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Visualization of Parameters and Results of Modeling Optimal Cargo Transportation Planning Tasks in Unmanned Aircraft Transport Systems

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Abstract

The peculiarities of unmanned vehicle application in the field of cargo transportation lead to the formulation of new problems for optimising cargo transportation plans, where several types of additional constraints and conditions must be taken into consideration simultaneously. The process of solving such problems requires considering and analysing numerous heterogeneous parameters, which is most effective when done interactively using visualisation techniques. We consider a problem involving the formation of heterogeneous cargo transportation plans using unmanned aerial vehicles, and propose an approach for constructing a visual model to support the interactive setting of problem parameters and to display optimisation results via a visual interface. This approach is based on the concept of visualisation metaphors, including spatial and representational metaphors. The structure and features of the metaphorical representation for different problem formulations and modelling stages are discussed.

Keywords: unmanned aerial vehicle, cargo transportation planning, maximum flow problem, visual model, visualization metaphor.

1. Introduction

One of the current directions in the development of unmanned aerial systems is the application of unmanned aviation in the field of cargo transportation [1, 2]. Specialized transport unmanned aerial vehicles (UAVs) can be effectively utilized for the delivery of essential goods to remote areas with limited or seasonal ground access, including regions affected by natural disasters. As noted in [1], the use of UAVs in such cases contributes to a reduction in flight-hour costs, decreases dependency on weather conditions, and eliminates risks to human crew members in emergency situations during mission execution. Other relevant and in-demand applications of UAVs in the cargo transportation domain include the transport of hazardous or condition-sensitive goods; delivery of seeds, fertilizers, and samples of soil or plants between remote field stations and laboratories; and the movement of cargo between warehouses and distribution centres, among others.

In light of the above, a pressing challenge is the development of robotic unmanned aerial transport systems (UATS) for cargo transportation applications. A key component in addressing this challenge lies in the development of mathematical models, information systems, and software tools for UATS control systems [3], including data storage, processing, and analysis platforms; automated control systems; communication subsystems; information-analytical platforms; and decision support systems. Decision-making support is required both during the execution of flight missions and at the planning stage.

Planning flight missions for UAV groups engaged in cargo transport involves a set of interrelated tasks, such as the formulation of cargo transportation plans, the selection of UAVs with specific operational characteristics, and the development of UAV loading plans that account for the properties of the transported cargo and a range of transportation-related constraints [4]. Each of these tasks demands the consideration and analysis of extensive, multidimensional data sets that may differ in format, structure, and source.

For example, when developing cargo transportation plans optimized according to specified performance metrics, it is necessary to account for various parameters, including the condition of the route network, cargo characteristics, their distribution across source locations, and the current status of delivery orders with respect to their priority levels. In turn, information about the route network must include data on the throughput capacity of individual routes and the resource costs associated with employing particular UAV types. These costs may include, for instance, total route traversal time (including time for preparatory and ancillary operations), the cost of transporting various types of cargo, and other relevant operational metrics.

These features give rise to novel formulations of cargo transportation plan optimization problems, which require the simultaneous consideration of multiple types of constraints and conditions. Several such problem statements are examined in [5, 6], where corresponding optimization models are developed and algorithms for determining optimal cargo transportation plans are proposed. At the same time, an essential aspect of implementing comprehensive software support for these models and algorithms is the development of visual interfaces that enable interactive specification of model parameters and facilitate the presentation of optimization results. This, in turn, necessitates the application of appropriate techniques and methods for the visualization of multidimensional data.

The problem of constructing visual models for cargo transportation optimization has been addressed in a number of studies, including [7, 8]. However, these works primarily focus either on the visualization of the graph structure of the transport network—without incorporating many of the aforementioned parameters that characterize the optimization model as a whole – or on simulation-based modelling of pre-constructed cargo transportation plans. In this paper, we propose an approach to the development of visual models intended to support the interactive specification of parameters for the cargo transportation planning problem, as well as the visualization of optimization results through a graphical user interface, including within geographic information system (GIS) environments. The proposed approach is grounded in the concepts of visualization metaphors [9] and the cognitive clarity of visual representations derived from them [10]. We illustrate this approach using the example of constructing a cargo transportation plan for heterogeneous cargoes delivered by UAVs under constraints imposed by limited route network capacity and considering the prioritization of delivery tasks [5].

2. The task of cargo transportation plan formation: formalized description and general principles of parameter setting and visualization

We address the problem of constructing an optimal cargo transportation plan between source nodes (hubs) and destination nodes (points of demand), considering the presence of intermediate nodes within the transport network, where both UAV maintenance and cargo redistribution operations may be performed. The objective is to determine which of the currently available routes—accounting for the state of the transport network – should be utilized for cargo delivery, as well as to specify the quantity of each cargo type to be transported along the selected routes in order to fulfil existing delivery requests. The model accounts not only for potential shortages of certain cargo types, but also for scenarios in which it is not possible to fully satisfy demand due to the limited throughput capacity of the available routes.

Let $\Gamma = \langle A, W \rangle$ be a directed graph representing the current state of the transport network, where A is the set of nodes corresponding to the network's vertices, and W is the set of arcs representing the connections between these nodes. The absence of an arc (i, j) in W indicates that, in the current state of the transport network, a direct UAV flight from node i to node j is not feasible.

For each node $i \in A$, we define two subsets associated with this node from the set A:

$A_i^{IN} = \{j \in A | (j, i) \in W\}$, which contains the nodes connected to node i by an incoming arc;

$A_i^{OUT} = \{j \in A | (i, j) \in W\}$, which contains the nodes to which node i is connected by an outgoing arc.

