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Research Article

Spatial Decision Support System for Efficient School Location-Allocation

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Keywords

Spatial Decision Support System, Location-Allocation, P-median, GIS, Spatial optimization

Abstract

In Greece, a lack of a planning strategy was identified in the context of allocating students to schools. Particularly, the Secondary Educational Management of Lesvos Prefecture along with school Principals decide upon student allocation based on empirical knowledge and approximation techniques. As a consequence, during the school season of 2018-2019 capacity and proximity limitations were violated. This study introduces a Spatial Decision Support System (SDSS) to assist school location-allocation decisions in future seasons. The objective of the proposed SDSS is to minimize commute-to-school distance concerning capacity and proximity limitations. For this purpose, a capacitated P-median approach is adopted and formulated as a mixed-integer linear problem. The SDSS is further evaluated using actual data for students' transition from primary to secondary education in the city of Mytilene, Greece. Evaluation of current allocation practices carried out and further compared to those obtained by the SDSS. The results indicate a decrease of 8% in total distance whereas proximity and capacity constraints were respected accordingly. The results may be potentially useful for school planners to assist the allocation decisions in the city of Mytilene.

Highlights:

-Use of the P-median Problem with Capacity Limitations to Minimize Commute-to-School Distance

-Development of an SDSS Suitable for School Location-Allocation Decision-Making

-Traveling Distance Decrease by 8% in Comparison with Current Student Allocations for the School Season 2018-2019

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1. INTRODUCTION

According to Article 16 of the Greek Constitution (Hellenic Parliament, 2008), all Greek citizens are entitled to free and equal access to the public education system. Educational equity and spatial accessibility to the school network are important and high prioritized aspects of public service planning in a quite fragmented geographical space such as Greece. Public education provision requires significant capital investments to build, maintain and manage the school network. Moreover, the school network should be well operating and easily accessible for a long time as well as resilient to urban and population changes (Owen & Daskin, 1998). It is though important to select the best school locations to optimally serve the student population. In Greece, due to lack of a common planning strategy for optimal school site selection accompanied by the unplanned expansion of Greek cities adds an extra layer of complexity especially when the aim is to minimize commute-to-school distance concerning enrollment constraints.

The problem arises annually when local educational authorities decide upon students' assignments to school units, based solely on empirical knowledge and approximation techniques. Student allocation is an important task that may affect the operation of school units as well as may cause resource allocation anomalies. For example, overcrowded school units may require more resources (financial, material, infrastructure, and human resources) in order to ensure the good operation of school units and the quality of the education provision as well. When such a problem occurs usually is resolved during the school season. Student allocation is a rather complex task that requires assignment to the closest facility with respect to school capacity limitations.

The conceptual framework of location-allocation modeling may be insightful in school network planning. Given a set of candidate facilities, a set of known demands, and a metric system to calculate costs, location-allocation finds the best locations that optimally serve the demand (Azarmand & Jami, 2009). According to ReVelle and Eiselt (2005), location-allocation modeling relies on the existence of four main features: a) supply of product/services, b) known demand for these products/services, c) a metric system to calculate costs and d) a geographical space in which all the above co-exist (ReVelle & Eiselt, 2005). Additionally, network and discrete models (for more see Revelle et al., 2008) use network data models conceptualized by Graph Theory as mathematical graphs. Network data models are complex relational data structures that are composed of edges (road segments) and vertices (junctions) (Sadeghi-Niaraki et al., 2011). In a GIS environment, real-world objects such as the aforementioned may be properly represented by geographic entities and further simulate real-world problems (Sadeghi-Niaraki et al., 2011). Therefore, modern GIS tools provide analytic and visualization tools suitable for location-allocation modeling and routing applications (Lei et al., 2016). Such applications may be disaster/emergency management (Batsaris et al., 2019; Kavroudakis et al., 2019), solid waste management (Yu & Solvang, 2017), administrative unit re-organization (Papafragkaki & Photis, 2014), health care services (Photis & Sirigos, 2015; Wang et al., 2018).

