both case studies of Trento and Genova, show that the compensation introduced by the parameters β_z^t must be suitably tuned depending on the goal of the decision-makers. Additional experimental results as reported in Appendix A (under Table A.1-A.3 during weekdays and Table A.4-A.6 during weekend days for a case study of Trento, while under Table A.7-A.9 during day time and Table A.10-A.12 during night time for the case study of Genova) show that if the shape parameter ℓ in (4.11) (Chapter 4) is increased to a value greater than or equal to 1.3, all resources are assigned to zones with $CAI^{t}_{PT,z} < 5$ for both case studies.

The evaluation of such dynamics depends on the general aim of the decision makers, who, after guaranteeing a minimum CAI_{TOT} for all zones, may focus on improving the general performance or the equity level. In the second case, it is still possible to apply the proposed methodology by emphasising the values of the beta weighing coefficients to increasingly reduce the relevance of the zones with high CAI_{PT}. In this connection, the major conclusion drawn from the application of the purposed methodology has been explained in the next chapter.

Chapter 6

Conclusions

In this thesis, the least accessible areas of PT stops are highlighted based on the indicators defined exclusively for the determination of CAI values of PT systems of the study area under consideration. Furthermore, a methodology for maximization of the minimum total CAI values for all zones through the determination of the optimal locations of CS depots is presented. The proposed approach consists of an MILP model that determines the best locations of a new set of CS depots and the optimal number of vehicles to assign to the depots. The proposed model is effective in terms of maximizing and equalizing the CAI values of the whole region through the effective distribution of CS resources.

To test its effectiveness, the proposed model was applied to a real-world case study of the Italian cities of Trento and Genova, representing the case for medium and large size cities, respectively. The results proved that

- The considered problem formulation is effective in maximising the minimum total CAI value among all districts of Trento as well as in Genova averaged over all considered time periods, considering cost and budget data sets;
- In general, the proposed approach is capable of significantly improving the total CAI level in a considered area;
- Section 5.3 of this thesis showed that the MILP problem can grant a minimum assignment to the most disadvantaged zones, but it can also be easily tuned by means of the unique shape parameter ℓ to increase or decrease the

focus on the zone with low CAI_{PT}, depending on the goals of the relevant decision maker.

The above considerations suggest a possible practical use of the proposed approach in providing recommendations to transport planners and administrative governments for the complete integration of CS systems with PT systems. Moreover, the model proposed in the thesis can easily be modified according to the interest of the stakeholders to assign CS resources to different groups of the population. Moreover, all data considered in the case study were public, and available online, so their collection was not a difficult task. Similarly, most of the data sets were collected either directly from the official Government websites or third-party sources, e.g. Google transit feed. However, their post-processing proved to be a complex and time-consuming process. Therefore, the presented approach can be easily applied to larger and more complex case studies considering different parameter setups.

More in detail, by re-formulating the objective function in (4.9) as $max - min$ instead of a simple max problem and using a very high value of shape parameter ℓ in the weight coefficient function β_z^t, the CS resources can only be restricted to the zones with the lowest value of CAI_{PT} and no resource can be assigned to other zones even if the budget is available as evident through Appendix D.

As already discussed, the stated methodological framework is efficient towards the identification of the least accessible areas of PT in terms of their CAI values. However, the feasibility design and operation of the proposed CS system in integration with the existing PT system can be challenging for some regions due to the following set of major limitations.

- As indicated in Chapter 5, the computational performance is very effective for the Trento case study, allowing easy analysis of different configurations of the considered case study, whereas for Genova case study computational effort is not that effective as compared to Trento due to the involvement of a higher number of variables. Therefore, the computational effort for similar cases of big cities can be improved using heuristics. Similarly, the Work is in progress to use heuristics for the Genova case study for studying the different configurations of the proposed methodological framework and application of MILP model to the entire city of Genova;

- The proposed methodology is suitable for the design and operation of CS systems in the areas characterized by small demand, whereas the areas with high demand can be connected by PT systems through the design and operation of other micro-mobility solutions. In this framework, the model proposed in this thesis can easily be modified to accommodate such solutions by using the appropriate constraints;
- As already described in Chapter 4 of this thesis, the proposed system is a two-way traditional CS system which requires the pick-up and drop-off of the vehicles to the same depots from where they were originally picked up. However, such a limitation can easily be addressed by introducing a one-way CS system by defining new constraints to accommodate such a system with appropriate relocation strategies used for such a system;
- Another major limitation is the type and nature of data sets required for the implementation of the proposed MILP model. These kinds of data sets are either not readily available or need to be modified according to the nature of the task performed. This limitation can be partially overcome at a political level by making all the data sets available to the general public. Alternatively, PT data can easily be obtained from the google transit feed and relevant PT systems information from the relevant agency website. In this connection, these data sets can easily be developed using arc GIS application at a cost of additional time required for the processing of such data set.

Despite the stated limitations existing in the proposed methodological framework, it is still efficient for the design and operation of proposed CS system towards the improvements in the total CAI values for the most of the regions which are proved using the real world case studies in Chapter 5 of this thesis. Similarly, some future works will be recommended by considering such limitations in the following.

The framework conceptualized in this thesis is effective in improving the performance of PT systems in terms of their accessibility and connectivity index, which provides a basis for studying the other dimensions of PT performance, especially the reliability. In another context, the reliability of PT is more related to temporal dimensions of PT performance, which can be improved through the improvements in headways of PT systems/the integration/replacement of PT systems with some innovative PT systems to meet commuters travel needs. In this connection, different innovative rapid transit systems can be designed to replace the conventional PT systems such that the reliability of PT system in terms of passenger travel times, and PT passenger demands can be improved.

Such modes can travel at higher speeds, providing direct connections to the passengers, whereas minimizing their travel times. Furthermore, these innovative solutions are relatively novel concepts in PT systems without any real-world example and the capital costs for their design are huge. In this connection, the work is also under progress for the development of optimization models with the aim of improving the reliability of PT in meeting passenger demands and minimization of travel times, especially in the least accessible areas of PT. In this connection, the feasibility of such innovative PT modes, being operated as a replacement of conventional PT modes/lines, is being tested using optimization models under various operational configurations.

Finally, the results from this thesis can also be utilized for various research projects related to the incorporation of dynamic management of the CS depots to allow different vehicle assignments during different time periods considering different times of the day and on a detailed economic analysis of time-dependent CS fares that differ from PT fares and the relevant effects on users' willingness to use such a transport mode.

Appendix A

Effects of shape parameter on the values of CAI

This appendix represents the tables showing the effects of shape parameter ℓ on the values of CAI indexes for both considered case studies of Trento (Table A.1-A.3 during weekdays and Table A.4-A.6 during weekend days) and Genova (Table A.7-A.9 during day time and Table A.10-A.12 during night time).

Table A.1: Results with $Q^{max} = 20$ & $\ell = 1.1$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	**Campotrentino**	**2.55**	**19.23**	**21.78**	**2.20**	**2**	**2**
3	**San Bartolomeo**	**2.24**	**13.20**	**15.44**	**1.00**	**1**	**2**
4	Villazzano	1.95	–	1.95	2.69	0	3
5	**Clarina**	**2.55**	**12.82**	**15.36**	**3.10**	**1**	**3**
6	**Melta**	**0.00**	**4.16**	**4.16**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	**Spini-Ghiaie**	**1.70**	**21.40**	**23.10**	**4.21**	**3**	**4**
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**1**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	**Santissimo**	**5.91**	**21.63**	**27.54**	**1.00**	**1**	**2**
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	**Roncafort**	**2.18**	**10.52**	**12.69**	**3.64**	**1**	**4**
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**32.02**	**34.90**	**2.99**	**3**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.80**	**0.80**	**0.16**	**1**	**2**
30	San Martino	5.47	–	5.47	1.19	0	2
31	**Sardagna**	**0.00**	**3.02**	**3.02**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**36.00**	**39.97**	**2.87**	**2**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.63**	**0.63**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**2.46**	**2.46**	**0.93**	**1**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**2.35**	**2.35**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	**Bolghera**	**3.95**	**29.07**	**33.02**	**2.05**	**2**	**2**
48	**Vigolo Baselga**	**0.00**	**2.19**	**2.19**	**0.39**	**1**	**2**
	Minimum CAI value	–	*0.04*	*0.04*			
	Average CAI value	*3.35*	*3.52*	*6.87*			

Table A.2: Results with $Q^{max} = 20$ & $\ell = 1.2$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.73	–	4.73	0.87	0	2
2	**Campotrentino**	**3.38**	**20.11**	**23.48**	**3.30**	**2**	**2**
3	**San Bartolomeo**	**2.80**	**13.43**	**16.22**	**1.51**	**1**	**2**
4	Villazzano	2.53	–	2.53	4.03	0	3
5	**Clarina**	**4.11**	**12.94**	**17.05**	**4.65**	**1**	**3**
6	**Melta**	**2.51**	**4.36**	**6.87**	**0.73**	**1**	**2**
7	Canova	3.42	–	3.42	1.31	0	2
8	Solteri-Centochiavi	4.82	–	4.82	3.69	0	2
9	San Dona'-Laste	1.83	–	1.83	0.32	0	2
10	**Spini-Ghiaie**	**2.89**	**20.55**	**23.45**	**6.32**	**2**	**4**
11	Cristo Re	6.17	–	6.17	1.99	0	2
12	Centro Storico	11.43	–	11.43	2.30	0	2
13	San Bernardino	7.93	–	7.93	0.98	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.04**	**0.04**	**0.03**	**1**	**2**
15	San Lazzaro	1.66	–	1.66	0.13	0	2
16	Povo	3.00	–	3.00	3.66	0	2
17	Ravina	2.84	–	2.84	4.44	0	3
18	Santissimo	7.87	–	7.87	1.50	0	2
19	Sopramonte	2.50	–	2.50	4.98	0	3
20	Mattarello	3.30	–	3.30	7.65	0	5
21	**Roncafort**	**2.18**	**10.90**	**13.08**	**5.46**	**1**	**4**
22	Madonna Bianca	2.65	–	2.65	1.81	0	2
23	Villazzano 3	2.98	–	2.98	1.00	0	2
24	**Gardolo**	**3.72**	**22.69**	**26.41**	**4.49**	**2**	**3**
25	Gazzadina	3.49	–	3.49	0.81	0	2
26	Meano	2.66	–	2.66	1.89	0	2
27	Cortesano	3.98	–	3.98	0.43	0	2
28	Martignano	2.49	–	2.49	3.98	0	3
29	**Gardolo Di Mezzo**	**0.61**	**0.87**	**1.48**	**0.23**	**1**	**2**
30	San Martino	8.19	–	8.19	1.78	0	2
31	**Sardagna**	**0.00**	**3.41**	**3.41**	**1.99**	**1**	**2**
32	Lamar	2.52	–	2.52	1.38	0	2
33	La Vela	3.25	–	3.25	1.61	0	2
34	Piedicastello	3.48	–	3.48	1.85	0	2
35	**San Giuseppe**	**4.86**	**36.29**	**41.15**	**4.30**	**2**	**3**
36	Vigo Meano	2.96	–	2.96	0.90	0	2
37	**Valsorda**	**0.00**	**0.70**	**0.70**	**0.20**	**1**	**2**
38	Oltrecastello	1.59	–	1.59	1.80	0	2
39	Cadine	2.27	–	2.27	2.22	0	2
40	Romagnano	2.57	–	2.57	2.10	0	2
41	**Villamontagna**	**1.82**	**2.76**	**4.58**	**1.39**	**1**	**2**
42	Cognola	2.84	–	2.84	3.18	0	2
43	Cappuccini	2.91	–	2.91	1.16	0	2
44	**Baselga Del Bondone**	**0.00**	**2.50**	**2.50**	**0.57**	**1**	**2**
45	San Dona di Cagnola	2.32	–	2.32	1.28	0	2
46	Belvedere-San Francesco	8.56	–	8.56	0.27	0	2
47	**Bolghera**	**6.13**	**15.08**	**21.22**	**3.07**	**1**	**2**
48	**Vigolo Baselga**	**0.00**	**2.33**	**2.33**	**0.59**	**1**	**2**
	Minimum CAI value	–	*0.04*	*0.04*			
	Average CAI value	*3.35*	*3.52*	*6.87*			

