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Decision Analysis for Transporting Critically Ill Patients with Cardiovascular Diseases

Yerbolat N. Kalpakov,[1,*] Yerkin G. Abdildin[1] and Dmitriy Viderman[2, 3]

Abstract

Transporting critically ill patients with cardiovascular diseases is often difficult due to patient's health condition and the remoteness of the cardiac centers. In countries with large territories, cardiovascular patients often require transportation to specialized clinics located in large cities. However, transportation should satisfy specific medical conditions, and the decision on the transportation mode may not be made quickly. We collected statistics from the National Coordination Center for Emergency Medicine (NCCEM) of Kazakhstan and experts in the field on five alternative modes of transport: airplane, helicopter, ambulance, train, and private clinical cars. Our model is based on a multiattribute utility (MAU) theory and considers the latter two alternatives in addition to those used in NCCEM. The novelty of our study is that it employs a MAU function $U(X_1, X_2, X_3)$ that captures the decision maker's preferences and uses three main attributes: transportation cost saving (X_1), transportation time saving (X_2), and the health effect of transportation (X_3). For the latter, we recommend using an internationally recognized scoring system (APACHE II) to assess patients' health status rather than a triage system (red/yellow/green) currently used in the country. APACHE II has a larger range (0-71) and gives more flexibility, but is more complex in assessment. An anesthesiologist with many years of experience provided an assessment for our model. The assessment showed utility interdependence among the attributes. The model ranked the alternatives in the following order: (1) airplane, (2) helicopter, (3) ambulance, (4) clinical cars, and (5) train. In practice, ambulances and clinical cars can be used over distances of up to 200 km (~124 miles). Finally, we compared the results of our model with the model based on the assumption of utility independence among the attributes (*i.e.*, multilinear form) as well as with the ranking of the alternatives based on only one attribute. To illustrate the use of our model, we presented two cases. The model introduced in this paper can be adapted for use in other large countries.

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1. Introduction

Cardiovascular diseases are one of the most common causes of mortality.[1] In 2021, according to the World Health Organization, 42844 people died from cardiovascular diseases (CVD) in Kazakhstan, which is 32% of non-communicable diseases. In addition, every 34 seconds in the USA, one person dies from cardiovascular disease.[2] Worldwide, one in five people dies from cardiovascular diseases.[3] Doctors often assert that cardiovascular issues are primarily due to an unhealthy diet,[4] alcohol,[5] cigarette consumption,[6] and pollution.[7]

Another issue contributing to the mortality of cardiovascular patients is the difficulty of their timely transportation to specialized surgical clinics (*e.g.*, due to a lack of adequate planning).[8] The fundamental problems in treating cardiovascular diseases in the remote and rural areas are the shortage of well-equipped hospitals and the scarcity of qualified doctors.[9] Transporting critically ill patients presents difficulties (*e.g.*, due to various requirements and patient conditions) that affect their long-term prognosis as well as their immediate safety.[10-12] Often in an unstable state, cardiovascular patients have possible consequences, including

[1] *Department of Mechanical and Aerospace Engineering, School of Engineering and Digital Sciences, Nazarbayev University, 53 Kabanbay Batyr Ave., Astana, 010000, Kazakhstan*
[2] *Department of Surgery, School of Medicine, Nazarbayev University, 5/1 Kerey and Zhanibek Khandar St., Astana, 020000, Kazakhstan*
[3] *Department of Anesthesiology, Intensive Care and Pain Medicine, National Research Oncology Center, 3 Kerey and Zhanibek khans ave., 020000, Astana, Kazakhstan*
**Email:* yerbolat.kalpakov@nu.edu.kz (Y. N. Kalpakov)

arrhythmias, hypotension, and respiratory trouble that call for ongoing medical attention. Access to advanced cardiac treatment depends on the pathway to specialist centers; nevertheless, logistical elements such as distance, transportation availability, and environmental conditions complicate the procedure. These difficulties highlight the requirement of a methodical approach to decision making in choosing the best transportation option, therefore balancing factors of time, cost, and health outcomes for critically ill patients.[13]

Constructing a multiattribute utility (MAU) function, U(X_1, X_2, …, X_n), helps to analyze complex decision problems.[14] The MAU function measures the decision maker's preference for projects that involve various attributes (*e.g.*, X_1 – reduction of transportation costs, X_2 – saving of transportation time). The MAU function will be in multilinear form when every attribute is utility independent of its complement.[15] Utility independence (UI) simply means that the risk aversion of the decision maker (DM) over an attribute does not change with the level of another attribute.

Utility independence allows the process of the MAU function assessment to be significantly simpler. According to Dyer *et al*., the independence assumptions lead to easier interpretations of the analysis results.[16] However, frequently, decision makers express a form of partial utility independence (PUI) among the attributes.[14] Various techniques have been proposed to tackle this issue, including addressing parametric dependence,[17] interpolation independence,[18] and attribute dominance conditions.[19] In related work, Abdildin and Abbas found that the utility independence assumption can lead to "recommendations that are different from the true preferences of the decision maker".[20] Following this, we focused on building a decision model based on the preferences of the DM in solving our problem of transporting critically ill patients with cardiovascular diseases in Kazakhstan.

In this work, we create a ranking of transport alternatives that considers economic, transportation, and medical issues by constructing an MAU function. We first determine the transportation modes and attributes for this decision problem with the experts and the President of the National Coordination Center for Emergency Medicine (NCCEM, Kazakhstan), and gather statistical data. We then assess from the DM the utility independence conditions among the attributes utilizing the number of questionnaires. Next, we construct the MAU function and assess its terms from the DM.[14] Finally, we calculate the expected utility of each alternative using all the previously gathered information and create a recommendation system for transport ranking.

