REVISTA FLORESTA
Engenharia Florestal
ISSN 1982-4688
Edição 54
Universidade Federal do Paraná
Setor de Ciências Agrárias

THE CHINESE POSTMAN PROBLEM AND SIMULATED ANNEALING APPLIED TO URBAN FOREST INVENTORY

Henrique Moreira Dabien Haddad[1], Carlos Delano Cardoso de Oliveira[2*], Carolina Souza Jarochinski e Silva[3], José Roberto Soares Scolforo[4], Lucas Rezende Gomide[5]

[1]Federal University of Lavras, Department of Forest Sciences, Lavras, Minas Gerais, Brazil – hmoreiradh4@gmail.com
[2*]Federal University of São Carlos, Natural Sciences Center, Campina do Monte Alegre, São Paulo, Brazil – carlosdelano.co@gmail.com
[3]Federal University of Lavras, Department of Forest Sciences, Lavras, Minas Gerais, Brazil – carolina.jsilva@ufla.br
[4]Federal University of Lavras, Department of Forest Sciences, Lavras, Minas Gerais, Brazil – josescolforo@ufla.br
[5]Federal University of Lavras, Department of Forest Sciences, Lavras, Minas Gerais, Brazil – lucasgomide@ufla.br

Received for publication: 16/ 12 / 2023 – Accepted for publication: 04 / 06 / 2024

Resumo

O Problema do Carteiro Chinês aplicado no inventário florestal urbano. O roteamento é o processo de definição de trajeto(s) entre pontos geograficamente distintos e tem sido aplicado na tomada de decisões em serviços que englobam deslocamento, com potencial aplicação no planejamento de inventários florestais urbanos. A Programação Linear é uma técnica de pesquisa operacional frequentemente aplicada na solução de problemas complexos, como aqueles relacionados ao roteamento. Assim, o objetivo deste estudo foi verificar se a aplicação de um modelo de roteamento via Programação Linear Inteira (PLI) aumenta a eficiência de um inventário florestal urbano utilizando dados reais. Primeiramente, nós comparamos a divisão empírica utilizada no inventário com a aplicação do método de PLI para roteamento. Nós também testamos um método aproximativo (Simulated Annealing, SA) para resolução do problema de roteamento e redução do tempo de processamento. Finalmente, nós simulamos as consequências da aplicação da PLI em diferentes cenários. Os resultados mostraram que a PLI melhorou em 6,36% a eficiência do inventário e o uso da SA reduziu em 43.200 vezes o tempo de processamento para o cenário mais complexo, resultando em uma solução a 1,87% do valor da resposta de PLI. Nossos achados evidenciam o potencial de aplicação da PLI no planejamento de inventários florestais urbanos, com ganhos diretamente proporcionais ao número de lotes do inventário.

Palavras-chave: Simulated annealing. Otimização em rede. Meta-heurísticas. Pesquisa Operacional. Programação Linear Inteira.

Abstract

The Chinese Postman Problem applied to urban forest inventory. Routing is the process of defining paths between geographically distinct points, and it has been applied in decision-making processes for services that include displacement, with potential application in the planning of urban forest inventories. Linear Programming is an operations research technique often applied to solve complex problems, such as those related to routing. Thus, the objective of this study was to verify whether the application of a routing model via Integer Linear Programming (ILP) increases the efficiency of an urban forest inventory using real data. First, we compared the empirical division used in the inventory with the application of the ILP method for routing. We also tested an approximate method (Simulated Annealing, SA) to solve the routing problem and reduce the processing time. Finally, we simulated the consequences of applying ILP in different scenarios. The results showed that the ILP improved the inventory efficiency by 6.36%, and the use of SA reduced the processing time by 43,200 times for the most complex scenario, resulting in a solution that was 1.87% of the ILP response value. Our findings show the potential application of ILP in the planning of urban forest inventories, with gains directly proportional to the number of lots in the inventory.

Keywords: Simulated annealing. Network optimization. Meta-heuristics. Operational research. Integer Linear Programming.

