PLANNING ROUTES IN ROAD FREIGHT MINIMIZING LOGISTICAL COSTS AND ACCIDENT RISKS

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ABSTRACT

The Vehicle Routing Problem (VRP) has been widely studied throughout time as a way of optimizing routes by minimizing distances, and the issue of risk in VRP has been received less attention, which is essential to increase transport safety, to reduce accident costs and to improve delivery reliability. In this way, this paper aims to support decision makers to plan routes for a road freight company considering both, i.e. logistics cost and safety. An analytical approach based on statistics was developed from a real-world data to estimate the risk cost of routes using the Monte Carlo simulation. The Capacitated Vehicle Routing Problem (CVRP) was employed and logistics and risk costs were minimized by varying a specific safety level coefficient and the model generated solutions with safer routes, reducing risk cost by up to approximately 18%. The accidents probabilities and risk costs of each arc represented values as expected and the main contributions of this paper is the applicability of the approach to support decision makers to choose routes considering safety and logistics costs, and to be a simple and adaptable methodology for any VRP model. In addition *Knime Analytics Platform* was also used to estimate the accidents probabilities and to simplify data exploration, analysis, visualization and interpretation.

KEYWORDS. VRP with risk. Monte Carlo Simulation. Knime Analytics Platform.

Paper topics (indicate in order of PRIORITY the paper topic(s))

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1. Introduction

In an increasingly globalized and connected world in which the population and urbanization grows over the years, the pressure for more efficient and sustainable road freight increases due to the greater demand for different types of products [Engström, 2016]. The reliability in road freight depends on some factors that can be the cause of many accidents, interrupting the supply chain and generating significant losses. According to the World Health Organization (WHO) data, road accidents costs on average around 3% of the Gross Domestic Product (GDP) of a country.

Therefore, when a route is chosen for the vehicle that will leave a depot to deliver to other cities, not only the logistics costs or distance should be considered, but also the measurement of the risks linked to that road. Many studies consider only the first factor using mathematical models like VRP as a way of solving it. Risk measurement is addressed in hazardous materials transportation and cash-in-transit problems also through the VRP, which basically is a mathematical model that aims to minimize the distances and accidents or robbery risks [Talarico et al., 2015; Holeczek, 2021].

Verifying the applications of the topic risks in VRP and the need to introduce a statistical approach, the main contributions of this paper are: the approach applicability to decision makers to choose routes considering logistical costs and safety; simple and adaptable methodology for any risk model in VRP; and use the statistical method to estimate accident costs and probabilities. Also it is expected that the company could select their routes using this methodology.

2. Analytical Approach

2.1. Description

This study followed the procedures described in the workflow (Figure 1) and started from the VRP definition that was employed with a set of cities and roads known by the authors. Then, the parameters were defined by the online tool [Qualp, 2022] to calculate the logistics costs of each route, which consider fuel expenses with tolls

In parallel, the literature on statistical analysis of risk in road freight was revised and from [Branko Milovanović, 2012] and from the data that was found, the approach to calculate the probabilities and costs related to the risk of accident for each route was developed. All collected and processed data used in this study is available at [Bilato, 2022].

Several databases of Brazilian roads were consulted from government agencies whose information is available for public viewing and among them there are: the National Transport Confederation (CNT), the Department of Roads and Highways of the State of Sao Paulo (DER- SP) and the National Department of Transport Infrastructure (DNIT). Through a load insurance, data was provided regarding the losses in monetary values that occurred due to accidents between the periods from January 2018 to March 2021.

The data were processed using the *Knime Analytics Platform* tool, which generated the accident probabilities for each route. Then, Monte Carlo simulation was programmed to obtain the risk cost of the arcs.

The objective function (Equation 1) minimizes logistics and risk-related costs, and it was weighted by the α parameter whose values vary between 0 and 1 and which consists of assigning weight to safety during the optimization.

After defining the objective function and the parameters of the VRP, the mathematical model was implemented in *Python* and the results were generated by CBC solver. The security level α must be adjusted by the decision maker to assess whether the results are suitable to the case. Depending on the cargo type or its value, α may have to be adjusted in order to have a greater or lesser level of safety prioritization of the routes.