The transportation of critically ill patients is a critical aspect of medical care,[21] requiring a well-informed decision-making process to ensure patient safety and optimal outcomes.[22] To our knowledge, this is the first practical study that applies the multiattribute utility analysis to a complex decision problem concerning the transportation of critically ill patients with cardiovascular diseases. This paper's major contribution is that it presents a comprehensive model for selecting transport for CVD patients and provides actionable recommendations. In addition to airplanes, helicopters, and ambulances, our model also incorporates trains and private clinical cars. These two alternatives enrich the model's flexibility on alternatives. For example, a train can be the only available alternative in bad weather or when there is heavy snow on the road. Another novelty of our model is that it incorporates an internationally recognized scoring system (APACHE II) to assess patients' health status instead of the existing triage system.

The subsequent sections of this paper are organized in the following manner: Section 2 describes a decision problem on transporting critically ill patients with cardiovascular disease. It outlines the specific objectives, attributes, alternatives, uncertainties, and the partial decision tree involved in this process. Section 3 involves evaluating the actual preferences of the decision maker, demonstrating the necessary evaluations, and presenting a multiattribute analysis of the problem based on the assessed preferences. A comparison of the results with ranking based on only one attribute and the assumption of utility independence is also provided (Section 4). Section 5 provides a concise overview of the work.

2. Materials and methods

2.1 Transporting critically ill cardiovascular patients

2.1.1 Problem related to roads

Kazakhstan, the ninth largest country globally, faces significant challenges in its transportation infrastructure, crucial for effective population mobility across its expansive 2.7249 million square kilometers. Despite having a mix of transportation modes—air, rail, and road—the efficacy and safety of these systems are compromised by several attributes (*i.e.*, factors) that critically affect service delivery, particularly in healthcare.

Firstly, the nation's road safety is notably poor, ranked 107th globally, with the likelihood of road-related deaths being 11 times higher than in developed countries.[23] This situation is exacerbated in rural areas where 42% of the population resides, and where roads are in dire need of rehabilitation. The current state results in approximately 5-6 fatalities daily indicating a severe public health and safety issue.[23]

Secondly, air transport, though available, is limited in terms of international standards compliance. There are 23 airports in Kazakhstan, and 17 of them could serve international flights. In addition, only two airports (in Astana and Almaty) could comply with the IIIA and IIIB standards of the International Civil Aviation Organization (ICAO).

Additionally, the healthcare transportation coordination faced by the Coordination Center (https://emcrk.kz/en/) is hindered by lengthy decision-making processes and the absence of viable options like train transport for patients, further limiting effective patient transfer solutions. The reliance on non-standardized methods such as clinical cars, which lack the necessary medical expertise and oversight, underscores the systemic inadequacies in policy and infrastructure. Between 2012 and 2022, the Center conducted 22634 flights and helped 31349 patients, as shown in Table 1, both the flight numbers and the number of patients have been increasing annually. According to the NCCEM, the diagnoses of the transported patients vary and approximately 15.2% of them are cardiovascular patients.

Table 1: Flights and medical treatment in 2012-2022 in Kazakhstan conducted by NCCEM.

Year	Flights		Medical treatments	
2012	1005	4.4%	1304	4.2%
2013	1355	6.0%	1756	5.6%
2014	1875	8.3%	2316	7.4%
2015	2149	9.5%	2700	8.6%
2016	2192	9.7%	2691	8.6%
2017	2210	9.8%	2689	8.6%
2018	2351	10.4%	2586	8.2%
2019	2369	10.5%	3104	9.9%
2020	2185	9.7%	3833	12.2%
2021	2586	11.4%	3950	12.6%
2022	2357	10.4%	4420	14.1%
Total	22634	100%	31349	100%

2.1.2 Triage system

According to the Ministry of National Economy, Nurlan Baybazarov (primeminister.kz), almost 40% of the Kazakhstan population lives in rural settlements, and that is around 7.6 million people.[24] Conventional modes of transportation are used within the country to transport people. People mostly use three types of transportation: air, railway, and road. Kazakhstan has been actively improving its healthcare system, specifically by implementing triage evaluation protocols for severely ill patients. The triage process commences with an initial evaluation when a patient arrives at a healthcare facility, employing a standardized scoring system to prioritize based on the level of medical urgency. According to Messova *et al*.,[25] the triage system in Kazakhstan divides patients into three groups: (i) green zone "patients who require minor medical care", (ii) yellow zone "patients who do not require care in the waiting room", and (iii) red zone with "patients who need emergency". Ongoing emphasis is placed on training and education for healthcare professionals to ensure they remain up to date with the newest methods in patient assessment and management. Moreover, the incorporation of technical innovations, such as electronic health records and telemedicine, is being implemented to simplify the triage process, particularly to enhance accessibility in rural or inaccessible regions. The Kazakhstani government facilitates these enhancements by making substantial investments in healthcare infrastructure, thereby bolstering the overall framework that facilitates the provision of efficient and effective emergency care services.

The selection of the transportation mode is the most difficult part of the decision-making at the National Coordination Center for Emergency Medicine. Sometimes it takes days or weeks due to the lack of availability of resources. In addition, transferring patients via train has not been included in their transportation alternatives. Moreover, some healthcare services provide private clinical cars to transport patients. Neither alternatives require experts and has not been included in the healthcare policy. Therefore, the NCCEM does not take responsibility for transporting critically ill patients via the aforementioned transports. We will discuss all alternatives in the next subsection.

