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RISK MANAGEMENT IN THE ALLOCATION OF VEHICLES TO TASKS IN TRANSPORT COMPANIES USING A HEURISTIC ALGORITHM

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Abstract:

The work deals with the issue of assigning vehicles to tasks in transport companies, taking into account the minimization of the risk of dangerous events on the route of vehicles performing the assigned transport tasks. The proposed risk management procedure based on a heuristic algorithm reduces the risk to a minimum. The ant algorithm reduces it in the event of exceeding the limit, which differs from the classic methods of risk management, which are dedicated only to risk assessment. A decision model has been developed for risk management. The decision model considers the limitations typical of the classic model of assigning vehicles to tasks, e.g. window limits and additionally contains limitations on the acceptable risk on the route of vehicles' travel. The criterion function minimizes the probability of an accident occurring along the entire assignment route. The probability of the occurrence of dangerous events on the routes of vehicles was determined based on known theoretical distributions. The random variable of the distributions was defined as the moment of the vehicle's appearance at a given route point. Theoretical probability distributions were determined based on empirical data using the STATISTICA 13 package. The decision model takes into account such constraints as the time of task completion and limiting the acceptable risk. The criterion function minimizes the probability of dangerous events occurring in the routes of vehicles. The ant algorithm has been validated on accurate input data. The proposed ant algorithm was 95% effective in assessing the risk of adverse events in assigning vehicles to tasks. The algorithm was run 100 times. The designated routes were compared with the actual hours of the accident at the bottom of the measurement points. The graphical interpretation of the results is shown in the PTV Visum software. Verification of the algorithm confirmed its effectiveness. The work presents the process of building the algorithm along with its calibration.

Keywords: *risk management, heuristic algorithm, ant algorithm, optimization*

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1. Introduction

The concept of risk is interpreted differently depending on the area under study. The risk of accidents is often examined in rail (Szaciłło et al., 2021), air (Izdebski et al., 2023), road (Huang et al., 2021) or intermodal (Kukulski et al., 2023) transport. The primary stage of risk management in various transport and logistics systems is calculating the probability of random events (Zabielska et al., 2023; Semenov & Jacyna, 2022). In road transport (Batarliene, 2020; Holeczek, 2019), risk means a measure of threat or danger that may result either from probable events beyond the control of a road user or from the possible consequences of making specific decisions. Risk in transporting goods is a set of factors that can damage the transported shipment. The risk in the transport of people in activities can lead to the loss of health and even the life of travellers.

Risk in transport companies is a complex decision problem. This is dictated by many aspects that need to be analyzed and factors that affect the proper solution to the problem. In general, the purpose of risk management in transport companies is to determine routes for vehicles that are characterized by a minimum probability of occurrence of various types of dangerous situations, e.g. traffic accidents or random weather events.

It is worth emphasizing that reducing the risk of dangerous events in transport companies increases the efficiency of transport processes and contributes to increasing the attractiveness of road transport compared to other modes of transportation, e.g. air or rail transport. Dangerous situations in transport companies appear when carrying out the ordered transport tasks. It is, therefore, advisable to plan the transportation of goods or people in such a way as to avoid collisions with other road users. Minimizing the risk of dangerous events and, thus, risk management should occur when planning vehicle routes by planners or organizers providing transport services.

In the transport process, various decisions are made with varying degrees of risk of performing the commissioned task. The critical decisions affecting the quality and efficiency of the transport service are the decisions on the choice of the vehicle route and the assignment of these vehicles to tasks. In both cases, the consequence of making a wrong decision is failure to perform the order, destruction of the means of transport, or even loss of health and life of the travellers. The work focuses on risk management in the issue of assigning vehicles to tasks.

The presented approach to risk management in transport companies is based on an approach that considers the use of a heuristic algorithm in minimizing dangerous events during the performance of transportation tasks by transport companies. The advantage of these algorithms is the quick time of generating the result, which is essential in the case of determining vehicle driving routes and their quick update (Agrawal et al., 2022; Ji et al., 2019; Ongcunaruk et al., 2021).

The risk management procedure in transport companies, according to which the assignment of vehicles to tasks was determined, consists of the classic stages of the risk management procedure and additionally considers the aspect of assigning vehicles to transport charges.

The stage of assigning vehicles to tasks aims to reduce the risk in the transport company to an acceptable level As a result of assigning vehicles to tasks in transport companies, vehicle routes are created. The tool controlling the level of risk is an optimization algorithm that assesses the risk of dangerous events on the route of vehicles. The algorithm calculates new driving routes and allocations if the limit is exceeded. At the risk analysis stage, potential dangerous points are indicated on the route of vehicles for which the probability of a dangerous event and its consequences is determined. Estimated probabilities are determined when the vehicle appears at a given point on the route. It is therefore necessary to designate routes for assigning vehicles to tasks in such a way as to reduce the probability of dangerous events at these points to a minimum. The optimization algorithm evaluates the generated allocation and calculates the likelihood of accident risk and its consequences. If the acceptable level of risk is exceeded, it rejects the developed solution and repeats the stage of selecting the assignment of tasks to vehicles. The ant algorithm was used to manage the selection of vehicles for tasks. The ant algorithm belongs to the group of heuristic algorithms that are often used in complex optimization problems (Giovanni et al., 2002). A valuable advantage of selected heuristic algorithms is their short calculation time.

The paper assumes that the probability of an accident on a given section of the transport network is determined based on theoretical distributions based on data measured on these sections of the road network. The fit of the empirical distribution to the theoretical one was carried out using the STATISTICA 13 program.

The complexity of transport processes means that risk management in transport companies should be supported by appropriate tools adapted to the nature of these processes. Risk management is the management of the route of vehicles in such a way as to avoid dangerous events with other road users or hazardous situations. The analysis of current approaches to risk management methods and tools in allocating vehicles to tasks in transport companies has shown that there are no models and algorithms to solve the problem comprehensively, determining the risk of dangerous events along the entire transport route, not only in its specific place. It should be noted that none of the risk assessment and management tools allows for assigning vehicles to tasks in such a way as to minimize this risk. From the point of view of research on risk management in transport companies, an essential aspect is not only the formulation of a model adequate to a given situation but also the selection of an appropriate algorithm to solve it.