ESRI's off-the-shelf GIS software provide location analysis functionalities (Chen et al., 2018) and has been used in school location-allocation literature. Møller-Jensen (1998) used *ArcInfo* to allocate students to their closest facilities by employing the *Allocate* functionality. Pizzolato et al. (2004) used *ArcView and the P-median* problem to support school location-allocation decisions. Alifi et al. (2017) use a newer version of ESRI's GIS software for school network planning and finally, Al-Sabbagh (2020) examined several location-allocation models provided in ArcGIS for school location-allocation planning.

Advances in technology and the evolution of geographical analysis methods allow us to combine spatial and non-spatial information to provide more informed decisions through the development of Spatial Decision Support Systems (SDSS) (Keenan & Jankowski, 2019). According to Keenan & Jankowski (2019), Hopkins and Armstrong introduced the term SDSS back in 1985. Armstrong et al. (1993) attempted to develop an SDSS that focuses on three functional modules: a) the population projection module, b) the locational analysis module and c) the display and report generator. The population projection module is used to produce estimations of the future student population. The locational analysis module utilizes several location-allocation approaches such as P-median, set covering, and maximal covering. The main objective is to minimize the total traveling distance with respect to distance constraints. It is important to mention that the SDSS provides the ability to interactively produce various scenarios regarding different student population projections and models as well. Finally, for a better understanding of the results, the display and report generator module offers the ability to export the results in thematic maps and tables. The SDSS was tested in the cities of Davenport and Iowa of the Iowa state in the USA.

A more recent study that attempts to develop an interactive SDSS named iGLASS (Interactive Graphical Location-Allocation System for Schools) is made by Chen et al. (2018). A multi-objective approach is used in order to minimize the total travel time or distance and to maximize the number of students attending the closest facility and/or minimize the students attending facilities away from their residential area with respect to minimum and maximum capacity limitations. The complexity and the size of this model require the use of several heuristics such as “Tabu Search” (TS), “Greedy Algorithm” and “Genetic Algorithm” (GAs). TS is used for the selection of school locations and GAs for the allocation of students. A standalone Windows application with a Graphical User Interface (GUI) was developed in C# programming language based on the dotNET framework.

Adding more constraints, the level of complexity and the need for computational resources are increased. As stated by Chen et al. (2018) there are several challenges in school location-allocation modeling. A few to mention, that successfully apply to the Greek case, are a) capacity constraints, b) assignments to the closest facility, and c) modification of the school network. For instance, due to student population increase or decline schools may need to re-adjust their capacity by extending the existing infrastructure or reducing the capacity, respectively.

The goal of this paper is to present a web-based open source SDSS that may enhance the school location-allocation decision-making in public schools of a Greek medium-sized city, such as Mytilene, by exploiting the capabilities of location-allocation modeling along with GIS analytics and visualization tools. The problem to be solved is the transition of students from primary school (~12 years of age) to the secondary level of education. Usually, in each city, there are quite a few primary schools and somehow fewer secondary schools as they require more staff and higher-level facilities. All primary school students are re-assigned to secondary education level. Nevertheless, the problem arises when decision-makers, must allocate students to secondary school, as they should fulfill some legislation guidelines regarding the assignment to the closest facility and school capacity limitations. The objective of the SDSS is to minimize the total distance from student residencies to schools with respect to school capacity limitations (upper and lower bounds). In order to cope with this complex problem, the P-median approach is adopted and formulated as a mixed-integer linear model concerning capacity constraints.

To the best of our knowledge, this is the first study that introduces an SDSS for efficient school location-allocation decision-making specifically developed for the Greek case based on the current legislation guidelines. This work focuses on the development of a user-friendly, ready-to-work SDSS for both experienced and inexperienced GIS users and users with basic computer skills as well. In contrast with off-the-shelf GIS solutions and other alternatives the proposed SDSS simplifies the decision-making process to a single “*click”* whereas it requires basic computer and office applications skills.

The rest of the paper is structured as follows. The data and methods section describes the collection and pre-processing of the required datasets and discusses the problem formulation and the development of the SDSS. The Case Study and Results section presents the outcomes and the computational process of this work and finally, the achievements of this paper are summarized along with potential future improvements in the Conclusions section.

2. MATERIALS & METHODS

According to the objectives of this paper, the development of an easy-to-use and ready-to-work SDSS suitable for student allocation planning is undertaken. The methodology of this paper emphasizes mainly on two parts: a) the problem formulation and b) the development of the SDSS.

