Formulation for the median tour problem generalized with cumulative time

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Contents

Introduction

The Median Tour Problem (MTP)

- The problem was proposed by Current and Schilling (1994).
- The MTP is a Bi-criterion routing problem.
- Minimize the total cost of the tour.
- Minimize the total travel distance of the $n - p$ nodes not included on the tour.
- The tour only visits p of the n nodes

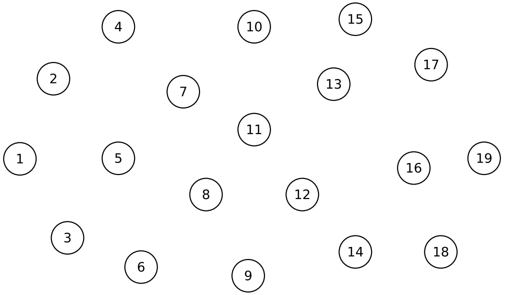

Figure: MTP feasible solution

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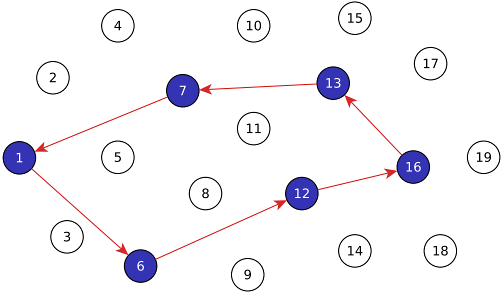

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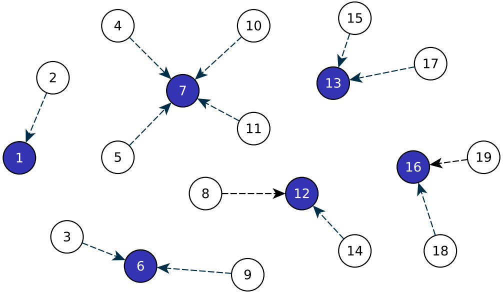

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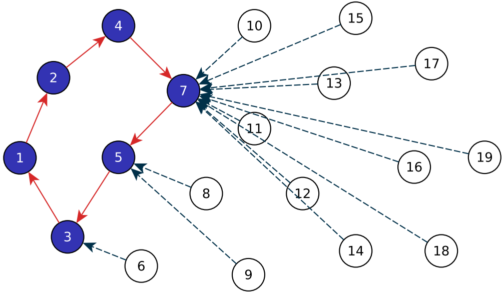

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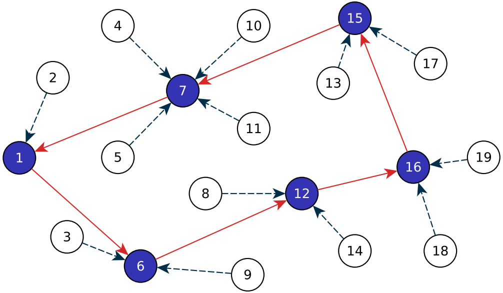

Figure: MTP feasible solution

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We will call *generalized median tour problem* if we combine the *p-median* problem with the *generalized traveling salesman problem*

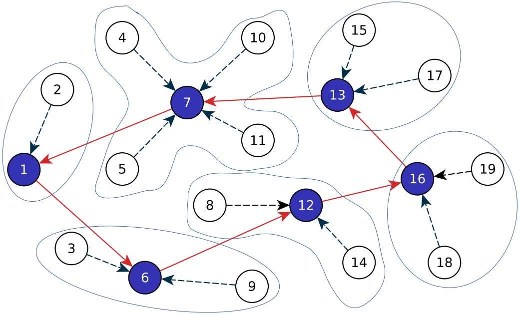

Figure: GMTP feasible solution

Applications of the problem include:

- The design of mobile service delivery systems.
- Bi-modal transportation systems.
- Distributed computer networks.

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The *median tour problem generalized with cumulative time* is a variation of the *median tour problem*.