Table A.3: Results with $Q^{max} = 20$ & $\ell = 1.3$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.73	–	4.73	0.87	0	2
2	**Campotrentino**	**3.38**	**20.11**	**23.48**	**3.30**	**2**	**2**
3	**San Bartolomeo**	**2.80**	**13.43**	**16.22**	**1.51**	**1**	**2**
4	Villazzano	2.53	–	2.53	4.03	0	3
5	**Clarina**	**4.11**	**12.94**	**17.05**	**4.65**	**1**	**3**
6	**Melta**	**2.51**	**4.36**	**6.87**	**0.73**	**1**	**2**
7	Canova	3.42	–	3.42	1.31	0	2
8	Solteri-Centochiavi	4.82	–	4.82	3.69	0	2
9	San Dona'-Laste	1.83	–	1.83	0.32	0	2
10	**Spini-Ghiaie**	**2.89**	**20.55**	**23.45**	**6.32**	**2**	**4**
11	Cristo Re	6.17	–	6.17	1.99	0	2
12	Centro Storico	11.43	–	11.43	2.30	0	2
13	San Bernardino	7.93	–	7.93	0.98	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.04**	**0.04**	**0.03**	**1**	**2**
15	San Lazzaro	1.66	–	1.66	0.13	0	2
16	Povo	3.00	–	3.00	3.66	0	2
17	Ravina	2.84	–	2.84	4.44	0	3
18	Santissimo	7.87	–	7.87	1.50	0	2
19	Sopramonte	2.50	–	2.50	4.98	0	3
20	Mattarello	3.30	–	3.30	7.65	0	5
21	**Roncafort**	**2.18**	**10.90**	**13.08**	**5.46**	**1**	**4**
22	Madonna Bianca	2.65	–	2.65	1.81	0	2
23	Villazzano 3	2.98	–	2.98	1.00	0	2
24	**Gardolo**	**3.72**	**32.69**	**36.42**	**4.49**	**3**	**3**
25	Gazzadina	3.49	–	3.49	0.81	0	2
26	Meano	2.66	–	2.66	1.89	0	2
27	Cortesano	3.98	–	3.98	0.43	0	2
28	Martignano	2.49	–	2.49	3.98	0	3
29	**Gardolo Di Mezzo**	**0.61**	**0.87**	**1.48**	**0.23**	**1**	**2**
30	San Martino	8.19	–	8.19	1.78	0	2
31	**Sardagna**	**0.00**	**3.41**	**3.41**	**1.99**	**1**	**2**
32	Lamar	2.52	–	2.52	1.38	0	2
33	La Vela	3.25	–	3.25	1.61	0	2
34	Piedicastello	3.48	–	3.48	1.85	0	2
35	**San Giuseppe**	**4.86**	**36.29**	**41.15**	**4.30**	**2**	**3**
36	Vigo Meano	2.96	–	2.96	0.90	0	2
37	**Valsorda**	**0.00**	**0.70**	**0.70**	**0.20**	**1**	**2**
38	Oltrecastello	1.59	–	1.59	1.80	0	2
39	Cadine	2.27	–	2.27	2.22	0	2
40	Romagnano	2.57	–	2.57	2.10	0	2
41	**Villamontagna**	**1.82**	**2.76**	**4.58**	**1.39**	**1**	**2**
42	Cognola	2.84	–	2.84	3.18	0	2
43	Cappuccini	2.91	–	2.91	1.16	0	2
44	**Baselga Del Bondone**	**0.00**	**2.50**	**2.50**	**0.57**	**1**	**2**
45	San Dona di Cagnola	2.32	–	2.32	1.28	0	2
46	Belvedere-San Francesco	8.56	–	8.56	0.27	0	2
47	Bolghera	6.13	–	6.13	3.07	0	2
48	**Vigolo Baselga**	**0.00**	**2.33**	**2.33**	**0.59**	**1**	**2**
	Minimum CAI value	–	*0.04*	*0.04*			
	Average CAI value	*3.35*	*3.41*	*6.76*			

Table A.4: Results with $Q^{max} = 20$ & $\ell = 1.1$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_2}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	**Campotrentino**	**2.55**	**19.23**	**21.78**	**2.20**	**2**	**2**
3	**San Bartolomeo**	**2.24**	**13.20**	**15.44**	**1.00**	**1**	**2**
4	Villazzano	1.95	–	1.95	2.69	0	3
5	**Clarina**	**2.55**	**12.82**	**15.36**	**3.10**	**1**	**3**
6	**Melta**	**0.00**	**4.16**	**4.16**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	**Spini-Ghiaie**	**1.70**	**20.13**	**21.84**	**4.21**	**2**	**4**
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**1**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	Santissimo	5.91	–	5.91	1.00	0	2
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	**Roncafort**	**2.18**	**10.51**	**12.69**	**3.64**	**1**	**4**
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**22.24**	**25.12**	**2.99**	**2**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.80**	**0.80**	**0.16**	**1**	**2**
30	San Martino	5.47	–	5.47	1.19	0	2
31	**Sardagna**	**0.00**	**3.02**	**3.02**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**36.00**	**39.97**	**2.87**	**2**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.63**	**0.63**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**2.46**	**2.46**	**0.93**	**1**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**2.35**	**2.35**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	**Bolghera**	**3.95**	**14.86**	**18.81**	**2.05**	**1**	**2**
48	**Vigolo Baselga**	**0.00**	**2.19**	**2.19**	**0.39**	**1**	**2**
	Minimum CAI value	–	*0.03*	*0.03*			
	Average CAI value	*2.43*	*3.43*	*5.86*			

Table A.5: Results with $Q^{max} = 20$ & $\ell = 1.2$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_2}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	**Campotrentino**	**2.55**	**19.23**	**21.78**	**2.20**	**2**	**2**
3	**San Bartolomeo**	**2.24**	**13.20**	**15.44**	**1.00**	**1**	**2**
4	Villazzano	1.95	–	1.95	2.69	0	3
5	**Clarina**	**2.55**	**12.82**	**15.36**	**3.10**	**1**	**3**
6	**Melta**	**0.00**	**4.16**	**4.16**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	**Spini-Ghiaie**	**1.70**	**20.13**	**21.84**	**4.21**	**2**	**4**
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**1**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	Santissimo	5.91	–	5.91	1.00	0	2
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	**Roncafort**	**2.18**	**10.51**	**12.69**	**3.64**	**1**	**4**
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**22.24**	**25.12**	**2.99**	**2**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.80**	**0.80**	**0.16**	**1**	**2**
30	San Martino	5.47	–	5.47	1.19	0	2
31	**Sardagna**	**0.00**	**3.02**	**3.02**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**36.00**	**39.97**	**2.87**	**2**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.63**	**0.63**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**2.46**	**2.46**	**0.93**	**1**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**2.35**	**2.35**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	**Bolghera**	**3.95**	**14.86**	**18.81**	**2.05**	**1**	**2**
48	**Vigolo Baselga**	**0.00**	**2.19**	**2.19**	**0.39**	**1**	**2**
	Minimum CAI value	–	*0.03*	*0.03*			
	Average CAI value	*2.43*	*3.43*	*5.86*			

Table A.6: Results with $Q^{max} = 20$ & $\ell = 1.3$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_2}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	**Campotrentino**	**2.55**	**19.23**	**21.78**	**2.20**	**2**	**2**
3	**San Bartolomeo**	**2.24**	**13.20**	**15.44**	**1.00**	**1**	**2**
4	Villazzano	1.95	–	1.95	2.69	0	3
5	**Clarina**	**2.55**	**12.82**	**15.36**	**3.10**	**1**	**3**
6	**Melta**	**0.00**	**4.16**	**4.16**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	**Spini-Ghiaie**	**1.70**	**20.13**	**21.84**	**4.21**	**2**	**4**
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**1**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	Santissimo	5.91	–	5.91	1.00	0	2
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	**Roncafort**	**2.18**	**10.51**	**12.69**	**3.64**	**1**	**4**
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**32.02**	**34.90**	**2.99**	**3**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.80**	**0.80**	**0.16**	**1**	**2**
30	San Martino	5.47	–	5.47	1.19	0	2
31	**Sardagna**	**0.00**	**3.02**	**3.02**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**36.00**	**39.97**	**2.87**	**2**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.63**	**0.63**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**2.46**	**2.46**	**0.93**	**1**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**2.35**	**2.35**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	Bolghera	3.95	–	3.95	2.05	0	2
48	**Vigolo Baselga**	**0.00**	**2.19**	**2.19**	**0.39**	**1**	**2**
	Minimum CAI value	–	*0.03*	*0.03*			
	Average CAI value	*2.43*	*3.32*	*5.75*			

