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Edited by Antônio Nélson Rodrigues da Silva
and Léa Cristina Lucas de Souza

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Session T8

Geographic Information Systems and Mapping

The positioning and registration of the residences of trip generator users can benefit from the use of **GIS** especially when there are existent data, usually available though public and oficial agencies. For the identification of the desire lines, it is necessary to divide the urban area of the city into traffic regions with relatively uniform land use and population characteristics. Therefore, it can be useful to associate traffic zones to other existing partition, as census districts, for exemple. Finally, the itineraries folowed by the users can be easily visualized with a **GIS** software.

A case study was carried out in two generators of utilitarian bicycle trips in the city of São Carlos, SP, Brazil. The **GIS** software chosen for this application was Trans**CAD**. The data on trip generators' users was obtained through 106 interviews. Each of the interviews included a questionnaire on the characteristics of the users and their travel behavior, along with a stated preference survey.

With TransCAD, the residences of the interviewed users (origin points of the trips) were mapped. The delimitation of the influence area of the trip generators was based on the ranges of travel time of the interviewed cyclists and converted into ranges of distance. Three categories of influence areas were defined and mapped as circular areas around the generators. The distribution of the cyclists' residences on the map of São Carlos with the categories of influence area showed that most of these points are located within the primary and secondary influence areas.

For the definition of the desire lines, the map of São Carlos was divided into 16 traffic zones based on the arrangement of existing micro-regions used in the Brazilian Demographic Census, generating two maps of desire lines. The analysis of both maps of desire lines indicate three traffic zones with higher flow of trips generated to both destinations.

Finally, the study of the itineraries of the interviewed residents of these zones to the considered destinations indicated which roads were used by them more often. Five roads were identified as the most used. Next, their bicycle Level-of-Service was evaluated, together with nine adjacent roads.

In general, the case study confirmed the applicability of the method, which, with a few adjustments, could be adopted by planners to assist in the bicycle transportation planning of urban areas. The paper aims to describe the proposed method, giving especial emphasis to the section developed with the use of **GIS**. Furthermore, it intends to contribute to the development of research in the area and to the dissemination of bicycle transportation.

COMBINING GEOGRAPHIC INFORMATION SYSTEMS (GIS) AND MATHEMATICAL MODELING TO LOCATION-ALLOCATION PROBLEMS IN EDUCATION FACILITIES MANAGEMENT

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Keywords: Location-Allocation Problems, Geographic Information System, Mixed Integer Linear Programming, Education Facilities Management, Urban Planning.

Location-allocation problems are generally complex as they involve a great number of variables and data. They have been approached through spatial decision support tools, mainly when a geographical database is available. In this case, Geographical Information Systems (GIS) are critical for the collection and analysis of data, as they include a sophisticated graphical interface for the exploration of geographically referenced data. GIS applied to Transportation (GIS-T) are a special category of GIS systems. Among other functionalities, GIS-T include tools to support facility location and the respective allocation of the demand subjected to an objective that can be the reduction or minimisation of travel costs.

Most of the software used to solve location problems works as a "black-box" where the solution models are not transparent. Previous experiences with the location-allocation modules of TransCAD GIS made clear that this software solves the problem through an indirect two-stage process. In the first stage, the Facility Location (FL) module identifies the best locations for the facilities, proposes the closing of existing units or the opening of new units, and allocates the demand to the offer. However, in this stage operational capacity limits of the units are not considered. In order to impose the capacity constraint, the solution coming out of the FL module must be submitted to the Transportation Problem (TP) routine, which will re-allocate the demand without allowing opening or closing units. This limitation, together with the fact that both routines use heuristic algorithms, results is a solution that may not be the optimal. This could only be checked using an optimising algorithm.

This is the starting point for this paper, which objective is to evaluate the quality of the solutions for the facility location-allocation problem generated by the routines of

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Abstract: The objective of this research was to evaluate the quality of the solutions for the facility location-allocation problem generated by the TransCAD GIS software, obtained after the combined use of its Facility Location and Transportation Problem routines, when compared with the optimal solutions obtained from an optimisation model based on Mixed Integer Linear Programming (MILP). For this purpose the models were applied to locate day-care centers and allocate the demand (0-3 year old children) in the city of São Carlos, State of São Paulo, Brazil. Different scenarios were developed to simulate the opening/closing of units and compare with the current situation. Results showed that when the capacity of the facilities is considered, the MILP model gives results 37% better than the TransCAD models, and additionally identifies different locations for the new facilities.