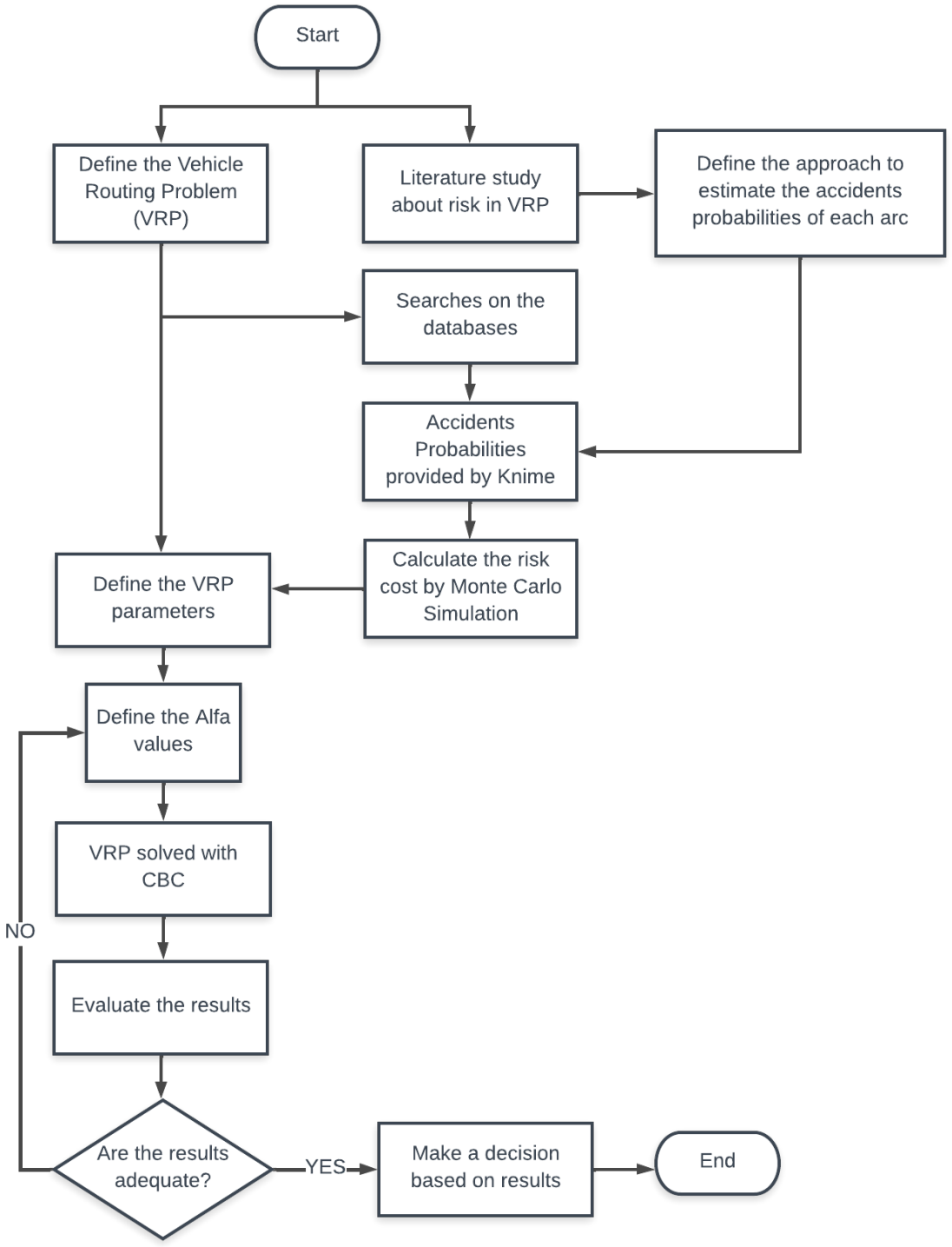


Figure 1: Workflow to employ this paper metodology.