Table A.7: Results with $Q^{max} = 40$ & $\ell = 1.1$ during day time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.79	–	5.79	2.76	0	6
2	**CALCINARA**	**3.00**	**7.04**	**10.04**	**0.78**	**1**	**4**
3	**CERTOSA**	**12.35**	**5.87**	**18.22**	**1.32**	**1**	**3**
4	**CORNIGLIANO**	**3.31**	**26.78**	**30.09**	**0.99**	**4**	**4**
5	**CAMPI**	**1.75**	**21.98**	**23.73**	**0.30**	**4**	**4**
6	**CAMPASSO**	**0.89**	**16.56**	**17.45**	**0.71**	**2**	**2**
7	**S.GAETANO**	**3.09**	**14.47**	**17.55**	**0.39**	**2**	**2**
8	SAMPIERDARENA	5.91	–	5.91	1.93	0	3
9	**BELVEDERE**	**1.31**	**12.83**	**14.14**	**0.62**	**2**	**2**
10	**S.BARTOLOMEO**	**2.61**	**15.68**	**18.30**	**0.64**	**2**	**2**
11	**ANGELI**	**2.12**	**25.54**	**27.66**	**0.64**	**3**	**3**
12	**S.TEODORO**	**2.55**	**11.60**	**14.15**	**0.66**	**2**	**3**
13	LAGACCIO	2.18	–	2.18	0.90	0	2
14	PRE'	6.40	–	6.40	3.24	0	2
15	MADDALENA	5.84	–	5.84	1.27	0	2
16	MOLO	12.98	–	12.98	1.97	0	3
17	S.NICOLA	2.75	–	2.75	0.96	0	3
18	CASTELLETTO	2.38	–	2.38	1.26	0	4
19	MANIN	4.09	–	4.09	0.70	0	2
20	S.VINCENZO	9.32	–	9.32	3.13	0	3
21	**CARIGNANO**	**5.03**	**7.43**	**12.47**	**0.46**	**1**	**3**
22	FOCE	5.55	–	5.55	0.21	0	2
23	BRIGNOLE	8.61	–	8.61	4.86	0	3
24	**S.AGATA**	**4.05**	**15.05**	**19.11**	**1.25**	**2**	**2**
25	**S.FRUTTUOSO**	**2.09**	**6.15**	**8.24**	**1.81**	**1**	**6**
26	FEREGGIANO	2.47	–	2.47	0.50	0	2
27	**MARASSI**	**4.68**	**7.29**	**11.97**	**0.82**	**1**	**2**
28	FORTE QUEZZI	2.09	–	2.09	0.40	0	2
29	PARENZO	3.21	–	3.21	0.84	0	3
30	**BORGORATTI**	**2.64**	**7.00**	**9.64**	**0.35**	**1**	**3**
31	**CHIAPPETO**	**1.94**	**5.90**	**7.84**	**0.70**	**1**	**2**
32	S.MARTINO	5.36	–	5.36	1.07	0	5
33	**ALBARO**	**4.27**	**32.79**	**37.06**	**1.09**	**4**	**4**
34	S.GIULIANO	4.14	–	4.14	0.38	0	3
35	LIDO	5.04	–	5.04	0.24	0	3
36	**PUGGIA**	**3.57**	**19.66**	**23.23**	**0.29**	**3**	**3**
37	STURLA	4.53	–	4.53	0.58	0	4
38	QUARTO	4.25	–	4.25	0.29	0	4
39	QUARTARA	4.61	–	4.61	0.90	0	3
40	**CASTAGNA**	**0.34**	**19.49**	**19.83**	**0.52**	**3**	**3**
41	QUINTO	3.26	–	3.26	0.24	0	3
42	NERVI	7.02	–	7.02	0.32	0	6
	Minimum CAI value	***–***	***5.87***	***7.84***			
	Average CAI value	***4.27***	***6.65***	***10.92***			

Table A.8: Results with $Q^{max} = 40$ & $\ell = 1.2$ during day time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.79	–	5.79	2.76	0	6
2	**CALCINARA**	**3.00**	**7.04**	**10.04**	**0.78**	**1**	**4**
3	**CERTOSA**	**12.35**	**5.87**	**18.22**	**1.32**	**1**	**3**
4	**CORNIGLIANO**	**3.31**	**26.78**	**30.09**	**0.99**	**4**	**4**
5	**CAMPI**	**1.75**	**21.98**	**23.73**	**0.30**	**4**	**4**
6	**CAMPASSO**	**0.89**	**16.56**	**17.45**	**0.71**	**2**	**2**
7	**S.GAETANO**	**3.09**	**14.47**	**17.55**	**0.39**	**2**	**2**
8	SAMPIERDARENA	5.91	–	5.91	1.93	0	3
9	**BELVEDERE**	**1.31**	**12.83**	**14.14**	**0.62**	**2**	**2**
10	**S.BARTOLOMEO**	**2.61**	**15.68**	**18.30**	**0.64**	**2**	**2**
11	**ANGELI**	**2.12**	**25.54**	**27.66**	**0.64**	**3**	**3**
12	**S.TEODORO**	**2.55**	**11.60**	**14.15**	**0.66**	**2**	**3**
13	LAGACCIO	2.18	–	2.18	0.90	0	2
14	PRE'	6.40	–	6.40	3.24	0	2
15	MADDALENA	5.84	–	5.84	1.27	0	2
16	MOLO	12.98	–	12.98	1.97	0	3
17	S.NICOLA	2.75	–	2.75	0.96	0	3
18	CASTELLETTO	2.38	–	2.38	1.26	0	4
19	MANIN	4.09	–	4.09	0.70	0	2
20	S.VINCENZO	9.32	–	9.32	3.13	0	3
21	CARIGNANO	5.03	–	5.03	0.46	0	3
22	FOCE	5.55	–	5.55	0.21	0	2
23	BRIGNOLE	8.61	–	8.61	4.86	0	3
24	**S.AGATA**	**4.05**	**15.05**	**19.11**	**1.25**	**2**	**2**
25	**S.FRUTTUOSO**	**2.09**	**11.34**	**13.43**	**1.81**	**2**	**6**
26	FEREGGIANO	2.47	–	2.47	0.50	0	2
27	**MARASSI**	**4.68**	**7.29**	**11.97**	**0.82**	**1**	**2**
28	FORTE QUEZZI	2.09	–	2.09	0.40	0	2
29	PARENZO	3.21	–	3.21	0.84	0	3
30	**BORGORATTI**	**2.64**	**7.00**	**9.64**	**0.35**	**1**	**3**
31	**CHIAPPETO**	**1.94**	**5.90**	**7.84**	**0.70**	**1**	**2**
32	S.MARTINO	5.36	–	5.36	1.07	0	5
33	**ALBARO**	**4.27**	**32.79**	**37.06**	**1.09**	**4**	**4**
34	S.GIULIANO	4.14	–	4.14	0.38	0	3
35	LIDO	5.04	–	5.04	0.24	0	3
36	**PUGGIA**	**3.57**	**19.66**	**23.23**	**0.29**	**3**	**3**
37	STURLA	4.53	–	4.53	0.58	0	4
38	QUARTO	4.25	–	4.25	0.29	0	4
39	QUARTARA	4.61	–	4.61	0.90	0	3
40	**CASTAGNA**	**0.34**	**19.49**	**19.83**	**0.52**	**3**	**3**
41	QUINTO	3.26	–	3.26	0.24	0	3
42	NERVI	7.02	–	7.02	0.32	0	6
	Minimum CAI value	–	***5.87***	***7.84***			
	Average CAI value	***4.27***	***6.59***	***10.86***			

Table A.9: Results with $Q^{max} = 40$ & $\ell = 1.3$ during day time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.79	–	5.79	2.76	0	6
2	**CALCINARA**	**3.00**	**7.04**	**10.04**	**0.78**	**1**	**4**
3	**CERTOSA**	**12.35**	**5.87**	**18.22**	**1.32**	**1**	**3**
4	**CORNIGLIANO**	**3.31**	**26.78**	**30.09**	**0.99**	**4**	**4**
5	**CAMPI**	**1.75**	**21.98**	**23.73**	**0.30**	**4**	**4**
6	**CAMPASSO**	**0.89**	**16.56**	**17.45**	**0.71**	**2**	**2**
7	**S.GAETANO**	**3.09**	**14.47**	**17.55**	**0.39**	**2**	**2**
8	SAMPIERDARENA	5.91	–	5.91	1.93	0	3
9	**BELVEDERE**	**1.31**	**12.83**	**14.14**	**0.62**	**2**	**2**
10	**S.BARTOLOMEO**	**2.61**	**15.68**	**18.30**	**0.64**	**2**	**2**
11	**ANGELI**	**2.12**	**25.54**	**27.66**	**0.64**	**3**	**3**
12	**S.TEODORO**	**2.55**	**11.60**	**14.15**	**0.66**	**2**	**3**
13	LAGACCIO	2.18	–	2.18	0.90	0	2
14	PRE’	6.40	–	6.40	3.24	0	2
15	MADDALENA	5.84	–	5.84	1.27	0	2
16	MOLO	12.98	–	12.98	1.97	0	3
17	S.NICOLA	2.75	–	2.75	0.96	0	3
18	CASTELLETTO	2.38	–	2.38	1.26	0	4
19	MANIN	4.09	–	4.09	0.70	0	2
20	S.VINCENZO	9.32	–	9.32	3.13	0	3
21	CARIGNANO	5.03	–	5.03	0.46	0	3
22	FOCE	5.55	–	5.55	0.21	0	2
23	BRIGNOLE	8.61	–	8.61	4.86	0	3
24	**S.AGATA**	**4.05**	**15.05**	**19.11**	**1.25**	**2**	**2**
25	**S.FRUTTUOSO**	**2.09**	**11.34**	**13.43**	**1.81**	**2**	**6**
26	FEREGGIANO	2.47	–	2.47	0.50	0	2
27	MARASSI	4.68	–	4.68	0.82	0	2
28	FORTE QUEZZI	2.09	–	2.09	0.40	0	2
29	PARENZO	3.21	–	3.21	0.84	0	3
30	**BORGORATTI**	**2.64**	**7.00**	**9.64**	**0.35**	**1**	**3**
31	**CHIAPPETO**	**1.94**	**11.27**	**13.21**	**0.70**	**2**	**2**
32	S.MARTINO	5.36	–	5.36	1.07	0	5
33	**ALBARO**	**4.27**	**32.79**	**37.06**	**1.09**	**4**	**4**
34	S.GIULIANO	4.14	–	4.14	0.38	0	3
35	LIDO	5.04	–	5.04	0.24	0	3
36	**PUGGIA**	**3.57**	**19.66**	**23.23**	**0.29**	**3**	**3**
37	STURLA	4.53	–	4.53	0.58	0	4
38	QUARTO	4.25	–	4.25	0.29	0	4
39	QUARTARA	4.61	–	4.61	0.90	0	3
40	**CASTAGNA**	**0.34**	**19.49**	**19.83**	**0.52**	**3**	**3**
41	QUINTO	3.26	–	3.26	0.24	0	3
42	NERVI	7.02	–	7.02	0.32	0	6
	Minimum CAI value	–	***5.87***	***9.64***			
	Average CAI value	***4.27***	***6.55***	***10.82***			