Let $G = \{G_1, G_2, \ldots, G_p\}$ denote the set of cargo types, and let $T = \{T_i^k | \, i \in A; k = 1, \ldots, p\}$ be the set of node capacity values for each cargo type G_k. The interpretation of T_i^k is as follows:

If $T_i^k > 0$, then node i is a source of cargo G_k, with T_i^k representing the available stock;

If $T_i^k < 0$, then node i is a sink (consumer) for cargo G_k, and T_i^k represents the demand volume;

If $T_i^k = 0$, then node i is a transit node for cargo G_k.

$C = \{c_{ij}^k | \, (i, j) \in W; k = 1, \ldots, p\}$ – denotes the cost of transporting a unit of cargo G_k along the route (i, j). It is assumed that $c_{ii}^k = 0, \forall i \in A$. If the transportation of cargo G_k along route (i, j) is prohibited for a given k, then the cost is set to $c_{ij}^k = \infty$. In practical implementations, this can be represented by a sufficiently large finite value, for instance, one or two orders of magnitude greater than the maximum cost value in the set C). Such routes are referred to as *forbidden for the k-th cargo type*.

$X = \{x_{ij}^k | \, (i, j) \in W; k = 1, \ldots, p\}$ represents the quantity of cargo units G_k, transported along the arc (i, j); thus, the set X defines the *cargo transportation plan*.

$U = \{u_{ij} | \, (i, j) \in W\}$ denotes the capacity constraints of the routes. If the capacity of route (i, j) is unbounded, it is formally assumed that $u_{ij} = \infty$. One may consider the subset $W' \subseteq W$, consisting exclusively of those arcs subject to capacity limitations, i.e.:

$W' = \{(i, j) \in W | \, u_{ij} < \infty\}$.

When it is infeasible to transport the entire volume of cargo due to these capacity restrictions and potential shortages of certain cargo types, the cargo transportation plan must be constructed to prioritize the fulfilment of the highest-priority demands, with the objective of maximizing the total cargo flow through the network.

Let us define the *cargo flow* G_k as the total volume (number of units) of the given cargo delivered to the nodes that serve as its sinks, i.e., nodes for which ($T_i^k < 0$):

$$H^k = \sum_{i \in A, \, T_i^k < 0} \left(\sum_{j \in A_i^{IN}} x_{ji}^k - \sum_{j \in A_i^{OUT}} x_{ij}^k \right).$$

The total flow is then defined as the aggregate volume of all cargo types delivered to all sink nodes.

Thus, the problem can be viewed as a generalization of the classical maximum flow problem [11], extended to account for cargo heterogeneity and an arbitrary topology of the routing network:

$$H = \sum_{k=1}^{p} \sum_{i \in A, \, T_i^k < 0} \left(\sum_{j \in A_i^{IN}} x_{ji}^k - \sum_{j \in A_i^{OUT}} x_{ij}^k \right) \to \max \qquad (1)$$

subject to the constraints

$$\begin{cases} \sum_{j \in A_i^{OUT}} x_{ij}^k - \sum_{j \in A_i^{IN}} x_{ji}^k \le T_i^k, i \in A, T_i^k > 0; \\ \sum_{j \in A_i^{OUT}} x_{ij}^k - \sum_{j \in A_i^{IN}} x_{ji}^k \ge T_i^k, i \in A, T_i^k < 0; \\ \sum_{j \in A_i^{OUT}} x_{ij}^k - \sum_{j \in A_i^{IN}} x_{ji}^k = 0, i \in A, T_i^k = 0; \\ \sum_{k=1}^{p} x_{ij}^k \le u_{ij}, (i, j) \in W'; \\ x_{ij}^k \ge 0, (i, j) \in W; \; k = 1, \ldots, p. \end{cases} \qquad (2)$$

Under the given conditions, where constructing a complete cargo transportation plan is infeasible, the following types of problems related to the prioritization of cargo delivery may arise [5]:

1. It is necessary to ensure the delivery of each cargo type to its most prioritized sinks. This problem will be referred to as the "*sink priority for cargo*" scheme.
2. It is necessary to supply each sink with the cargo types that are most prioritized for it. This problem will be referred to as the "*cargo priority for sink*" scheme.
3. The needs of the highest priority sinks must be satisfied first. In other words, there is a comprehensive requirement to prioritize the provision of all necessary cargoes to priority sinks. This problem will be referred to as the "*unconditional sink priority*" scheme.
4. The delivery of the highest priority cargoes must be prioritized above all else. In this case, the primary objective is to transport cargoes according to their priority level. This problem will be referred to as the "*unconditional cargo priority*" scheme.

The prioritization mechanisms for each of the aforementioned tasks depend on the nature of preferences. In the present work, we focus on lexicographic preferences [12], which are based on the strict ordering of priorities, whereby the underperformance of a higher-priority request cannot be compensated by fulfilling a lower-priority one.

Consequently, the modeling of the considered problem involves multiple stages that necessitate interactive task formulation and/or data visualization.

At the initial stage, through an interactive interface supported by visualization techniques, general parameters characterizing the problem formulation can be specified:

- The set of nodes A and arcs W defining the route network;
- The set of cargo types G;
- The set T of node capacity values corresponding to all cargo types in G;
- The cost values C associated with transporting cargoes along the available routes;
- The throughput capacity values U for the routes.