INTRODUCTION

The routing problem typically involves a delivery service with available financial resources (BODIN, 1975). The vehicle routing problem (VRP) is a classical optimization problem with high degree of complexity and computational effort (BRACKERS *et al.*,2016). One of its most common variants is the Chinese Postman Problem (CPP), an arc-routing set of problems (YILMAZ *et al.*, 2017) that aims to define the shortest path to visit, at least once, all edges of a graph (CORBENRÁN *et al.*, 2002). In terms of application, the VRP problem has a mathematical model to achieve a minimum distance, time, or cost within given technical constraints (OYOLA *et al.*, 2016). Consequently, an optimal solution increases efficiency of resource allocation within any management system (HASSANZADEH; RASTI-BARZOKI, 2017). Under these circumstances, an optimal route is a set of paths or a connected subgraph with a lower cost of the objective function. In forest sciences, these NP-hard (nondeterministic polynomial-time hard) combinatorial optimization problems have been utilized to solve issues such as forest logistics (MONTI *et al.*, 2020) and forest plantation inventories (MENEGUZZI *et al.*, 2020), with potential applications in urban forest sampling routes.

Urban forests encompass a variety of shapes, sizes, and aesthetic principles within cities. Their primary purposes are to promote human health and create fauna and flora zones, contributing to a better living environment (SOLOMOU *et al.*, 2019). However, the planning and management of these areas have a set of tasks (pruning, felling, and replacing tree programs) to maintain for the next generations (MILLER *et al.*, 2015). Unfortunately, these silvicultural activities are constrained by limited resources and annual financial support from governmental councils, necessitating more effective decision-making at the managerial level (VOGT *et al.*, 2015). For instance, the initial stage of the process relies on the tree's information gathered during the census procedure, which include size, canopy, species, site, and health. Data acquisition may involve digital data collection systems, several tree attributes, and exhaustive trekking over streets, parks, and avenues. Moreover, the waste of time due to non-optimal routing increases the final cost of the inventory (PÉLLICO NETTO; BRENA, 1997). The street network presents a complex array of potential routes, with daily field operations affected by human decision-making. The physical exhaustion of the field team is another side effect of the campaign execution. Consequently, the use of heuristics and algorithms to solve this challenging problem is encouraged.

The Linear Programming (LP) is an operational research technique designed to solve optimization problems under a set of constraints and an objective function (WOLSEY, 2021). The model has a gradient that guides the function direction for maximizing or minimizing a certain objective and the final solution achieved is optimal (BAZARAA *et al.*, 2010). This technique has been applied with high degree of success. Nevertheless, the nature of decision variables may increase the problem complexity and dimensionality (instance), while exact methods often demand long processing times (COOK *et al.*, 1997). Contrastingly, approximate methods (heuristics and meta-heuristics) require lower computational effort (HOSSEINI *et al.*, 2023; GOMIDE *et al.*, 2013), and the solution is usually close to the optimal one. Consequently, optimality cannot be assured in most instances. Many routing problems have been approached in the CPP context. Yilmaz *et al.* (2017) used the CPP formulation to shorten the total distance covered by machines in the inspection of railways in Turkey. Rasul *et al.* (2022) applied this formulation to optimize routes for snowplowing trucks for efficient road maintenance, with consideration of operational constraints. In some cases, finding the exact solution for complex CPP is challenging, and applying optimization methods can contribute to achieve efficient results.

In this study, we applied optimization methods to improve the trekking routes of an urban forest inventory. The objective of our research was to develop a novel methodology to guide the decision-maker for street campaign task. Here, we have highlighted a range of assumptions: (a) lot division effects, (b) ILP model versus metaheuristic Simulated Annealing solutions, (c) empirical inventory versus the tested models, and (d) optimal solution within anticipated scenarios. We hypothesized that the application of the Linear Programming optimization would improve urban forest inventory by reducing total travel distance.