Table A.10: Results with $Q^{max} = 40$ & $\ell = 1.1$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_2}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.64	–	5.64	1.88	0	6
2	**CALCINARA**	**3.75**	**5.15**	**8.90**	**0.22**	**1**	**4**
3	**CERTOSA**	**0.00**	**3.94**	**3.94**	**0.30**	**1**	**3**
4	**CORNIGLIANO**	**3.78**	**18.81**	**22.59**	**0.34**	**4**	**4**
5	**CAMPI**	**2.35**	**15.43**	**17.78**	**0.05**	**4**	**4**
6	**CAMPASSO**	**0.00**	**12.59**	**12.59**	**0.21**	**2**	**2**
7	**S.GAETANO**	**0.00**	**11.48**	**11.48**	**0.34**	**2**	**2**
8	SAMPIERDARENA	5.33	–	5.33	1.03	0	3
9	**BELVEDERE**	**1.17**	**9.31**	**10.48**	**0.21**	**2**	**2**
10	**S.BARTOLOMEO**	**1.40**	**12.37**	**13.77**	**0.32**	**2**	**2**
11	**ANGELI**	**1.52**	**19.87**	**21.38**	**0.24**	**3**	**3**
12	**S.TEODORO**	**2.57**	**8.09**	**10.66**	**0.46**	**2**	**3**
13	LAGACCIO	1.35	–	1.35	0.24	0	2
14	PRE'	4.27	–	4.27	1.36	0	2
15	MADDALENA	8.42	–	8.42	0.91	0	2
16	MOLO	3.62	–	3.62	1.35	0	3
17	S.NICOLA	2.10	–	2.10	0.09	0	3
18	CASTELLETTO	2.77	–	2.77	0.40	0	4
19	MANIN	3.14	–	3.14	0.43	0	2
20	S.VINCENZO	5.71	–	5.71	3.40	0	3
21	**CARIGNANO**	**3.67**	**5.76**	**9.43**	**0.65**	**1**	**3**
22	FOCE	4.38	–	4.38	0.18	0	2
23	BRIGNOLE	7.21	–	7.21	1.21	0	3
24	**S.AGATA**	**3.01**	**11.28**	**14.30**	**0.34**	**2**	**2**
25	**S.FRUTTUOSO**	**1.47**	**4.17**	**5.64**	**0.49**	**1**	**6**
26	FEREGGIANO	1.84	–	1.84	0.07	0	2
27	**MARASSI**	**3.25**	**5.33**	**8.58**	**0.35**	**1**	**2**
28	FORTE QUEZZI	1.57	–	1.57	0.08	0	2
29	PARENZO	2.89	–	2.89	0.21	0	3
30	**BORGORATTI**	**2.56**	**5.46**	**8.02**	**0.19**	**1**	**3**
31	**CHIAPPETO**	**3.24**	**3.66**	**6.90**	**0.02**	**1**	**2**
32	S.MARTINO	5.16	–	5.16	1.23	0	5
33	**ALBARO**	**3.74**	**24.99**	**28.73**	**0.40**	**4**	**4**
34	S.GIULIANO	3.97	–	3.97	0.12	0	3
35	LIDO	5.62	–	5.62	0.10	0	3
36	**PUGGIA**	**2.19**	**14.76**	**16.95**	**0.02**	**3**	**3**
37	STURLA	4.85	–	4.85	0.30	0	4
38	QUARTO	7.41	–	7.41	0.37	0	4
39	QUARTARA	6.43	–	6.43	0.00	0	3
40	**CASTAGNA**	**0.41**	**14.65**	**15.06**	**0.26**	**3**	**3**
41	QUINTO	8.29	–	8.29	0.18	0	3
42	NERVI	5.23	–	5.23	0.20	0	6
	Minimum CAI value	–	***3.66***	***3.94***			
	Average CAI value	***3.51***	***4.93***	***8.44***			

Table A.11: Results with $Q^{max} = 40$ & $\ell = 1.2$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_2}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.64	–	5.64	1.88	0	6
2	**CALCINARA**	**3.75**	**5.15**	**8.90**	**0.22**	**1**	**4**
3	**CERTOSA**	**0.00**	**3.94**	**3.94**	**0.30**	**1**	**3**
4	**CORNIGLIANO**	**3.78**	**18.81**	**22.59**	**0.34**	**4**	**4**
5	**CAMPI**	**2.35**	**11.87**	**17.78**	**0.05**	**4**	**4**
6	**CAMPASSO**	**0.00**	**12.59**	**12.59**	**0.21**	**2**	**2**
7	**S.GAETANO**	**0.00**	**11.48**	**11.48**	**0.34**	**2**	**2**
8	SAMPIERDARENA	5.33	–	5.33	1.03	0	3
9	**BELVEDERE**	**1.17**	**9.31**	**10.48**	**0.21**	**2**	**2**
10	**S.BARTOLOMEO**	**1.40**	**12.37**	**13.77**	**0.32**	**2**	**2**
11	**ANGELI**	**1.52**	**19.87**	**21.38**	**0.24**	**3**	**3**
12	**S.TEODORO**	**2.57**	**4.19**	**10.66**	**0.46**	**2**	**3**
13	LAGACCIO	1.35	–	1.35	0.24	0	2
14	PRE'	4.27	–	4.27	1.36	0	2
15	MADDALENA	8.42	–	8.42	0.91	0	2
16	MOLO	3.62	–	3.62	1.35	0	3
17	S.NICOLA	2.10	–	2.10	0.09	0	3
18	CASTELLETTO	2.77	–	2.77	0.40	0	4
19	MANIN	3.14	–	3.14	0.43	0	2
20	S.VINCENZO	5.71	–	5.71	3.40	0	3
21	CARIGNANO	3.67	5.76	3.67	0.65	0	3
22	FOCE	4.38	–	4.38	0.18	0	2
23	BRIGNOLE	7.21	–	7.21	1.21	0	3
24	**S.AGATA**	**3.01**	**11.28**	**14.30**	**0.34**	**2**	**2**
25	**S.FRUTTUOSO**	**1.47**	**4.17**	**8.86**	**0.49**	**2**	**6**
26	FEREGGIANO	1.84	–	1.84	0.07	0	2
27	**MARASSI**	**3.25**	**5.33**	**8.58**	**0.35**	**1**	**2**
28	FORTE QUEZZI	1.57	–	1.57	0.08	0	2
29	PARENZO	2.89	–	2.89	0.21	0	3
30	**BORGORATTI**	**2.56**	**5.46**	**8.02**	**0.19**	**1**	**3**
31	**CHIAPPETO**	**3.24**	**3.66**	**6.90**	**0.02**	**1**	**2**
32	S.MARTINO	5.16	–	5.16	1.23	0	5
33	**ALBARO**	**3.74**	**24.99**	**28.73**	**0.40**	**4**	**4**
34	S.GIULIANO	3.97	–	3.97	0.12	0	3
35	LIDO	5.62	6.44	5.62	0.10	0	3
36	**PUGGIA**	**2.19**	**14.76**	**16.95**	**0.02**	**3**	**3**
37	STURLA	4.85	5.47	4.85	0.30	0	4
38	QUARTO	7.41	–	7.41	0.37	0	4
39	QUARTARA	6.43	–	6.43	0.00	0	3
40	**CASTAGNA**	**0.41**	**14.65**	**15.06**	**0.26**	**3**	**3**
41	QUINTO	8.29	–	8.29	0.18	0	3
42	NERVI	5.23	–	5.23	0.20	0	6
	Minimum CAI value	–	***3.66***	***3.67***			
	Average CAI value	***3.51***	***4.87***	***8.38***			

Table A.12: Results with $Q^{max} = 40$ & $\ell = 1.3$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_2}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.64	–	5.64	1.88	0	6
2	**CALCINARA**	**3.75**	**5.15**	**8.90**	**0.22**	**1**	**4**
3	**CERTOSA**	**0.00**	**3.94**	**3.94**	**0.30**	**1**	**3**
4	**CORNIGLIANO**	**3.78**	**18.81**	**22.59**	**0.34**	**4**	**4**
5	**CAMPI**	**2.35**	**15.43**	**17.78**	**0.05**	**4**	**4**
6	**CAMPASSO**	**0.00**	**12.59**	**12.59**	**0.21**	**2**	**2**
7	**S.GAETANO**	**0.00**	**11.48**	**11.48**	**0.34**	**2**	**2**
8	SAMPIERDARENA	5.33	–	5.33	1.03	0	3
9	**BELVEDERE**	**1.17**	**9.31**	**10.48**	**0.21**	**2**	**2**
10	**S.BARTOLOMEO**	**1.40**	**12.37**	**13.77**	**0.32**	**2**	**2**
11	**ANGELI**	**1.52**	**19.87**	**21.38**	**0.24**	**3**	**3**
12	**S.TEODORO**	**2.57**	**8.09**	**10.66**	**0.46**	**2**	**3**
13	LAGACCIO	1.35	–	1.35	0.24	0	2
14	PRE’	4.27	–	4.27	1.36	0	2
15	MADDALENA	8.42	–	8.42	0.91	0	2
16	MOLO	3.62	–	3.62	1.35	0	3
17	S.NICOLA	2.10	–	2.10	0.09	0	3
18	CASTELLETTO	2.77	–	2.77	0.40	0	4
19	MANIN	3.14	–	3.14	0.43	0	2
20	S.VINCENZO	5.71	–	5.71	3.40	0	3
21	CARIGNANO	3.67	–	3.67	0.65	0	3
22	FOCE	4.38	–	4.38	0.18	0	2
23	BRIGNOLE	7.21	–	7.21	1.21	0	3
24	**S.AGATA**	**3.01**	**11.28**	**14.30**	**0.34**	**2**	**2**
25	**S.FRUTTUOSO**	**1.47**	**7.39**	**8.86**	**0.49**	**2**	**6**
26	FEREGGIANO	1.84	–	1.84	0.07	0	2
27	MARASSI	3.25	–	3.25	0.35	0	2
28	FORTE QUEZZI	1.57	–	1.57	0.08	0	2
29	PARENZO	2.89	–	2.89	0.21	0	3
30	**BORGORATTI**	**2.56**	**5.46**	**8.02**	**0.19**	**1**	**3**
31	**CHIAPPETO**	**3.24**	**6.78**	**10.02**	**0.02**	**2**	**2**
32	S.MARTINO	5.16	–	5.16	1.23	0	5
33	**ALBARO**	**3.74**	**24.99**	**28.73**	**0.40**	**4**	**4**
34	S.GIULIANO	3.97	–	3.97	0.12	0	3
35	LIDO	5.62	–	5.62	0.10	0	3
36	**PUGGIA**	**2.19**	**14.76**	**16.95**	**0.02**	**3**	**3**
37	STURLA	4.85	–	4.85	0.30	0	4
38	QUARTO	7.41	–	7.41	0.37	0	4
39	QUARTARA	6.43	–	6.43	0.00	0	3
40	**CASTAGNA**	**0.41**	**14.65**	**15.06**	**0.26**	**3**	**3**
41	QUINTO	8.29	–	8.29	0.18	0	3
42	NERVI	5.23	–	5.23	0.20	0	6
	Minimum CAI value	–	***3.94***	***3.94***			
	Average CAI value	***3.51***	***4.82***	***8.32***			

Appendix B

Effects on the values of CAI without considering weight coefficient

This appendix represents the tables showing the effects of on the values of CAI indexes if β_z^t is not considered, for both considered case studies of Trento (Table B.1 during weekdays and Table B.2 during weekend days) and Genova (Table B.3 during day time and Table B.4 during night time).