Subsequently, a delivery prioritization scheme is selected, and its parameters are specified, also with the aid of various visualization techniques. These parameters serve to supplement or refine those established at the initial stage. The specific procedure for parameter specification depends on the chosen prioritization scheme:

When employing the "*sink priority for cargo*" scheme, for each cargo type G_k, a subset of nodes $D^k = \{d_1^k, d_2^k, \dots, d_{q_k}^k\}$ is selected, representing the sinks for given cargo, and ordered in accordance with descending priority;

When applying the "*cargo priority for sink*" scheme, for each sink node A_l a subset of cargo types $E^l = \{e_1^l, e_2^l, \dots, e_{m_l}^l\}$ is identified and ranked in descending order of importance for that particular sink;

When applying the "*unconditional sink priority*" scheme, a set of nodes $D = \{d_1, d_2, \dots, d_q\}$ is formed, comprising all sinks for at least one cargo type, and ordered according to the overall priority of cargo provision;

When applying the "*unconditional cargo priority*" scheme, the full set of cargo types $G = \{G_1, G_2, \dots, G_p\}$ is ordered in descending delivery priority.

Finally, based on the obtained optimization results, the visualization of the resulting optimal cargo transportation plan X must be carried out.

Each of these stages involves visualizing a distinct set of parameters; therefore, each step requires a corresponding type of visual representation.

3. General principles of constructing a visualization metaphor for the task of forming a cargo transportation plan

The approach to constructing a visual model based on the concept of a visualisation metaphor was originally proposed in [9] and further developed in a number of subsequent works, including [10], in the context of visualising graph-based models.

A visualisation metaphor is a formalised framework for mapping the characteristics of the source model data into the feature space of a visual model. It comprises a set of principles and rules that establish correspondences between model elements and visual representations, as well as between their respective attributes and visual properties. The visualisation metaphor consists of two key components: the spatial metaphor and the representation metaphor. The spatial metaphor defines the general principles for embedding the visualised object into the space of the visual model. The representation metaphor, applied within the framework of the chosen spatial metaphor, is responsible for refining the visual representation in such a way as to emphasise those components that are most significant for the problem at hand. Its primary purpose is to direct the viewer's attention to the semantically meaningful aspects of the visual image that require interpretation.

In the context of the problem under consideration, the spatial metaphor defines the positioning of the route network graph nodes within the coordinate space of the territorial map. To construct this spatial arrangement, various algorithms for graph layout in two-dimensional space may be employed [13].

Based on the resulting spatial configuration, a representation metaphor is then applied to generate visual representations of the graph's nodes and arcs, corresponding respectively to the points of the transport network and the routes connecting them. Within the representation metaphor, a central role is played by the mapping between the attributes of nodes and routes and the applied visualisation techniques.

The degree of cognitive clarity of the resulting visual representation, as well as the usability of the interactive interface for specifying cargo transportation plan parameters, depends significantly on the choice and design of the corresponding representation metaphor.

In accordance with the representation metaphor, the visual representation of the problem under consideration comprises a set of visual features, including the following:

- for nodes (in addition to their spatial positioning determined by the spatial metaphor): shape, colour, and size of the graphical object representing the node, as well as supplementary graphical elements such as labels or infographic markers;
- for routes between nodes: primarily the colour and thickness of the corresponding arcs, along with possible textual annotations.

The construction of a representation metaphor requires the establishment of a mapping between the model parameters to be visualised (i.e., the attributes of the formal model) and the corresponding visual attributes outlined above. Given that the number of parameters subject to visualisation often exceeds the number of visual features that can be employed without compromising the clarity and interpretability of the visual image, it is reasonable to introduce multiple representation metaphors. Each such metaphor is designed to convey specific properties of the problem or to reflect distinct stages of the modelling process.

4. Metaphor of representation of the task of cargo transportation plan formation

As noted earlier, the visualisation of the cargo transportation planning problem is based on representing the route network as a graph, comprising nodes and arcs enriched with attributive information. In this representation, the nodes are geographically anchored and correspond to specific locations on the map.

To visualise the nodes, pictograms or geometric primitives are employed, which are connected by straight lines representing the arcs of the graph. The colour and thickness of these lines are used to convey key properties of the routes, such as cost or throughput capacity. Adjacent to the nodes, infographic elements are displayed to indicate their capacity values with respect to different types of cargo.

The overall structure of the representation metaphor used at the problem formulation stage is summarised in Table 1. These parameters are universal across all prioritisation schemes and are designed to provide a clear and concise visual representation of the core characteristics of the problem formulation.

Table 1 – General structure of the representation metaphor at the problem formulation stage

Attribute	**Value Domain**	**Visual Representation**
Node identifier	String	A circle positioned at the node's coordinates, containing a label (letter with a number)
Capacity by cargo type	Vector of integers	A set of infographic elements near the node indicating stock (green, positive) or demand (red, negative)
Cargo transportation cost for a route	Vector of integers	Colour intensity of the arc; green brightness indicates lower transportation cost; red indicates higher transportation cost
Route capacity for cargoes	Vector of integers	Arc thickness; greater thickness indicates higher capacity

Figure 1 presents an example of the visualisation of initial parameters based on the representation metaphor described above.