Keywords: Location-Allocation Problems, Geographic Information System, Mixed Integer Linear Programming, Education Facilities Management, Urban Planning.

1. INTRODUCTION

Location-allocation problems are generally complex as they involve a great number of variables and data. The increase of the complexity of the problem requires new information technologies which enable an effective system's integration (Lacerda, 1999). According to Bowersox e Closs (1996), the significant advances in computational technologies and the increasing complexity of the decision-making processes have stimulated the interest of the first to improve the efficacy of spatial decisions, especially the facility location decisions.

The location of facilities has been approached through spatial decision support tools, mainly when a geographical database is available. In this case, Geographical Information Systems (GIS) are critical for the collection and analysis of data, as they include a sophisticated graphical interface for the exploration of geographically referenced data (Lima, 2003).

GIS applied to Transportation (GIS-T) are a special category of GIS systems. Among other functionalities, GIS-T include tools to support facility location and the respective allocation of the demand subjected to an objective that can be the reduction or minimisation of travel costs.

Most of the software used to solve location problems works as a “black-box” where the solution models are not transparent. Previous experiences with the location-allocation modules of TransCAD GIS made clear that this software solves the problem through an indirect two-stage process. In the first stage, the Facility Location (FL) module identifies the best locations for the facilities, proposes the closing of existing units or the opening of new units, and allocates the demand to the offer. However, in this stage operational capacity limits of the units are not considered.

In order to impose the capacity constraint, the solution coming out of the FL module must be submitted to the Transportation Problem (TP) routine, which will re-allocate the demand without allowing opening or closing units. This limitation, together with the fact that both routines use heuristic algorithms, results is a solution that may not be the optimal. This could only be checked using an optimising algorithm.

This is the starting point for this paper, which objective is to evaluate the quality of the solutions for the facility location-allocation problem generated by the routines of TransCAD when compared with the optimal solutions obtained from an optimisation model based on Mixed Integer Linear Programming (MILP). Differently from the successive use of the TransCAD routines, the MILP model is able to perform location and allocation considering simultaneously capacity constraints of facilities.

Both TransCAD and MILP models, with and without capacity constraints, were applied to the location of day-care centers and allocation of demand (0-3 year old children) in the city of São Carlos, SP, Brazil.

2. RESEARCH METHODOLOGY

The model developed in this work (MILP) falls within the static-deterministic category (for a full classification of facility location models, see Owen and Daskin, 1998), solved by a variation of the p-median method, where the objective is to find the location of p facilities, minimising the overall distance travelled by the demand to reach the facilities. For a discussion on the use of Mixed Integer Linear Programming in facility location, see Church and Sorensen (1996), Lacerda (1999), and Vallim Filho (2004).

For the implementation of the model, the optimization software LINGO®, version 7.0, was used. This software is a computational environment for modelling and optimisation which interfaces with Excel® in order to organise and visualise model outputs.

The objective function and constraints of the model are as follows:

Objective Function :

$$\min fo = \sum_i \sum_j C_{i,j} * X_{i,j} * d_j \tag{1}$$

Subject to :

$$\sum_i z_i = p \tag{2}$$

$$X_{i,j} \le z_i \qquad \forall_{i,j} \tag{3}$$

$$\sum_i X_{i,j} = 1 \qquad \forall_j \tag{4}$$

$$\sum_j d_j * X_{i,j} \le m_i * z_i \qquad \forall_i \tag{5}$$

$$z_i \quad \in \quad (0,1) \qquad \forall_i \tag{6}$$

$$X_{i,j} \quad \in \quad Z^{+} \qquad \forall_{i,j} \tag{7}$$

where:

$X_{i,j}$ is the solution matrix (percentage of the demand at *j* served by *i*);

$C_{i,j}$ is the cost matrix (distances between points *i* and *j*);

z_i is a binary vector that indicates which facilities are open. If $z_i = 1$, facilty *i* is open; if $z_i = 0$, then facility *i* is not operating;

d_j is the demand vector (clients at *j*);

m_i is the capacity vector (maximum capacity of facility *i*);

p is the number of facilities to be opened.

The methodology adopted for this research is shown in Figure 1 and can be classified as modelling & simulation (Bertrand and Fransoo, 2002).