2.1 Problem Formulation

It is essential to have a clear view of the current legislation regarding school management and student allocation planning. In this paper, we focus on two main challenges that can successfully conceptualize the Greek case: a) assignment to the closest facility and b) minimum and maximum capacity constraints.

Given a set of student locations, a set of school units, and a road network as an undirected routable network the objective of this paper is to minimize the total traveling distance satisfying minimum and maximum capacity constraints. For this purpose, a capacitated P-median approach is proposed, formulated as a mixed-integer linear model in *R* programming language (R Core Team, 2015) using *ompr* library (Schumacher, 2018) and its dependencies.

The objective function (1) aims to minimize the total traveling distance subjected to four constraints (2)-(5). Constraint (2) ensures that each student *i* will be strictly associated with a single facility *j*. Student flow should not exceed the maximum reported capacity (3) while it should be greater or equal to the minimum reported capacity (4). Constraint (5) provides the integer (binary) condition which indicates whether a student *i* is assigned to facility *j*.

$$D = min \sum_{i=1}^{N} \sum_{j=1}^{M} d_{ij} x_{ij} \tag{1}$$

Subject to:

$$\sum_{j=1}^{M} x_{ij} = 1 \tag{2}$$

$$\sum_{i=1}^{M} a_i x_{ij} \leq Q_j \tag{3}$$

$$\sum_{i=1}^{M} a_i x_{ij} \geq q_j \tag{4}$$

$$x_{ij} \in \{0,1\} \tag{5}$$

Where *D* is the total traveling distance to be minimized, d_{ij} is the distance of student *i* to facility *j*, x_{ij} is the integer conditional variable (binary) q_j and Q_j are the minimum and maximum capacities of *j* facility respectfully, and a_i is the demand of building *i*.

2.2 Development of the SDSS

Location-allocation decision-making may require a high level of knowledge in operational research and expertise in GIS analytics and visualization tools for the interpretation of the results. Too much information and functionality may be overwhelming and difficult for the user to understand. It is essential, though, to keep both SDSS interface and functionality simple and focused to assist the decision-making process even by non-specialists by a single *"click"*. Data collection and pre-processing seem to be the key to provide an SDSS in this direction.

2.2.1 Data collection

Student allocation is a rather complex task, especially for non-specialists. It requires a strong background in spatial optimization as well as GIS skills. Additionally, the decision-making process may be time and resource-consuming as it includes data collection and pre-processing problem formulation, and interpretation of the results in a meaningful way. To overcome such limitations datasets are already collected and pre-processed and additionally, the problem is defined and modeled with open-source tools and spatial optimization approaches.

Location-allocation problems depend on various data to investigate a typical origin-destination relationship regarding a metric system to calculate costs (e.g. transportation costs). Therefore, the main datasets needed for the development of the proposed SDSS are a) school locations and capacity limitations, b) student addresses and c) a road network. Table 1 presents the derived datasets and their corresponding source, format, and year. It is also important to mention that both student and school locations are subsets of the buildings of the study area.

Table 1. Datasets by name, source, format, and year of reference.

Name	Source	Format	Year
Building footprints	Hellenic Statistical Authority	Spatial	2001
Road Network	Open Street Map	Spatial	2019
School Units and Capacity Bounds	Secondary Educational Management Service of Lesvos Prefecture	Tabular	2019
Student Addresses		Tabular	2019
School Catchment Areas		Tabular	2019

Building footprints were provided in spatial format by the Hellenic Statistical Authority and correspond to the 2001 census of population and housing. The road network dataset was retrieved by the Open Street Map (OSM) collaborative database under the Open Data Commons Database License (OdbL) of the OSM Foundation. The rest of the datasets were provided in tabular format by the Secondary Educational Management Service of Lesvos Prefecture for the school season of 2018-2019. It is important to mention that data regarding student addresses were provided anonymously due to General Data Protection Regulation (GDPR – https://gdpr-info.eu) compliance.

2.2.2 Data pre-processing

Data storage and organization are critical for the success of the SDSS. *PostgreSQL* relational database management system was exploited, extended by *PostGIS* (PostGIS contributors, 2019) and *pgRouting* (PgRouting Contributors, 2018) for spatial data manipulation and routing on spatial networks.