Table B.1: Results with $Q^{max} = 20$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.73	–	4.73	0.87	0	2
2	Campotrentino	3.38	–	3.38	3.30	0	2
3	San Bartolomeo	2.80	–	2.80	1.51	0	2
4	**Villazzano**	**2.53**	**1.85**	**4.37**	**4.03**	**1**	**3**
5	Clarina	4.11	–	4.11	4.65	0	3
6	**Melta**	**2.51**	**4.33**	**6.84**	**0.73**	**1**	**2**
7	Canova	3.42	–	3.42	1.31	0	2
8	Solteri-Centochiavi	4.82	–	4.82	3.69	0	2
9	San Dona'-Laste	1.83	–	1.83	0.32	0	2
10	Spini-Ghiaie	2.89	–	2.89	6.32	0	4
11	Cristo Re	6.17	–	6.17	1.99	0	2
12	Centro Storico	11.43	–	11.43	2.30	0	2
13	San Bernardino	7.93	–	7.93	0.98	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.04**	**0.04**	**0.03**	**2**	**2**
15	San Lazzaro	1.66	–	1.66	0.13	0	2
16	**Povo**	**3.00**	**4.14**	**7.13**	**3.66**	**1**	**2**
17	Ravina	2.84	–	2.84	4.44	0	3
18	Santissimo	7.87	–	7.87	1.50	0	2
19	**Sopramonte**	**2.50**	**3.33**	**5.83**	**4.98**	**2**	**3**
20	Mattarello	3.30	–	3.30	7.65	0	5
21	Roncafort	2.18	–	2.18	5.46	0	4
22	Madonna Bianca	2.65	–	2.65	1.81	0	2
23	Villazzano 3	2.98	–	2.98	1.00	0	2
24	**Gardolo**	**3.72**	**10.26**	**13.98**	**4.49**	**1**	**3**
25	Gazzadina	3.49	–	3.49	0.81	0	2
26	Meano	2.66	–	2.66	1.89	0	2
27	Cortesano	3.98	–	3.98	0.43	0	2
28	Martignano	2.49	–	2.49	3.98	0	3
29	**Gardolo Di Mezzo**	**0.61**	**0.87**	**1.48**	**0.23**	**1**	**2**
30	**San Martino**	**8.19**	**13.44**	**21.63**	**1.78**	**1**	**2**
31	**Sardagna**	**0.00**	**2.25**	**2.25**	**1.99**	**1**	**2**
32	Lamar	2.52	–	2.52	1.38	0	2
33	La Vela	3.25	–	3.25	1.61	0	2
34	Piedicastello	3.48	–	3.48	1.85	0	2
35	**San Giuseppe**	**4.86**	**19.64**	**24.50**	**4.30**	**1**	**3**
36	Vigo Meano	2.96	–	2.96	0.90	0	2
37	**Valsorda**	**0.00**	**0.26**	**0.26**	**0.20**	**1**	**2**
38	Oltrecastello	1.59	–	1.59	1.80	0	2
39	Cadine	2.27	–	2.27	2.22	0	2
40	Romagnano	2.57	–	2.57	2.10	0	2
41	**Villamontagna**	**1.82**	**1.68**	**3.50**	**1.39**	**2**	**2**
42	Cognola	2.84	–	2.84	3.18	0	2
43	Cappuccini	2.91	–	2.91	1.16	0	2
44	**Baselga Del Bondone**	**0.00**	**0.69**	**0.69**	**0.57**	**1**	**2**
45	San Dona di Cagnola	2.32	–	2.32	1.28	0	2
46	Belvedere-San Francesco	8.56	–	8.56	0.27	0	2
47	Bolghera	6.13	–	6.13	3.07	0	2
48	**Vigolo Baselga**	**0.00**	**0.64**	**0.64**	**0.59**	**1**	**2**
	Minimum CAI value	*–*	*0.04*	*0.04*			
	Average CAI value	*3.35*	*1.32*	*4.67*			

Table B.2: Results with $Q^{max} = 20$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	Campotrentino	2.55	–	2.55	2.20	0	2
3	San Bartolomeo	2.24	–	2.24	1.00	0	2
4	**Villazzano**	**1.95**	**1.42**	**3.37**	**2.69**	**1**	**3**
5	Clarina	2.55	–	2.55	3.10	0	3
6	**Melta**	**0.00**	**4.13**	**4.13**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	Spini-Ghiaie	1.70	–	1.70	4.21	0	4
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**2**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	**Povo**	**2.51**	**3.82**	**6.33**	**2.44**	**1**	**2**
17	Ravina	2.52	–	2.52	2.96	0	3
18	Santissimo	5.91	–	5.91	1.00	0	2
19	**Sopramonte**	**2.03**	**2.48**	**4.51**	**3.32**	**2**	**3**
20	Mattarello	2.70	–	2.70	5.10	0	5
21	Roncafort	2.18	–	2.18	3.64	0	4
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**10.04**	**12.92**	**2.99**	**1**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.80**	**0.80**	**0.16**	**1**	**2**
30	**San Martino**	**5.47**	**13.07**	**18.53**	**1.19**	**1**	**2**
31	**Sardagna**	**0.00**	**1.86**	**1.86**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**19.50**	**23.46**	**2.87**	**1**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.20**	**0.20**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**1.28**	**1.28**	**0.93**	**2**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**0.54**	**0.54**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	Bolghera	3.95	–	3.95	2.05	0	2
48	**Vigolo Baselga**	**0.00**	**0.50**	**0.50**	**0.39**	**1**	**2**
	Minimum CAI value	–	*0.04*	*0.04*			
	Average CAI value	*2.43*	*1.24*	*3.67*			

Table B.3: Results with $Q^{max} = 40$ during day time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	**SESTRI**	**5.79**	**7.43**	**13.22**	**2.76**	**1**	**6**
2	**CALCINARA**	**3.00**	**7.04**	**10.04**	**0.78**	**1**	**4**
3	**CERTOSA**	**12.35**	**5.87**	**18.22**	**1.32**	**1**	**3**
4	**CORNIGLIANO**	**3.31**	**5.90**	**9.21**	**0.99**	**1**	**4**
5	**CAMPI**	**1.75**	**5.19**	**6.94**	**0.30**	**1**	**4**
6	**CAMPASSO**	**0.89**	**6.83**	**7.72**	**0.71**	**1**	**2**
7	**S.GAETANO**	**3.09**	**5.96**	**9.04**	**0.39**	**1**	**2**
8	**SAMPIERDARENA**	**5.91**	**6.67**	**12.58**	**1.93**	**1**	**3**
9	**BELVEDERE**	**1.31**	**6.91**	**8.21**	**0.62**	**1**	**2**
10	**S.BARTOLOMEO**	**2.61**	**5.28**	**7.90**	**0.64**	**1**	**2**
11	**ANGELI**	**2.12**	**7.46**	**9.58**	**0.64**	**1**	**3**
12	**S.TEODORO**	**2.55**	**4.97**	**7.52**	**0.66**	**1**	**3**
13	**LAGACCIO**	**2.18**	**6.90**	**9.08**	**0.90**	**2**	**2**
14	**PRE'**	**6.40**	**5.04**	**11.44**	**3.24**	**1**	**2**
15	**MADDALENA**	**5.84**	**7.07**	**12.91**	**1.27**	**1**	**2**
16	MOLO	12.98	–	12.98	1.97	0	3
17	**S.NICOLA**	**2.75**	**4.73**	**7.48**	**0.96**	**1**	**3**
18	**CASTELLETTO**	**2.38**	**5.06**	**7.44**	**1.26**	**1**	**4**
19	**MANIN**	**4.09**	**4.65**	**8.74**	**0.70**	**1**	**2**
20	S.VINCENZO	9.32	–	9.32	3.13	0	3
21	**CARIGNANO**	**5.03**	**5.47**	**10.50**	**0.46**	**1**	**3**
22	**FOCE**	**5.55**	**5.33**	**10.88**	**0.21**	**1**	**2**
23	BRIGNOLE	8.61	–	8.61	4.86	0	3
24	**S.AGATA**	**4.05**	**7.15**	**11.20**	**1.25**	**1**	**2**
25	**S.FRUTTUOSO**	**2.09**	**5.19**	**7.28**	**1.81**	**1**	**6**
26	**FEREGGIANO**	**2.47**	**5.11**	**7.58**	**0.50**	**1**	**2**
27	**MARASSI**	**4.68**	**5.03**	**9.71**	**0.82**	**1**	**2**
28	**FORTE QUEZZI**	**2.09**	**6.58**	**8.67**	**0.40**	**2**	**2**
29	**PARENZO**	**3.21**	**5.83**	**9.05**	**0.84**	**1**	**3**
30	**BORGORATTI**	**2.64**	**5.22**	**7.86**	**0.35**	**1**	**3**
31	**CHIAPPETO**	**1.94**	**5.36**	**7.30**	**0.70**	**1**	**2**
32	**S.MARTINO**	**5.36**	**5.82**	**11.18**	**1.07**	**1**	**5**
33	**ALBARO**	**4.27**	**7.12**	**11.39**	**1.09**	**1**	**4**
34	**S.GIULIANO**	**4.14**	**4.31**	**8.45**	**0.38**	**1**	**3**
35	**LIDO**	**5.04**	**7.76**	**12.79**	**0.24**	**1**	**3**
36	**PUGGIA**	**3.57**	**5.67**	**9.24**	**0.29**	**1**	**3**
37	**STURLA**	**4.53**	**7.07**	**11.60**	**0.58**	**1**	**4**
38	**QUARTO**	**4.25**	**2.71**	**6.96**	**0.29**	**1**	**4**
39	**QUARTARA**	**4.61**	**4.48**	**9.10**	**0.90**	**1**	**3**
40	**CASTAGNA**	**0.34**	**7.12**	**7.46**	**0.52**	**1**	**3**
41	**QUINTO**	**3.26**	**3.08**	**6.33**	**0.24**	**1**	**3**
42	NERVI	7.02	–	7.02	0.32	0	6
	Minimum CAI value	–	***2.71***	***6.33***			
	Average CAI value	***4.27***	***5.27***	***9.52***			