2.2 Alternatives

During the literature review and consulting with experts, we found that treating cardiovascular diseases in Kazakhstan is not possible everywhere. There are only two cities with specialized clinics, Almaty and Astana, to which cardiovascular patients are often transported. As aforementioned, there are five transportation methods; however, none of them have lucid dominance over other methods. There is a choice of transporting the patient with a high probability of success, but at a high cost, and the choice is not always available due to limited resources.

Therefore, in practice, we use the following five alternatives:

1. Airplane: Longer trips, those with challenging road access, or when it would be quicker for other reasons, should be given serious thought. The perceived speed of air transport must be balanced against organizational delays and inter-vehicle transfers at either end of the journey.
2. Helicopters, while versatile, are more comfortable and spacious than ground ambulances or fixed-wing aircraft. They are costly, have poorer safety records, and often require alternative arrangements for returning staff and equipment to the base hospital due to their cost.
3. Ambulance cars have advantages of low overall cost, rapid mobilization time, less disruption from adverse weather conditions, less potential for physiological disturbance, and easier patient monitoring. Staff are also more familiar with this environment.
4. Train: The national train company provides transportation for critically ill patients when there is no availability for planes, helicopters, or ambulances.
5. Clinical cars: In some cases, people use private clinical

cars to avoid waiting for ambulances or other transportation modes.

Furthermore, experts eliminated certain choices based on the transportation challenges associated with those options. For instance, an alternative method of transporting severely ill patients was available through the use of private automobiles. Nevertheless, research has revealed that private vehicles lack the necessary equipment to safely transport patients in critical condition. Consequently, relying on private cars for transportation could pose a significant risk to the patient. Drivers lack experience in transporting under harsh circumstances, and the cars are not equipped with flashers. Although the NCCEM does not use the latter two alternative modes, we have included them for analysis due to the modes' utilization by people in such situations.

2.3 Objectives and attributes

To select a suitable option, it is imperative to explicitly specify all characteristics. Thus, those measurements could serve as indicators for our objectives. The main objective of addressing the issue of transporting critically ill patients, as seen from the perspective of the head doctor, is to efficiently and cost-effectively transfer these patients while maximizing transportation safety. The availability of alternative modes of transportation is also a crucial aspect in decision analysis. Therefore, the overall goal encompasses the following objectives:

• Maximize transportation cost savings
• Maximize savings on transportation
• Maximize safety during patient transportation.

Table 2: Attributes of the decision problem for transporting critically ill patients.

Attribute	Measure	Range	
		Best	Worst
X1 – cost saving	Tenge	7 496 000	0
X2 – saving time	minutes	3254	0
X3 – patients' safety	APACHE II	25	0

The decision alternatives will be compared based on the following three attributes (criteria) in relation to the aforementioned objectives (Table 2). Transportation cost saving (X_1) is the difference between the maximum cost for transportation (an airplane) and the cost of other modes of transportation. For instance, if we use trains, we may save 7,496,000 tenge compared to airplanes. This feature pertains to the costs incurred in transporting critically ill patients. Thanks to the availability of free healthcare in Kazakhstan, the expenses incurred by patients are constantly monitored, and the NCCEM provides documentation for every treatment rendered. We should note that the cost of transporting patients does not include the salary of medical personnel, *i.e.*, it includes only the transportation cost. We use local currency, the Tenge, which had an approximate exchange rate of 1 USD = 450 Tenge during the calculations.

Saving time on transportation (X_2) is the difference between the maximum duration for transporting critically ill patients (*e.g.*, train) and the time by other modes of transport. We have analyzed 88 routes (from 44 cities to Astana and from 44 cities to Almaty, see map in Fig. 1). All data have been developed from several sources (Table 3). Some cities do not have airports, and to calculate delivery time via plane to Astana and Almaty, we have added transportation time by ambulance/car to the airports of the nearest cities. We also calculated round trips for both airplane and helicopter modes.

Table 3: Sources used to estimate transport time.

Modes of transportation	Website address
Helicopter	https://www.sennair.at/en/flugrechner
Ambulance / Clinical Car	https://www.google.com/maps
Airplane	https://www.google.com/maps
Train	https://bilet.railways.kz/

Transport safety of patients' health (X_3) is the difference between the maximum score of APACHE II that is raised during the transportation of the patient and other scores that may rise when we transport via other modes of transportation. The APACHE II (Acute Physiology and Chronic Health Evaluation II) scoring system is a widely utilized method for assessing the severity and prognosis of critically ill patients admitted to intensive care units (ICUs). Developed by Knaus *et al.*[26] in 1985, the APACHE II model incorporated a combination of twelve physiological variables, the patient's age, and previous health status to compute a score that correlates with the risk of hospital mortality. This score helps in identifying patients who are at higher risk of mortality, thereby aiding clinicians in making informed decisions regarding the level of care and resource allocation. Moreover, APACHE II is valuable for clinical research and benchmarking ICU performance. The calculation has been shown in Table S1.