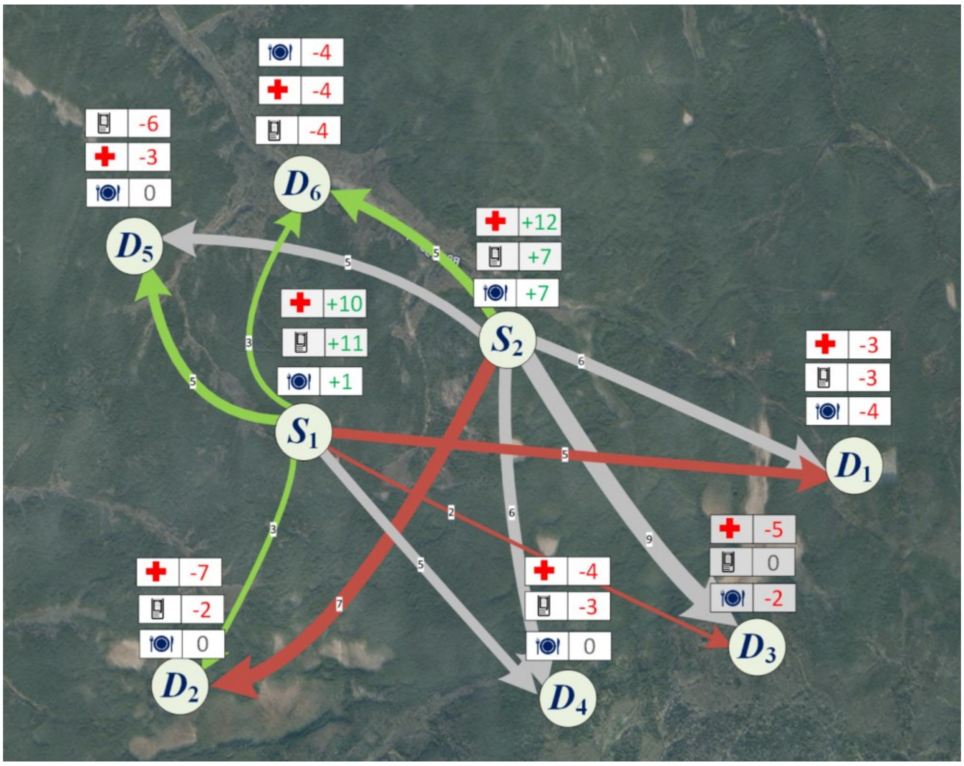

Figure 1 – Visualisation of initial parameters of the task of cargo transportation plan formation

Attributes that depend on the selected prioritisation scheme are summarised separately in Table 2.

Table 2 – Additional attributes of the representation metaphor depending on the prioritisation cheme

Attribute	Value Domain	Visual Representation
Sink priorities for a cargo	Ordered set	Infographics of different cargo types arranged vertically by descending delivery priority to sinks
Cargo priorities for a sink	Ordered set	Infographics of cargo types arranged vertically by descending priority of delivery requests for each node
Unconditional cargo priorities	Ordered set	Global infographic scale representing the relative priority of each cargo type across the entire network
Unconditional sink priorities	Ordered set	Node fill colour reflecting the relative priority of cargo provision for each sink

Let us now examine in more detail the visualisation of parameters specific to each prioritisation scheme.

"Sink priority for cargo" scheme. An example of the visual representation of this scheme is provided in Figure 2. The scheme considers the prioritization of cargo delivery requests across all sink nodes. As noted earlier, for each cargo type G_k, a corresponding subset of sink nodes is defined as $D^k = \{d_1^k, d_2^k, \dots, d_{q_k}^k\}$, where the elements are ordered in descending order of delivery priority. In this scheme, the infographic illustrates the delivery request for a specific cargo type. The fill colour of the corresponding visual elements reflects the relative priority of delivering the cargo to each sink node. Nodes associated with higher-priority requests are visually distinguished using more saturated or darker tones, enabling intuitive assessment of delivery urgency within the transport network.

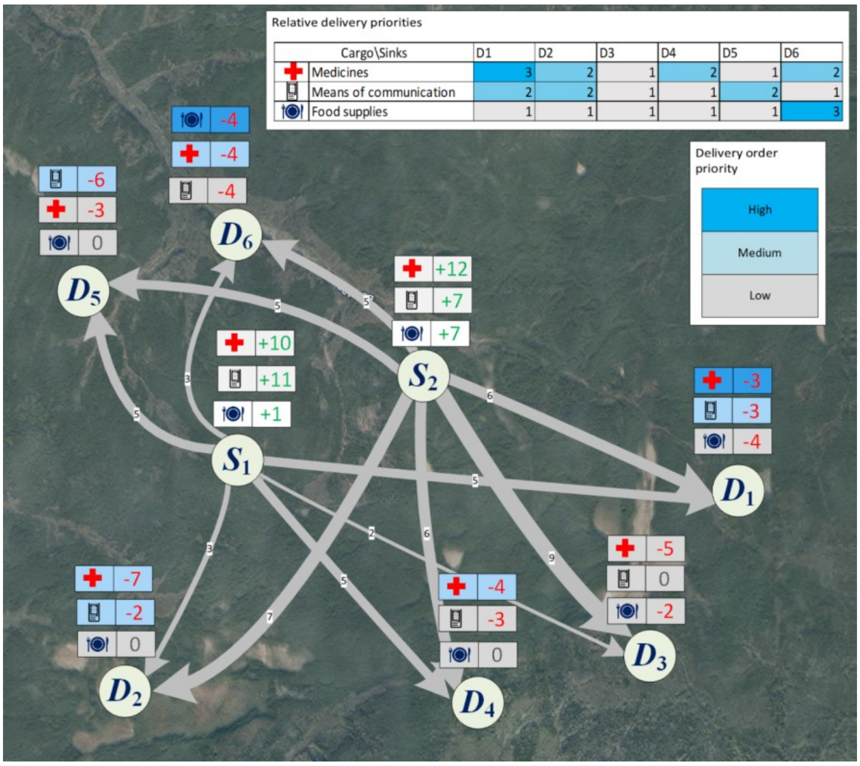

Figure 2 – Visualisation of the parameters in the scheme "*Sink priority for cargo*"

"Cargo priority for sink" scheme. An illustrative example of this scheme is presented in Figure 3. It reflects the prioritisation of different cargo types within each individual sink node. For each sink A_l, a corresponding subset of cargo types is defined as $E^l = \{e_1^l, e_2^l, \dots, e_{m_l}^l\}$

which includes the cargo types required at node A_l, ordered by descending priority specific to that sink. The visual representation of the set E^l for sink A_l consists of a sequence of infographic elements, each corresponding to a specific cargo type.