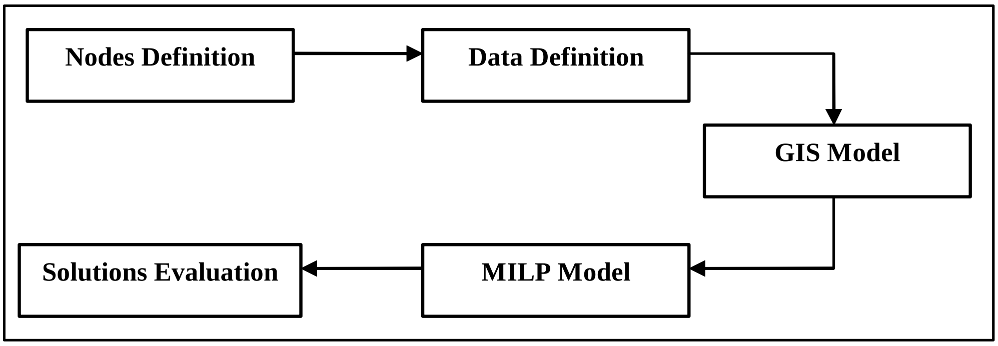

Figure 1 – Research Methodology

3. MODELLING AND SIMULATION

The proposed simulation is about day-care centers in the city of São Carlos, State of São Paulo, in Brazil. The urban area of this city has 45 Km^2 and is mainly organised in an orthogonal street network. The first stage of the development of the location-allocation model was the data acquisition in order to create the relevant GIS layers. The Local Government provided the data about the attendance of 1.014 children to 10 existing day-care centers.

3.1 Simulation by the GIS model

In order to get a first view of the current allocation of students to day-care centers, a thematic map was created in the GIS, where demand served by each facility is represented with the same colour (Figure 2)