Building footprints were corrected topologically and updated accordingly using the National Cadastre's base-map and manual digitization techniques in *QGIS* software and stored in the database system. Additional information was also included by joining school units and their attributes with building footprints.

Spatial analysis and Graph Theory approaches were used to build a fully-routable, undirected spatial network (with edges and vertices) in the database system and then use it as the basis for our spatial calculations. Across the spatial network, additional vertices were included representing the buildings of the study area and splitting the edges accordingly. This process includes the transformation of building polygons into point geometries (centroids), snapping the centroids to the road network, and re-split the edges as shown in Figure 1. The network dataset created is used to measure distances using Dijkstra's shortest path algorithm (Dijkstra, 1959).

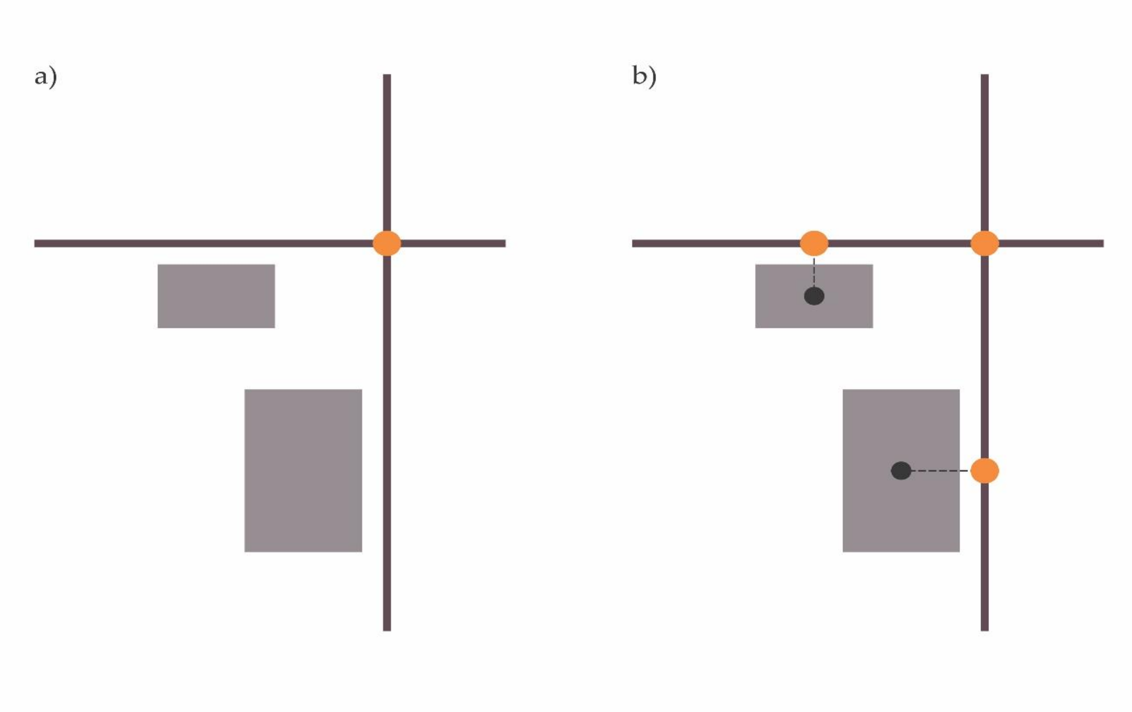

Figure 1. Part of the routable network after including building footprints and re-spltting the edges. **(a)** Before the transformation and **(b)** after the transformation.

2.2.3 SDSS

Web applications created in R using *rshiny* (RStudio, 2013) usually consist of a graphical user interface (GUI) script, a server script, and optionally a database management system. The architecture of the proposed SDSS is depicted in Figure 2. Input and output actions are being handled by the GUI script which directly communicates with the server script. The functionality of the SDSS resides in the server script while the database is responsible for data storage, retrieval, and communication with the server script through queries and responses.

