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Development of logistics chains: Engineering and technical perspectives

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Abstract The article discusses the development and implementation of logistics chains to address the evacuation of casualties from aviation incidents. It considers publications that propose solutions for selecting forced landing sites for civil aviation vehicles and optimizing evacuation routes. Medical helicopter evacuation offers several benefits, including reducing the pre-hospitalization period, transporting casualties from hard-to-reach areas directly to high-level trauma centres, and providing extended pre-hospital care by highly qualified aeromedical teams. However, it is important to note that the use of helicopters carries risks to the crew's life, requires significant financial expenditures, and specialized equipment. The effectiveness of medical aviation helicopter usage depends on geographic and demographic trauma factors, the condition of the road network in the region, the proximity of emergency stations, helicopter bases, trauma centres, and the level of coordination between rescue services and hospital specialists. The evacuation of casualties from the scene of an incident using medical aviation helicopters can significantly reduce mortality in cases of severe injuries. The article explores the use of various technologies, such as computer and mathematical modelling, to optimize evacuation speed for civilian and military casualties during armed conflicts or emergencies. It examines international experience in managing transportation, particularly air transport, among participants in international chains/networks.

Keywords: road transport, victim evacuation, optimal route, supply chain management, supply chain resilience, logistics landscape

1. Introduction

Logistic chains are organizational and technological interconnections of elements at different hierarchical levels, subordinated to each other, and implement logistic functions to achieve the common goal of building a logistic system. The hierarchical mathematical principle of constructing logistic chains manifests in the necessity to identify individual structural elements, realizing both managerial and production functions at each level. Specific structural elements are divided into several types depending on the degree of specialization. The consolidation of these elements into larger structures during the building of the logistic structure is based on complex relationships formed by industry-specific features of engineering and technical work execution (Williams et al., 2017).

In emergencies, the rescue of lives is often a matter of minutes or even seconds, depending on the stage of the specific emergency event. Constructing logistic chains using an engineering and technical approach can reduce the number of casualties in critical situations. This work addresses the task of constructing logistic chains using an engineering and technical approach. Analysis of usage and justification of perspectives for developing logistical routes, engineering and technical devices for the evacuation of the wounded and injured during emergencies in both peacetime and wartime (Wernecke et al., 2019; Kruhlov et al., 2023).

The principles of logistical chains are widely applied in civil aviation, including the evacuation of casualties from aviation incidents to specialized medical care locations. Finding optimal evacuation routes for casualties is a well-established task that encompasses various life domains, particularly those related to conducting rescue operations by various emergency services (Strelnykov et al., 2016). An analysis of medical evacuations revealed that moderate-severity extrahospital pneumonia was responsible for engaging (27 ± 2.6)% of resuscitation-therapeutic brigades between 2013 and 2023.

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For instance, Nystoyl et al. (2018) developed a system for the shortest safe route to rescue people from a building on fire, while Mandryk (2015) optimized the search for a route on topographic maps. Shapovalova and Radchenko (2013) studied the optimization of evacuating casualties during flooding using ground transportation.

The use of digital technologies based on blockchain has found application in port evacuation. For instance, the Port of Hamburg requires all companies to connect to a unified information system that uses blockchain technology for port evacuation. In 2017, the Maritime and Port Authority of Singapore launched the Smart Port Challenge systems to enhance the efficiency of maritime logistics during delivery at the Port of Rotterdam (Nedilko et al., 2017; Kryshtal et al., 2023). Also in 2017, British Airways conducted a study on the potential application of blockchain technology in collaboration with Heathrow, Miami, and Geneva airports. This study presents the effectiveness of evacuation technology in aviation for secure information exchange organization (Apodaca et al., 2013).

In the study by Borne et al. (2012), the issue of ensuring the survival of passengers and crew members of aircraft during a forced landing on the water surface is explored. In particular, the situation where casualties will be transported by air medical transport helicopter is considered, and the components of evacuation processes based on integer programming principles are analysed. The paper by Ingalls et al. (2014) discusses the problems of forced landings of aircraft on water surfaces, proposing ways to address tasks related to selecting the landing site and optimizing evacuation route tasks (Grant-Thompson, 1997). The optimization problem is solved using graph theory approaches and methods, relying on the concept of the “Golden Hour”.

2. Materials and methods

The study analysed the Ukrainian and international experience of medical evacuation of casualties during emergencies, both in peacetime and wartime. A retrospective analysis was conducted on the use of various logistical systems for the medical evacuation of the wounded and injured during emergencies. The study explored the engineering and technical characteristics, the effectiveness of utilization, and the prospects for developing methods of logical and systemic analysis and forecasting.