The primary purpose of the work is to develop a tool to support decision-making in the allocation of vehicles to tasks in transport companies, considering minimizing the risk of dangerous events in routes generated by the assignment. A new approach presented in the work is to consider the risk aspect in assigning vehicles to tasks.

The research presented in the work is contained in six chapters. The first chapter gives an introduction to the undertaken research topic. The second chapter presents an overview of the literature on the issue of assigning vehicles to tasks and methods of risk management in transport companies. The third chapter describes the risk management model in a transport company and presents its formal record. The fourth chapter describes the optimization algorithm used to reduce the risk of dangerous events on routes generated by assigning vehicles to tasks. Verification of the algorithm and its calibration are presented in the fifth chapter. The summary emphasizes the originality of the proposed research and its further direction.

2. The state of the art

2.1. The assignment problem in transportation companies

The problem of assigning vehicles to tasks is similarly an optimization problem (Tian et al., 2022; Wei et al., 2021; Munapo, 2020). The issue of assigning vehicles to tasks belongs to a broad group of problems of allocating resources to tasks. This issue is known in the literature and interpreted differently depending on the problems under consideration (Yu et al., 2023; Dhouib, 2022). This issue involves assigning available resources, e.g. vehicles and employees, to assigned tasks. The classic assignment assumes that each task, if possible, is assigned to precisely one performer, and each performer completes only one task. The measures of a correctly generated assignment usually determine the minimum execution time for all tasks or the minimum cost of task execution. The issue is often modified by introducing various combinations of the number of tasks assigned to resources, e.g. an equal number of tasks and resources, more tasks than resources, or fewer tasks than resources. In general, the assignment problem is the association of resources with tasks (Karsu et al., 2021). The consequence of this association is a specific benefit that gets worse or better depending on the combination chosen. In transport issues, the issue of allocation becomes more complex. There are constraints on driving time, work time and task completion time, making assignments even more difficult. The single contractor constraint has been modified to allow multiple tasks to be performed by one vehicle. The number of vehicles is only determined after assigning them to tasks. If the risk factor is taken into account in the assignment of vehicles to tasks, the limit for exceeding the acceptable risk level should be additionally taken into account.

The allocation problem also plays a fundamental role in determining transport routes (Lyu & Andrew, 2021; Fuentes et al., 2021). The allocation problem also determines the minimum number of resources, e.g. vehicles, to complete all routes. An appropriate set of tasks, e.g., routes to be completed, is determined for each means of transport. The allocation measure is the minimum length of the route of the vehicles performing all the ordered transport tasks. Hence, determining the minimum access routes to individual tasks and loading routes is decisive in the allocation problem. In resource allocation problems, tasks take different forms, but the meaning of the problem is always the same. Tasks should be combined with available resources so that the benefit from this combination is as good as possible. An essential assignment in transport issues is the problem of determining work schedules. Scheduling can be defined as the time allocation of available resources to tasks. The assignment characterized in scheduling differs from the classic assignment model, where one agent (device, employee) performs precisely one task and one task is performed by only one agent. The sense of scheduling is to determine the order of tasks and assign them to the performers of these tasks (employees, devices) so that these performers complete these tasks in the minimum time. One contractor can perform tasks sequentially in a given period. The problem of assigning vehicles to tasks is a complex decision problem belonging to NP-hard problems. To solve it, it is required to use artificial intelligence algorithms, e.g. genetic algorithms (Jia et al., 2018).

2.2. Risk management in transport companies

In transport companies, the risk is very often examined in the context of transporting dangerous goods and minimizing the number of accidents on the route of vehicles (Mohri et al., 2022). The transport of hazardous goods is a specific type that requires the development of such technology and transport organization that will minimize the probability of an accident risk on a given transport route (Hosseini & Verma 2021; Timajchi et al., 2019). The consequences of accidents in transporting dangerous goods may lead to loss of health or life of people in the danger zone, the need to immediately evacuate people from hazardous areas, contamination of air, water and soil, degradation of the natural environment, and severe material losses.

Research (Huang et al., 2021) shows that the leading cause of accidents in transporting dangerous goods should be sought in the human factor. Accidents are caused by bravado, alcohol, stress, and weather conditions, but also by overloading the body in terms of health, mental and physical. Transporting dangerous goods is associated with the possibility of accidents causing fires, explosions or toxic environmental contamination. To avoid such serious consequences, mechanisms should be introduced to reduce the risk of accidents in road transport. Certain random events in road transport occur with a very low probability and therefore are not considered for risk estimation, e.g. lightning strikes. Certain dangerous circumstances, e.g., vehicle breakdowns or driver errors, are among the most common events contributing to road accidents. The frequency of these events can be reduced through thorough technical inspections of vehicles, or ensuring adequate rest for drivers, e.g. introducing a two-person crew for a given transport task. An essential mechanism for reducing the number of accidents is the determination of such driving routes characterized by a minimum probability of dangerous situations independent of the person performing transport tasks, e.g., threats from other road users.

In road transport, the main threats are traffic accidents caused by various factors depending or not on the driver performing the transport task (Ebrahim et al., 2021; Mahdi et al., 2020). The effect of an accident has a different weight depending on the size of losses, damage, or the number of injured or killed (Mujalli et al., 2023; Mokhtarimousavi et al., 2020). In most cases, determining the risk in transport companies is based on analysing historical data on accidents, such as their frequency, consequences, and identifying factors contributing to their occurrence (Hossaina et al., 2019).

When making decisions under risk conditions in the transport of cargo or passengers, confident choices are made, leading to various consequences, and it is essential to be able to assess the likelihood of these consequences. Therefore, determining the probability of a dangerous event and its implications is critical in risk estimation. The measure of risk is, thus, a combination of the size of the possible loss and the probability of incurring this loss (Stojanovic et al., 2023).