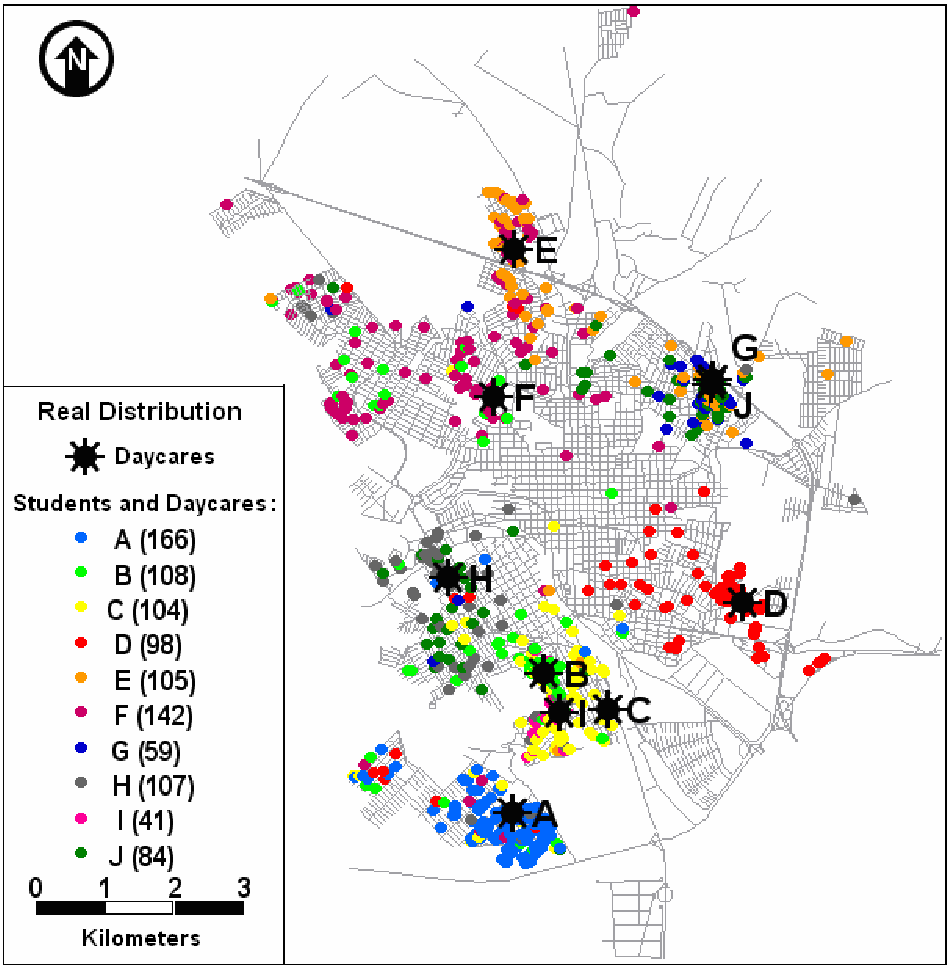

Figure 2 – Real distribution of day-care centers (day-cares) and students

It is expectable that the demand served by a facility is located next to it so the transportation costs can be minimised. However, Figure 2 shows a significant dispersion. Based on this analysis, different scenarios were proposed for the satisfaction of the demand (Table 1)

Table 1: Description of Scenarios

Real	Current location-allocation between students and day-care centers
Scenario 1	Re-allocation of students to the current day-care centers, without considering any new opening or closing.
Scenario 2	10 existing day-care centers plus the opening of 1 new.
Scenario 3	10 existing day-care centers plus the opening of 2 new.
Scenario 4	Closing of 1 existing day-care center and opening of a new one.

In Scenario 1 the capacity limits considered were the number of children actually enrolled in each day-care center, without any further consideration regarding overload or underload. This is not critical as the objective is to compare the GIS and MILP models, as long as the same assumptions are considered for both solutions.

For Scenarios 2 and 3 the capacity of new units was established as being 10% of the overall demand (101, based on 1.014 enrolled students). The very same percentage was subtracted to the capacity of the other day-care centers. Scenario 4 assumes that the capacity of the closed unit is reallocated to the new unit to be open.

One of the main limitations in this research is viability in terms of computational effort. For the GIS heuristic, the complexity of the problem is not really a problem. However, for the MILP model, this can be a serious limitation, so the number of candidate places for new units in this case has to be limited. The option was to consider the points defined by a 0,7 Km regular grid covering the entire city, which results in 120 points (Figure 3). Together with the existing 10 day-care centers, it makes 130 points.

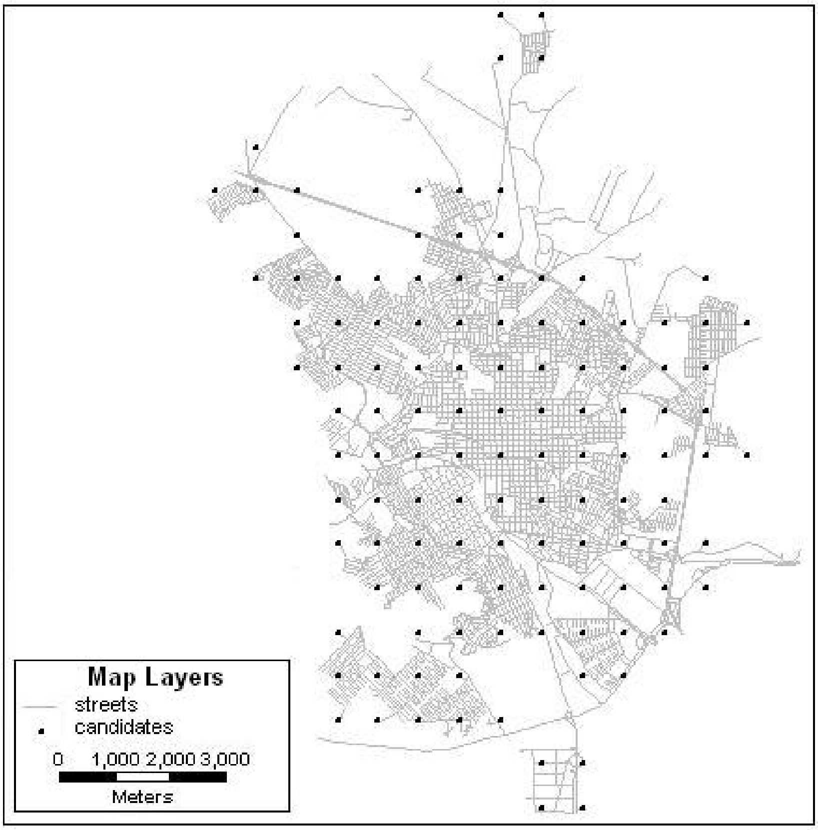

Figure 3 – Candidate places for location-allocation

Given these 4 scenarios, the simulation was first developed using both routines of the TransCAD software. Results are presented in Table 2 (Scenarios 1 and 2), Table 3 (Scenarios 3 and 4), and Figure 4 (allocation). The comparison between Scenarios is made standing on the variation (%) of costs when compared with the current (real) scenario (equation 8).

$$var\ (\%) = \frac{simulated\ scenario - real\ scenario}{real\ scenario} * 100 \qquad (8)$$

The solutions obtained show that every scenario simulated resulted in lower transportation costs for both routines (FL and TP). This conclusion is quite obvious in Figure 4, where the demand allocated to each unit appears to be geographically clustered.