Table B.4: Results with $Q^{max} = 40$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	**SESTRI**	**5.64**	**5.45**	**11.09**	**1.88**	**1**	**6**
2	**CALCINARA**	**3.75**	**5.15**	**8.90**	**0.22**	**1**	**4**
3	**CERTOSA**	**0.00**	**3.94**	**3.94**	**0.30**	**1**	**3**
4	**CORNIGLIANO**	**3.78**	**3.91**	**7.69**	**0.34**	**1**	**4**
5	**CAMPI**	**2.35**	**3.55**	**5.90**	**0.05**	**1**	**4**
6	**CAMPASSO**	**0.00**	**4.84**	**4.84**	**0.21**	**1**	**2**
7	**S.GAETANO**	**0.00**	**4.46**	**4.46**	**0.34**	**1**	**2**
8	**SAMPIERDARENA**	**5.33**	**4.67**	**10.00**	**1.03**	**1**	**3**
9	**BELVEDERE**	**1.17**	**5.14**	**6.32**	**0.21**	**1**	**2**
10	**S.BARTOLOMEO**	**1.40**	**3.63**	**5.03**	**0.32**	**1**	**2**
11	**ANGELI**	**1.52**	**5.57**	**7.09**	**0.24**	**1**	**3**
12	**S.TEODORO**	**2.57**	**3.21**	**5.78**	**0.46**	**1**	**3**
13	**LAGACCIO**	**1.35**	**3.03**	**4.38**	**0.24**	**2**	**2**
14	**PRE’**	**4.27**	**3.08**	**7.36**	**1.36**	**1**	**2**
15	**MADDALENA**	**8.42**	**5.15**	**13.58**	**0.91**	**1**	**2**
16	MOLO	3.62	–	3.62	1.35	0	3
17	**S.NICOLA**	**2.10**	**2.35**	**4.46**	**0.09**	**1**	**3**
18	**CASTELLETTO**	**2.77**	**3.23**	**6.00**	**0.40**	**1**	**4**
19	**MANIN**	**3.14**	**2.87**	**6.01**	**0.43**	**1**	**2**
20	S.VINCENZO	5.71	–	5.71	3.40	0	3
21	**CARIGNANO**	**3.67**	**3.80**	**7.46**	**0.65**	**1**	**3**
22	**FOCE**	**4.38**	**4.06**	**8.44**	**0.18**	**1**	**2**
23	BRIGNOLE	7.21	–	7.21	1.21	0	3
24	**S.AGATA**	**3.01**	**5.26**	**8.28**	**0.34**	**1**	**2**
25	**S.FRUTTUOSO**	**1.47**	**3.22**	**4.69**	**0.49**	**1**	**6**
26	**FEREGGIANO**	**1.84**	**3.32**	**5.16**	**0.07**	**1**	**2**
27	**MARASSI**	**3.25**	**3.08**	**6.32**	**0.35**	**1**	**2**
28	**FORTE QUEZZI**	**1.57**	**3.30**	**4.87**	**0.08**	**2**	**2**
29	**PARENZO**	**2.89**	**3.87**	**6.76**	**0.21**	**1**	**3**
30	**BORGORATTI**	**2.56**	**3.68**	**6.24**	**0.19**	**1**	**3**
31	**CHIAPPETO**	**3.24**	**3.12**	**6.36**	**0.02**	**1**	**2**
32	**S.MARTINO**	**5.16**	**3.82**	**8.99**	**1.23**	**1**	**5**
33	**ALBARO**	**3.74**	**5.17**	**8.91**	**0.40**	**1**	**4**
34	**S.GIULIANO**	**3.97**	**2.81**	**6.78**	**0.12**	**1**	**3**
35	**LIDO**	**5.62**	**6.44**	**12.06**	**0.10**	**1**	**3**
36	**PUGGIA**	**2.19**	**4.04**	**6.22**	**0.02**	**1**	**3**
37	**STURLA**	**4.85**	**5.35**	**10.20**	**0.30**	**1**	**4**
38	**QUARTO**	**7.41**	**2.19**	**9.60**	**0.37**	**1**	**4**
39	**QUARTARA**	**6.43**	**5.51**	**11.94**	**0.00**	**1**	**3**
40	**CASTAGNA**	**0.41**	**1.87**	**2.28**	**0.26**	**1**	**3**
41	**QUINTO**	**8.29**	**–**	**8.29**	**0.18**	**1**	**3**
42	NERVI	5.23	–	5.23	0.20	0	6
	Minimum CAI value	*–*	***1.87***	***2.28***			
	Average CAI value	***3.51***	***3.50***	***7.01***			

Appendix C

Effects on the values of CAI when only weight coefficient is considered without considering null CAI Constraint

This appendix represents the tables showing the effects on the values of CAI indexes if only β_z^t is considered without considering null CAI_{PT}^t constraint, for both considered case studies of Trento (Table C.1 during weekdays and Table C.2 during weekend days) and Genova (Table C.3 during day time and Table C.4 during night time).

Table C.1: Results with $Q^{max} = 20$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	**San Pio X**	**4.73**	**11.56**	**16.29**	**0.87**	**1**	**2**
2	**Campotrentino**	**3.38**	**20.11**	**23.48**	**3.30**	**2**	**2**
3	**San Bartolomeo**	**2.80**	**13.43**	**16.22**	**1.51**	**1**	**2**
4	Villazzano	2.53	–	2.53	4.03	0	3
5	**Clarina**	**4.11**	**23.08**	**27.19**	**4.65**	**2**	**3**
6	Melta	2.51	–	2.51	0.73	0	2
7	Canova	3.42	–	3.42	1.31	0	2
8	**Solteri-Centochiavi**	**4.82**	**23.09**	**27.90**	**3.69**	**2**	**2**
9	San Dona'-Laste	1.83	–	1.83	0.32	0	2
10	**Spini-Ghiaie**	**2.89**	**20.55**	**23.45**	**6.32**	**2**	**4**
11	Cristo Re	6.17	–	6.17	1.99	0	2
12	Centro Storico	11.43	–	11.43	2.30	0	2
13	San Bernardino	7.93	–	7.93	0.98	0	2
14	Campo Nomadi Rav.	0.00	–	–	0.03	0	2
15	San Lazzaro	1.66	–	1.66	0.13	0	2
16	Povo	3.00	–	3.00	3.66	0	2
17	Ravina	2.84	–	2.84	4.44	0	3
18	**Santissimo**	**7.87**	**21.83**	**29.70**	**1.50**	**1**	**2**
19	Sopramonte	2.50	–	2.50	4.98	0	3
20	Mattarello	3.30	–	3.30	7.65	0	5
21	**Roncafort**	**2.18**	**10.90**	**13.08**	**5.46**	**1**	**4**
22	Madonna Bianca	2.65	–	2.65	1.81	0	2
23	Villazzano 3	2.98	–	2.98	1.00	0	2
24	**Gardolo**	**3.72**	**32.69**	**36.42**	**4.49**	**3**	**3**
25	Gazzadina	3.49	–	3.49	0.81	0	2
26	Meano	2.66	–	2.66	1.89	0	2
27	Cortesano	3.98	–	3.98	0.43	0	2
28	Martignano	2.49	–	2.49	3.98	0	3
29	Gardolo Di Mezzo	0.61	–	0.61	0.23	0	2
30	**San Martino**	**8.19**	**21.88**	**30.07**	**1.78**	**1**	**2**
31	Sardagna	0.00	–	–	1.99	0	2
32	Lamar	2.52	–	2.52	1.38	0	2
33	La Vela	3.25	–	3.25	1.61	0	2
34	Piedicastello	3.48	–	3.48	1.85	0	2
35	**San Giuseppe**	**4.86**	**36.29**	**41.15**	**4.30**	**2**	**3**
36	Vigo Meano	2.96	–	2.96	0.90	0	2
37	Valsorda	0.00	–	–	0.20	0	2
38	Oltrecastello	1.59	–	1.59	1.80	0	2
39	Cadine	2.27	–	2.27	2.22	0	2
40	Romagnano	2.57	–	2.57	2.10	0	2
41	Villamontagna	1.82	–	1.82	1.39	0	2
42	Cognola	2.84	–	2.84	3.18	0	2
43	Cappuccini	2.91	–	2.91	1.16	0	2
44	Baselga Del Bondone	0.00	–	–	0.57	0	2
45	San Dona di Cagnola	2.32	–	2.32	1.28	0	2
46	Belvedere-San Francesco	8.56	–	8.56	0.27	0	2
47	**Bolghera**	**6.13**	**29.52**	**35.66**	**3.07**	**2**	**2**
48	Vigolo Baselga	0.00	–	–	0.59	0	2
	Minimum CAI value	–	***10.90***	***13.08***			
	Average CAI value	***3.35***	***5.52***	***8.87***			

Table C.2: Results with $Q^{max} = 20$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	**San Pio X**	**4.08**	**11.39**	**15.46**	**0.58**	**1**	**2**
2	**Campotrentino**	**2.55**	**19.23**	**21.78**	**2.20**	**2**	**2**
3	**San Bartolomeo**	**2.24**	**13.20**	**15.44**	**1.00**	**1**	**2**
4	Villazzano	1.95	–	1.95	2.69	0	3
5	**Clarina**	**2.55**	**22.83**	**25.38**	**3.10**	**2**	**3**
6	Melta	0.00	–	–	0.49	0	2
7	Canova	3.10	–	3.10	0.87	0	2
8	**Solteri-Centochiavi**	**4.11**	**22.20**	**26.31**	**2.46**	**2**	**2**
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	**Spini-Ghiaie**	**1.70**	**20.13**	**21.84**	**4.21**	**2**	**4**
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	Campo Nomadi Rav.	0.00	–	–	0.02	0	2
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	**Santissimo**	**5.91**	**21.63**	**27.54**	**1.00**	**1**	**2**
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	**Roncafort**	**2.18**	**10.51**	**12.69**	**3.64**	**1**	**4**
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	**Gardolo**	**2.88**	**32.02**	**34.90**	**2.99**	**3**	**3**
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	Gardolo Di Mezzo	0.00	–	–	0.16	0	2
30	**San Martino**	**5.47**	**21.51**	**26.98**	**1.19**	**1**	**2**
31	Sardagna	0.00	–	–	1.32	0	2
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	**San Giuseppe**	**3.97**	**36.00**	**39.97**	**2.87**	**2**	**3**
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	Valsorda	0.00	–	–	0.13	0	2
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	Villamontagna	0.00	–	–	0.93	0	2
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	Baselga Del Bondone	0.00	–	–	0.38	0	2
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	**Bolghera**	**3.95**	**29.07**	**33.02**	**2.05**	**2**	**2**
48	Vigolo Baselga	0.00	–	–	0.39	0	2
	Minimum CAI value	–	***10.51***	***12.69***			
	Average CAI value	***2.43***	***5.41***	***7.84***			