The risk in road transport depends on the choice of the vehicle route (Haixing & Qiangian, 2022; Fornalchyk et al., 2021), so it is necessary to designate such a route to minimize dangerous situations along the entire vehicle route. The routing issue is an optimization issue, so it is advisable to use heuristic algorithms.

The literature analysis confirmed that the problem of allocation in transport companies is presented in a classical approach without considering the minimization of the risk of accidents in routes generated by the realized allocation. The issue of assigning vehicles to tasks in transport companies is a complex decision-making issue and requires the use of heuristic algorithms.

3. Risk management model in assigning vehicles to tasks

3.1. The assumption of the model

In the developed decision-making model, risk management in assigning vehicles to tasks comes down to assigning vehicles to transport tasks so that a minimum probability of dangerous situations on this route characterizes the route generated due to this assignment. The developed risk management model can transport cargo and passengers, depending on the defined transport task. A transport task in cargo transportation is defined as picking up a load from the loading point and transporting it to the unloading point. In public transport, a transport task can be defined as a communication line to which vehicles are assigned to serve it. The assignment in the model is interpreted as a decision to assign a vehicle leaving the base to the first transport task or to assign a vehicle completing the current task to the next one. A random variable was introduced into the model to determine the theoretical distribution of the probability of a dangerous situation occurring on assignment routes or task routes. The risk of a hazardous condition on the access routes to the tasks and the task routes depended on the moment of the vehicle's appearance on these routes. Therefore, the task of the risk management model in assigning vehicles to tasks is to assign cars to tasks at such moments when the risk is minimal. The developed risk management model is an optimization model with a designated objective function minimizing the risk of dangerous situations along the entire vehicle route. In addition, the model determines the minimum number of vehicles of a particular type that should be used to complete the assigned tasks. To construct the risk management model, the following assumptions were made:

- Vehicle routes between the base and tasks and between tasks are known.
- Routes of transport tasks are known.
- The number of vehicles to be assigned is known.
- The random variable determining the probability distribution of a dangerous event has an interpretation of the moment (time) of the occurrence of the event on a given section of the route. Therefore, the vehicle must appear on a given section of the route at such a moment that the probability of a dangerous situation and its consequences is minimal.
- The vehicle's driving route is interpreted as a route to the first task, an optional return to the base, or the execution of subsequent tasks and return to the base.
- Vehicles can be assigned to multiple tasks.
- Tasks must be completed within one working day.

3.2. The data input and the decision variables

To develop a risk management model in the allocation of vehicles to tasks, the input data were defined:

- ***WB*** **-** A set of transportation bases.
- ***Z*** **-** A set of loading points.
- ***WW*** **-** A set of unloading points.
- ***T*** **-** A set of time intervals.
- ***Q*** **-** The size of the load collected at the sender.
- **T1 -** Loading time.
- **T2 -** Unloading time.
- **T3 -** Waiting time for loading.
- **T4 -** Waiting time for unloading.
- **TPP1 -** Travel time between drop-off points and pick-up points.
- **TPP2 -** Travel time between unloading points and shipping points.
- **TPP3 -** Travel time between the base and the points of departure.
- **TPP4 -** Travel time between the landing point and the base.
- **PP1 -** The probability of a dangerous event occurring between the points of origin and the points of receipt.
- **PP2 -** Probability of a dangerous event occurring between unloading points and shipping points.
- **PP3 -** The probability of a dangerous event occurring between the base and the points of departure.
- **PP4 -** The probability of a dangerous event occurring between the unloading point and the base.
- **PPS1 -** Probability of the occurrence of the result of a dangerous event between the points of origin and the points of receipt.
- **PPS2 -** Probability of the occurrence of the result of a dangerous event between the unloading points and the points of dispatch.
- **PPS3 -** Probability of the result of a dangerous event between the base and the points of departure.

- **PPS4 -** Probability of the result of a hazardous event occurring between the unloading point and the base.
- ***ST* -** A set of means of transport.
- **V -** Vehicle capacity.
- **LD -** Vehicle payload.
- **TBP -** Vehicle parking time.
- **TDP -** The time allowed for the task to be completed by the vehicle.
- *A*1 - The lower bound of the time window for the base.
- *B*2 - The upper limit of the time window for the base.

To formally record the risk management model in the assignment of vehicles to tasks, it is necessary to define the decision variables of the model. The first type of variables are binary variables describing connections between network objects carried out by a given vehicle in a specific time interval and assigned to a given task. The second type of variable determines the moment of departure of vehicles from the base for the ordered transport tasks. The purpose of introducing such types of decision variables is the same as in the risk management model in cargo transport. The driving time of vehicles should be regulated so that the vehicles appear on a given section at the time, generating the minimum probability of a dangerous event.

To develop a risk management model in the allocation of vehicles to tasks, the decision variables were defined:

- **XP1 -** Connection between drop-off points and pick-up points.
- **XP2 -** Connection between unloading points and shipping points.
- **XP3 -** Connection between the base and the points of origin.
- **XP4 -** Connection between the landing point and the base.
- **HP -** The moment of departure of the vehicles from the transport base.