- The GMTPL is a Bi-criterion routing problem.
- This problem is looking for a balance between the costs of the route and the quality of the service
- Each node belongs to a cluster.
- The assignment can only be made between nodes of the same cluster.

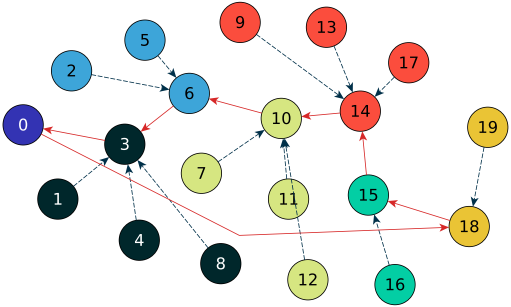

Figure: GMTPL feasible solution

Definition

Let $G = (N, A)$ be a complete undirected graph and V a partition of N into m clusters ($V := \{C_1, \ldots, C_m\}$ and $C_i \cap C_j = \emptyset$ for each $i, j \in \{1, \ldots, m\}$). We define the traveling cost c_{ij} and a traveling time t_{ij} associated with each arc $(i, j) \in A$.

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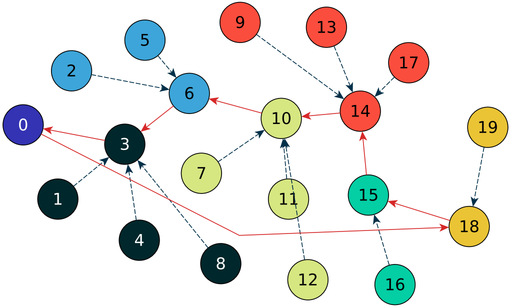

Figure: GMTPL feasible solution

Definition

The GMTPL consists of finding a route that starts at $0 \in N$ and visits each cluster. The nodes that are not in the tour are assigned to a node of the route within its cluster.
The objective is to minimize the cost associated with the tour and the cumulative time spent on the tour.

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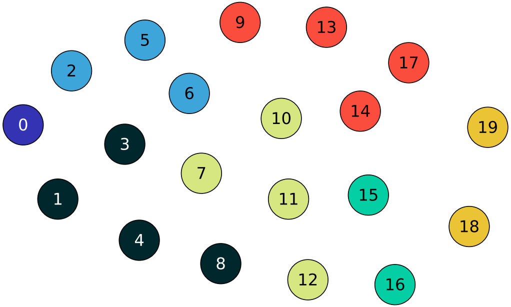

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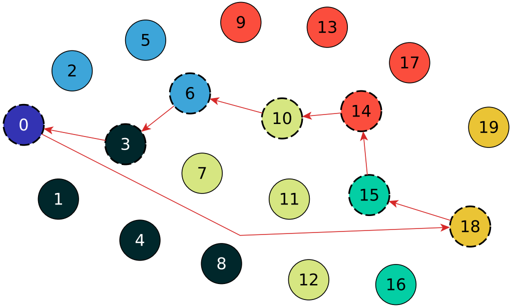

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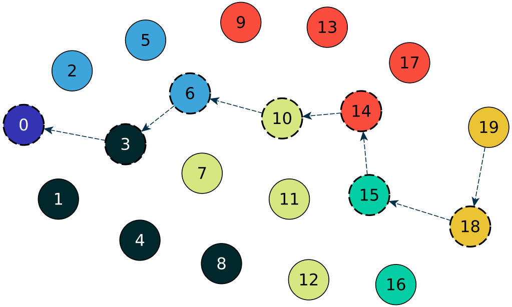

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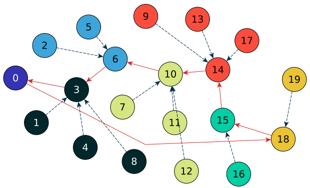
MTP applications are maintained.