MATERIAL AND METHODS

Urban tree inventory optimization

The displacement of field teams in an urban forest inventory is a typical vehicle routing problem (VRP), in which neighborhoods or lots represent graphs, streets, and avenues, while sidewalks represent arcs and the trees to be measured represent vertices. In our study, the streets within the study area buffer were grouped into continuous clusters with limited bounds to reduce complexity (Figure 1). Thus, lots consisted of a set of streets grouped together for an inventory campaign within a fraction of the city. Each lot constitute a daily target and encompasses an unknown number of trees. Additionally, the entire area was also tested as a single lot for an optimization analysis. The optimal solution for this problem is a route that allows visiting all vertices while minimizing travel distance, considering existing constraints such as directional limitations on streets and avenues for vehicles.

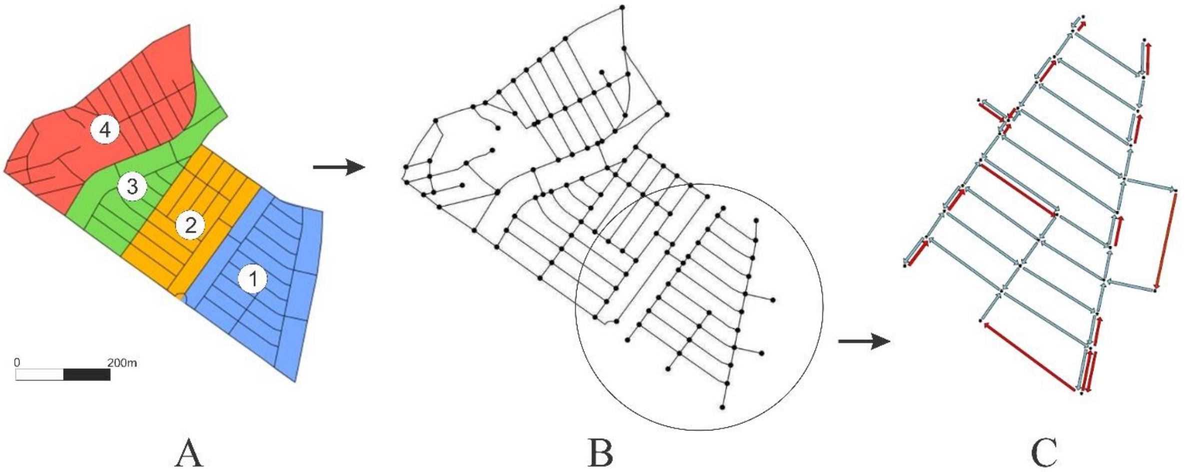

Figure 1. Studied area divided into 4 lots (A) and all available streets access as a mathematical graph (B). Red arrows represent a symbolic trekking without work, and gray arrows represent the way for acquire tree information (C).

Figura 1. Área estudada dividida em 4 lotes (A) e todas as ruas de acesso disponíveis conforme grafo matemático (B). A seta vermelha é uma caminhada simbólica sem trabalho e a seta cinza é a forma de adquirir informações sobre as árvores (C).

The data used in this study were obtained in a real urban forest inventory. This inventory was performed during 2015 to improve mechanisms for monitoring and controlling urban forests through the development of a database. Firstly, the city was hierarchically divided into sub regions and lots to optimize inventory planning. Then, each lot was assigned to a field team. Field teams moved to one of the addresses located in the lot to initiate the inventory, using a tablet. Field teams collected data using a form composed of 58 technical attributes related to tree features, including species, health, and stem characteristics, for each tree within a lot. Additionally, field teams captured pictures (3-5) and recorded geographical coordinates for each tree. In this study, we used only displacement data of field teams from one sub region composed of four lots (Figure 1). The displacement data during the work day were tracked using a GPS application installed in the tablets.

Optimization methods

Integer Linear Programming (ILP)

The mathematical problem was addressed using the Chinese Postman Problem (CPP), also known as the Postman Tour or Route Inspection Problem, which falls under the category of routing problems. In this context, the most efficient flow route is the one that covers all arcs of a connected graph G = (V, E) while minimizing the overall distance (cost). The graph's vertices *v* represents street segments, and edges *e* represent street junctions connecting multiple streets. The work team must collect various attributes of trees on sidewalks and in public squares and gardens. There was no prior information about the distribution of trees across street segments, which is why the team must track all arcs. Under this circumstance, the tested graphs increase the problem's complexity because they are not a Euler trail. The work service's starting and ending points are located at the same vertex of the graph. A variety of exact methods and algorithms have been proposed in the literature to address this challenge. The exact solution involves formulating an integer decision variable *x* to represent the displacement between two adjacent vertices {i, j} within a connected graph. The objective function (1) minimized the overall team tracking subject to a set of constraints under the connected and undirected graph. The first constraint (2) ensures that all streets should be visited at least once, and the second constraint (3) defines the flow sequence within the graph.