Therefore, this evaluation is necessary for the decision maker to consider logistics costs and security, if the result is not adequate, a new change of α must be carried out until the solution fits to the best choice of the decision maker.

2.2. The VRP model

The capacitated VRP (CVRP) is employed in a real problem of a transportation company and the arcs are defined through the indirect graph $G = (N, E)$. The problem presents a single depot that is located in Limeira/SP. Two vertices are created to represent exit and arrival in the depot, respectively ($\{0, n+1\}$). Set $C = \{1, ..., n\}$ represents the delivery points in nine cities ($n = 9$). The total number of vertices is represented by $N = C \cup \{0, n+1\}$. Set ($K = \{k_1, k_2, k_3\}$) is the vehicles with equal capacity q.

The expressions of the mathematical model are presented next. Firstly it is defined the sets.

$$N = C \cup \{0, n+1\}, C = \{1, ..., n\}, E = \{(i,j) : i, j \in N, i \neq j, i \neq n+1, j \neq 0\}$$

$$minz = (1-\alpha) \sum_{k \in K} \sum_{(ij) \in E} c_{ij} X_{ijk} + \alpha \sum_{k \in K} \sum_{(ij) \in E} r_{ij} X_{ijk} \tag{1}$$

$$\sum_{k \in K} \sum_{j \in E} X_{ijk} = 1, \forall i \in C \tag{2}$$

$$\sum_{i \in E} d_i \sum_{j \in E} X_{ijk} \leq q, \forall k \in K \tag{3}$$

$$\sum_{j \in E} X_{0jk} = 1, \forall k \in K \tag{4}$$

$$\sum_{i \in E} X_{ihk} - \sum_{j \in E} X_{hjk} = 0, \forall h \in C, k \in K \tag{5}$$

$$\sum_{i \in E} X_{i,n+1,k} = 1, \forall k \in K \tag{6}$$

$$u_{ik} - (n+1) X_{ijk} \leq u_{jk} - n, \forall (i,j) \in E, k \in K \tag{7}$$

$$X_{ijk} \in \{0, 1\}, \forall (i,j) \in E, k \in K \tag{8}$$

Parameters: c_{ij}: logistics cost; r_{ij}: Risk cost; α: security level; d_i: demand of node i; q: vehicle capacity; X_{ijk}: binary variable.

The Equation (1) is the objective function that minimizes logistics c_{ij} and risks r_{ij} costs. The Equation (2) describes each arc must receive only one vehicle. The vehicle capacity constraint is represented by the Expressions (3). Equations (4) and (6) show every vehicle must leave and arrive at the depot, respectively. The flow restriction for each node is represented by the Equation (5). Finally, the sub-tour elimination is indicated by the Constraints (7) and the binary variables are defined by Expression (8).

Expressions (9) is introduced to ensure a strong formulation to eliminate sub-tour because of its LP relaxation but the number of these constrains could be too high (2^n) to the model. Because of this, it was used *cut callbacks* and *lazy constraints* to insert only constrains which violated the model [Haroldo G. Santos e Toffolo, 2019].