2.4 Influence diagram

An influence diagram for transporting critically ill patients is shown in Fig. 2. Basically, the influence diagram is a qualitative description of the decision problem.[27] The influence diagram shows the utility function in a hexagonal figure, random variables in an oval, needed calculations in a double oval, and alternatives represented in a rectangle. For example, according to APACHE II (see Table S1), transportation safety will be calculated based on several variables like temperature, breathing rate, and so on (Fig. 2). Influence diagrams have been used in medicine before.[28,29]

2.5 Decision tree

The decision tree represents a decision node (rectangle) at which the DM considers five alternative transportation modes

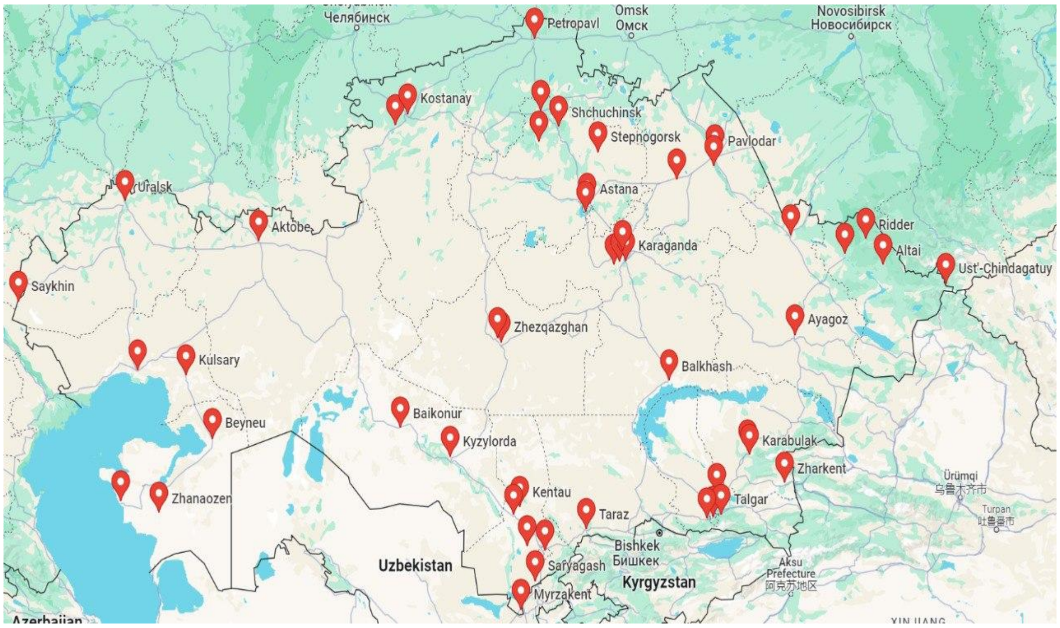

Fig. 1: Map of the Republic of Kazakhstan (Source: yandex.com).

to use for the patient transportation, and the chance nodes (circles), where the outcomes of each attribute may take high, base, or low values with certain probabilities (0.25, 0.5, and 0.25, respectively). There are 135 (namely, 5*3^3) outcomes in this decision tree (Fig. 3). The overall goal is to find the best alternative by comparing its expected utility values, which should be calculated. Hence, first of all, we assess the statistical values (*i.e.*, high, base, low) of each attribute for all alternatives. Secondly, we need to assess utility interdependence among the three following attributes, i.e., we should capture the DM′ s preferences in terms of these three attributes by the use of a questionnaire. Thirdly, based on interdependencies, we should determine the functional form of the MAU function, $U(X_1, X_2, X_3)$. Next, we need to assess the MAU function (another questionnaire) and calculate the expected utility for each alternative. Finally, choose the alternative with the highest expected utility value.

2.6 Uncertainties

Data in Tables 4 and 5 were collected from the NCCEM, National Railway Company, and private clinical centers. The data in Table 6 was estimated by an expert in the field. Each attribute has maximum, high (corresponds to the 90th percentile of a cumulative distribution function), base (50th percentile), low (10th percentile), and minimum values for each alternative transportation mode.[30]

Table 4: X_1 attribute values, KZT (tenge).

	Max	High	Base	Low	Min
Airplane	3,500,000	3,000,000	1,500,000	500,000	0
Helicopter	4,000,000	3,500,000	1,700,000	1,000,000	500,000
Train	7,496,000	7,495,000	7,490,000	7,472,000	7,470,000
Ambulance	7,492,000	7,491,000	7,485,000	7,478,000	7,477,000
Clinical cars	7,472,000	7,470,000	7,460,000	7,440,000	7,430,000

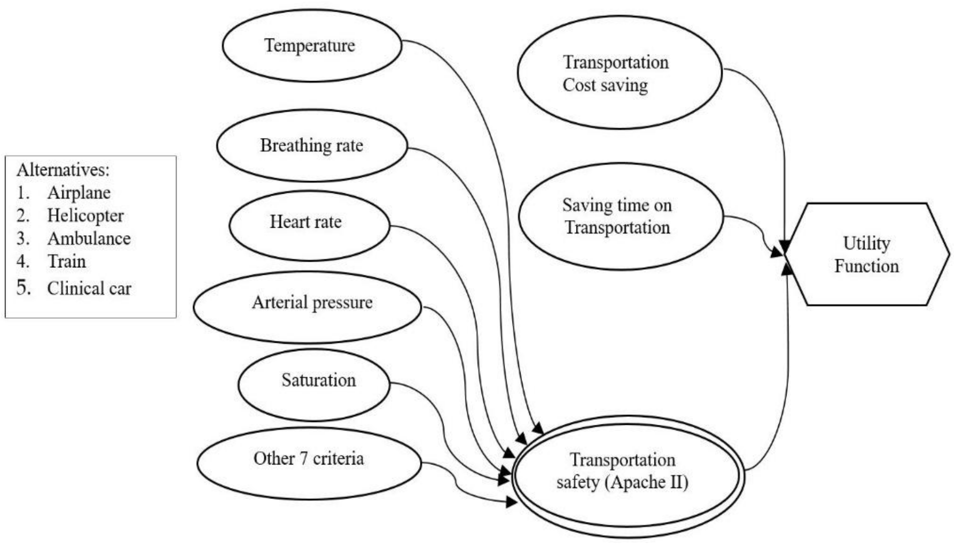

Fig. 2: The influence diagram for transporting critically ill patients with CVD.