Objective function:

$$MIN \sum_{(i,j)\in V} C_{ij} x_{ij} \tag{1}$$

Subject to:

$$X_{ij} + X_{ij} \geq 1; \forall (i,j) \in V \tag{2}$$

$$\sum_{(i,j)\in V} x_{ij} - \sum_{(i,j)\in V} x_{ji} = 0; \forall_j \in V \tag{3}$$

$$x_{ij} \in \mathbb{Z}^+ \tag{4}$$

Simulated Annealing (SA)

Approaches for the routing problem typically necessitate high computational efforts, particularly when dealing with graphs with a high number of odd vertices. These odd vertices can significantly increase the problem's complexity and processing time. Moreover, the walk flow requests multiple displacements for those streets (odd conjunctions), increasing the overall cost. Under this circumstance, a subproblem is introduced to determine the shortest path between odd vertices to connect these pairs (Figure 2). By adding an extra number of walks, the graph will be balanced, finding a complete Euler tour with a perfect flow. As an approximate method, we have applied the simulated annealing (SA) to solve the addressed routing problem. Simulated Annealing is a probabilistic algorithm usually applied to optimization problem (MENDONÇA *et al.*, 2022). The algorithm starts with a randomized solution and later explores the neighborhood according to metropolis criteria and physical properties. The algorithm finds a closed walk with minimum-cost reached visiting all streets at least once, and others with multiple walks. The key steps of the algorithm are as follows: 1) visiting all vertices of the graph; 2) identifying the odd vertices; 3) applying the shortest-paths algorithm (Floyd-Warshall) between odd vertices; 4) determining the Euler Tour to create an efficient route; and 5) evaluating the performance of the solution. The achieved solution represents the overall cost of the round trip, accounting for all vertices visited with single or multiple walks along the streets. Previously, we have applied an extensive number of tests to optimize the algorithm's performance. Thus, the selected parametrization included an initial temperature (3,000), iterations (30,000), local search within vertices swapping (10%) from the current solution, and a decreasing temperature (ti) values strategy: ti=t(i-1)*0.001. Finally, the function (1) guided the SA for finding the best solution performance. Due to the stochastic nature of this algorithm, we have chosen the best solution after 100 runs to increase the chances of finding a globally optimal solution.