- The total time to reach the destination is considered instead of the assignment times
- It can be used for passenger pick up

Two cases of the problem will be analyzed:

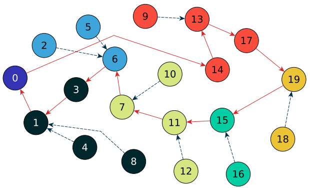
Problem 1

Only one node is visited per cluster and the tour contains m nodes



Problem 2

There are no restrictions regarding the number of tour nodes



For problem 2, we will define two parameters:

Definition

We define the *traveling time 1* (t_{ij}^1) and the *traveling time 2* (t_{ij}^2) associated with each arc $(i, j) \in A$. The the *traveling time 1* represents the time to reach the tour and the *traveling time 2* is the time on the tour

Definition

$t_{ij}^1 \geq t_{ij}^2$ for each arc $(i, j) \in A$

Mathematical formulations

Before reviewing the mathematical formulations, some sets will be defined

Definition

For any $S \subseteq N$, we define $\delta^+(S) := \{(i,j) \in A : i \in S, j \in N \backslash S\}$ and $\delta^-(S) := \{(i,j) \in A : i \in N \backslash S, j \in S\}$. we will use the notation $\delta^+(i)$ and $\delta^+(i)$ when $S = \{i\}$

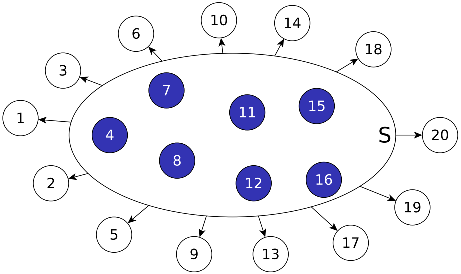


Figure: $\delta^+(S)$

Median Tour Problem Generalized with Cumulative Time

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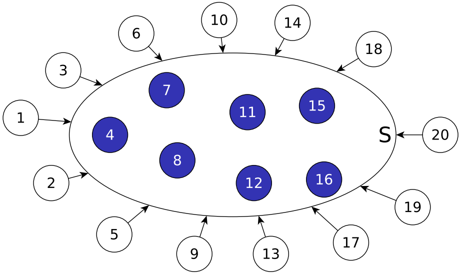

Figure: $\delta^-(S)$

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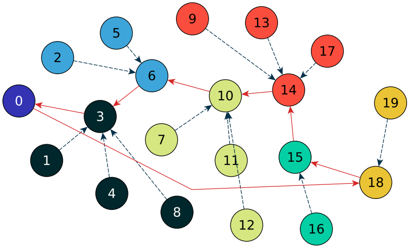
Formulations for Problem 1



Formulation 1

- It is based on Fischetti, Laporte, and Martello (1993) formulation for the Delivery Man Problem.
- We use a flow variable that represents the number of times each arc is used.

Decision Variables

$$x_{ij} = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is used} \\ 0 & \text{if not} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if node i is assigned to node j} \\ 0 & \text{if not} \end{cases}$$

$$f_{ij} = \text{flow from i to j}$$

Objective Function

- Total cost of the tour.

$$Z_1 = \sum_{(i,j)\in A} c_{ij}x_{ij}$$

- The cumulative time spent on the tour

$$Z_2 = \sum_{(i,j)\in A} t_{ij}f_{ij}$$

Constraint

- Assignment of vertices:

$$\sum_{j \in C_p} y_{ij} = 1 \qquad \forall p = 1, ..., m; i \in C_p \quad (1)$$

- Stops on the tour:

$$y_{jj} = \sum_{(i,j) \in \delta^-(C_p)} x_{ij} \qquad \forall p = 1, ..., m; j \in C_p \quad (2)$$

- Flow conservation:

$$\sum_{(i,j) \in \delta^-(C_p)} x_{ij} = \sum_{(j,k) \in \delta^+(C_p)} x_{jk} \quad \forall p = 1, ..., m; j \in C_p \quad (3)$$

- Number of Stops:

$$\sum_{(i,j) \in A} x_{ij} = m \qquad (4)$$

- Assignment at stops:

$$y_{ij} \le y_{jj} \qquad \forall (i,j) \in A \qquad (5)$$

Constraint (cont.)