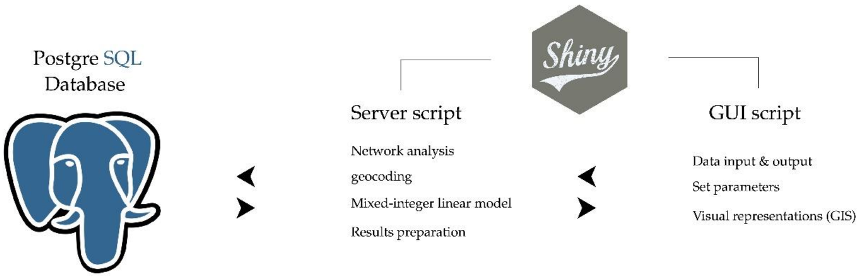

Figure 2. Graphical representation of the architecture of the SDSS

The workflow of the SDSS is depicted in Figure 3. Initially, the user feeds the SDSS with student addresses, makes the necessary capacity adjustments, and hits the solve button. The geocoding component is then activated to translate student addresses into point geometries using Google Maps Geocoding API through the *ggmap* library (Kahle & Wickham, 2013). These points are associated with their closest vertices (representing buildings) of the road network which is used by *iGraph* library (Gsardi & Nepusz, 2006) to build a distance matrix between student and school buildings by using Dijkstra's shortest path algorithm (Dijkstra, 1959). Finally, the distance matrix is used by the MILM to produce the solution.

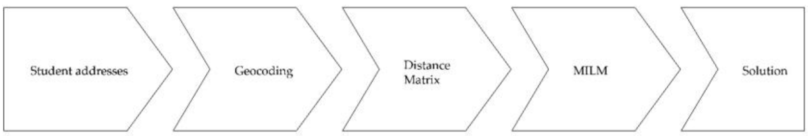

Figure 3. SDSS workflow for identifying optimal spatial allocation of students to school units

Users interact with the SDSS through a simple and minimalistic GUI presented in Figure 4. The SDSS offers only a few interactions such as data import, capacity limitation adjustments, search, and export of the results in spatial and tabular format.

The data import tab consists of a sidebar and the main window. The sidebar offers a) a file selection button for easy data import in popular tabular format (.xls, .xlsx), b) adjustment of upper and lower school units capacity bounds and c) a button to start the optimization solving process. In the main window of the data import tab, the GUI offers the ability to view and search the imported dataset as a table. Moreover, there is a small inspection popup window during the solving process.

In the geocoding tab of the GUI, the user can check geocoding results on the table or the map by using the *R leaflet* library (Cheng et al., 2019) functionality. The last two tabs provide information about the allocation results through tables and spider maps and additionally allow exporting the results in spatial format by using the functionality of *rgdal* library (Bivand et al., 2019).

3. CASE STUDY & RESULTS

In order to demonstrate the usability and efficiency of the proposed SDSS based on actual data, the city of Mytilene was chosen as the case study. Mytilene is a Greek medium-sized city located in the southeast part of Lesvos Island and is the capital of both Lesvos Prefecture and the North Aegean Region. According to the Secondary Educational Management Service of Lesvos Prefecture, in Mytilene, there are 360 students to allocate from the 6th grade of 12 primary schools to the 1st grade of 6 secondary schools (General High Schools) for the school season of 2018-2019.