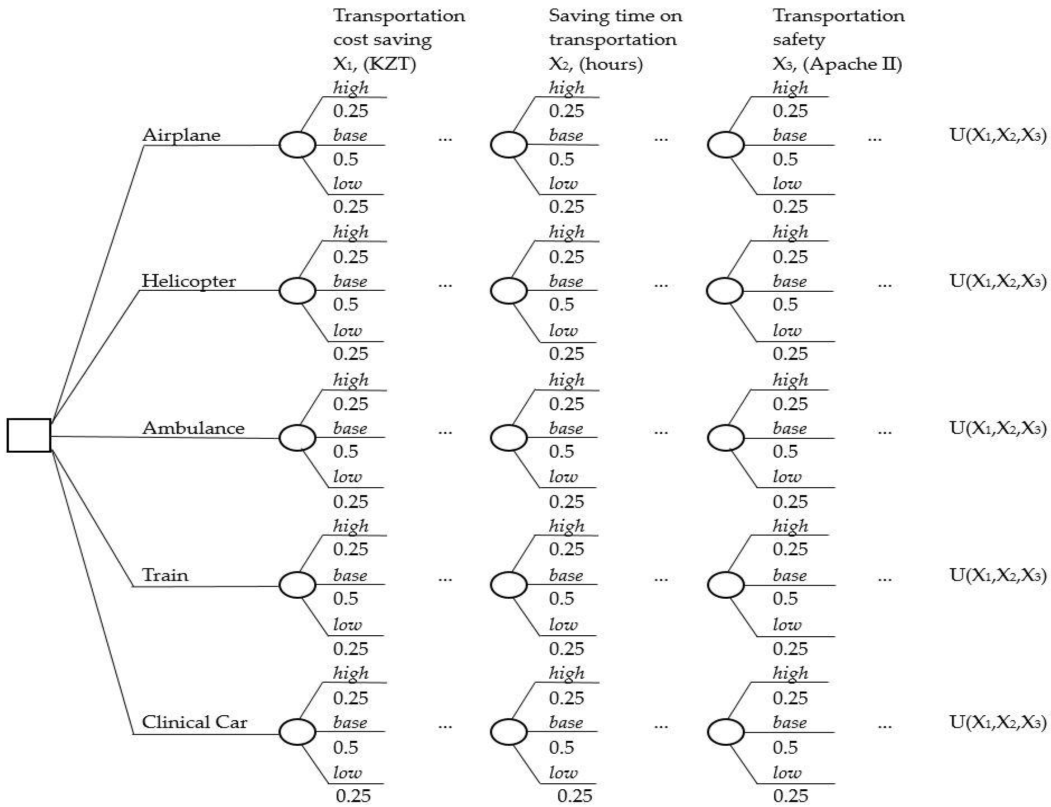

Fig. 3: Partial decision tree constructed for transporting critically ill patients with CVD.

Table 5: X_2 attribute values, minutes.

	Max	High	Base	Low	Min
Airplane	3236	3189	3042	2611	1806
Helicopter	3254	3101.8	2830	2386.6	2004
Train	3164	2873.6	2206	807	0
Ambulance	3201	2995.8	2383.5	1244.2	706
Clinical cars	3201	2995.8	2383.5	1244.2	706

Table 6: X_3 attribute values, (APACHE II score).

	Max	High	Base	Low	Min
Airplane	25	22	20	17	15
Helicopter	23	22	21	18	15
Train	22	21	17	15	10
Ambulance	21	20	15	10	5
Clinical cars	20	18	10	4	0

2.7 Single-criteria ranking

The data in Tables 4-6 do not definitively indicate the superior method. Should a decision maker in the field prioritize the methods based on cost, time, or the likelihood of successful transportation separately, they might rank them as depicted in Table 7. This ranking reveal that no single option consistently outperforms the others. For instance, train is the cheapest transport mode, but it is also the slowest. Thus, a systematic approach is necessary to determine the optimal choice.

3. Results and discussion

3.1 Utility dependence matrix

Utility dependence and utility independence (UI) conditions among n attributes can be represented in the form of the utility dependence matrix (UDM),[14] an n×n incidence matrix with non-vacant cells in the main diagonal. According to Abbas,[14] a vacant cell in row i and column j of UDM asserts the utility independence (UI) relation of X_i from X_j. The UDM for the multilinear form of the MUF is represented by an identity matrix, as shown in Fig. 4(a). Thus, all three attributes are utility independent from their complements. UDM in Fig. 4(b) has been constructed through assessing DM's preferences via a formal test adapted from the study of Abdildin and Abbas.[20] The matrix shows that attribute X_1 is UI from its complement, and X_3 UI X_2. The concept of UDM was explained in more detail by Abbas (2018).[31] UDM of a decision problem can be created by assessing the DM's preferences by the use of a questionnaire and influences the functional form of MAU function.

Table 7: Ranking of transport modes by cost reduction, time saving, and transportation safety separately.