- Vertices flow:

$$\sum_{(i,j)\in A} f_{ij} + 1 = \sum_{(j,k)\in A} f_{jk} \qquad \forall j \in N, j \neq 0 \quad (6)$$

- Assignment flow:

$$f_{ij} \leq y_{ij} \qquad \forall p = 1, ..., m; i, j \in C_p, i \neq j \quad (7)$$

- Tour flow:

$$f_{ij} \leq |N - 1| x_{ij} \qquad \forall p = 1, ..., m; (i, j) \in \delta^+(C_p) \quad (8)$$

- Variable's domain:

$$f_{ij} \geq 0 \qquad \forall (i, j) \in A \quad (9)$$

$$x_{ij} \in \{0, 1\} \qquad \forall (i, j) \in A \quad (10)$$

$$y_{ij} \in \{0, 1\} \qquad \forall (i, j) \in A \quad (11)$$

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Formulation 2

- Based on multicommodity flow formulation.
- Requires at least $|N|^3$ variables.

Decision Variables

$$x_{ij} = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is used} \\ 0 & \text{if not} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if node } i \text{ is assigned to node } j \\ 0 & \text{if not} \end{cases}$$

$$f_{ij}^{k} = \text{flow through the arc } (i,j), \text{ originating in node } k$$

Objective Function

- Total cost of the tour.

$$Z_1 = \sum_{(i,j)\in A} c_{ij} x_{ij}$$

- The cumulative time spent on the tour

$$Z_2 = \sum_{k\in N} \sum_{(i,j)\in A} t_{ij} f_{ij}^k$$

Constraint

(1) - (5)

- Flow conservation:

$$\sum_{(i,j)\in A: i\neq 0} f_{ij}^k = \sum_{(j,h)\in A} f_{jh}^k \qquad \forall j,k \in N\setminus\{0\}, j \neq k \tag{12}$$

- Assignment flow:

$$f_{ij}^k \leq y_{ij} \qquad \forall p = 1,\dots,m; i,j,k \in C_p, i \neq j \tag{13}$$

- Tour flow:

$$f_{ij}^k \leq x_{ij} \qquad \forall p = 1,\dots,m; i \in N, j \in N\setminus C_p, k \in C_p \tag{14}$$

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Constraint (cont.)

- Flow source:

$$\sum_{(k,j)\in A} f_{kj}^k = 1 \qquad \forall k \in N \backslash \{0\} \qquad (15)$$

- Flow destination:

$$\sum_{(i,0)\in A} f_{i0}^k = 1 \qquad \forall k \in N \backslash \{0\} \qquad (16)$$

- Variable's domain:

$$f_{ij}^k \geq 0 \qquad \forall (i,j) \in A, k \in N \qquad (17)$$

$$x_{ij} \in \{0,1\} \qquad \forall (i,j) \in A \qquad (18)$$

$$y_{ij} \in \{0,1\} \qquad \forall (i,j) \in A \qquad (19)$$

Formulation 3

- The MTZ restriction determine the cumulative time.
- The linear relaxation of the problem is of lower quality.

Decision Variables

$$x_{ij} = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is used} \\ 0 & \text{if not} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if node } i \text{ is assigned to node } j \\ 0 & \text{if not} \end{cases}$$

$$u_j = \text{cumulative time of node } j$$

Objective Function

- Total cost of the tour.

$$Z_1 = \sum_{(i,j)\in A} c_{ij}x_{ij}$$

- The cumulative time spent on the tour

$$Z_2 = \sum_{j\in N} u_j$$

Constraint

(1) - (5)

- Deposit time:

$$u_0 = 0 \tag{20}$$

- MTZ with cumulative time:

$$u_i \geq u_j + t_{ij} - M(1 - x_{ij} - y_{ij}) \quad \forall (i,j) \in A, i \neq 0 \tag{21}$$