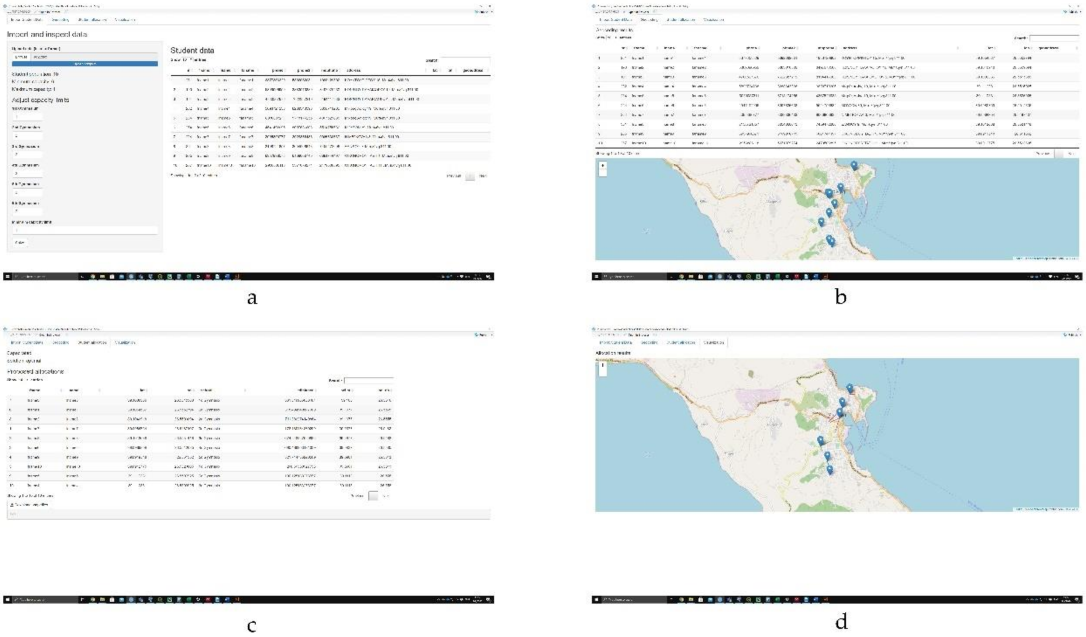

Figure 4. GUI: **(a)** Data import and constraint adjustment, **(b)** geocoding results, **(c)** student allocation results in tabular and spatial format, and **(d)** spider map of the results

In this context, allocation decisions (current allocations) for the school season of 2018-2019 were examined to seek for potential violations. Then, the SDSS was used to provide an alternative allocation scenario (proposed allocations) and further compare it with the current allocations.

3.1 Overview of the Current Allocation

School catchment areas are delineated manually by local educational authorities in coordination with school managers without always considering traveling distance, or the geographical distribution and demographical composition of new students as well as school capacity requirements. It is therefore important to investigate the characteristics and the practicality of the currently applied allocation decisions and further compare them with the proposed ones. Given the origin-destination information of the current allocation practices, traveling distances are calculated by using Dijkstra's shortest path algorithm. Additionally, student enrollment is also calculated and compared with the reported capacity.

School locations along with their catchment areas delineated for the school season 2018-2019 are graphically represented in Figure 5. The geographical distribution of school units in the city of Mytilene is spatially uneven as they are located somehow at the edges of their catchment area polygon. This is mainly related to the effects of the urban sprawl of the city and the availability of suitable building infrastructure during the last few decades.

Regarding schools' capacity, limits are set for the 1st grade of each High-School by the local Secondary Educational Authority of Lesvos Prefecture in coordination with school principals. Given the student addresses, traveling distances are calculated along with enrollment and capacity slacks. The results of this evaluation are depicted in Table 2.

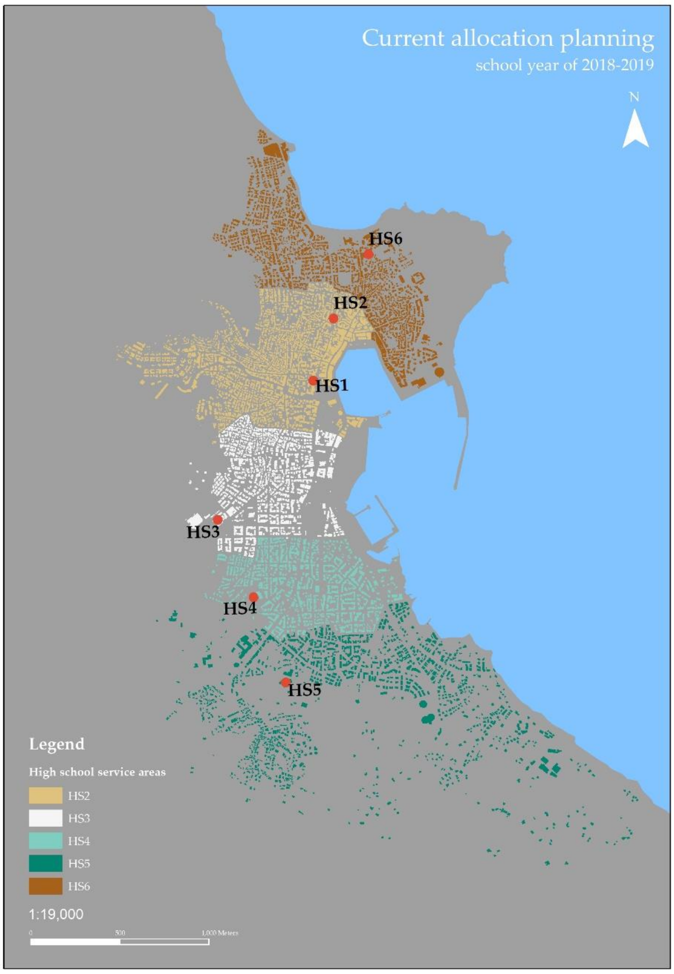

Figure 5. Current allocation planning for the school season of 2018-2019. HS1 mainly accepts students from surrounding villages and southern city suburbs.