The arrangement of these elements reflects the prioritisation order, with higher-priority cargo types placed earlier in the sequence. To enhance interpretability, elements representing cargoes of the same type are consistently coloured. This uniform colouring aids in visually distinguishing priority shifts across different sink nodes and facilitates comparative analysis.

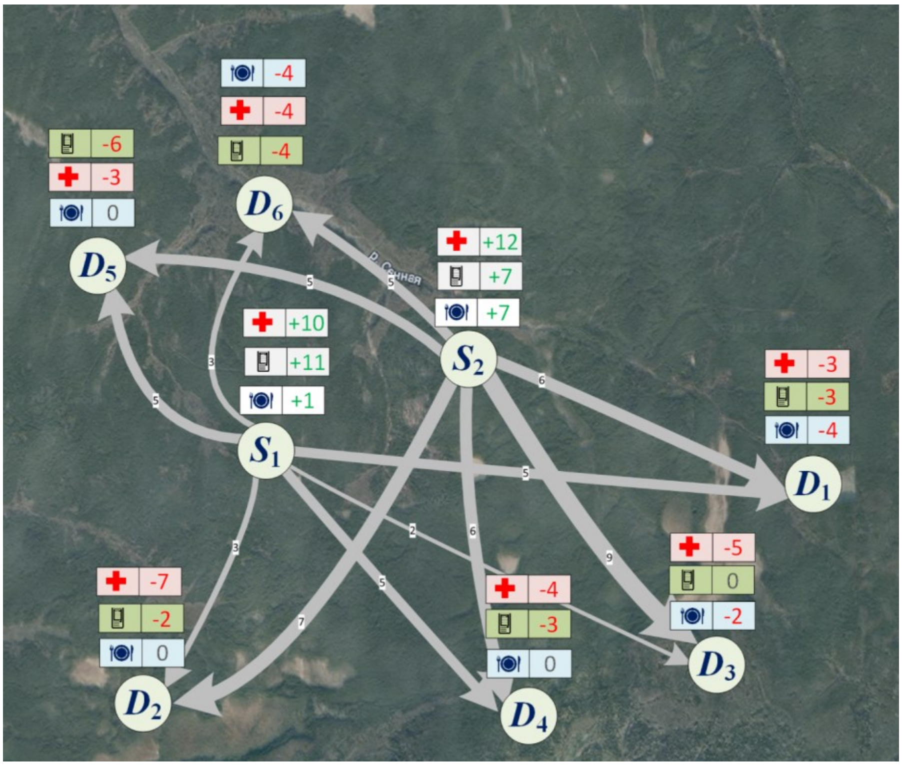

Figure 3 – Visualisation of parameters in the “*Cargo priority for sink*” scheme

“Unconditional Sink Priority” scheme. An example visualisation of this scheme is presented in Figure 4. In this scheme, the overall priority of each sink node is considered with respect to the delivery of all cargo types collectively, without distinguishing between them. The set $D = \{d_1, d_2, \dots, d_q\}$ includes all nodes that act as sinks for at least one type of cargo, and is ordered by descending priority of cargo provision.

To convey this information visually, a colour gradient is applied to the sink nodes: warm colours (e.g., orange) indicate higher priority levels, while cool colours (e.g., light blue) represent lower priority. The infographic elements within this visualisation depict cargo delivery requests; however, they do not explicitly encode priority data. This approach provides a clear and intuitive overview of the relative urgency of servicing each sink node across all cargo types.

“Unconditional Cargo Priority” scheme. An example of the visualisation corresponding to this scheme is shown in Figure 5. In this approach, cargo priorities are considered globally – that is, across all sink nodes simultaneously. The set of cargo types $G = \{G_1, G_2, \dots, G_p\}$, is ordered in descending order of delivery priority and forms the basis of the visual representation.

For visual encoding, colour saturation is applied to infographic elements: cargoes with higher priority levels are shown in more saturated colours along a predefined gradient scale. Additionally, infographic elements are arranged in descending order of priority, enhancing clarity and enabling rapid interpretation of the most urgent cargo types.

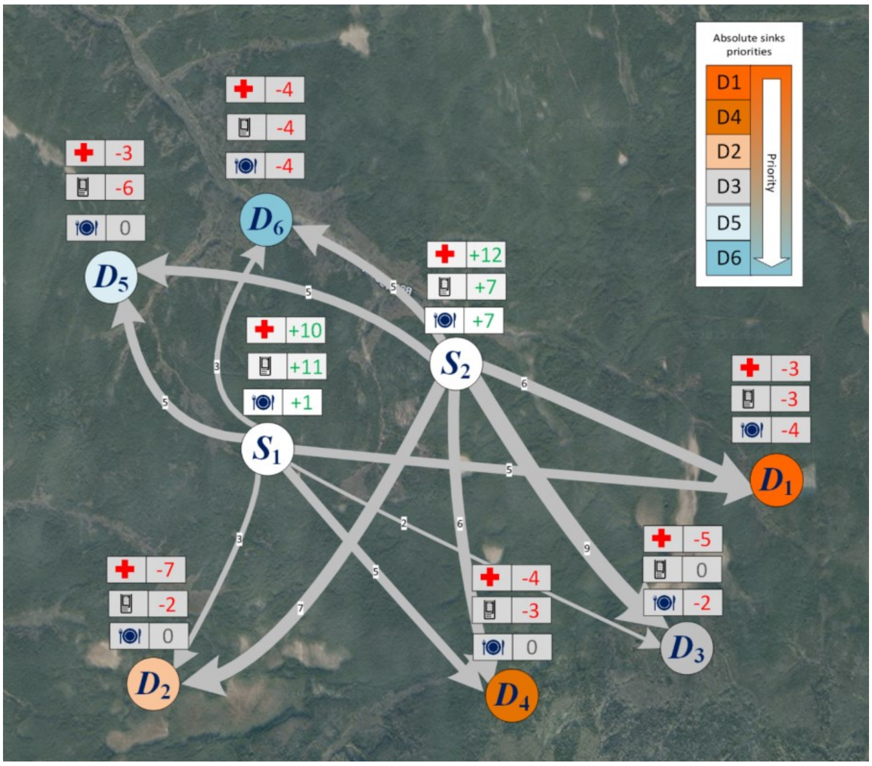

Figure 4 – Visualisation of parameters in the "*Unconditional sink priority*" scheme