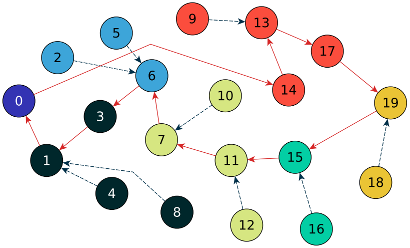
- Variable's domain:

$$u_j \geq 0 \qquad \forall j \in N \tag{22}$$

$$x_{ij} \in \{0,1\} \qquad \forall (i,j) \in A \tag{23}$$

$$y_{ij} \in \{0,1\} \qquad \forall (i,j) \in A \tag{24}$$

Formulations for Problem 2



Formulation 4

- It is based on the formulation 3.
- It is allowed to visit more than one node per cluster.

Decision Variables

$$x_{ij} = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is used} \\ 0 & \text{if not} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if node } i \text{ is assigned to node } j \\ 0 & \text{if not} \end{cases}$$

$$u_j = \text{cumulative time of node } j$$

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Objective Function

- Total cost of the tour.

$$Z_1 = \sum_{(i,j)\in A} c_{ij} x_{ij}$$

- The cumulative time spent on the tour

$$Z_2 = \sum_{j\in N} u_j$$

Constraint

- Assignment of vertices:

$$\sum_{j \in C_p} y_{ij} = 1 \qquad \forall p = 1, ..., m; i \in C_p \qquad (25)$$

- Stops on the tour:

$$y_{jj} = \sum_{(i,j) \in A} x_{ij} \qquad \forall j \in N \qquad (26)$$

- Flow conservation:

$$\sum_{(i,j) \in A} x_{ij} = \sum_{(j,k) \in A} x_{jk} \qquad \forall j \in N \qquad (27)$$

- Incidence arcs to the cluster:

$$\sum_{(i,j) \in \delta^-(C_p)} x_{ij} = 1 \quad \forall p = 1, ..., m \qquad (28)$$

- Assignment at stops

$$y_{ij} \leq y_{jj} \qquad \forall (i,j) \in A \qquad (29)$$

- Deposit time:

$$u_0 = 0 \qquad (30)$$

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Constraint (cont.)

- MTZ with cumulative time:

$$u_i \geq u_j + t^1_{ij} y_{ij} + t^2_{ij} x_{ij} - M(1 - x_{ij} - y_{ij}) \qquad \forall (i,j) \in A, i \neq 0 \qquad (31)$$

- Variable's domain:

$$u_j \geq 0 \qquad \forall j \in N \qquad (32)$$

$$x_{ij} \in \{0, 1\} \qquad \forall (i,j) \in A \qquad (33)$$

$$y_{ij} \in \{0, 1\} \qquad \forall (i,j) \in A \qquad (34)$$

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Formulation 5

- It is based on the formulation 2.
- It is allowed to visit more than one node per cluster

Decision Variables

$$x_{ij} = \begin{cases} 1 & \text{if the arc } (i,j) \text{ is used} \\ 0 & \text{if not} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if node } i \text{ is assigned to node } j \\ 0 & \text{if not} \end{cases}$$

$$f_{ij}^{k} = \text{flow through the arc } (i,j) \text{, originating in node } k$$

Objective Function

- Total cost of the tour.

$$Z_1 = \sum_{(i,j)\in A} c_{ij} x_{ij}$$

- The cumulative time spent on the tour

$$Z_2 = \sum_{(i,j)\in A} t^1_{ij} y_{ij} + \sum_{k\in N} \sum_{(i,j)\in A: i\neq k} t^2_{ij} f^k_{ij} + \sum_{p=1}^{m} \sum_{(k,j)\in\delta^+(C_p)} t^2_{kj} f^k_{kj} + \sum_{p=1}^{m} \sum_{i,j\in C_p: i\neq j} t^2_{ij} x_{ij}$$

Constraint

(25) - (29)

- Flow conservation:

$$\sum_{(i,j)\in A: i\neq 0} f_{ij}^{k} = \sum_{(j,h)\in A} f_{jh}^{k} \qquad \forall j,k \in N\backslash\{0\}, j\neq k \qquad (35)$$