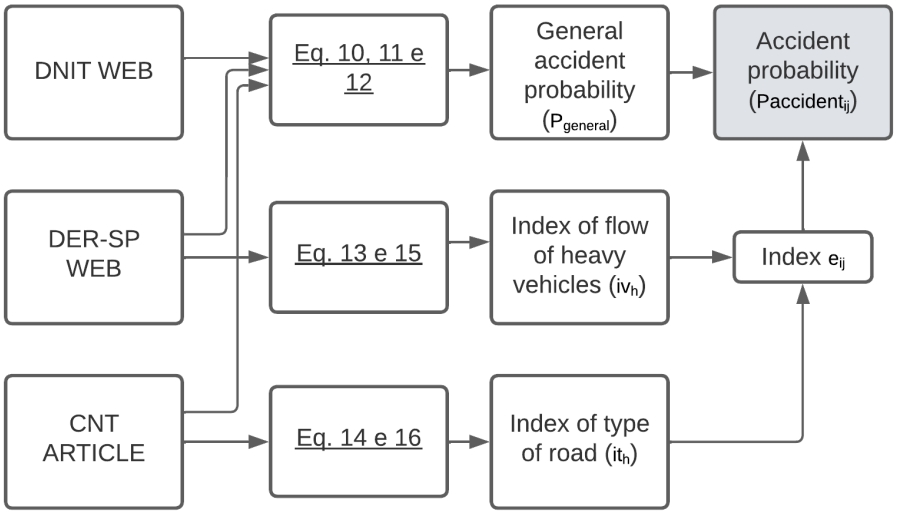


Figure 2: Workflow to calculate $Paccident_{ij}$.

$$\sum_{ij \in S} X_{ijk} \leq |S| - 1, \forall S \subseteq C, k \in K \tag{9}$$

Where: S is a set of sub-tour.

The *cut callbacks* are used only to improve the LP relaxation but not to define feasible solutions, which need to define by the initial formulation. So, it is included a weak sub-tour elimination constraints presented by Expression (7) in the initial model and then add Constraints (9) as cuts.

In this way, *Python MIP* ([Haroldo G. Santos e Toffolo, 2019]) package was introduced to the model because it is possible to eliminate sub-tour with *cut callbacks* and *lazy constraints* that makes it more efficient. The free solver CBC was used to optimize this problem and it was solved in 44 seconds for all twenty different values of α resulting in 363 variables and 289 constrains for each instance.

2.3. Calculating the risk cost r_{ij}

As already mentioned, the accidents probabilities $Paccident_{ij}$ were generated for each arc *ij* by *Knime Analytics Platform*, according to the workflow (Figure 2) and Equations (10), (11), (12), (13), (14), (15), (16), (17) e (18).

In a first moment, it was necessary to estimate a general probability ($Pgeneral$) of accidents occurring on any road in Brazil. Data were obtained from the free websites of [DER-SP, 2018; DNIT, 2020] and from the article [CNT, 2019]. [DNIT, 2020] provides the average volume V of all vehicles that travel daily on federal roads, while [DER-SP, 2018] extracted the percentage P_{sp} of heavy vehicles HV_{sp} over the total V_{sp} that circulates in Sao Paulo State roads that was calculated by Equation (10) and assumed that the percentage in federal roads as the same. From this point of view, Equation (11) resulted in the amount of heavy vehicles HV that is used in Equation (12) with the number of accidents $Naccidents$, extracted from [CNT, 2019], and then $Pgeneral$ was found.

$$P_{sp} = HV_{sp}/V_{sp} \tag{10}$$

Road type	Death rate per 100 accidents
two lanes two way road with central safety lane	12.3
two lanes two way road with central barrier	8.5
two lanes two way road with central line	18.0
Single lane one way road	11.9
Single lane two way road	22.3

Table 1: Death rate per type of road CNT [2019].

$$HV = P_{sp}.V \tag{11}$$

$$Pgeneral = \frac{Naccidents}{HV}.100\% \tag{12}$$

The factors considered to the calculation of r_{ij} were: the types of roads and the traffic of heavy vehicles. The first is considered because in Brazil there are several types of roads that show different safety levels. The Accident Panel Report prepared by [CNT, 2019] breaks it into five categories ($T = \{t1, ..., t5\}$) as presented by Table 1. It is also shown that the number of deaths per hundred accidents was extracted from this report and it is considered in the calculation for the risk of accidents.

The flow of heavy vehicles was obtained from [DER-SP, 2018] by speed radars installed on the roads and it was considered as directly proportional to the accidents probabilities because two roads with the same characteristics but one have a bigger flow than other so the first has greater chances of an accident occurring.