3.3. Limits and the risk assessment function

Assignment constraints take the form:

- Limitation of the allocation resulting from the capacity and load capacity of the vehicles:

$$\forall (w,w') \in \boldsymbol{LBZ}, \forall t \in \boldsymbol{T}, \forall st \in \mathbf{ST}, \forall zad \in \boldsymbol{ZAD}$$

$$xp1\big((w,w'),zad,st,t\big) \cdot v(st) \le q(z,zad) \tag{1}$$

$$xp2\big((w,w'),zad,st,t\big) \cdot v(st) \le q(z,zad) \tag{2}$$

$$xp1\big((w,w'),zad,st,t\big) \cdot ld(st) \le q(z,zad) \tag{3}$$

$$xp2\big((w,w'),zad,st,t\big) \cdot ld(st) \le q(z,zad) \tag{4}$$

- Limitation for the duration of tasks for a single vehicle:

$$\forall (w,w') \in \boldsymbol{LBZ}, \forall t \in \boldsymbol{T}, \forall st \in \boldsymbol{ST}, \forall (w,w') \in \boldsymbol{LWB}$$

$$\begin{aligned} &xp1\big((w,w'),zad,st,t\big) \\ &\cdot [tpp1(w,w',t) + t1(z,zad) + t3(z,t,zad)] \\ &+ \sum_{(w,w')\in \boldsymbol{LZW}} \sum_{zad\in \boldsymbol{ZAD}} xp4\big((w,w'),zad,st,t\big) \\ &\cdot [tpp4(w,w',t) + t2(z,zad) + t4(z,t,zad)] \\ &+ \sum_{(w,w')\in \boldsymbol{LWZ}} \sum_{zad\in \boldsymbol{ZAD}} xp2\big((w,w'),zad,st,t\big) \\ &\cdot [tpp2(w,w',t) + t1(z,zad) + t3(z,t,zad)] \\ &+ xp3\big((w,w'),st,t\big) + tbp(st) \le tdp(st) \end{aligned} \tag{5}$$

- Restriction on meeting the condition of acceptable risk on the road:

$$\forall (w,w') \in \boldsymbol{LBZ}, \forall t \in \boldsymbol{T}, \forall st \in \boldsymbol{ST}, \forall (w,w') \in \boldsymbol{LWB}$$

$$\begin{aligned} &\Bigg[1 - xp1\big((w,w'),zad,st,t\big) \\ &\cdot [1 - pp\mathrm{E}1(w,w') \cdot pps\mathrm{E}1(w,w')] \\ &\cdot \prod_{(w,w')\in \boldsymbol{LZW}} \prod_{zad\in \boldsymbol{ZAD}} xp4\big((w,w'),zad,st,t\big) \\ &\cdot [1 - pp\mathrm{E}4(w,w') \cdot pps\mathrm{E}4(w,w')] \\ &\cdot \prod_{(w,w')\in \boldsymbol{LWZ}} \prod_{zad\in \boldsymbol{ZAD}} xp2\big((w,w'),zad,st,t\big) \cdot [1 \\ &- pp\mathrm{E}2(w,w') \cdot pps\mathrm{E}2(w,w')] \cdot xp3\big((w,w'),st,t\big) \\ &\cdot [1 - pp\mathrm{E}3(w,w') \cdot pps\mathrm{E}3(w,w')]\Bigg] \le Rdo \end{aligned} \tag{6}$$

− Limitation on fulfilment of time windows:

$$\forall (w,w') \in \boldsymbol{LBZ}, \forall t \in \boldsymbol{T}, \forall st \in \boldsymbol{ST}, \forall (w,w') \in \boldsymbol{LWB}, w \in \boldsymbol{WB}$$

$$\begin{aligned} &\mathrm{hp}(st,w,zad) + xp1\big((w,w'), zad,st,t\big) \\ &\cdot [tpp1(w,w',t) + t1(z,zad) + t3(z,t,zad)] \\ &+ \sum_{(w,w')\in \boldsymbol{LZW}} \sum_{zad\in \boldsymbol{ZAD}} xp4\big((w,w'), zad,st,t\big) \\ &\cdot [tpp4(w,w',t) + t2(z,zad) + t4(z,t,zad)] \\ &+ \sum_{(w,w')\in \boldsymbol{LWZ}} \sum_{zad\in \boldsymbol{ZAD}} xp2\big((w,w'), zad,st,t\big) \\ &\cdot [tpp2(w,w',t) + t1(z,zad) + t3(z,t,zad)] \\ &+ xp3\big((w,w'),st,t\big) + tbp(st) \geq a1(wb) \end{aligned} \tag{7}$$

$$\begin{aligned} &\mathrm{hp}(st,w,zad) + xp1\big((w,w'), zad,st,t\big) \\ &\cdot [tpp1(w,w',t) + t1(z,zad) + t3(z,t,zad)] \\ &+ \sum_{(w,w')\in \boldsymbol{LZW}} \sum_{zad\in \boldsymbol{ZAD}} xp4\big((w,w'), zad,st,t\big) \\ &\cdot [tpp4(w,w',t) + t2(z,zad) + t4(z,t,zad)] \\ &+ \sum_{(w,w')\in \boldsymbol{LWZ}} \sum_{zad\in \boldsymbol{ZAD}} xp2\big((w,w'), zad,st,t\big) \\ &\cdot [tpp2(w,w',t) + t1(z,zad) + t3(z,t,zad)] \\ &+ xp3\big((w,w'),st,t\big) + tbp(st) \leq b1(wb) \end{aligned} \tag{8}$$

The criterion function minimizes the probability of dangerous events in the routes of vehicles:

$$\forall (w,w') \in \boldsymbol{LBZ}, \forall t \in \boldsymbol{T}, \forall st \in \boldsymbol{ST}, \forall (w,w') \in \boldsymbol{LWB}$$

$$\begin{aligned} &F(\mathbf{X1},\mathbf{X2},\mathbf{X3},\mathbf{X4}) \\ &= \Bigg[1 - xp1\big((w,w'), zad,st,t\big) \\ &\cdot [1 - pp\mathrm{E1}(w,w') \cdot pps\mathrm{E1}(w,w')] \\ &\cdot \prod_{(w,w')\in \boldsymbol{LZW}} \prod_{zad\in \boldsymbol{ZAD}} xp4\big((w,w'), zad,st,t\big) \\ &\cdot [1 - pp\mathrm{E4}(w,w') \cdot pps\mathrm{E4}(w,w')] \\ &\cdot \prod_{(w,w')\in \boldsymbol{LWZ}} \prod_{zad\in \boldsymbol{ZAD}} xp2\big((w,w'), zad,st,t\big) \cdot [1 \\ &- pp\mathrm{E2}(w,w') \cdot pps\mathrm{E2}(w,w')] \cdot xp3\big((w,w'),st,t\big) \\ &\cdot [1 - pp\mathrm{E3}(w,w') \cdot pps\mathrm{E3}(w,w')] \Bigg] \longrightarrow min \end{aligned} \tag{9}$$

4. Ant algorithm in risk management in assigning vehicles to tasks

The concept of an artificial ant was introduced to define the ant algorithm. Each ant from the population creates its route with the interpretation of the assignment of vehicles to tasks. Waypoints are located in three layers. The route takes a given vehicle's departure from the base at a specific time to the tasks and then returns to the base. Route elements are located in layers:

- Layer I: vehicles to be assigned.
- Layer II: points on the interpretation of the vehicle's departure time from the transport base.
- Layer III: tasks to be assigned.