Table 2. Analysis of the current allocation planning for the school season of 2018-2019

School name	Max. capacity	Student enrollment	Capacity slacks	Travel distance (meters)	Mean travel distance (meters)
HS1	60	34	26	162.548	4780,80
HS2	60	47	13	31.809	676,80
HS3	85	73	12	130.305	1785,00
HS4	90	78	12	38.138	488,90
HS5	90	75	15	56.856	758,00
HS6	44	53	-9	25.898	602,30
Total	**429**	**360**	**69**	**445.553**	**1.237,65**

Although the results indicate a surplus of capacity, HS6 appears to receive some more students than its reported capacity. This is a typical problem that is usually resolved gradually during the school season. For instance, the principal of HS6 in coordination with the educational management service decided upon the re-assignment of some students to another High-School.

3.2 Proposed Allocations

In order to demonstrate the strengths of the proposed tool, this study investigates a new student-allocation scenario based on spatial optimization approaches aiming to minimize the travel distance of students with respect to capacity limitations.

Figure 6 presents the solution obtained from the SDSS in the study area regarding capacity constraints. In comparison with the existing allocations, students from nearby villages and suburbs are allocated to the closest facility considering the shortest traveling distance.

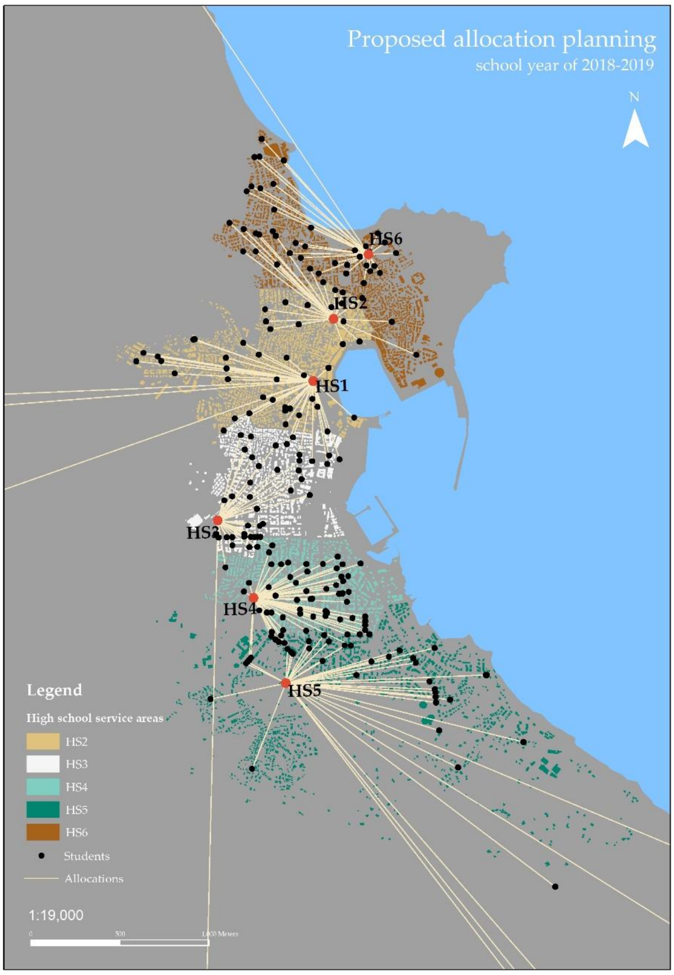

Figure 6. Proposed allocations for the school season of 2018-2019

Furthermore, more detailed results of the proposed allocation scenario are presented in Table 3. According to the results the SDSS, both minimum and maximum capacity limits were applied. There is a capacity surplus of 69 seats which can be potentially used by Administration Authorities and planners for exploring alternative allocation scenarios considering capacity adjustments. Higher transportation costs by means of traveling distances are concentrated mainly on HS3 and HS5 while HS2 and HS4 have the lowest transportation cost values. The total traveling distance of the proposed allocation scenario is 410.231 meters and the mean traveling distance is 1.139, 6 meters.