The indexes it_h and iv_h represents, respectively, the types of road and the flow of vehicles were calculated according to the workflow of the Figure 2 and where $h \in H$ which means that road h is on the set $H = \{h1, ..., h12\}$ of problems roads. The data was extracted from [CNT, 2019; DER-SP, 2018]. First, it was necessary to find the averages $\bar{x}$ and $\bar{y}$ by the Equations (13) and (14) that represent, respectively, the average flow of vehicles x_h running on the twelve roads of the problem $NH = 12$ and the average death rate per 100 accidents y_t among the five types of roads $NT = 5$. Then, the indexes iv_h and it_h were calculated by the Equations (15) and (16).

$$\bar{x} = \frac{\sum_{h \in H} x_h}{NH} \tag{13}$$

$$\bar{y} = \frac{\sum_{t \in T} y_t}{NT} \tag{14}$$

$$iv_h = 1 + \frac{x_h - \bar{x}}{\bar{x}}, \forall h \in H \tag{15}$$

$$it_h = 1 + \frac{y_h - \bar{y}}{\bar{y}}, \forall h \in H \tag{16}$$

Where x_h means the flow of vehicles represented by road h and y_h the death rate of the type of road h.

In some arcs between the nodes of the VRP, the vehicle may pass through more than one road, e. g., the arc Limeira-Cosmópolis has two roads SP330 and SP133 whose flows and

Range of values	occurrence
$ 0.01 to $ 200,000.00	37.91%
$ 200,000.00 to $ 300,000.00	24.17%
$ 300,000.00 to $ 500,000.00	19.91%
$ 500,000.00 to $ 1,000,000.00	16.11%
$ 1,000,000.00 or more	1.90%

Table 2: Percentage of accidents divided by the range of losses in load values.

characteristics are different. Thus, it is necessary a index e_{ij} that is weighted by iv_h, it_h and l_h, and represented by the Equation (17). Where l_h is the length that the truck travels in each road h of the arc ij and l_{ij} represents the total length of the arc ij.

$$e_{ij} = \frac{\sum_{h \in H} iv_h.it_h.l_h}{l_{ij}}, \forall (i,j) \in E \tag{17}$$

Finally, Equation (18) describes the accident $Paccident_{ij}$ occurring among ij.

$$Paccident_{ij} = Pgeneral.e_{ij}, \forall (i,j) \in E \tag{18}$$

After to calculate $Paccident_{ij}$, it is possible to estimate r_{ij} by Monte Carlo simulation. This was possible through data provided by the load insurance, which extracted the percentages of accidents divided into intervals of losses in load values according to Table 2.

The Figure 3 illustrates an example of how the probabilities were distributed. The maximum load value for each range and the cost to the road freight company was considered as being 1% of its value, a deductible that load insurances usually charge. Thus, the occurrence of the event in the range between $0.01 and R$200,000.00, the value to be considered will always be the highest of the range, which in this case will be $200,000.00 and deductible cost for the carrier would be $2,000.00.

Also through Figure 3 it is possible to verify the accumulated percentage values, between 0 and 1, for each accident cost on the right. This will be important for the Monte Carlo simulation, which at each iteration selects a random value between 0 and 1 that will correspond to a accident cost. For example, according to Figure 3 each percentage range is equivalent to its cost, so any value selected in the range between 0 and 0.990971 will correspond to a accident cost equal to $0.00.

In this way, 1,000,000 iterations were performed for each arc of the problem and the average of accident costs was calculated and it generates r_{ij} that will be used in the objective function of this VRP.

3. Results and Discussions

3.1. Probabilities and costs of risks

Figure 4 represent the results for r_{ij} and it was in line with what was expected. When comparing arcs that have the same type of roads as Piracicaba-Santa Bárbara and Limeira-Mogi Mirim, it was verified that r_{ij} for the first ($ 788.70) is greater than the second ($ 61.61). It was expected because the vehicles flow on the Piracicaba-Santa Barbara arc (6,943 heavy vehicles) is greater than the other (535 heavy vehicles).