The number of points in layer I depends on the vehicles allocated. The number of elements in layer II is determined the same way as in the risk management model in cargo transport, i.e. on the number of potential departure hours in a given period. The number of points in layer III depends on the number of tasks to be completed.

The starting point of the ant route is the vehicle base. The other route of the ant, and thus the selection of subsequent route points, occurs with a certain probability:

$$\mathrm{PR}^{mr}{}_{yz}(t) = \begin{cases} \dfrac{\left[\tau_{yz}(t)\right]^{\alpha} \cdot \left[\eta_{yz}(t)\right]^{\beta}}{\sum_{l\in\Omega^{mr}} \left[\tau_{yl}(t)\right]^{\alpha} \cdot \left[\eta_{yl}(t)\right]^{\beta}} & , z \in \Omega^{mr} \\ 0 & , z \notin \Omega^{mr} \end{cases} \tag{10}$$

where:

$\tau_{yz}(t)$ – the intensity of the pheromone trace between the y-th point of the ant track and the z-th point in the t-iteration of the algorithm,

$\eta_{yz}(t)$ – heuristic information:

$$\eta_{yz}(t) = \frac{1}{p(\mathrm{y,z}) \cdot ps(\mathrm{y,z})} \tag{11}$$

where:

$p(y,z)$ – the probability of an event on network sections,

$ps(y,z)$ – the probability of the event's effect on network sections,

α, β – the influence of pheromones and heuristic data on the behavior of ants,

Ω^{mr} – the set of all point elements of the transport network, l - potential ant route points taken into account when selecting the next ant route point.

In subsequent iterations, the pheromone trace is calculated according to the formula:

$$\tau_{yz}(t+1) = (1-\rho)\tau_{yz}(t) + \sum_{mr=1}^{MR} \Delta\tau_{yz}{}^{mr}(t) \quad (12)$$

where:
mr – another ant in the anthill $mr \in \boldsymbol{MR}$,
ρ – pheromone volatilization factor ($0 < \rho \leq 1$),
$\tau_{yz}(t+1)$ – pheromone amplification, for the first iteration takes the value on each connection equal τ_0.

The first component of the formula (12) determines the pheromone volatilization rate, while the second determines the pheromone gain and takes the value:

$$\Delta\tau_{yz}{}^{mr}(t) = \begin{cases} \frac{1}{P^{mr}(t)} - K1^{mr}(t) - K2^{mr}(t) - K3^{mr}(t) - K4^{mr}(t) & \text{when segment (y,z) is used by the ant} \\ 0 & \text{otherwise 0;} \end{cases} \quad (13)$$

where:
$P^{mr}(t)$ – the probability of the occurrence of a dangerous event and its effect in the entire route created by the *mr*-th ant in the *t*-th iteration according to the formula (9);
$K1^{mr}(t)$ – penalty for exceeding time window limits (in model (7)-(8)) in the route created by the *m*-th ant in the *t*-th iteration of the algorithm, it is assumed that this penalty is half of the pheromone accumulated on the route;
$K2^{mr}(t)$ – penalty for exceeding the task completion time (5) in the route created by the *m*-th ant in the *t*-th iteration of the algorithm, it is assumed that this penalty is half of the pheromone accumulated on the route;
$K3^{mr}(t)$ – penalty for exceeding the limit on vehicle capacity and load capacity (in model (1)-(4)) in the route created by the *m*-th ant in the *t*-th iteration of the algorithm, it is assumed that this penalty is half of the pheromone accumulated on the route;
$K4^{mr}(t)$ – penalty for exceeding the acceptable risk limit (in model (6)) it is assumed that this penalty is half of the pheromone accumulated on the route.

The ant algorithm is an iterative algorithm, in the next iteration its solution is improved. The algorithm runs until the stop condition is reached. The stop condition is a fixed number of iterations. The number of ants in the population creating individual vehicle routes (solutions) and the number of iterations is set at the beginning of the algorithm implementation.
The main steps of the ant algorithm can be presented as:
- Step 1 - The first ant in the population starts making a route.
- Step 2 - Selection of subsequent route points according to the defined probability (10) until the ant reaches the end point of the route (fulfillment of all tasks).
- Step 3 - Repeat steps 1-2 for the next ant in the population.
- Step 4 - Pheromone update (12).
- Step 5 - Repeating steps 1-4 until the algorithm reaches the stopping condition. Selection of the ant route with the highest pheromone intensity among all routes generated in the population. This route is the final solution and determines the allocation of vehicles to tasks.

5. An example of using the ant algorithm for risk management in assigning vehicles to tasks

5.1. The input data

To verify the optimization algorithms in the risk management model in the assignment of vehicles to tasks, the transport network presented in Fig. 1 was defined, in which the transport base and tasks were determined. The tasks are carried out in the complete truckload system and are characterized as picking up the load from the loading place and transporting it to the unloading point. Dangerous points of the route were determined in four places, and the time of accidents, collisions and road incidents was measured in these places. For the remaining sections of the route, it was assumed that these sections were accident-free. It was also believed that the capacity and payload of a single vehicle are adapted to each task. Tasks must be completed between 6:00 a.m. and 5:00 p.m. The acceptable probability of a road accident risk is 0.55. One time interval and one task to be performed have been defined in the transport. Waiting times for loading have been omitted. Loading and unloading time was set at 15 minutes. It was assumed that the execution time for all tasks is 2 hours.