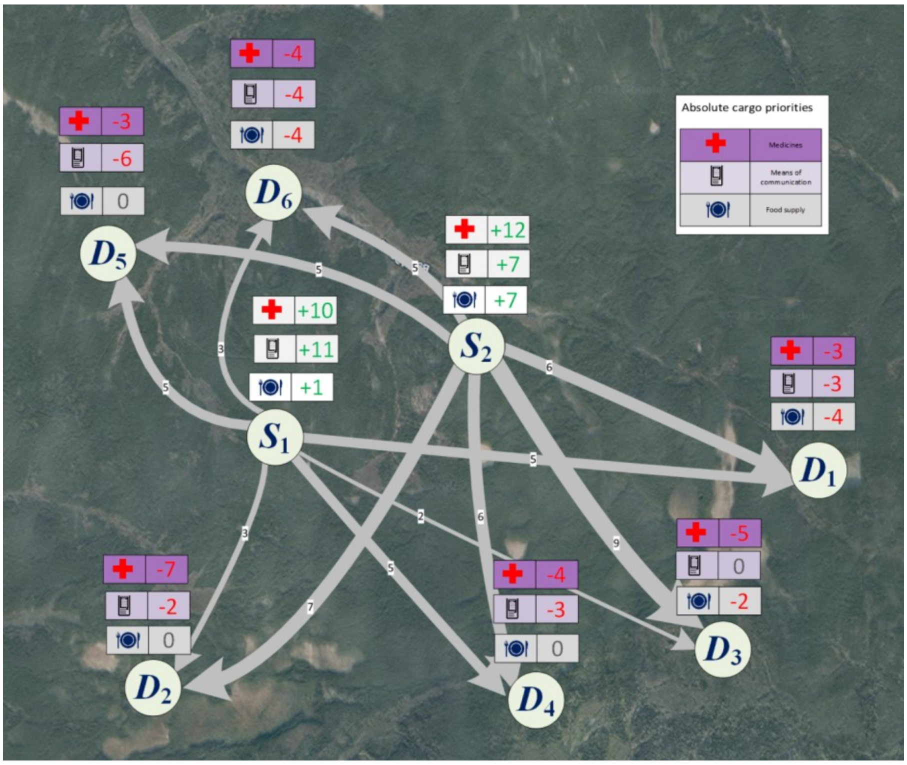

Figure 5 – Visualisation of parameters in the "*Unconditional cargo priority*" scheme

Finally, attributes associated with the presentation of optimisation results are summarised in Table 3. The goal of this visualisation is to support the analysis of the computed cargo transportation plan by providing a clear, interpretable display. This facilitates initial evaluation and the identification of patterns or inconsistencies that could inform the refinement of the original problem formulation or optimisation parameters.

Table 3 – Structure of the visualisation metaphor for representing the cargo transportation plan

Attribute	Value Domain	Visual Representation
Cargo transportation plan for a route	Vector of integers	Numeric labels displayed next to each arc, indicating the volume of each cargo type transported along the route.
Aggregate cargo flow	Integer	Arc thickness reflects the total cargo flow along the respective route.
Degree of unfulfilled delivery requests	Vector of integers	Infographic elements representing different cargo types, showing the volume of outstanding (unfulfilled) delivery requests.
Residual throughputs	Integer	Arc colour encodes the residual throughput, i.e., the difference between the total cargo flow along the route and its maximum capacity.

An example of the visualisation of a cargo transportation plan, obtained as the result of solving the corresponding optimisation problem, is presented in Figure 6.

In accordance with the structure of the visual representation metaphor described in Table 3, the infographic elements adjacent to the nodes reflect the state of the route network after the execution of the transport plan. Specifically, they display the volumes of unfulfilled delivery requests as well as the remaining cargo stocks at the source nodes.

The thickness of the arrows (arcs) indicates the aggregate cargo flow along the respective routes, while the numerical values of the cargo volumes for each cargo type are shown as labels on the arcs. The arc colour denotes the residual (i.e. unused) throughput of the route, allowing for the identification of underutilised transport links within the network.