Modes of transportation	Rank		
	Cheapest	Fastest	Less harmful
Airplane	#5	#4	#1
Helicopter	#4	#3	#2
Train	#1	#5	#3
Ambulance	#2	#1	#4
Clinical cars	#3	#2	#5

Two authors (YK and YA) instructed the medical expert about the questions in the questionnaires. The expert did not

	X_1	X_2	X_3
X_1	○		
X_2		○	
X_3			○

(a)

	X_1	X_2	X_3
X_1	○		
X_2	○	○	○
X_3	○		○

(b)

Fig. 4: (a) UDM represents mutual utility independence; (b) UDM assessed by the expert.

have much difficulty in answering questions. The whole assessment took around eight hours with two lengthy breaks. First, the UDM matrix was assessed, and then, the terms of the MUF. UDM in Fig. 4b allows the simplification of conditional functions,[31] as follows in Eqs. (1) and (2):

$$X_1 \; UI \; \overline{X_1} \Rightarrow U(x_1|x_2,x_3) = U(x_1|x_2^0,x_3^0) = U(x_1|x_2^*,x_3^*) \tag{1}$$

$$X_3 \; UI \; X_2 \Rightarrow U(x_3|x_1,x_2) = U(x_3|x_1,x_2^0) = U(x_3|x_1,x_2^*) \tag{2}$$

where $\overline{X_1}$ implies complement of X_1, while 0 and * in superscripts repesent the worst and best values of the attributes, respectively, such as in x_2^0 and x_2^*.

3.2 Assessments of the MAU function using the assessed partial utility independence conditions

The multiattribute utility function can be created using the basic expansion theorem when there are partial utility independence (PUI) constraints.[14] After the incorporation of the UI conditions from UDM in Fig. 4b, assessed from the medical expert, the MAU function took the following form Eqs. (3) and (4):

$$\begin{aligned} U(x_1,x_2,x_3) &= U(x_1^*,x_2,x_3^*)U(x_1|x_2^*,x_3^*)U(x_3|x_1^*,x_2^*) \\ &+ U(x_1^*,x_2,x_3^0)U(x_1|x_2^*,x_3^*)\overline{U}(x_3|x_1^*,x_2^*) \\ &+ U(x_1^0,x_2,x_3^*)\overline{U}(x_1|x_2^*,x_3^*)U(x_3|x_1^0,x_2^*) \\ &+ U(x_1^0,x_2,x_3^0)U(x_1|x_2^*,x_3^*)\overline{U}(x_3|x_1^0,x_2^*) \end{aligned} \tag{3}$$

where

$$\overline{U}(x_3|x_1^*,x_2^*) = 1 - U(x_3|x_1^*,x_2^*) \tag{4}$$

In this MAU function, we need to assess from the DM the following terms: $U(x_1^*,x_2,x_3^*)$, $U(x_1^*,x_2,x_3^0)$, $U(x_1^0,x_2,x_3^*)$, $U(x_1^0,x_2,x_3^0)$, $U(x_1|x_2^*,x_3^*)$, $U(x_3|x_1^*,x_2^*)$, $U(x_3|x_1^0,x_2^*)$.

In order to find all terms, we used assessment and fitted to the curve as mentioned in Fig. 5. After that, all equations Eq. (5)-(11) have been calculated. The assessment has shown the following results:

$$U(x_1|x_2^*,x_3^*) = 1.0207859 + \frac{0.0049153858 - 1.0207859}{[1+(\frac{x}{222452340})^{2.5247176}]^{21142.084}} \tag{6}$$

$$U(x_3|x_1^*,x_2^*) = 2.3880566 + \frac{0.0015504509 - 2.3880566}{[1+(\frac{x}{37350.861})^{1.7889595}]^{260137}} \tag{7}$$

$$U(x_1^*,x_2,x_3^0) = 2.8380897 + \frac{0.0022215658 - 2.8380897}{[1+(\frac{x}{540724.23})^{2.4485195}]^{119575.96}} \tag{8}$$

$$U(x_1^0,x_2,x_3^*) = 1.0714433 + \frac{0.0066709782 - 1.0714433}{[1+(\frac{x}{1190957})^{2.037712}]^{465025.91}} \tag{9}$$

$$U(x_3|x_1^0,x_2^*) = 1.3701224 + \frac{0.0030758215 - 1.3701224}{[1+(\frac{x}{49895.524})^{1.7161175}]^{608051.37}} \tag{10}$$

$$U(x_1^0,x_2,x_3^0) = 5845.0496 + \frac{0.0048378124 - 5845.0496}{[1+(\frac{x}{44362.359})^{2.2052529}]^{0.053736436}} \tag{11}$$

This MAU function captures the decision maker's preferences. The construction of the MAU function under partial utility independence involves the following steps:

1. Evaluate decision maker’s preferences using the formal method outlined in Abdildin and Abbas and represent them with a utility dependence matrix (Fig. 4b).[32]
2. Determine the MAU function from the UDM using the basic expansion Theorem. Incorporate assessed partial utility independence criteria.
3. Gather necessary specifications for the MAU function from the DM.