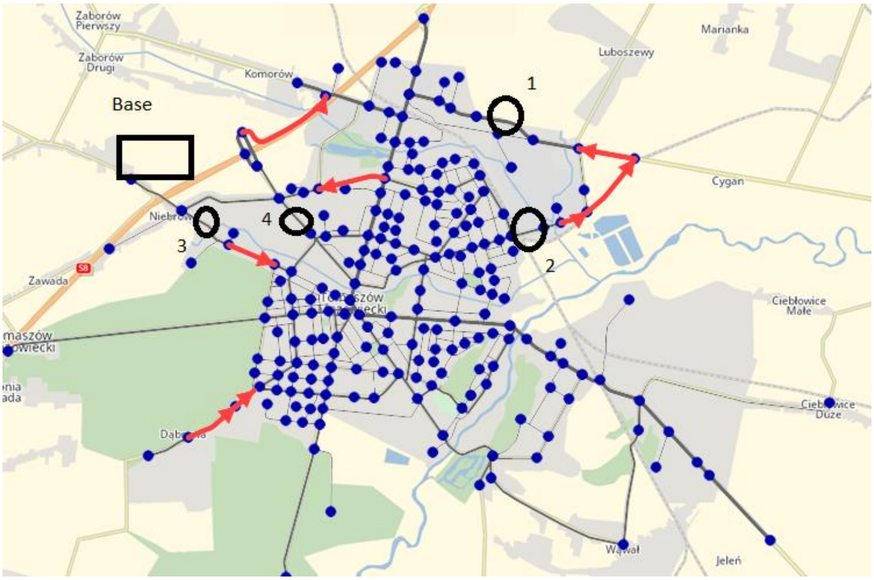

Fig. 1. Transport network with tasks

5.2. Theoretical distributions of the probability of accidents and their consequences in the assignment of vehicles to tasks

Theoretical accident probability distributions were determined based on measurement data. The hours of accidents at the measurement points are presented in Table 1 (S - serious accident, C - collision). The time of the accident is presented in minute format, measuring period from 6:00 to 17:00. Theoretical distributions of the accident random variable are shown in Fig. 2. The linear scatterplot confirms the normal distribution of the examined variable. The chi-square test and the Kolmogorov-Smirnov (K-S) test were used to determine the distributions.

The null hypothesis stating the adopted type of distribution is rejected when the calculated value of the statistics falls within the critical area determined by the assumed significance level α=0.05. The values of the Chi-square and Kolmogorov-Smirnov tests and the parameters of the examined distributions are presented in Table 2.

Tests of compliance for theoretical distributions of the random variable of accidents classified as a collision at individual measurement points are presented in Table 3.

Table 1. Measuring points [hour expressed in minutes]

Point 1 Type	Point 2 Type	Point 3 Type	Point 4 Type
712 C	422 C	715 C	710 C
743 S	621 S	745 C	740 C
720 C	472 C	728 C	721 C
620 C	474 C	628 C	622 S
655 C	555 C	651 S	654 C
783 C	713 C	781 C	781 C
755 S	585 C	771 C	776 C
812 C	661 S	817 C	813 C
835 C	674 C	833 S	834 C
642 C	782 C	872 C	1023 C
936 C	730 C	931 C	935 C
533 C	744 S	967 C	961 C
878 C	722 C	871 C	872 S
972 C	811 S	757 C	754 C
754 S	857 C	793 C	788 C
793 C	642 C	843 C	849 S
844 S	913 C	977 C	970 C
872 C	681 C	865 C	859 C
861 S	934 S	662 S	660 C
664 C	942 S	913 C	916 C
910 S	823 C	844 S	840 C
843 C	876 C	871 C	870 C
1010 C	1062 C	1061 S	550 S

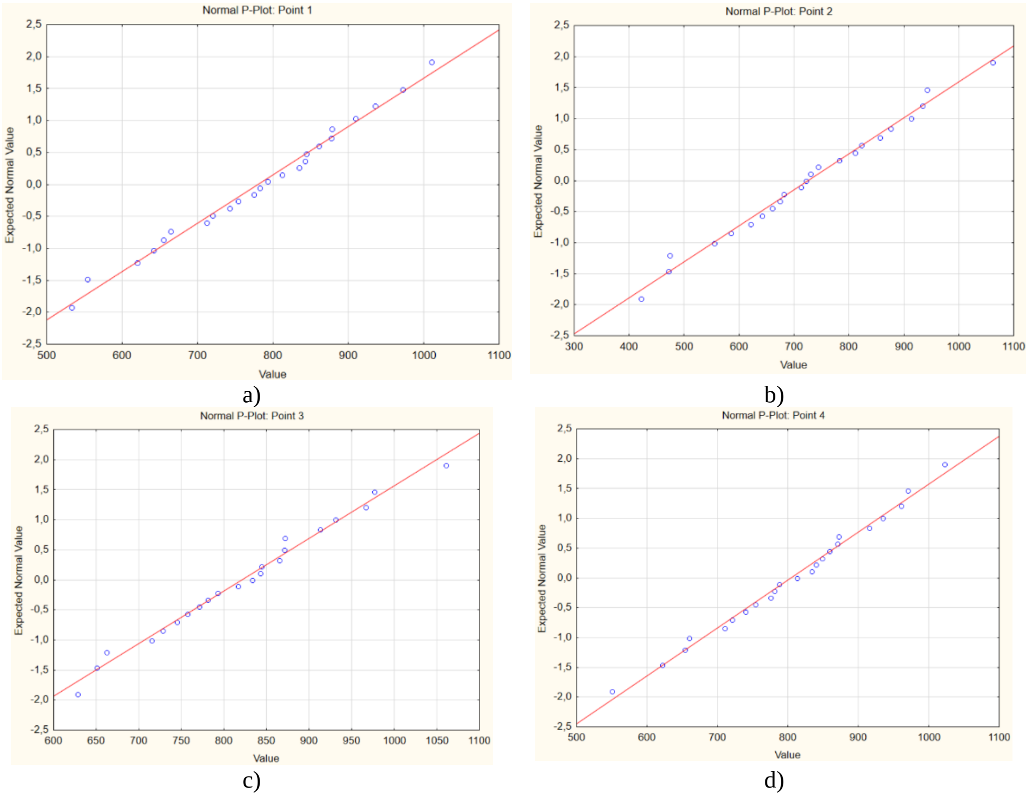

Fig. 2. Fitting the theoretical distribution of the random variable of the moment of road accidents at the measurement points a) point 1 b) point 2 c) point 3 d) point 4