Table C.3: Results with $Q^{max} = 40$ during day time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.79	–	5.79	2.76	0	6
2	**CALCINARA**	**3.00**	**7.04**	**10.04**	**0.78**	**1**	**4**
3	CERTOSA	12.35	–	12.35	1.32	0	3
4	**CORNIGLIANO**	**3.31**	**26.78**	**30.09**	**0.99**	**4**	**4**
5	**CAMPI**	**1.75**	**16.79**	**18.54**	**0.30**	**3**	**4**
6	**CAMPASSO**	**0.89**	**16.56**	**17.45**	**0.71**	**2**	**2**
7	**S.GAETANO**	**3.09**	**14.47**	**17.55**	**0.39**	**2**	**2**
8	SAMPIERDARENA	5.91	–	5.91	1.93	0	3
9	**BELVEDERE**	**1.31**	**12.83**	**14.14**	**0.62**	**2**	**2**
10	**S.BARTOLOMEO**	**2.61**	**15.68**	**18.30**	**0.64**	**2**	**2**
11	**ANGELI**	**2.12**	**25.54**	**27.66**	**0.64**	**3**	**3**
12	**S.TEODORO**	**2.55**	**11.60**	**14.15**	**0.66**	**2**	**3**
13	LAGACCIO	2.18	–	2.18	0.90	0	2
14	PRE’	6.40	–	6.40	3.24	0	2
15	MADDALENA	5.84	–	5.84	1.27	0	2
16	MOLO	12.98	–	12.98	1.97	0	3
17	S.NICOLA	2.75	–	2.75	0.96	0	3
18	CASTELLETTO	2.38	–	2.38	1.26	0	4
19	MANIN	4.09	–	4.09	0.70	0	2
20	S.VINCENZO	9.32	–	9.32	3.13	0	3
21	**CARIGNANO**	**5.03**	**7.43**	**12.47**	**0.46**	**1**	**3**
22	FOCE	5.55	–	5.55	0.21	0	2
23	BRIGNOLE	8.61	–	8.61	4.86	0	3
24	**S.AGATA**	**4.05**	**15.05**	**19.11**	**1.25**	**2**	**2**
25	**S.FRUTTUOSO**	**2.09**	**6.15**	**8.24**	**1.81**	**1**	**6**
26	FEREGGIANO	2.47	–	2.47	0.50	0	2
27	**MARASSI**	**4.68**	**7.29**	**11.97**	**0.82**	**1**	**2**
28	FORTE QUEZZI	2.09	–	2.09	0.40	0	2
29	PARENZO	3.21	–	3.21	0.84	0	3
30	**BORGORATTI**	**2.64**	**7.00**	**9.64**	**0.35**	**1**	**3**
31	**CHIAPPETO**	**1.94**	**5.90**	**7.84**	**0.70**	**1**	**2**
32	**S.MARTINO**	**5.36**	**7.91**	**13.27**	**1.07**	**1**	**5**
33	**ALBARO**	**4.27**	**32.79**	**37.06**	**1.09**	**4**	**4**
34	S.GIULIANO	4.14	–	4.14	0.38	0	3
35	LIDO	5.04	–	5.04	0.24	0	3
36	**PUGGIA**	**3.57**	**19.66**	**23.23**	**0.29**	**3**	**3**
37	**STURLA**	**4.53**	**7.19**	**11.72**	**0.58**	**1**	**4**
38	QUARTO	4.25	–	4.25	0.29	0	4
39	QUARTARA	4.61	–	4.61	0.90	0	3
40	**CASTAGNA**	**0.34**	**19.49**	**19.83**	**0.52**	**3**	**3**
41	QUINTO	3.26	–	3.26	0.24	0	3
42	NERVI	7.02	–	7.02	0.32	0	6
	Minimum CAI value	*–*	***5.90***	***7.84***			
	Average CAI value	***4.27***	***6.74***	***11.01***			

Table C.4: Results with $Q^{max} = 40$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.64	–	5.64	1.88	0	6
2	**CALCINARA**	**3.75**	**5.15**	**8.90**	**0.22**	**1**	**4**
3	CERTOSA	0.00	–	0.00	0.30	0	3
4	**CORNIGLIANO**	**3.78**	**18.81**	**22.59**	**0.34**	**4**	**4**
5	**CAMPI**	**2.35**	**11.87**	**14.22**	**0.05**	**3**	**4**
6	**CAMPASSO**	**0.00**	**12.59**	**12.59**	**0.21**	**2**	**2**
7	**S.GAETANO**	**0.00**	**11.48**	**11.48**	**0.34**	**2**	**2**
8	SAMPIERDARENA	5.33	–	5.33	1.03	0	3
9	**BELVEDERE**	**1.17**	**9.31**	**10.48**	**0.21**	**2**	**2**
10	**S.BARTOLOMEO**	**1.40**	**12.37**	**13.77**	**0.32**	**2**	**2**
11	**ANGELI**	**1.52**	**19.87**	**21.38**	**0.24**	**3**	**3**
12	**S.TEODORO**	**2.57**	**8.09**	**10.66**	**0.46**	**2**	**3**
13	LAGACCIO	1.35	–	1.35	0.24	0	2
14	PRE’	4.27	–	4.27	1.36	0	2
15	MADDALENA	8.42	–	8.42	0.91	0	2
16	MOLO	3.62	–	3.62	1.35	0	3
17	S.NICOLA	2.10	–	2.10	0.09	0	3
18	CASTELLETTO	2.77	–	2.77	0.40	0	4
19	MANIN	3.14	–	3.14	0.43	0	2
20	S.VINCENZO	5.71	–	5.71	3.40	0	3
21	**CARIGNANO**	**3.67**	**5.76**	**9.43**	**0.65**	**1**	**3**
22	FOCE	4.38	–	4.38	0.18	0	2
23	BRIGNOLE	7.21	–	7.21	1.21	0	3
24	**S.AGATA**	**3.01**	**11.28**	**14.30**	**0.34**	**2**	**2**
25	**S.FRUTTUOSO**	**1.47**	**4.17**	**5.64**	**0.49**	**1**	**6**
26	FEREGGIANO	1.84	–	1.84	0.07	0	2
27	**MARASSI**	**3.25**	**5.33**	**8.58**	**0.35**	**1**	**2**
28	FORTE QUEZZI	1.57	–	1.57	0.08	0	2
29	PARENZO	2.89	–	2.89	0.21	0	3
30	**BORGORATTI**	**2.56**	**5.46**	**8.02**	**0.19**	**1**	**3**
31	**CHIAPPETO**	**3.24**	**3.66**	**6.90**	**0.02**	**1**	**2**
32	**S.MARTINO**	**5.16**	**5.91**	**11.07**	**1.23**	**1**	**5**
33	**ALBARO**	**3.74**	**24.99**	**28.73**	**0.40**	**4**	**4**
34	S.GIULIANO	3.97	–	3.97	0.12	0	3
35	LIDO	5.62	–	5.62	0.10	0	3
36	**PUGGIA**	**2.19**	**14.76**	**16.95**	**0.02**	**3**	**3**
37	**STURLA**	**4.85**	**5.47**	**10.32**	**0.30**	**1**	**4**
38	QUARTO	7.41	–	7.41	0.37	0	4
39	QUARTARA	6.43	–	6.43	0.00	0	3
40	**CASTAGNA**	**0.41**	**14.65**	**15.06**	**0.26**	**3**	**3**
41	QUINTO	8.29	–	8.29	0.18	0	3
42	NERVI	5.23	–	5.23	0.20	0	6
	Minimum CAI value	–	***3.66***	***5.64***			
	Average CAI value	***3.51***	***5.02***	***8.53***			

Appendix D

Effects on the values of CAI when resource assignment is restricted only to the disadvantaged zones

This appendix represents the tables showing the effects on the values of CAI indexes by forcing the model to limit the resource assignment to the disadvantaged zones, for both considered case studies of Trento (Table D.1 during weekdays and Table D.2 during weekend days) and Genova (Table D.3 during day time and Table D.4 during night time). The values are adjusted by increasing the shape parameter ℓ till the resource assignment is restricted only to the disadvantaged zones.

Table D.1: Results with $Q^{max} = 20$ and $\ell = 7$ during weekdays for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.73	–	4.73	0.87	0	2
2	Campotrentino	3.38	–	3.38	3.30	0	2
3	San Bartolomeo	2.80	–	2.80	1.51	0	2
4	Villazzano	2.53	–	2.53	4.03	0	3
5	Clarina	4.11	–	4.11	4.65	0	3
6	**Melta**	**2.51**	**4.33**	**6.84**	**0.73**	**1**	**2**
7	Canova	3.42	–	3.42	1.31	0	2
8	Solteri-Centochiavi	4.82	–	4.82	3.69	0	2
9	San Dona'-Laste	1.83	–	1.83	0.32	0	2
10	Spini-Ghiaie	2.89	–	2.89	6.32	0	4
11	Cristo Re	6.17	–	6.17	1.99	0	2
12	Centro Storico	11.43	–	11.43	2.30	0	2
13	San Bernardino	7.93	–	7.93	0.98	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.04**	**0.04**	**0.03**	**1**	**2**
15	San Lazzaro	1.66	–	1.66	0.13	0	2
16	Povo	3.00	–	3.00	3.66	0	2
17	Ravina	2.84	–	2.84	4.44	0	3
18	Santissimo	7.87	–	7.87	1.50	0	2
19	Sopramonte	2.50	–	2.50	4.98	0	3
20	Mattarello	3.30	–	3.30	7.65	0	5
21	Roncafort	2.18	–	2.18	5.46	0	4
22	Madonna Bianca	2.65	–	2.65	1.81	0	2
23	Villazzano 3	2.98	–	2.98	1.00	0	2
24	Gardolo	3.72	–	3.72	4.49	0	3
25	Gazzadina	3.49	–	3.49	0.81	0	2
26	Meano	2.66	–	2.66	1.89	0	2
27	Cortesano	3.98	–	3.98	0.43	0	2
28	Martignano	2.49	–	2.49	3.98	0	3
29	**Gardolo Di Mezzo**	**0.61**	**0.48**	**1.09**	**0.23**	**1**	**2**
30	San Martino	8.19	–	8.19	1.78	0	2
31	**Sardagna**	**0.00**	**2.66**	**2.66**	**1.99**	**1**	**2**
32	Lamar	2.52	–	2.52	1.38	0	2
33	La Vela	3.25	–	3.25	1.61	0	2
34	Piedicastello	3.48	–	3.48	1.85	0	2
35	San Giuseppe	4.86	–	4.86	4.30	0	3
36	Vigo Meano	2.96	–	2.96	0.90	0	2
37	**Valsorda**	**0.00**	**0.26**	**0.26**	**0.20**	**1**	**2**
38	Oltrecastello	1.59	–	1.59	1.80	0	2
39	Cadine	2.27	–	2.27	2.22	0	2
40	Romagnano	2.57	–	2.57	2.10	0	2
41	**Villamontagna**	**1.82**	**1.40**	**3.22**	**1.39**	**1**	**2**
42	Cognola	2.84	–	2.84	3.18	0	2
43	Cappuccini	2.91	–	2.91	1.16	0	2
44	**Baselga Del Bondone**	**0.00**	**0.69**	**0.69**	**0.57**	**1**	**2**
45	San Dona di Cagnola	2.32	–	2.32	1.28	0	2
46	Belvedere-San Francesco	8.56	–	8.56	0.27	0	2
47	Bolghera	6.13	–	6.13	3.07	0	2
48	**Vigolo Baselga**	**0.00**	**0.70**	**0.70**	**0.59**	**1**	**2**
	Minimum CAI value	–	*0.04*	*0.04*			
	Average CAI value	*3.35*	*0.22*	*3.57*			