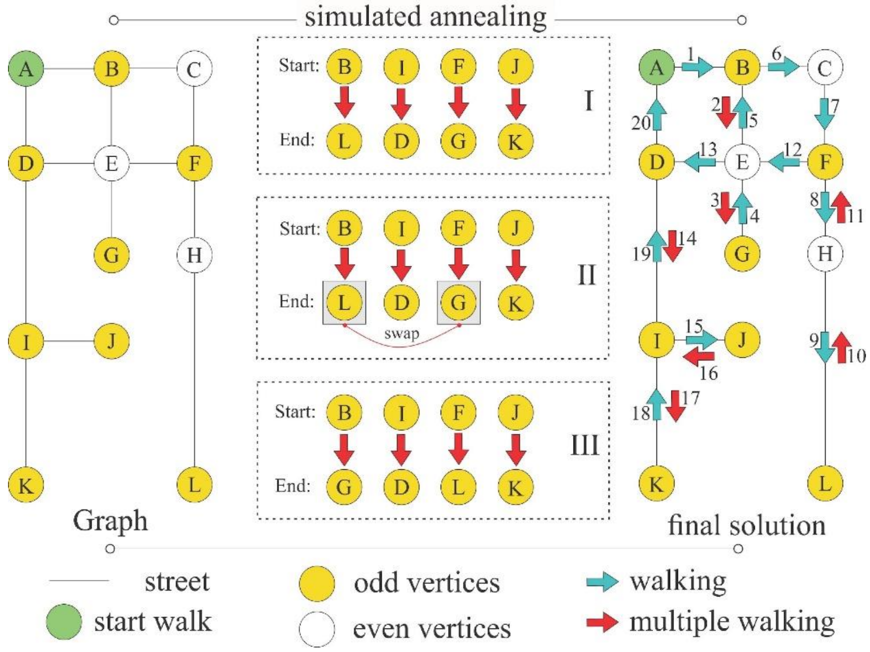

Figure 2. Flowchart of simulated annealing strategy for solving the Chinese Postman Problem applied to urban forest inventory. Numerals I, II, and III correspond to the approach of local search procedure, and the arrow direction defines the walk flow sequence from the start-end vertices.

Figura 2. Fluxograma da estratégia *Simulated Annealing* para solução do Problema do Carteiro Chinês aplicado ao inventário florestal urbano. Os numerais I, II e III são a abordagem do procedimento de busca local e a direção da seta define a sequência do fluxo de caminhada a partir dos vértices início-fim.

Problem instances and data analyses

The optimization methods were applied based on eight instances of urban inventory that define the number of available lots (Table 1). Instances 5-8 simulated increasing complexity by combining the neighborhood within 2-4 lots for the model performance. Regardless of the method, we compared computational solutions from lot 1 with the real trekking execution, called Empirical. Unfortunately, this was the only instance measured during the street campaign. In the field, we used a digital map to track the real routes taken and later determined the overall distance covered from this lot. Finally, the solution analysis was conducted based on a set of parameters: a) effective daily work: 5 h; b) average trekking speed: 5 km h^{-1} = 1.39 m s^{-1}; c) average time to collect data from a tree = 5 min; and d) technician salary = R$2,000.00 $month^{-1}$. The Integer Linear Programming model was built in the LINGO 9.0 solver using the branch-and-bound algorithm. The meta-heuristic simulated annealing was programmed according to Kirkpatrick *et al.* (1983) and implemented in the Microsoft VB6 language. The computational performance was evaluated on an Intel® core i5 3210 MHz processor with 4 Gb of RAM.

Table 1. Urban inventory applied instances to evaluate the optimization methods performance.
Tabela 1. As instâncias de inventário urbano aplicadas para avaliar o desempenho dos métodos de otimização.

Instances	Municipality lots	Number of arcs
1	1	41
2	2	44
3	3	45
4	4	61
5	1-2	85
6	3-4	94
7	1-2-3	121
8	1-2-3-4	170

RESULTS

A total of 6,997 trees were sampled during the urban forest inventory. The number of trees sampled in the four lots considered in this study varied from 1,465 to 1,968. Field teams required seven to eight days to complete the inventory for each lot.

The analysis of the route data for Instance 1 showed a total travel distance of 7,111.13 m and 62 movements to cover the entire area. Twenty-one of these movements (approximately 1,898.20 m) were performed with no tree measurements. The Integer Linear Programming (ILP) model for Instance 1 comprised 175 decision variables and 74 constraints, with 254 iterations. Its processing time was less than one second. Applying this model, we obtained a total travel distance of 6,658.52 m and 57 movements. In 16 of these movements, there were no measurements (approximately 1,445.59 m). The ILP application resulted in an absolute reduction of 452.61 m, which represented a variation of 6.36% compared to the empirical method execution.

The Simulated Annealing (SA) meta-heuristics solved the problem with low deviation from the exact method. In most instances, the SA showed the same response as the ILP (Figure 3). For the most complex problem (Instance 8), the meta-heuristic had its function approximately 1.87% below the value of the ILP response (Figure 3a), but with a processing time 43,200 times shorter. Contrastingly, the exact ILP model processing was stopped after 24 hours, with the best solution obtained so far being 27,115.20 m (Figure 3b).