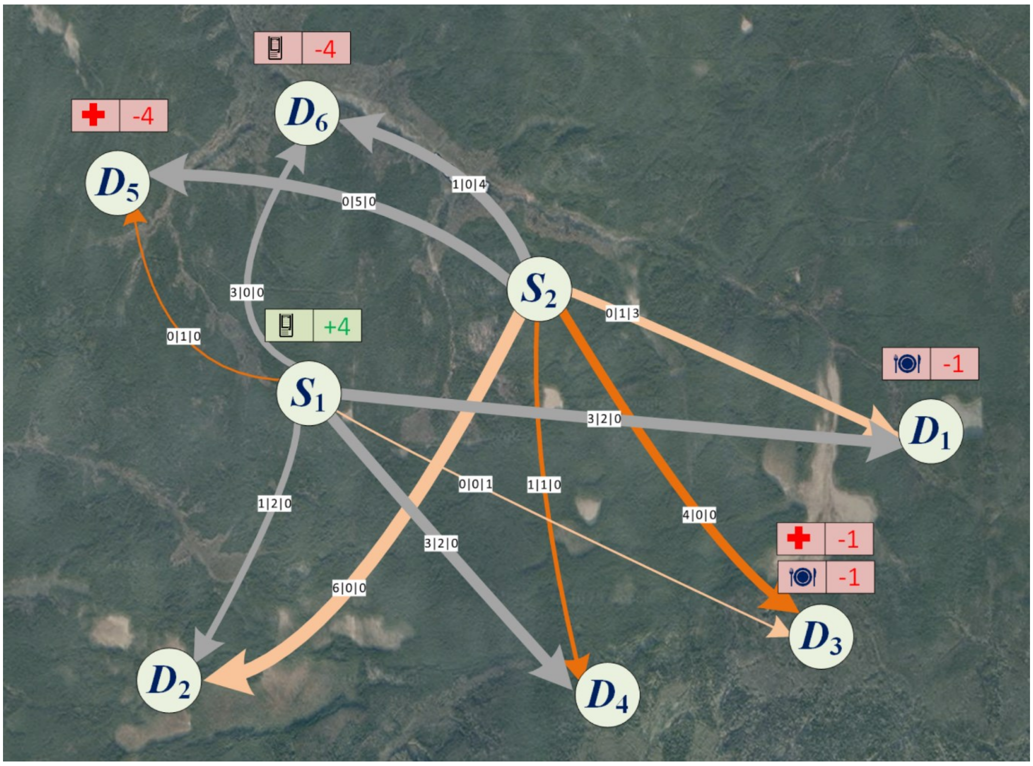

Figure 6 – Visualisation of the resulting cargo transportation plan

5. Software support for visual models

To support the implementation of the proposed approach to the construction of visual models, a dedicated software module has been developed. This module is integrated into a broader software framework designed for the modelling of planning and optimisation tasks related to cargo transportation in unmanned aerial transport systems. It functions as a subsystem responsible for the visualisation and interactive specification of optimisation model parameters.

The direct solution of the corresponding optimisation problem, as formalised in expressions (1)-(2), is handled by a separate computational module, which operates as a plug-in and implements the algorithms described in [5].

An example of the user interface of the visualisation module –demonstrating the use of the “Cargo Priority for Sink” visual scheme for setting optimisation problem parameters – is presented in Figure 7.

Figure 7 – Interface of the software module

The software module was developed using the Python programming language and the PyQt5 framework, in conjunction with a suite of libraries provided by the QGIS geographic information system [14]. This combination of technologies ensures both cross-platform compatibility and integration with spatial data processing tools.

The module enables users to load preconfigured datasets containing information about the current state of the route network, interactively define and modify parameters for the problem formulation, and visualise the problem using the proposed visual metaphor. Additionally, the system supports saving the constructed model for future reuse or further refinement.

6. Experimental research

To assess the clarity and informativeness of the developed visual models, consider the following example. Figure 1 illustrates the visual model representing the formulation of the optimization problem. Table 4 provides the capacity values of the nodes for each cargo type used in the model’s construction; for source nodes S_1 and S_2 these values correspond to cargo stock levels, whereas for sink nodes D_1, D_2, …, D_6, they represent demand volumes. Table 5 details the capacity values of the routes, which were also incorporated into the construction of the visual model under consideration.

Table 4 – Capacity of nodes by cargo type

Node / Cargo type	S_1	S_2	D_1	D_2	D_3	D_4	D_5	D_6
Medicines	10	12	-3	-7	-5	-4	-3	-4
Means of communication	11	7	-3	-2	0	-3	-6	-4
Food supplies	1	7	-4	0	-2	0	0	-4

Table 5 – Capacity of routes

Source \ Sink	D_1	D_2	D_3	D_4	D_5	D_6
S_1	5	3	2	5	5	3
S_2	6	7	9	6	5	3

According to the representation metaphor, the thickness of the arrows in Figure 1 corresponds to the throughput capacity of the respective routes. For instance, the arc from node S_1 to D_3, exhibits the smallest thickness, whereas the arc from S_2 to D_3 demonstrates the greatest thickness. This observation aligns with the data presented in Table 5, where the throughput capacity for these routes are 2 and 9, respectively, while the throughput capacity for other routes range from 3 to 7.

The priority information for delivery tasks in the context of the current problem is specified using the "*sink priority for cargo*" scheme and is presented in Table 6.

Table 6 – Sink priorities for cargoes

Cargo type \ Sink	D_1	D_2	D_3	D_4	D_5	D_6
Medicines	3	2	1	2	1	2
Means of communication	2	2	1	1	2	1
Food supplies	1	1	1	1	1	3

The priority values from Table 6 were utilized to construct the visual model shown in Figure 2. It is evident from Figure 2 that the most intense fill colours correspond to the delivery requests for medicines to sink D_1 and food to sink D_6. This observation is consistent with the priority data presented in Table 6, where these requests are assigned the highest priority.

The cargo transportation plan resulting from the solution of the optimisation problem is provided in Table 7.

Table 7 – Cargo transportation plan

Sink		D_1	D_2	D_3	D_4	D_5	D_6
Source	Cargo type	*Number of transported cargo units*					
S_1	*Medicines*	3	1	0	1	0	3
	Means of communication	2	2	0	1	1	0
	Food supplies	0	0	1	0	0	0
S_2	*Medicines*	0	6	4	3	0	1
	Means of communication	1	0	0	2	5	0
	Food supplies	3	0	0	0	0	4

Due to cargo shortages and the limited capacity of the route network, certain cargo delivery requests were only partially fulfilled. Information regarding residual cargo volumes remaining at the sources and cargo deficits at the sinks — that is, the residual capacities of sources and sinks — is summarized in Table 8.