When comparing arcs that present similar or close vehicle flow such as Mogi Mirim-Araras and Mogi Mirim-Limeira, it is noted that r_{ij} for the first ($ 125.66) is greater than the second ($ 56.95). And this is due to the fact that the arc Mogi Mirim-Araras is a single lane two

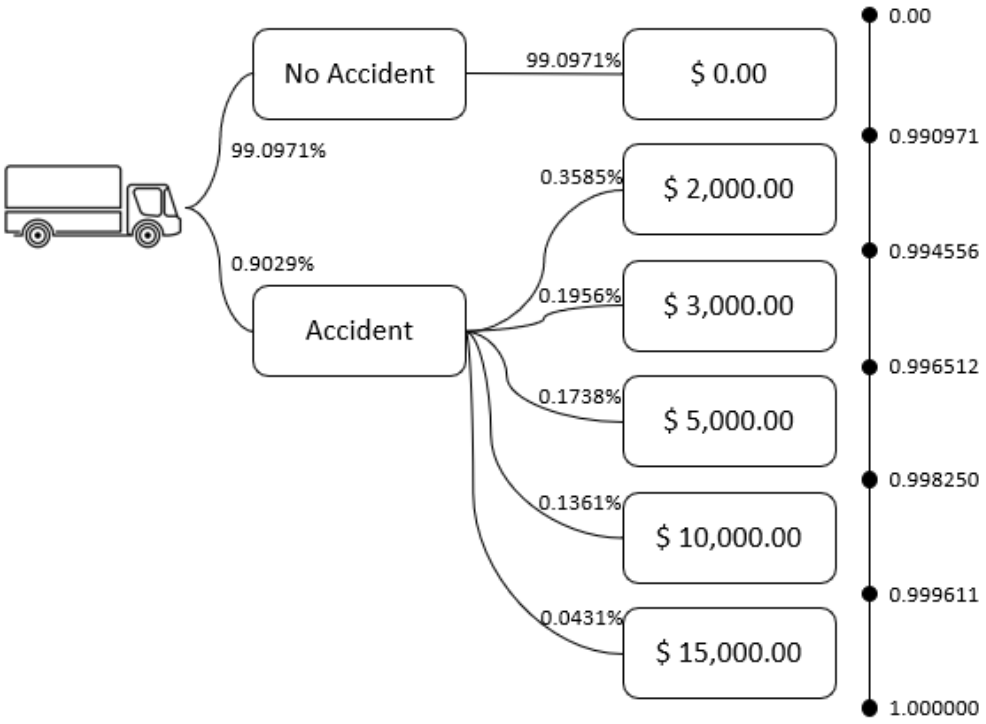


Figure 3: Accident probabilities and its costs to Monte Carlo Simulation.

	Limeira	Cosmópolis	Mogi Mirim	Santa Barbara	Holambra	Rio Claro	Araras	Piracicaba	Sumaré	Paulínia
Limeira	0.00	637.88	61.61	336.68	180.31	508.67	577.76	58.63	564.39	442.38
Cosmópolis	637.75	0.00	113.66	689.89	285.71	567.80	604.65	712.02	607.22	178.88
Mogi Mirim	56.95	114.70	0.00	346.91	395.09	230.16	125.66	62.37	284.68	124.44
Santa Barbara	345.28	677.03	340.71	0.00	566.20	369.15	376.54	782.16	330.51	560.02
Holambra	173.15	278.32	392.83	573.73	0.00	295.14	190.13	124.02	465.72	241.32
Rio Claro	513.24	558.61	219.31	377.51	303.39	0.00	127.67	117.80	535.77	477.55
Araras	583.51	607.49	122.98	385.87	182.59	127.61	0.00	243.35	566.57	487.67
Piracicaba	65.62	722.74	61.25	788.70	127.72	115.88	239.29	0.00	513.75	611.36
Sumaré	556.34	598.14	283.38	328.94	464.88	536.80	564.29	509.03	0.00	392.31
Paulínia	443.51	175.74	127.37	553.38	245.13	476.63	501.81	613.43	392.40	0.00

Figure 4: Risk cost r_{ij} in $.