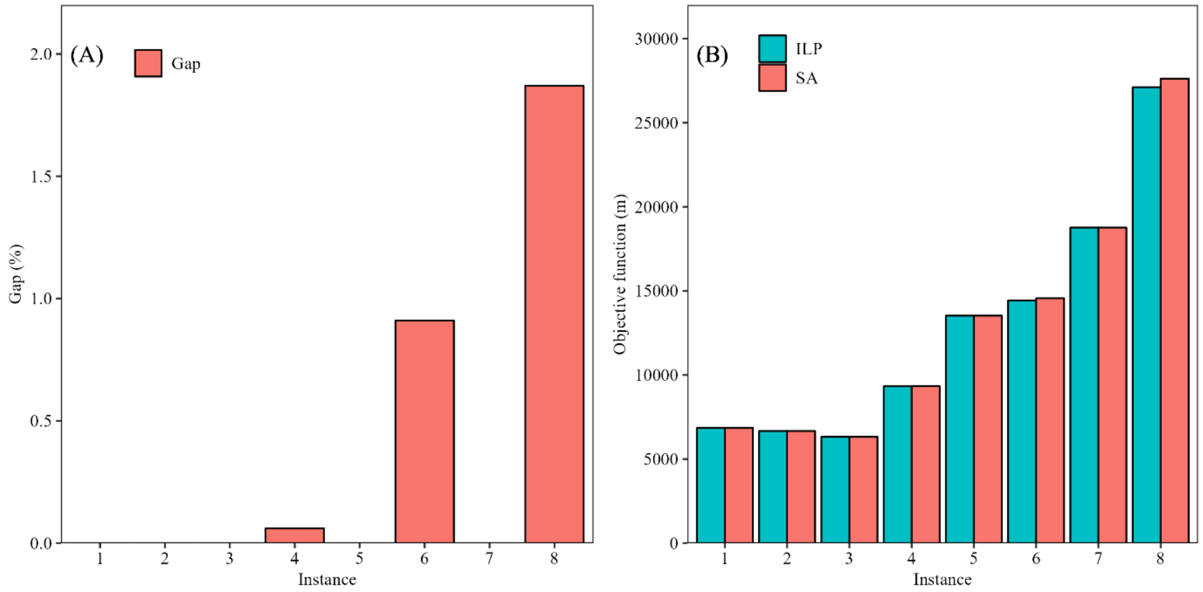

Figure 3. Gap (%) (A) and objective function (m) values for the testing scenarios to compare Simulated Annealing (SA) and Integer Linear Programming (ILP) (B).
Figura 3. Valores de gap (%) (A) e função objetivo (m) para os cenários de teste para comparação entre *Simulated Annealing* (SA) e Programação Linear Inteira (ILP) (B).

We also found good results considering large-scale scenarios. Based on the reduction of the total travel distance in the real lot (452.61 m) and converting to saved walking time (4.27 minutes), the simulation results indicated percentual gains in large scenarios, i.e., with a high number of team members and lots (Table 4). As an example of such gains, the Integer Linear Programming (ILP) model resulted in a saving of 40,734.90 minutes or 678.92 hours for the team, corresponding to 45.26 effective hours of work for each team member. By converting the saved idle time into tree measurement, we projected a gain of 1.09 trees per team member for one lot, generating a gain of 16.29 trees for a team of 15 people on one lot. Extrapolating the number of lots to 500, the gain for each team member is 543.13 trees, and 8,146.98 trees for a team of 15 people. Regarding the financial metrics, the use of the ILP may result in savings of R$ (BRL) 1.65 for one team member in one lot and R$ (BRL) 12,343.91, considering 500 lots and a team with 15 members.

Table 2. Scenarios involving variations in number of team members (N), lots, and their saved variable by Integer Linear Programming model application, considering the measurement time as constant.
Tabela 2. Cenários envolvendo variações no número de membros da equipe (N), lotes e suas variáveis salvas pela aplicação do modelo de Programação Linear Inteira, considerando o tempo de medição como constante.