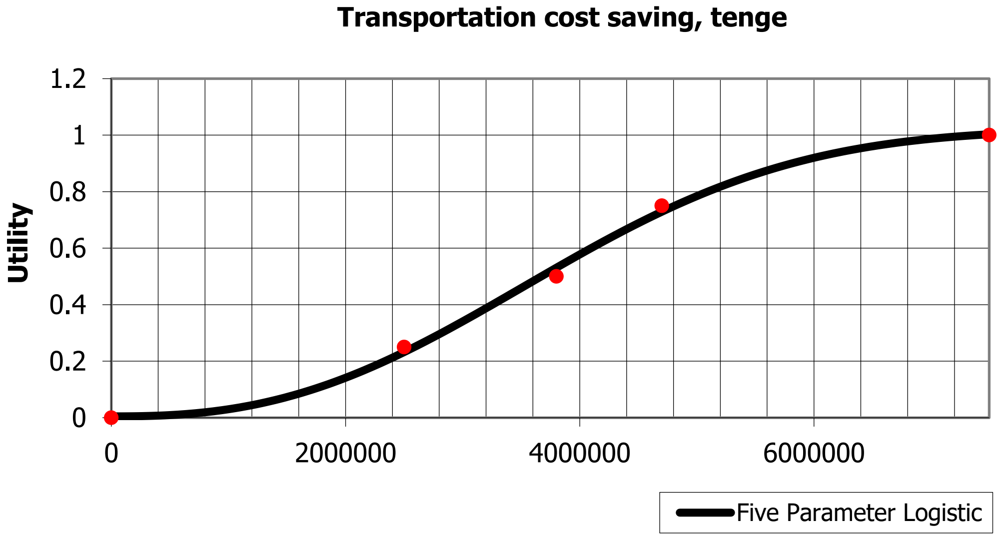

Fig. 5: Fitting a curve to the evaluated (actual utility) data points for function $U(x_1|x_2^*, x_3^*)$.

4. Substitute these specifications into the MAU functional equation and rank order alternatives based on expected utility value.

3.3 Ranking of the options under conditions of evaluated partial utility independence.

The expected utility of each alternative has been calculated using the MAU function as shown in Table 8. Then, the rank-order of alternatives for the given problem has been developed. While airplanes and helicopters are placed as preferred transportation modes for transferring critically ill patients with CVD, trains have taken the last rank-order in the list with an expected utility value of 0.559.

Table 8: The order of alternatives under PUI condition

Rank order	Alternatives	E-value of U-value
#1	Airplane	0.930
#2	Helicopter	0.885
#3	Ambulance	0.611
#4	Clinical Cars	0.569
#5	Train	0.559

3.4 Multiattribute analysis under utility independence assumption

What happens if we do not assess the DM's preferences and simply assume UI among the attributes? If every attribute is UI of its complement, the MAU function can be expressed in the form of a multilinear equation,[15] as shown in Eq.(12):

$$\begin{aligned} U(x_1, x_2, x_3) &= k_1 U_1(x_1) + k_2 U_2(x_2) + k_3 U_3(x_3) \\ &+ k_{12} U_1(x_1) U_2(x_2) + k_{13} U_1(x_1) U_3(x_3) \\ &+ k_{23} U_2(x_2) U_3(x_3) \\ &+ k_{123} U_1(x_1) U_2(x_2) U_3(x_3) \end{aligned} \tag{12}$$

All constants have been assessed from the DM. The assessment has shown the following results Eqs.(13)-(19):

$$k_1 = U(x_1^*, x_2^0, x_3^0) = 0.25 \tag{13}$$

$$k_2 = U(x_1^0, x_2^*, x_3^0) = 0.20 \tag{14}$$

$$k_3 = U(x_1^0, x_2^0, x_3^*) = 0.65 \tag{15}$$

$$\begin{aligned} k_{12} = U(x_1^*, x_2^*, x_3^0) - k_1 - k_2 \\ = 0.30 - 0.25 - 0.20 \\ = -0.15 \end{aligned} \tag{16}$$

$$\begin{aligned} k_{13} = U(x_1^*, x_2^0, x_3^*) - k_1 - k_3 \\ = 0.80 - 0.25 - 0.65 \\ = -0.10 \end{aligned} \tag{17}$$

$$\begin{aligned} k_{23} = U(x_1^0, x_2^*, x_3^*) - k_2 - k_3 \\ = 0.70 - 0.20 - 0.65 \\ = -0.15 \end{aligned} \tag{18}$$

$$\begin{aligned} k_{123} = 1 - k_1 - k_2 - k_3 - k_{12} - k_{13} - k_{23} \\ = 1 - 0.25 - 0.20 - 0.65 \\ - (-0.15) - (-0.10) \\ - (-0.15) = 0.30 \end{aligned} \tag{19}$$

The scaling constants were assessed from the expert using questions as shown below for k_3. *What probability p makes you indifferent between: (i) receiving (x_1^0, x_2^0, x_3^*) for sure and (ii) gambling between (x_1^*, x_2^*, x_3^*) with p and (x_1^0, x_2^0, x_3^0) with $(1-p)$?* In this example, the expert's answer was $p = 65\% \Rightarrow k_3 = U(x_1^0, x_2^0, x_3^*) = 0.65$. Using this multilinear form, we have results presented in Table 9.

3.5 Discussion

In Table 10, we present a comparison of the outcomes obtained from three different approaches: MAU function assessed from the DM (partial utility independence condition holds), the approach based on UI assumption, and a single-criteria ranking (transportation cost saving). When evaluating the options for solving the transportation of critically ill patients with CVD problems based solely on transportation cost savings (X_1), it is evident that transporting via train is the least costly alternative, while airplane mode is the most expensive approach.

Table 9: The order of alternatives under the utility independence condition.

Rank order	Alternatives	E-value of U-value
#1	Train	0.671
#2	Helicopter	0.614
#3	Ambulance	0.602
#4	Airplane	0.585
#5	Clinical cars	0.477

Table 10: The rank-order of alternatives assessed by three methods.