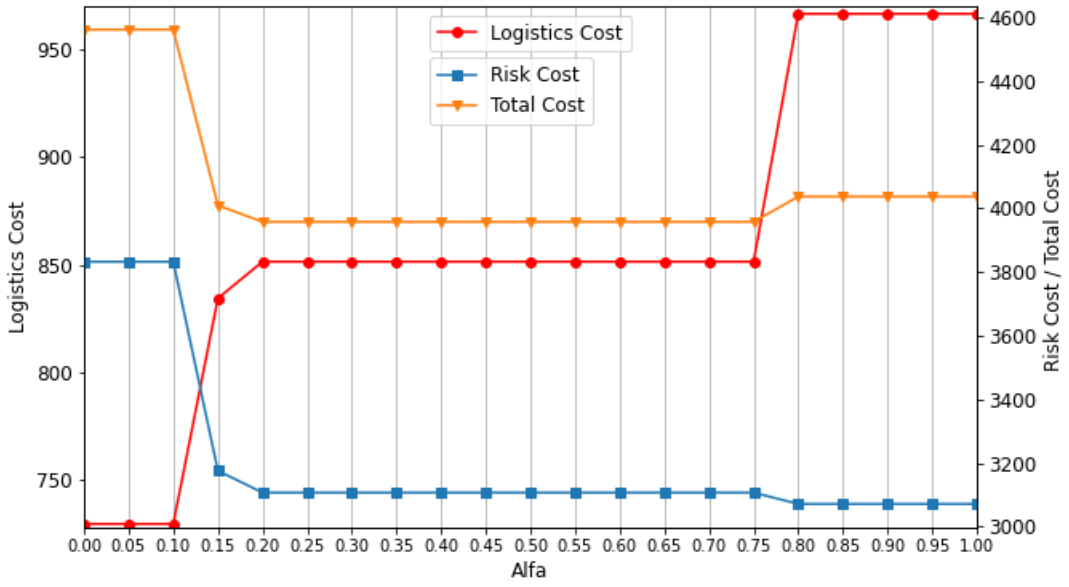


Figure 5: Results of c_{ij}, r_{ij} and z

way road, according to the nomenclature of [CNT, 2019], which has the highest death rate among all type of roads.

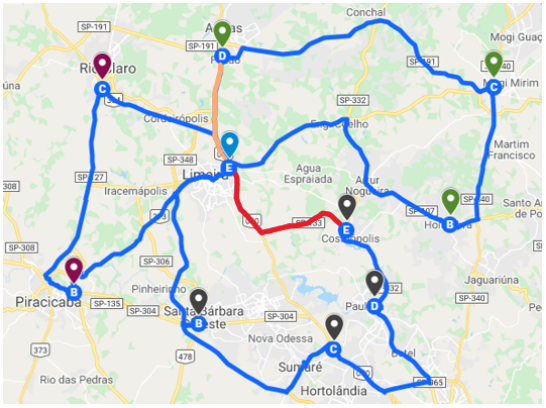
Other analyzes like this were also carried out and the same conclusions were reached. In this way, it is possible to state that the methodology followed to find r_{ij} was satisfactory, since consistent results were found according to the results obtained.

3.2. Optimization results

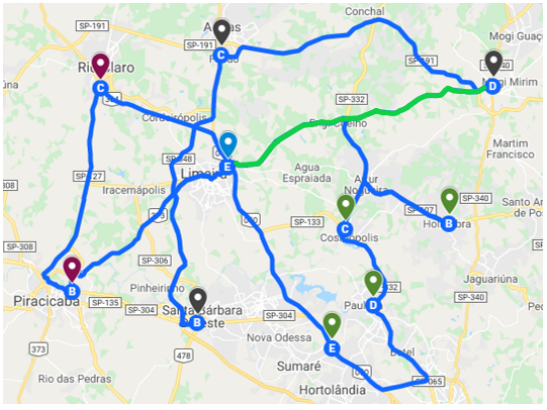
Figure 5 represents the graph with the results of each parcel, logistics and risk cost, and the sum between them for the optimization varying α. Note for $\alpha = 0$, the logistic cost assumes the minimum value and the risk is the highest. When increasing α, the risk cost starts to decrease and the logistic cost increases. This occurs because the model starts to prioritize arcs with lower risks and thus reducing the concern with the cost of tolls and fuel.