Metric		**Lots**					
Variable	**N**	**1**	**10**	**50**	**100**	**250**	**500**
Minutes	1	5.43	54.31	271.57	543.13	1,357.83	2,715.66
	5	27.16	271.57	1,357.83	2,715.66	6,789.15	13,578.30
	10	54.31	543.13	2,715.66	5,431.32	13,578.30	27,156.60
	15	81.47	814.70	4,073.49	8,146.98	20,367.45	40,734.90
Trees	1	1.09	10.86	54.31	108.63	271.57	543.13
	5	5.43	54.31	271.57	543.13	1,357.83	2,715.66
	10	10.86	108.63	543.13	1,086.26	2,715.66	5,431.32
	15	16.29	162.94	814.70	1,629.40	4,073.49	8,146.98
R$ (Brazilian Real -BRL)	1	1.65	16.46	82.29	164.59	411.46	822.93
	5	8.23	82.29	411.46	822.93	2,057.32	4,114.64
	10	16.46	164.59	822.93	1,645.85	4,114.64	8,229.27
	15	24.69	246.88	1,234.39	2,468.78	6,171.95	12,343.91

DISCUSSION

Urban forest inventories require extensive displacements for the field team to collect data. Thus, optimizing team displacement may promote gains by saving routes and time. Here, we used Integer Linear Programming (ILP) methods in the Chinese Postman Problem context to optimize the displacement of a field team using data from a real urban forest inventory. Our results demonstrate that ILP may optimize urban forest inventories planning by reducing the travel distances and saving time of the field team.

Displacements without data collection negatively impact the objective function of the model, increasing the total travel distance. Nonetheless, our results show that ILP reduced total displacement and movements with no tree measurements. Similar results were found by Detofeno and Steiner (2010), with a reduction of approximately 7.83% in one waste collection route and 8.6% in the total daily journey. The travel distance and the number of movements with no measurements reduced by applying the Integer Linear Programming (ILP) compared to the empirical method. This is explained by the fact that the optimization method considers the spatial distribution and the distances between trees to be measured, promoting a better grouping of trees based on the greater proximity between them (MENEGUZZI *et al.*, 2020).

The application of the metaheuristic was efficient, yielding similar results to ILP but with reduced processing time. The SA potential for solving complex problems when compared to ILP was also identified by Crowe and Nelson (2005). However, it may be the best alternative for addressing large-scale or complex problems that cannot be solved using exact methods (REDI *et al.*, 2020). In our study, database manipulation for the Simulated Annealing application was simpler than for the ILP model, denoting an advantage in using SA. However, minimal difference between the processing times of SA were observed across the different SA instances. Conversely, the application of SA may have considerable impacts on the processing time, depending on the complexity of the addressed problem. The application of the SA showed near-optimum solutions to medium and large-sized green vehicle routing problems within short computation time (KÜÇÜKOĞLU *et al.*, 2015). Reducing the processing time is relevant in optimization, especially in contexts in which the problem is complex, such as the planning of urban forest inventories in large cities.

The inventory is fundamental in the planning and management of urban forests (MILLER *et al.*, 2015) and involves complex tasks (ROMAN *et al.*, 2017) and allocation of resources. Our findings demonstrate that the proposed ILP application optimizes the planning of urban forest inventories by reducing travel distances. Although initially expected to be effective for solving low-complexity problems, our results indicate the model's ability to solve more complex problems. Moreover, our projections suggest proportional gains from the application of ILP. The larger the number of lots, the greater the time, the number of trees measured, and the financial resources saved. Thus, we recommend applying ILP in the planning of urban forests inventories, especially in large cities where the high number of neighborhoods makes this task more challenging.

CONCLUSIONS

- The Integer Linear Programming (ILP) model effectively addressed and solved the routing problem of the urban forest inventory.
- The use of Simulating Annealing (SA) is effective for simple and complex problems, and it may achieve the same solutions as the exact method in several scenarios with a reduced processing time.
- The developed ILP model presents potential for application and may contribute to planning of urban forests inventories, ordering the activities, and reducing costs.
- The data simulation and projection show that the use of the model and ILP improves the total execution time and the yield of inventoried trees.

ACKNOWLEDGEMENTS

We thank the field team for the data collection; the Coordenação de Aperfeiçoamento Pessoal de Nível Superior (CAPES; Finance Code 001) for granting a masters' scholarship to HMDH; and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for granting a research fellowship to LRG (grant number 304572/2021-7).

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