Rank order	Methods		
	MAU function under assessed PUI conditions	MAU function under utility independence assumption	Ranking based on transportation cost savings
#1	Airplane	Train	Train
#2	Helicopter	Helicopter	Ambulance
#3	Ambulance	Ambulance	Clinical cars
#4	Clinical Cars	Airplane	Helicopter
#5	Train	Clinical cars	Airplane

Let us examine the outcomes using the evaluated PUI conditions. Following the decision maker's preferences, the most favourable option is the airplane, while the train remains the least favourable. The helicopter was placed as the second most favourable option, with the ambulance and clinical car transportation being less preferred. It is evident that the other two approaches yield different rankings. By employing these methods, none of the options align with the ranking established by the MAU function when considering the expert's preferences. Thus, without assessing the conditions of utility interdependence among the attributes, the decision maker may choose suboptimal alternatives.

Apart from cost, travel duration, and patient health risk, factors like patient comfort and the availability of medical staff are absolutely vital in deciding the best means of transportation for critically ill patients. Patient comfort may affect physiological stability. Smoother, more roomy transportation options can help reduce stress and the risk of problems. Likewise, early medical intervention, made possible by the presence of medical professionals during transportation, is vital for controlling possible difficulties en route. Our current model focuses on core logistical aspects, but future versions may include other elements to improve the model's applicability and offer a more all-encompassing framework for decisions on critical care transportation.

Although this study mostly addresses Kazakhstan's transportation and healthcare sectors, the model can be modified for other nations by adjusting particular criteria and decision-making guidelines to local settings. Important areas for adaptation are the organization of emergency response systems, the availability and expense of different means of transportation, and degrees of medicalization among the several possibilities. For example, in European countries with highly urbanized areas and large ambulance networks, the model may prioritize ambulances over sanitary aviation. For rural populations in countries like Australia, which face comparable challenges with long-distance patient transport, the model could emphasize rapid air ambulance services. This is just a hypothesis, and the model needs to be adapted to local realities. Our multiattribute utility framework provides a flexible tool that may be used in many healthcare environments by changing these factors, therefore enabling stakeholders to make data-informed transport decisions reflecting local needs and limits.

Our study has some limitations even if it offers insightful analysis of the decision-making process for moving critically ill cardiovascular patients. The reliance on expert assessments for data collecting and utility ratings raises one possible constraint. Expert judgment is by nature subjective, hence differences in experience or viewpoint could inject prejudice into the assessment of different transportation choices and qualities. Our questionnaires have a mechanism for checking the consistency of answers, but some degree of subjectivity may still influence the results.

Furthermore, our model is developed for Kazakhstan's transportation and healthcare systems. Although the multiattribute utility function design can be modified to fit other areas, the particular data, including infrastructure, medical capacity, and transportation expenses, may vary greatly abroad. Applying the concept in various settings would thus need changes to consider local conditions and resources. Future studies should investigate these modifications by means of pilot studies in different geographic and healthcare environments, therefore enhancing the general relevance of the model.

Case 1: Suppose that we have a CVD patient in Akkol town (141 km from Astana, see map in Fig. 1) who is ready to be transported after a medical check. According to our model (see Table 8), the first choice is Airplane. However, the town does not have an airport. Therefore, we move to the next alternative, which is a helicopter. If helicopter is not available at this time, we have to use an ambulance, because the city is located within 200 km to Astana city.

Case 2: Suppose we have a CVD patient in Kulsary town (2090 km from Astana by car) who is ready to be transported after medical check. According to our model, the first choice must be Airplane. However, the town does not have an airport, so we move to the next choice, which is helicopter. If helicopter is not available at this time, then ambulance and private clinical cars are not an option (because the distance is more than 200 km), therefore, we go for train (alternative ranked as #5).

4. Conclusion

In conclusion, we introduced a multiattribute model for addressing the complex decision problem of transporting critically ill patients with cardiovascular diseases. Our model ranked alternative modes of transport based on three important attributes (transportation cost saving, time saving, and impact on patients' health) so that decision makers could easily use the model in their work. The assessed expert preferences (partial utility independence conditions) demonstrated the following rank-order of alternatives: airplane, helicopter, ambulance, clinical cars, and train. This means that the decision maker should first use an airplane to transport a patient with a cardiovascular disease. If there is no airport in that location, then a helicopter should be sent. The use of ambulances and clinical cars is recommended for distances up to 200 km. The train can be used when all other alternatives are unavailable (*e.g.*, due to severe weather conditions).

We also compared our model with two different methods. The assumptions of utility independence yielded a different ranking. When one attribute (transportation expenses) is considered, the rank-order of alternatives is listed from the cheapest mode to the most expensive one. Our comparative analysis revealed disparities in rankings when considering transportation options based solely on transportation cost savings. When three attributes are being considered, the DM faces some challenges with the assumption of UI among the attributes. The decision maker's preferences satisfied the partial utility independence conditions. Our study emphasizes the importance of accurately reflecting the decision maker's preferences.

The practical aspect of our model is yet to be evaluated. We believe that our model will help the national healthcare system to reduce transportation time, transportation expenses, and minimize the adverse health effects. The model can be further expanded to include the comfort of patients during transportation as the fourth attribute.

Future research might incorporate case studies or pilot experiments proving the model's usefulness in real-world situations, hence stressing its practical relevance. Such uses would enable us to demonstrate the decision-making process and results while moving critically ill cardiovascular patients, therefore offering concrete illustrations of the value of the model. Moreover, interacting with important players such as policy advisers, emergency response teams, and medical professionals will present chances for cooperation and ongoing development. Including comments from those directly involved in patient transportation logistics helps the model to be improved to better handle pragmatic issues and changes to meet the needs of the healthcare system.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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