In Scenario 1, the reallocation of children, without any new unit, resulted in a reduction between 46% and 50% of the travelling costs. Opening new units (Scenarios 2, 3 and 4) resulted in a greater cost reduction

3.2 Simulation in MILP model

The very same scenarios were simulated using the MILP model. This model may also be used to solve the problem disregarding capacity constraints, a version that we name here as Non-Capacited (NC), which is in practice parallel to the FL routine. When capacity constraints are considered, we name it Capacited (C) and the model performs location and allocation simultaneously. Like this, for comparison purposes, MILP's C routine corresponds to the GIS's TP routine, keeping in mind that the output of TP is in fact the combined use of FL and TP routines.

Results obtained with MILP model are presented in Tables 4 and 5 and do not differ substantially from the ones obtained with the TransCAD models. However, for the scenarios proposing the opening/closing of units (2, 3 and 4), NC and C solutions are different for the same scenario.

4. COMPARISON

Table 6 presents the comparison of results from the GIS model (Tables 2 and 3) and MILP model (Tables 4 and 5). For the calculation of the variation of the MILP model compared with the GIS model, equation (9) was used.

$$var\ (\%) = \frac{GIS\ model - MILP\ model}{MILP\ model} * 100 \qquad (9)$$

Table 6 shows that the results for the routines disregarding capacity constraints are exactly the same. Differently, the results from the TP and C models reveal a lower cost for the later.

Table 2: Results of Scenarios 1 and 2 for GIS model

		GIS Model								
		Real	**Scenario 1**				**Scenario 2**			
		Scenario	**FL**	**var**	**TP**	**var**	**FL**	**var**	**TP**	**Var**
DAYCARES	**A**	**166**	196	18%	166	0%	196	18%	149	-10%
	B	**108**	115	6%	108	0%	115	6%	97	-10%
	C	**104**	22	-79%	104	0%	22	-79%	94	-10%
	D	**98**	78	-20%	98	0%	78	-20%	88	-10%
	E	**105**	105	0%	105	0%	105	0%	95	-10%
	F	**142**	147	4%	142	0%	69	-51%	128	-10%
	G	**59**	37	-37%	59	0%	37	-37%	53	-10%
	H	**107**	88	-18%	107	0%	88	-18%	96	-10%
	I	**41**	125	205%	41	0%	125	205%	37	-10%
	J	**84**	101	20%	84	0%	101	20%	76	-10%
	K						78		101	
	L									
Medium Cost (Km)		**2,04**	0,99	-52%	1,10	-46%	0,86	-58%	1,23	-40%
Highest Cost (Km)		**10,52**	5,28	-50%	5,34	-49%	5,20	-51%	5,20	-51%
Total Cost (Km)		**2070**	1001	-52%	1120	-46%	877	-58%	1244	-40%

Table 3: Results of Scenarios 3 and 4 for GIS model

		GIS Model								
		Real	**Scenario 3**				**Scenario 4**			
		Scenario	**FL**	**var**	**TP**	**var**	**FL**	**var**	**TP**	**var**
DAYCARES	**A**	**166**	169	2%	133	-20%	196	18%	166	0%
	B	**108**	115	6%	86	-20%	119	10%	108	0%
	C	**104**	22	-79%	83	-20%	closed	-	closed	-
	D	**98**	78	-20%	78	-20%	78	-20%	98	0%
	E	**105**	105	0%	84	-20%	105	0%	105	0%
	F	**142**	69	-51%	114	-20%	69	-51%	142	0%
	G	**59**	37	-37%	47	-20%	37	-37%	59	0%
	H	**107**	88	-18%	86	-20%	88	-18%	107	0%
	I	**41**	125	205%	34	-17%	143	249%	41	0%
	J	**84**	101	20%	67	-20%	101	20%	84	0%
	K		78		101		78		104	
	L		27		101					
Medium Cost (Km)		**2,04**	0,81	-60%	1,09	-47%	0,87	-57%	1,43	-30%
Highest Cost (Km)		**10,52**	5,20	-51%	5,20	-51%	5,20	-51%	5,57	-47%
Total Cost (Km)		**2070**	822	-60%	1102	-47%	885	-57%	1452	-30%