Table 3. Analysis of the proposed allocations for the school season of 2018-2019

School name	Reported capacity	Proposed enrollment	Capacity slacks	Travel distance (meters)	Mean travel distance (meters)
HS1	60	60	0	54.751	912,52
HS2	60	30	30	12.946	431,54
HS3	85	61	24	117.503	1942,66
HS4	90	81	9	39.635	489,33
HS5	90	90	0	160.399	1782,21
HS6	44	38	6	23.996	631,48
Total	**429**	**360**	**69**	**410.231**	**1.139,6**

As the main objective of this study is to minimize the total traveling distance by taking into consideration minimum and maximum capacity constraints, compared with the current student allocation the proposed allocation scenario provides a somehow better allocation of students in terms of traveling distance. The total traveling distance of the results is approximately 35.000 meters less than the current allocation which is about an 8% decrease in travel distance.

4. DISCUSSION

The results of this study highlight the importance of using GIS analytics and visualization tools for supporting the decision-making process for school network planning and student allocation decisions. The proposed approach provides an optimal solution. The outcomes of the implementation of the SDSS are improved compared with the current allocation practices with a decrease of 8 percent of the total traveling distance. The results can be potentially useful to the educational authority of Lesvos Prefecture for future student allocation planning.

Although results showed a decrease of 8 percent with respect to capacity bounds, future improvements of the SDSS may include some extra functionality to enhance the overall usefulness of the proposed SDSS. A possible improvement could be the addition of extra constraints such as custom traveling distance per school. Within the next few years, students will choose the school unit of their preference. In order to improve the SDSS, student choices could also be taken into consideration. Nevertheless, this would increase computational expenses as it would transform the problem into a Voting Optimization problem and would require some more additional computational resources.

Another potential improvement could be to identify optimal locations for establishing new school units and finally, to utilize more transportation modes such as car, bus, bicycle to name a few.

Students' allocation to schools is currently a decision-making task that is not always related to quantifiable criteria. Currently, this task includes arbitrary opinions of authorities regarding balancing students per school over the city as well as a favorable school over not-so-popular schools with a relatively bad reputation and scores. In this work, an equal way of allocating students to schools mainly in terms of distance and school's capacity which is quantifiable and spatially balanced is proposed.

5. CONCLUSIONS

Students' allocation to schools is a quite important decision especially when it affects schools' resources and involves transportation expenses. During the Greek Economic crisis, there have been issues with public spending regarding schools' resources and capacity especially in terms of reducing public spending and minimizing public authorities' expenses. The decision-making approach of allocating new High School students to existing school units is a crucial process that may affect some school units.

In this work, the use of Spatial Decision Support Systems for student allocation decisions in the city of Mytilini, Lesvos, Greece is examined. An interactive web SDSS is developed and demonstrated in contrast to current allocation decisions based on mixed-integer linear programming techniques along with the P-median approach. The objective of this study is to minimize the total traveling distance from student residencies to school units concerning minimum and maximum capacity limits on a spatial network. Our approach is based on open-source technologies and tools and in the existence of spatial information and other formats of data. One of the main advantages of the developed application is that it is a ready-to-work SDSS. It is a web-based system that is quite helpful as no installation or extra configuration/tuning is needed and requires very basic knowledge of the internet and computer usage to run the application and acquire results. The end-user should be familiar at least with Office-related applications because the SDSS requires data import in tabular format. We overcome the NP-hardness and complexity of the location-allocation problems by using a mixed-integer linear programming approach. The overall running times of the SDSS are reasonable and provide an optimal solution even on a regular low-budget PC and therefore we strongly believe that the SDSS can provide optimal solutions for problems with similar size and complexity levels. It is also very important to mention that the application gives the ability to adjust numerical parameters such as capacity limits and reduce the number of schools by setting a zero maximum capacity and rerun the solver by clicking a single button. Thus, it may be helpful for future school location-allocation planning decisions and may help towards informed-decision making.

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