- Assignment flow:

$$f_{kj}^{k} \leq y_{kj} + x_{kj} \qquad \forall p = 1, ..., m; k,j \in C_p, i \neq j \qquad (36)$$

- Tour flow 1:

$$f_{ij}^{k} \leq x_{ij} \qquad \forall k \in N, (i,j) \in A, i \neq k \qquad (37)$$

Constraint

- Tour flow 2:

$$f_{kj}^{k} \leq x_{kj} \qquad \forall p = 1, ..., m; (k,j) \in \delta^{+}(C_p) \qquad (38)$$

- Flow source:

$$\sum_{(k,j)\in A} f_{kj}^{k} = 1 \qquad \forall k \in N \backslash \{0\} \qquad (39)$$

- Flow destination:

$$\sum_{(i,0)\in A} f_{i0}^{k} = 1 \qquad \forall k \in N \backslash \{0\} \qquad (40)$$

- Variable's domain:

$$f_{ij}^{k} \geq 0 \qquad \forall (i,j) \in A, k \in N \qquad (41)$$

$$x_{ij} \in \{0,1\} \qquad \forall (i,j) \in A \qquad (42)$$

$$y_{ij} \in \{0,1\} \qquad \forall (i,j) \in A \qquad (43)$$

Results

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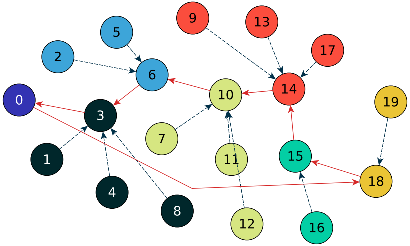
- We use TSPLIB instances for the GTSP involving between 14 and 127 vertices (problems burma14 to bier127)
- The models were implemented in the C++ programming language, using the CPLEX solver
- A maximum time of 5,000 seconds was set.
- All code is found at https://github.com/alexfabianb94/GMTPL/

Results for Problem 1



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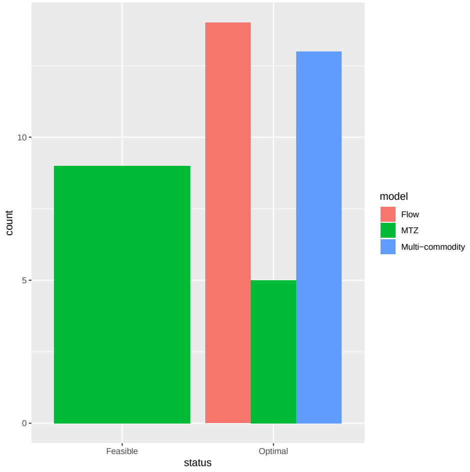