It is verified by Figure 5 for this problem a variation is perceived in $\alpha = 0.15$ which the logistic cost suffers an increase from $ 729.70 to $834.36 while the risk decreases from $3832.44 to $3175.29 representing a decrease of approximately 17.15 %. Between $\alpha = 0.20$ and $\alpha = 0.75$, the minimum logistics costs remain at $851.38 and risks at $3106.47, which further increases the level of safety fact.

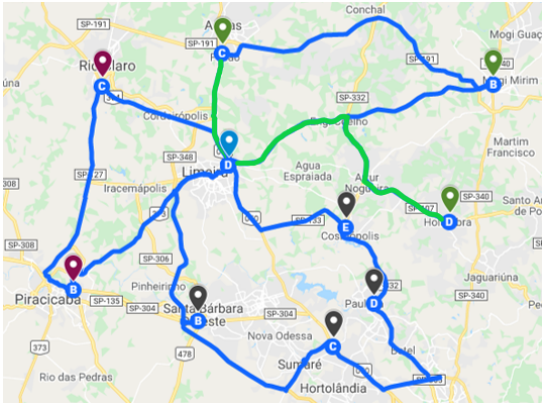
It is important to a decision maker to see it because the choice of routes will depend on what level of security it wants to work for its fleet. If security is considerable in the process of the company, it is important to work with $\alpha \geq 0.15$ but if the logistics cost is still relevant, the level of security should be $\alpha \leq 0.75$, because for $\alpha \geq 0.80$ the logistics cost will reach R$ 966.34 and the risk R$ 3070.95 which allows us to say that, due to the first parcel, there will be a considerable increase of approximately 13.50 % and the second reduce only 1.1 %, it would not be worth working in this range.



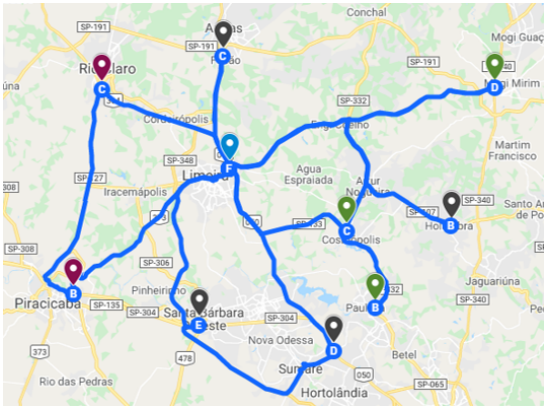
(a) $\alpha = 0,00$



(b) $\alpha = 0,15$



(c) $\alpha = 0,20$



(d) $\alpha = 1,00$

Figure 6: Routes obtained for different values of α.

The routes were also evaluated and it is represented by Figures 6(a), 6(b), 6(c) and 6(d) which each delivery point is identified with a marker and letter, referring to the sequence of deliveries made by each truck. It is also noted that there are different colors for the markers that identify which truck is carrying out the delivery, facilitating the evaluation of the results. For example, the markers in red represent truck 1, in black truck 2, in green truck 3 and in blue the warehouse.

For $0.10 \leq \alpha \leq 0.15$ there were some variations, the main one being eliminating the Cosmópolis-Limeira ($r_{ij} = 637.75$, red arc in Figure 6(a)) and adding Mogi Mirim-Limeira ($r_{ij} = 61.61$, green arc in the Figure 6(b)) and thus reducing the risk, in this case alone, by approximately 85% in relation to the total amount that was reduced for this comparison.

4. Conclusion

It is possible to say that the statistical approach worked in a positive way by verifying the accidents probabilities and risk cost and it can support the decision maker of a road freight company to select the best routes considering distance and accident risk. In addition, the whole approach developed here is simple and adaptable to any VRP model. Finally *Knime Analytics Platform* helps to deal with the use of real data in this paper simplifying data exploration, analysis, visualization and interpretation.

For future studies, the approach will be applied to solve a data-set with larger instances than that presented.

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