Table D.2: Results with $Q^{max} = 20$ and $\ell = 7$ during weekend days for Trento

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	San Pio X	4.08	–	4.08	0.58	0	2
2	Campotrentino	2.55	–	2.55	2.20	0	2
3	San Bartolomeo	2.24	–	2.24	1.00	0	2
4	Villazzano	1.95	–	1.95	2.69	0	3
5	Clarina	2.55	–	2.55	3.10	0	3
6	**Melta**	**0.00**	**4.13**	**4.13**	**0.49**	**1**	**2**
7	Canova	3.10	–	3.10	0.87	0	2
8	Solteri-Centochiavi	4.11	–	4.11	2.46	0	2
9	San Dona'-Laste	1.55	–	1.55	0.21	0	2
10	Spini-Ghiaie	1.70	–	1.70	4.21	0	4
11	Cristo Re	4.50	–	4.50	1.32	0	2
12	Centro Storico	8.31	–	8.31	1.53	0	2
13	San Bernardino	5.55	–	5.55	0.65	0	2
14	**Campo Nomadi Rav.**	**0.00**	**0.03**	**0.03**	**0.02**	**1**	**2**
15	San Lazzaro	0.99	–	0.99	0.09	0	2
16	Povo	2.51	–	2.51	2.44	0	2
17	Ravina	2.52	–	2.52	2.96	0	3
18	Santissimo	5.91	–	5.91	1.00	0	2
19	Sopramonte	2.03	–	2.03	3.32	0	3
20	Mattarello	2.70	–	2.70	5.10	0	5
21	Roncafort	2.18	–	2.18	3.64	0	4
22	Madonna Bianca	1.60	–	1.60	1.21	0	2
23	Villazzano 3	1.65	–	1.65	0.67	0	2
24	Gardolo	2.88	–	2.88	2.99	0	3
25	Gazzadina	1.99	–	1.99	0.54	0	2
26	Meano	1.35	–	1.35	1.26	0	2
27	Cortesano	1.79	–	1.79	0.29	0	2
28	Martignano	2.15	–	2.15	2.65	0	3
29	**Gardolo Di Mezzo**	**0.00**	**0.41**	**0.41**	**0.16**	**1**	**2**
30	San Martino	5.47	–	5.47	1.19	0	2
31	**Sardagna**	**0.00**	**2.27**	**2.27**	**1.32**	**1**	**2**
32	Lamar	1.85	–	1.85	0.92	0	2
33	La Vela	2.32	–	2.32	1.07	0	2
34	Piedicastello	2.21	–	2.21	1.23	0	2
35	San Giuseppe	3.97	–	3.97	2.87	0	3
36	Vigo Meano	1.81	–	1.81	0.60	0	2
37	**Valsorda**	**0.00**	**0.20**	**0.20**	**0.13**	**1**	**2**
38	Oltrecastello	2.10	–	2.10	1.20	0	2
39	Cadine	1.68	–	1.68	1.48	0	2
40	Romagnano	1.88	–	1.88	1.40	0	2
41	**Villamontagna**	**0.00**	**1.10**	**1.10**	**0.93**	**1**	**2**
42	Cognola	2.20	–	2.20	2.12	0	2
43	Cappuccini	5.33	–	5.33	0.77	0	2
44	**Baselga Del Bondone**	**0.00**	**0.54**	**0.54**	**0.38**	**1**	**2**
45	San Dona di Cagnola	1.54	–	1.54	0.85	0	2
46	Belvedere-San Francesco	5.93	–	5.93	0.18	0	2
47	Bolghera	3.95	–	3.95	2.05	0	2
48	**Vigolo Baselga**	**0.00**	**0.56**	**0.56**	**0.39**	**1**	**2**
	Minimum CAI value	–	***0.03***	***0.03***			
	Average CAI value	***2.43***	***0.19***	***2.62***			

Table D.3: Results with $Q^{max} = 40$ and $\ell = 26$ during day time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.79	–	5.79	2.76	0	6
2	CALCINARA	3.00	–	3.00	0.78	0	4
3	**CERTOSA**	**12.35**	**10.93**	**23.28**	**1.32**	**3**	**3**
4	CORNIGLIANO	3.31	–	3.31	0.99	0	4
5	CAMPI	1.75	–	1.75	0.30	0	4
6	**CAMPASSO**	**0.89**	**8.51**	**9.41**	**0.71**	**1**	**2**
7	**S.GAETANO**	**3.09**	**5.96**	**9.04**	**0.39**	**1**	**2**
8	SAMPIERDARENA	5.91	–	5.91	1.93	0	3
9	BELVEDERE	1.31	–	1.31	0.62	0	2
10	S.BARTOLOMEO	2.61	–	2.61	0.64	0	2
11	ANGELI	2.12	–	2.12	0.64	0	3
12	S.TEODORO	2.55	–	2.55	0.66	0	3
13	LAGACCIO	2.18	–	2.18	0.90	0	2
14	PRE’	6.40	–	6.40	3.24	0	2
15	MADDALENA	5.84	–	5.84	1.27	0	2
16	MOLO	12.98	–	12.98	1.97	0	3
17	S.NICOLA	2.75	–	2.75	0.96	0	3
18	CASTELLETTO	2.38	–	2.38	1.26	0	4
19	MANIN	4.09	–	4.09	0.70	0	2
20	S.VINCENZO	9.32	–	9.32	3.13	0	3
21	CARIGNANO	5.03	–	5.03	0.46	0	3
22	FOCE	5.55	–	5.55	0.21	0	2
23	BRIGNOLE	8.61	–	8.61	4.86	0	3
24	S.AGATA	4.05	–	4.05	1.25	0	2
25	S.FRUTTUOSO	2.09	–	2.09	1.81	0	6
26	FEREGGIANO	2.47	–	2.47	0.50	0	2
27	MARASSI	4.68	–	4.68	0.82	0	2
28	FORTE QUEZZI	2.09	–	2.09	0.40	0	2
29	PARENZO	3.21	–	3.21	0.84	0	3
30	BORGORATTI	2.64	–	2.64	0.35	0	3
31	CHIAPPETO	1.94	–	1.94	0.70	0	2
32	S.MARTINO	5.36	–	5.36	1.07	0	5
33	ALBARO	4.27	–	4.27	1.09	0	4
34	S.GIULIANO	4.14	–	4.14	0.38	0	3
35	LIDO	5.04	–	5.04	0.24	0	3
36	PUGGIA	3.57	–	3.57	0.29	0	3
37	STURLA	4.53	–	4.53	0.58	0	4
38	QUARTO	4.25	–	4.25	0.29	0	4
39	QUARTARA	4.61	–	4.61	0.90	0	3
40	CASTAGNA	0.34	–	0.34	0.52	0	3
41	QUINTO	3.26	–	3.26	0.24	0	3
42	NERVI	7.02	–	7.02	0.32	0	6
Minimum CAI value		–	***5.96***	***9.04***			
Average CAI value		***4.27***	***0.60***	***4.88***			

Table D.4: Results with $Q^{max} = 40$ and $\ell = 26$ during night time for Genova

Zone ID	Zone Name	CAI_{PT}	CAI_{CS}	CAI_{Tot}	$D_z^{t_1}$	$\sum_v x_{k,z,v}$	Q_z^{max}
1	SESTRI	5.64	–	5.64	1.88	0	6
2	CALCINARA	3.75	–	3.75	0.22	0	4
3	**CERTOSA**	**0.00**	**4.52**	**4.52**	**0.30**	**3**	**3**
4	CORNIGLIANO	3.78	–	3.78	0.34	0	4
5	CAMPI	2.35	–	2.35	0.05	0	4
6	**CAMPASSO**	**0.00**	**6.53**	**6.53**	**0.21**	**1**	**2**
7	**S.GAETANO**	**0.00**	**4.46**	**4.46**	**0.34**	**1**	**2**
8	SAMPIERDARENA	5.33	–	5.33	1.03	0	3
9	BELVEDERE	1.17	–	1.17	0.21	0	2
10	S.BARTOLOMEO	1.40	–	1.40	0.32	0	2
11	ANGELI	1.52	–	1.52	0.24	0	3
12	S.TEODORO	2.57	–	2.57	0.46	0	3
13	LAGACCIO	1.35	–	1.35	0.24	0	2
14	PRE’	4.27	–	4.27	1.36	0	2
15	MADDALENA	8.42	–	8.42	0.91	0	2
16	MOLO	3.62	–	3.62	1.35	0	3
17	S.NICOLA	2.10	–	2.10	0.09	0	3
18	CASTELLETTO	2.77	–	2.77	0.40	0	4
19	MANIN	3.14	–	3.14	0.43	0	2
20	S.VINCENZO	5.71	–	5.71	3.40	0	3
21	CARIGNANO	3.67	–	3.67	0.65	0	3
22	FOCE	4.38	–	4.38	0.18	0	2
23	BRIGNOLE	7.21	–	7.21	1.21	0	3
24	S.AGATA	3.01	–	3.01	0.34	0	2
25	S.FRUTTUOSO	1.47	–	1.47	0.49	0	6
26	FEREGGIANO	1.84	–	1.84	0.07	0	2
27	MARASSI	3.25	–	3.25	0.35	0	2
28	FORTE QUEZZI	1.57	–	1.57	0.08	0	2
29	PARENZO	2.89	–	2.89	0.21	0	3
30	BORGORATTI	2.56	–	2.56	0.19	0	3
31	CHIAPPETO	3.24	–	3.24	0.02	0	2
32	S.MARTINO	5.16	–	5.16	1.23	0	5
33	ALBARO	3.74	–	3.74	0.40	0	4
34	S.GIULIANO	3.97	–	3.97	0.12	0	3
35	LIDO	5.62	–	5.62	0.10	0	3
36	PUGGIA	2.19	–	2.19	0.02	0	3
37	STURLA	4.85	–	4.85	0.30	0	4
38	QUARTO	7.41	–	7.41	0.37	0	4
39	QUARTARA	6.43	–	6.43	0.00	0	3
40	CASTAGNA	0.41	–	0.41	0.26	0	3
41	QUINTO	8.29	–	8.29	0.18	0	3
42	NERVI	5.23	–	5.23	0.20	0	6
	Minimum CAI value	–	***4.46***	***4.46***			
	Average CAI value	***3.51***	***0.37***	***3.88***			

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