Figure: Solutions for the cost of the tour

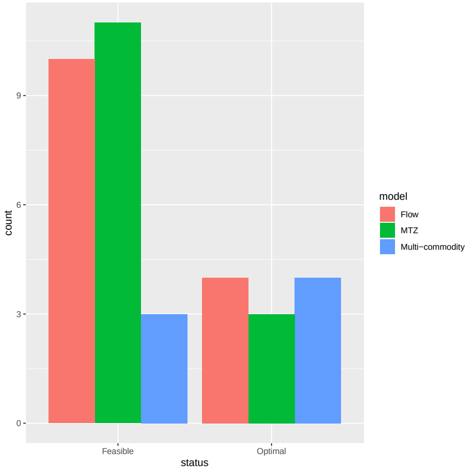


Figure: Solutions for cumulative time

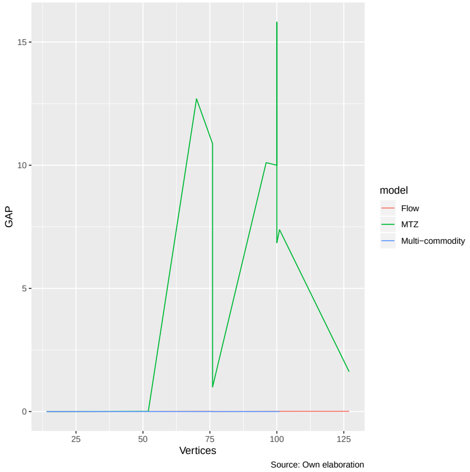


Figure: GAP for the cost of the tour

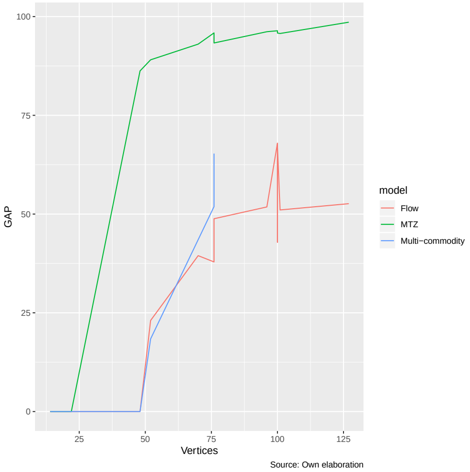


Figure: GAP for cumulative time

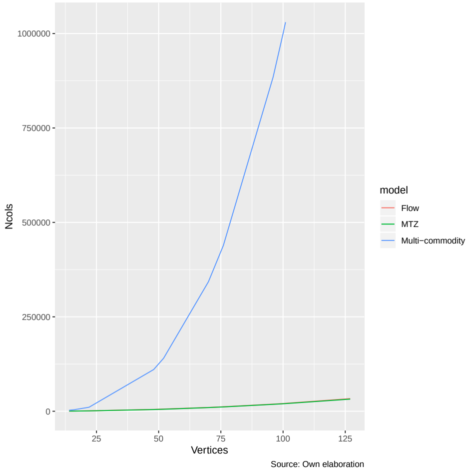


Figure: Number of variables

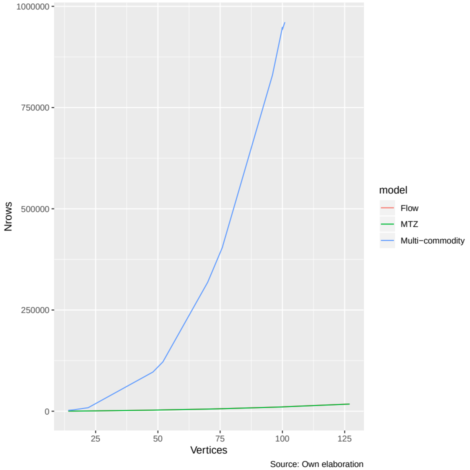


Figure: Number of restrictions

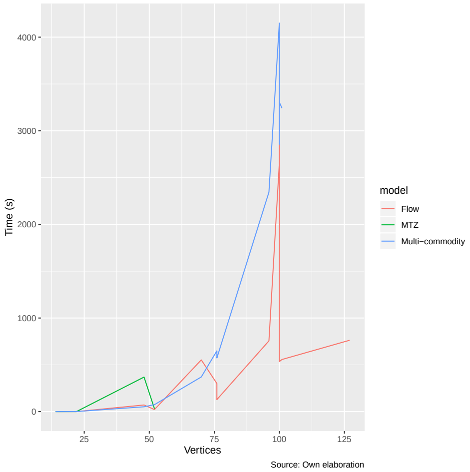


Figure: Resolution times for the cost of the tour

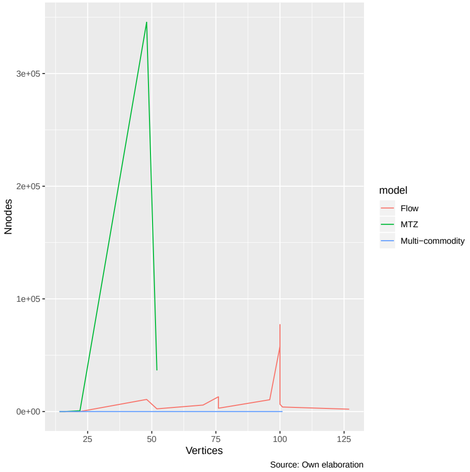
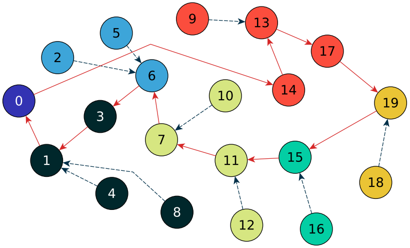