Table 8 – Residual capacities of nodes by cargo type

Cargo type \ Node	S_1	S_2	D_1	D_2	D_3	D_4	D_5	D_6
Medicines	0	0	0	0	-1	0	-4	0
Means of communication	4	0	0	0	0	0	0	-4
Food supplies	0	0	-1	0	-1	0	0	0

The cargo transportation plan obtained corresponds to the one previously presented in Figure 7. Visual analysis of Figure 7 allows for several observations. For instance, the delivery request for communication equipment to sink D_6 was not fulfilled, despite the availability of sufficient units of this cargo at source S_2. It is evident that the arcs leading to sink D_6 are greyed out, indicating that the capacities of these routes are fully utilized. This observation is corroborated by the comparison of data presented in Tables 5 and 7. Moreover, Table 6 reveals that the delivery requests for communication equipment had the lowest priority among all cargo delivery requests to sink D_6.

Therefore, the proposed representational metaphor for the visual model of the cargo transportation plan effectively visualizes the underlying causes for non-fulfilment of certain requests—namely, the low priority assigned to communication equipment deliveries to sink D_6 combined with the insufficient capacity of the corresponding routes. Potential solutions to this issue include increasing the priority of communication equipment requests for the given sink, which may result in a more complete fulfilment of these requests, potentially at the expense of partial non-fulfilment of other cargo deliveries. Alternatively, if feasible, increasing the capacity of the route from S_2 to D_6 could also alleviate the issue.

A different situation is observed with respect to the delivery requests for medicines and foodstuffs to sinks D_1, D_3 and D_4. For each of these nodes, at least one brightly colored arc is directed toward it, indicating the presence of unused capacity on the routes connecting the sources to these sinks. This observation is substantiated by the comparison of data in Tables 5 and 7. However, the infographic elements associated with these sinks indicate that the stock of medicines and food at all sources has been depleted, a fact further confirmed by the data in Table 8.

Therefore, the visual model allows us to conclude that the partial non-fulfilment of transportation requests for certain cargoes to nodes D_1, D_3 and D_4 is attributable to cargo shortages at the sources. Resolving this issue necessitates an increase in the overall stock levels of these cargoes within the system.

7. About the cognitive clarity of the proposed visual models

We demonstrate that the proposed methodology for constructing representation metaphors adheres to the foundational principles of their design as outlined in [10], thereby enhancing the cognitive clarity of the resulting visual models.

1. *Principle of partial visualisation.* According to this principle, only a subset of model elements and their attributes (or, in terms introduced earlier, one representation) is visualised at each moment of time. This is due to both the high structural and parametric complexity of models, often exceeding the cognitive capabilities of the analyst, and the phase of the analysis process, within which at a certain stage there is a need to display only part of the information related to the model. Compliance with the principle of partial visualisation is manifested in the choice of different representation metaphors for the data corresponding to different stages of the cargo transportation plan generation problem. This ensures that only those properties of the model that are required for analysis at each particular stage are visualised.

2. *Principle of injective visualisation.* According to this principle, each model attribute within one visualisation metaphor should correspond to a unique visual feature. In other words, one and the same visual element should not simultaneously represent two or more different attributes, as this leads to the confusion of model properties and complicates their correct interpretation by the analyst. Compliance with the principle of injective visualisation is due to the fact that different attributes of the model are visualised in different ways. For example, the metaphors for representing problem formulation and problem-solving use thematically coloured arrows, but since this technique is used to represent different properties, the colour of the arrows is chosen differently. A similarity in visualization techniques for related concepts can be noted. For example, arrow thickness represents route capacity in the initial problem visualization, while in the results visualization, it represents the actual cargo flow.

3. *Principle of surjective visualisation.* This principle means that each visual attribute should represent an attribute that is significant in the context of the problem to be solved. The representation should not include visual attributes that do not carry meaningful load within the current analysis, as this leads to perception overload and reduces the effectiveness

of visual analysis. Compliance with this principle is conditioned by the absence of superfluous, non-significant attributes in visual models.

4. *Principle of subordination*. According to this principle, the visual representation of subordinate elements should provide the possibility of unambiguous identification of their relationship to specific superior elements of the model. A special case of realisation of the subordination principle is the display of logical nesting of elements in the form of the corresponding visual hierarchy. An example confirming compliance with the principle of subordination is the correspondence of infographic elements reflecting the capacity for different cargo types to the nodes to which they visually relate.

5. *Principle of restructuring*. In some cases, it is possible to combine two discrete attributes into one by means of the Cartesian product of their value areas. Application of this principle contributes to optimizing visual perception by making more effective use of available visual parameters. An example of compliance with the principle of restructuring is the allocation of residual route throughput as a separate visualised property having a composite nature — it is the difference between the initial route throughput and the volume of the cargo flow that actually passed through it.

8. Conclusion

The use of visual models for displaying of a set of heterogeneous parameters that characterise the problem of forming an optimal plan for the transportation of heterogeneous cargoes using UAVs provides interactivity of the Decision-Maker's interaction with the optimisation model and, in general, contributes to increasing their situational awareness when solving the tasks of planning flight assignments. The paper proposes an approach to building a visual model for one type of cargo transportation plan formation problem - maximisation of cargo flow in conditions of limited capacity of the route network, where different prioritization schemes for cargo delivery to sinks acted as additional conditions. In the future, it is planned to consider visual models for other types of problems, for example, the problem of forming a cargo transportation plan optimal by the criterion of minimum time [6], or the problem of maximising the cargo flow under the transport time constraint. Another area of further research is the development of visual models for the tasks of operational monitoring and management of flight task execution.

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