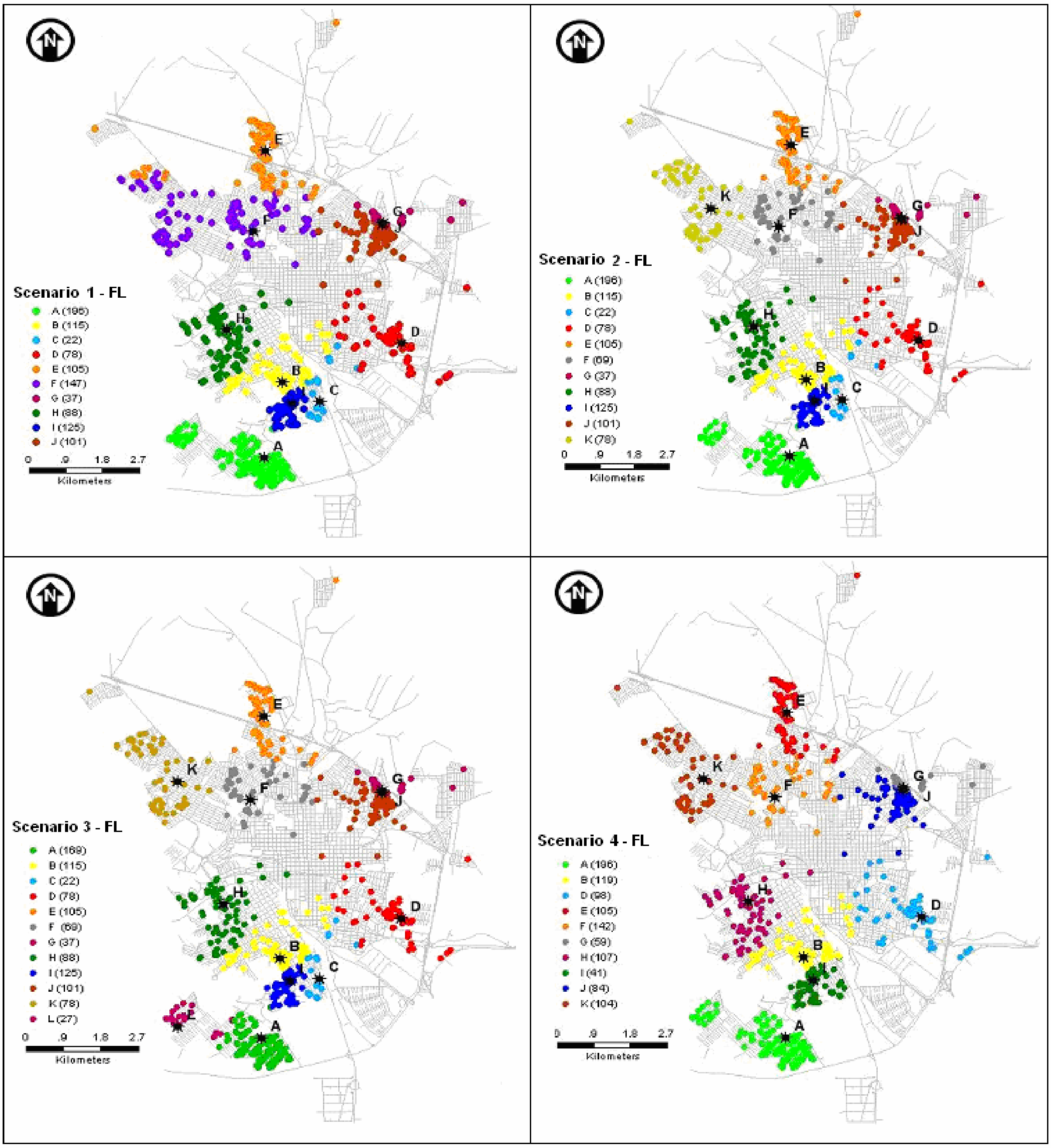

Figure 4 – Facility Location results for Scenarios 1, 2, 3, 4

Table 4: Scenarios 1 and 2 results for MILP model

		MILP Model								
		Real Scenario	**Scenario 1**				**Scenario 2**			
			NC	**var**	**C**	**V**	**NC**	**var**	**C**	**var**
DAYCARES	**A**	**166**	196	18%	166	0%	196	18%	149	-10%
	B	**108**	115	6%	108	0%	115	6%	97	-10%
	C	**104**	22	-79%	104	0%	22	-79%	94	-10%
	D	**98**	78	-20%	98	0%	78	-20%	88	-10%
	E	**105**	105	0%	105	0%	105	0%	95	-10%
	F	**142**	147	4%	142	0%	69	-51%	128	-10%
	G	**59**	37	-37%	59	0%	37	-37%	53	-10%
	H	**107**	88	-18%	107	0%	88	-18%	96	-10%
	I	**41**	125	205%	41	0%	125	205%	37	-10%
	J	**84**	101	20%	84	0%	101	20%	76	-10%
	K						78			
	L									
	M								101	
	N									
Medium Cost (Km)		**2,04**	0,99	-52%	1,10	-46%	0,86	-58%	1,08	-47%
Highest Cost (Km)		**10,52**	5,28	-50%	5,34	-49%	5,20	-51%	5,28	-50%
Total Cost (Km)		**2070**	1001	-52%	1120	-46%	877	-58%	1095	-47%

Table 5: Scenarios 3 and 4 results for MILP model

		MILP Model								
		Real Scenario	**Scenario 3**				**Scenario 4**			
			NC	**var**	**C**	**V**	**NC**	**var**	**C**	**var**
DAYCARES	**A**	**166**	169	2%	133	-20%	196	18%	166	0%
	B	**108**	115	6%	86	-20%	119	10%	108	0%