Table 2. Compliance testing and distribution parameters for road accidents of any type

Measurement points	Statistics	Chi-square test (p)	Statistics	K-S test	Distribution parameters	Distribution
1	7,280	0,94	0,15	-	μ=737; s^2=34281	normal
2	9,898	0,77	0,05	-	μ=723; s^2=26941	normal
3	5,116	0,77	0,14	-	μ=812; s^2=22130	normal
4	1,620	0,89	0,11	-	μ=805=; s^2=14161	normal

Table 3. Compliance testing and distribution parameters for collision-type road accidents

Measurement points	Statistics	Chi-square test (p)	Statistics	K-S test	Distribution parameters	Distribution
1	5,641	0,91	0,11	-	μ=729; s^2=33914	normal
2	4,983	0,91	0,12	-	μ=723; s^2=24128	normal
3	5,33	0,93	0,06	-	μ=811; s^2=22410	normal
4	2,67	0,90	0,04	-	μ=817; s^2=9921	normal

5.3. Results of calibration and verification of the ant algorithm in the assignment of vehicles to tasks

The tested combinations of ant algorithm settings are shown in Table 4. Table 5 shows the aggregate results of the algorithm. Experimentally, the number of iterations of the algorithm was set at 200 repetitions, and the population size at 100 ants.

Table 5 shows that the minimum collision probability value was 0.44 for test no. 24 with the algorithm parameters α=1, β=1, ρ=0.8. The route generated by the ant assigned three vehicles to the assigned tasks. A graphical presentation of the routes of the three vehicles is shown in the Fig. 3 (green line – vehicle 1, blue line – vehicle 3, red line – vehicle 3). The departure time of the first vehicle was set at 8:15, the second and third vehicles at 8:30. Based on Table 6, it can be concluded that the efficiency of the ant algorithm is 93%. The algorithm verification process compares N algorithm solutions with actual data specifying the times of dangerous events on route sections.

Table 4. Test settings of the ant algorithm parameters

Test	α	β	ρ	Test	α	β	ρ	Test	α	β	ρ
1	1	0,5	0,2	21	1	1	0,2	41	1	5	0,2
2	1	0,5	0,4	22	1	1	0,4	42	1	5	0,4
3	1	0,5	0,6	23	1	1	0,6	43	1	5	0,6
4	1	0,5	0,8	24	1	1	0,8	44	1	5	0,8
5	3	0,5	0,2	25	3	1	0,2	45	3	5	0,2
6	3	0,5	0,4	26	3	1	0,4	46	3	5	0,4
7	3	0,5	0,6	27	3	1	0,6	47	3	5	0,6
8	3	0,5	0,8	28	3	1	0,8	48	3	5	0,8
9	5	0,5	0,2	29	5	1	0,2	49	5	5	0,2
10	5	0,5	0,4	30	5	1	0,4	50	5	5	0,4
11	5	0,5	0,6	31	5	1	0,6	51	5	5	0,6
12	5	0,5	0,8	32	5	1	0,8	52	5	5	0,8
13	10	0,5	0,2	33	10	1	0,2	53	10	5	0,2
14	10	0,5	0,4	34	10	1	0,4	54	10	5	0,4
15	10	0,5	0,6	35	10	1	0,6	55	10	5	0,6
16	10	0,5	0,8	36	10	1	0,8	56	10	5	0,8
17	20	0,5	0,2	37	20	1	0,2	57	20	5	0,2
18	20	0,5	0,4	38	20	1	0,4	58	20	5	0,4
19	20	0,5	0,6	39	20	1	0,6	59	20	5	0,6
20	20	0,5	0,8	40	20	1	0,8	60	20	5	0,8

Table 5. Results of tests (P – probability of a collision in the route, T – running time [minutes:seconds])

Test	P	T	Test	P	T	Test	P	T	Test	P	T	Test	P	T
1	0,50	5:26	13	0,71	5:35	25	0,67	4:12	37	0,80	4:11	49	0,49	4:31
2	0,55	5:13	14	0,72	4:12	26	0,59	4:23	38	0,78	5:12	50	0,47	4:22
3	0,57	4:21	15	0,71	4:33	27	0,65	4:23	39	0,79	4:21	51	0,48	4:53
4	0,61	4:22	16	0,72	4:45	28	0,68	3:31	40	0,84	4:21	52	0,53	4:11
5	0,60	4:03	17	0,71	4:23	29	0,51	4:44	41	0,55	4:35	53	0,61	4:21
6	0,61	4:32	18	0,78	4:11	30	0,52	4:25	42	0,47	4:34	54	0,77	4:22
7	0,66	4:43	19	0,75	4:34	31	0,64	4:21	43	0,47	4:12	55	0,77	4:22
8	0,61	4:12	20	0,48	4:21	32	0,71	4:21	44	0,47	4:32	56	0,77	4:22
9	0,61	4:31	21	0,47	4:42	33	0,85	4:22	45	0,49	4:32	57	0,81	4:22
10	0,62	4:32	22	0,46	4:32	34	0,71	4:27	46	0,49	4:42	58	0,85	4:15
11	0,61	4:33	23	0,44	4:23	35	0,71	4:31	47	0,50	4:21	59	0,86	4:22
12	0,62	4:32	24	0,46	4:12	36	0,80	4:12	48	0,50	4:23	60	0,81	4:42

Table 6. Efficiency of the ant algorithm in assigning vehicles to tasks (P – probability, E – efficiency)