Figure: Number of Branch & Bounds nodes explored

Problem 1

- The flow formulation finds feasible solutions in a greater number of instances.
- The flow formulation presented a better GAP in the instances studied.
- The multicommodity formulation generates good results, but requires a greater amount of memory
- The multicommodity formulation finds solutions without exploring the Branch & Bound tree

Results for Problem 2



The ϵ-constraints method was used to find the efficient frontier:

$$Z_2 = \sum_{(i,j)\in A} t^1_{ij} y_{ij} + \sum_{k\in N} \sum_{(i,j)\in A: i\neq k} t^2_{ij} f^k_{ij} + \sum_{p=1}^{m} \sum_{(k,j)\in \delta^+(C_p)} t^2_{kj} f^k_{kj} + \sum_{p=1}^{m} \sum_{i,j\in C_p: i\neq j} t^2_{ij} x_{ij}$$

$$\Downarrow$$

$$Z_2 \leq T_{max} \tag{44}$$

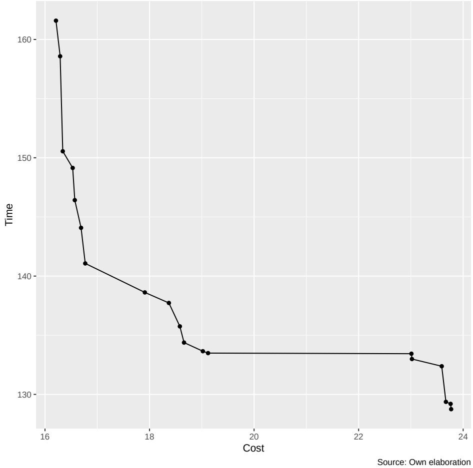


Figure: Efficient frontier for burma14

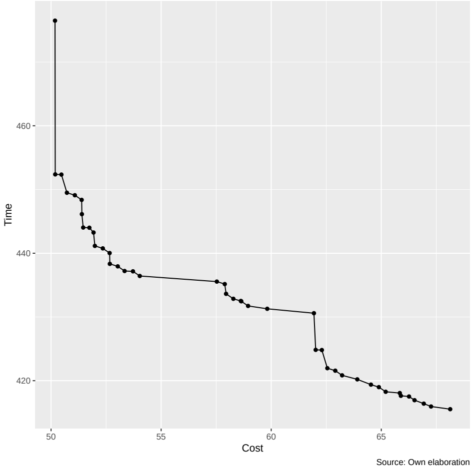


Figure: Efficient frontier for ulysses16

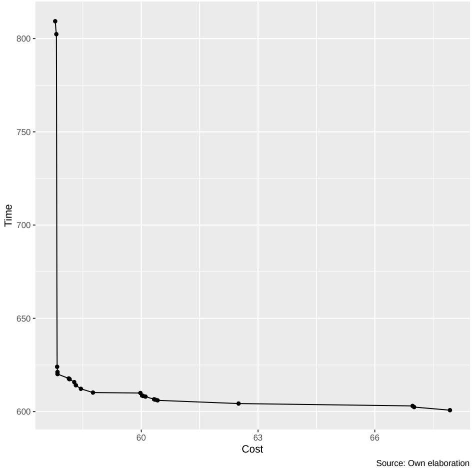


Figure: Efficient frontier for ulysses22

Conclusions

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- The proposed problem allows modeling situations where a balance between cost and quality of service is sought.
- The proposed models are valid tools to support decision making in logistics contexts.
- More efficient solution methods are needed to solve large instances

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Formulation for the median tour problem generalized with cumulative time

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