	C	**104**	22	-79%	83	-20%	closed	-	Closed	-
	D	**98**	78	-20%	78	-20%	78	-20%	98	0%
	E	**105**	105	0%	84	-20%	105	0%	105	0%
	F	**142**	69	-51%	114	-20%	69	-51%	142	0%
	G	**59**	37	-37%	47	-20%	37	-37%	59	0%
	H	**107**	88	-18%	86	-20%	88	-18%	107	0%
	I	**41**	125	205%	34	-17%	143	249%	41	0%
	J	**84**	101	20%	67	-20%	101	20%	84	0%
	K		78		101		78			
	L		27							
	M								104	
	N				101					
Medium Cost (Km)		**2,04**	0,81	-60%	1,01	-50%	0,87	-57%	1,05	-49%
Highest Cost (Km)		**10,52**	5,20	-51%	5,20	-51%	5,20	-51%	5,34	-49%
Total Cost (Km)		**2070**	822	-60%	1027	-50%	885	-57%	1063	-49%

Table 6: Comparison between GIS and MILP models

Scenarios	Costs (km)	GIS		MILP		Var (%)	
		FL	**TP**	**NC**	**C**	**FL** vs. **NC**	**TP** vs.**C**
1	Medium Cost	0,99	1,10	0,99	1,10	0%	0%
	Highest Cost	5,28	5,34	5,28	5,34	0%	0%
	Total Cost	1001	1120	1001	1120	0%	0%
2	Medium Cost	0,86	1,23	0,86	1,08	0%	14%
	Highest Cost	5,20	5,20	5,20	5,28	0%	-2%
	Total Cost	877	1244	877	1095	0%	14%
3	Medium Cost	0,81	1,09	0,81	1,01	0%	7%
	Highest Cost	5,20	5,20	5,20	5,20	0%	0%
	Total Cost	822	1102	822	1027	0%	7%
4	Medium Cost	0,87	1,43	0,87	1,05	0%	37%
	Highest Cost	5,20	5,57	5,20	5,34	0%	4%
	Total Cost	885	1452	885	1063	0%	37%