Test	P	E	Test	P	E	Test	P	E	Test	P	E	Test	P	E
1	0,44	Yes	21	0,46	Yes	41	0,49	Yes	61	0,46	Yes	81	0,49	Yes
2	0,46	Yes	22	0,44	Yes	42	0,47	Yes	62	0,46	Yes	82	0,49	Yes
3	0,47	Yes	23	0,44	Yes	43	0,47	Yes	63	0,47	Yes	83	0,48	Yes
4	0,44	Yes	24	0,44	Yes	44	0,47	Yes	64	0,47	Yes	84	0,48	Yes
5	0,44	Yes	25	0,46	Yes	45	0,48	Yes	65	0,48	Yes	85	0,47	Yes
6	**0,49**	**No**	26	0,46	Yes	46	0,45	Yes	66	0,48	Yes	86	0,46	Yes
7	0,49	Yes	27	0,44	Yes	47	0,45	Yes	67	0,49	Yes	87	0,45	Yes
8	0,49	Yes	28	**0,46**	**No**	48	**0,49**	**No**	68	0,49	Yes	88	**0,53**	**No**
9	0,46	Yes	29	0,47	Yes	49	0,47	Yes	69	0,45	Yes	89	0,46	Yes
10	0,41	Yes	30	0,47	Yes	50	0,45	Yes	70	0,45	Yes	90	0,46	Yes
11	0,44	Yes	31	0,49	Yes	51	0,47	Yes	71	0,44	Yes	91	0,45	Yes
12	**0,49**	**No**	32	0,49	Yes	52	0,47	Yes	72	0,46	Yes	92	0,44	Yes
13	0,50	Yes	33	0,46	Yes	53	0,48	Yes	73	**0,52**	**No**	93	0,44	Yes
14	0,47	Yes	34	0,44	Yes	54	0,49	Yes	74	0,46	Yes	94	0,47	Yes
15	0,47	Yes	35	**0,44**	**No**	55	0,48	Yes	75	0,47	Yes	95	0,47	Yes
16	0,44	Yes	36	0,49	Yes	56	0,45	Yes	76	0,46	Yes	96	0,48	Yes
17	0,47	Yes	37	0,46	Yes	57	0,49	Yes	77	0,47	Yes	97	0,45	Yes
18	0,45	Yes	38	0,48	Yes	58	0,48	Yes	78	0,45	Yes	98	0,45	Yes
19	0,46	Yes	39	0,48	Yes	59	0,48	Yes	79	0,48	Yes	99	0,45	Yes
20	0,44	Yes	40	0,47	Yes	60	0,47	Yes	80	0,48	Yes	100	0,48	Yes

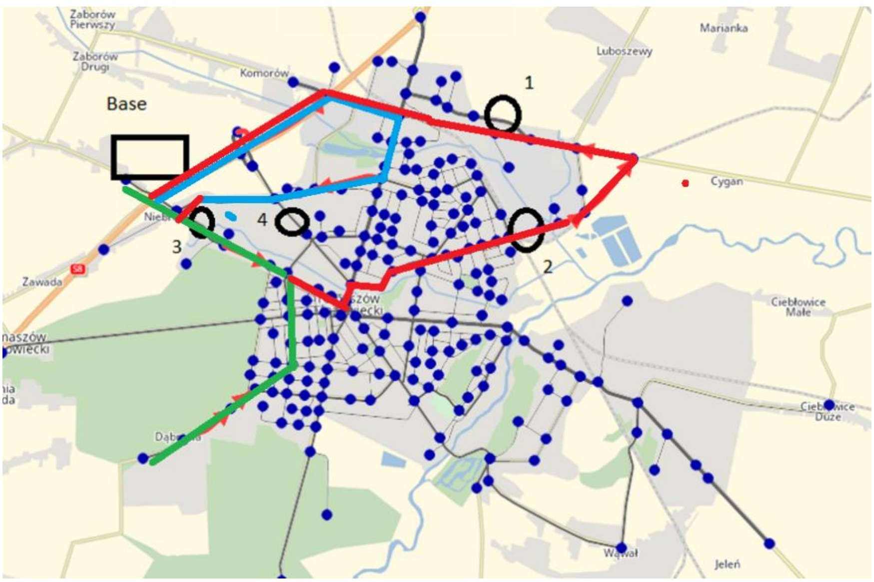

Fig. 3. The assignment vehicles to tasks

6. Conclusions

The paper presents a new approach to risk management in allocating vehicles to tasks in a transport company using the ant algorithm. Dangerous events on the route of vehicles have been described with theoretical probability distributions. Using the STATISTICA 13 package, the distributions at each of the measurement points presented in the example were determined. A new approach in the study of the risk of accidents in the assignment of vehicles to tasks

was the introduction of a random variable describing the distribution of the probability of accidents as a variable interpreting the moment of the vehicle's appearance at a given point on the route.
The decision model considers the limitations typical of the classic model of assigning vehicles to tasks, e.g. window limits and additionally contains limitations on the acceptable risk on the route of vehicles' travel. The criterion function minimizes the probability of an accident occurring along the entire assignment route.
The proposed risk management procedure based on a heuristic algorithm reduces the risk to a minimum. The ant algorithm reduces it in the event of exceeding the limit, which differs from the classic methods of risk management, which are dedicated only to risk assessment.
The paper analyses the algorithm's sensitivity to changes in its input parameters. Sixty combinations of these parameters were tested, and the combination with the best result generated by the algorithm was selected. It should be emphasized that the ant algorithm is probabilistic, so the result is suboptimal.
The proposed ant algorithm was 95% effective in assessing the risk of adverse events in assigning vehicles to tasks. The algorithm was run 100 times. The designated routes were compared with the actual hours of the accident at the bottom of the measurement points.
In the scope of further work on the problem of risk management in the allocation of vehicles to tasks in transport companies, the effectiveness of other optimization algorithms, e.g. the genetic algorithm, should be examined, and the development of multicriteria risk management models with additional criteria functions, e.g. cost or task execution time.

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