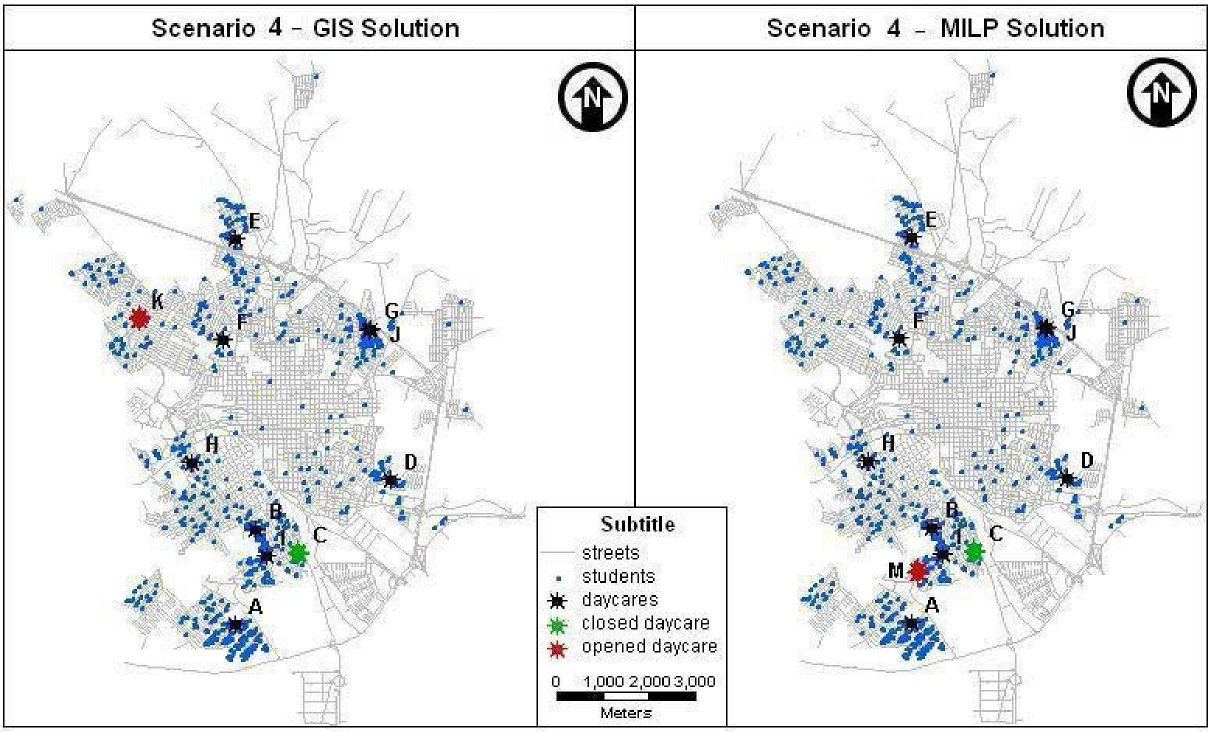

Figure 5 – Scenario 4 solutions comparison between GIS model and MILP model

Besides the numerical results, the C model generated a location for the new unit different from the one proposed by the TP model in every scenario where a new unit was to be open. Figure 5 shows the different locations generated for Scenario 4. It is quite visible that the GIS model locates new unit K in the northern part of the city and the MILP model locates new unit M in the south, this last one with a 37% reduction in costs.

5. CONCLUSION

Knowing that the FL routine is a heuristic and gives exactly the same results as the optimal solution obtained from the exact MILP model, a first important conclusion is the acknowledgement of the good quality of the heuristic. Moreover, the location-allocation obtained through the FL routine optimises the capacity of the kidergartens. Thus, considering for instance Scenario 1, which purpose is to reallocate the demand to the existing units, it could be recommended to adjust the capacity of all the units to the allocated values. Like this the savings in transportation costs would be up to 52% without any need of new units.

A deep look to the results shows that generally when the capacity constraints are applied, the MILPS model gives better results. On the other hand, the performance of simulations is sensitive to the number of candidate places for new units; this fact represents an advantage of the GIS model as the heuristic works more efficiently with a larger number of variables. In fact, in every scenario simulated the GIS model worked out a solution in less than 5 seconds; the optimisation algorithm MILPS needed systematically a much larger computing time, which in one case arrived to almost 2 hours (1:52:14) (Table 7).

Table 7: MILP model computing time consumed

MILP Model Time Consumed (hh:mm:ss)							
Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
NC	**C**	**NC**	**C**	**NC**	**C**	**NC**	**C**
00:01:39	00:00:48	00:01:39	00:42:46	00:02:56	01:52:14	00:01:46	00:07:50

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