Historical and logical analysis, comparison, expert assessments, systemic analysis, and forecasting methods were employed. The research materials included the medical-technical characteristics of devices used for medical evacuation. The following aircraft and medical platforms are used for rescue and medical transport: the AN 26M 'Rescuer' resuscitation-operating aircraft, the IL 76MD 'Scalpel' operational-resuscitation laboratory aircraft, Sukhoi Superjet 100, Mi-8 and 'Ansat' helicopters, the Life Support for Trauma and Transport (LSTAT) patient care platform during transportation (USA), the Strategic Air Medical Evacuation medical module (STRATAIRMEDEVAC - Germany), and the Mobile Intensive Care Rescue Facility (MIRF - Australia).

3. Results

3.1. Transportation

From a healthcare organization's perspective, there are two ways to optimize medical evacuation. The first involves creating specialized medical transport, while the second involves devices that allow casualties to be evacuated on any mode of transport while simultaneously monitoring physiological functions and the ability to perform basic resuscitation methods.

During the 1970s and 1980s, medical evacuation was improved through the development of specialized sanitary transport, including aviation. Examples of specialized medical transport for evacuating the wounded and providing qualified assistance on board, including in-flight, were developed during this period. These included the AN 26M 'Rescuer' resuscitation-operating aircraft and the IL 76MD 'Scalpel' operational-resuscitation laboratory aircraft (Johnson et al., 2002).

The IL 76MD 'Scalpel' aircraft has been extensively used for evacuating the wounded during military conflicts. It has successfully conducted medical evacuations of over 10,000 wounded and injured individuals from Afghanistan, Tajikistan, and other hotspots. The experience gained from military conflicts, disasters, earthquakes, terrorist acts, and other emergencies has demonstrated that specialized evacuation transport, such as the IL 76MD 'Scalpel,' is significantly limited (Kotwal et al., 2018).

Considerable economic resources and corresponding infrastructure are required for the takeoff and landing of aircraft. One critical issue that remains is the transportation of casualties from the active combat zone, also known as the 'red' zone, to the relatively peaceful 'green' zone where the aircraft can land (Maddry et al., 2018). There is now considerable positive experience in using mobile medical complexes (MMCs) for medical evacuation of casualties in emergencies, as well as patients with severe and extremely severe conditions (Maule et al., 2007; Atstaja et al., 2022).

Aviation medical modules have several drawbacks. These include their inability to be used in ground transport, their significant weight (around 300 kg), lengthy installation time, insufficient battery-operated equipment working time, and the need to disconnect the patient from life support systems for transfer to another vehicle, especially in wartime situations.

In NATO countries, tactical medical evacuation of the wounded is carried out using automotive, maritime, and aviation transport (Madhwal et al., 2017). Military transport aircraft allocated by European Military Transport Command member countries (Belgium, Germany, Spain, Italy, Luxembourg, the Netherlands, and France) or the U.S. are used for strategic medical evacuation of the wounded and injured. The most commonly used aircraft for strategic aviation medical evacuation are Airbus A310 aircraft in the Multi-Role Transporter Systems modification. The Airbus A310 MRT aircraft has a capacity of up to 56 bed spaces, which may include up to 6 patient transport modules and up to 16 continuous care modules, depending on the configuration (Olasveengen, 2008). All modules are equipped with wireless monitoring of medical indicators, oxygen delivery, and administration of necessary medications using syringe pumps.Since the early 1990s, developed countries worldwide, particularly within the NATO bloc, have been actively developing, testing, and implementing medical evacuation devices. The first device of this kind was the Mobile Intensive Care Rescue Facility (MIRF), designed initially for aeromedical evacuation purposes in the Australian Armed Forces and capable of providing urgent care. The Medical Instrumentation and Research Foundation (MIRF) served as a prototype for an autonomous patient life support system that could be attached to almost any platform of automotive, maritime, or aviation transport for medical evacuation.

Representatives of the U.S. Army Medical Department (AMEDD) found that the rapid advancement of troops resulted in delays in evacuating the wounded during the Persian Gulf War (Robert et al., 2017). Therefore, there was a need for a transport system capable of providing intensive care. To tackle this challenge, the development of the Life Support for Trauma and Transport (LSTAT) began in 1998.

Recent studies from other countries indicate a reduction in the use of helicopters to transport trauma patients. This is due to rational resource allocation, increased use of ground transport, and trauma centres. For instance, in the United States between 2010 and 2020, the proportion of patients transported by Helicopter Emergency Medical Services (HEMS) decreased by almost 40%, with no significant impact on mortality (Levytska et al., 2020).

However, aeromedical evacuation is expensive and requires careful justification. According to Schaefer et al. (2009), the cost of helicopter transportation for a trauma patient from the scene to a level 1 trauma centre ranges from 10.5 to 28.0 thousand US dollars, which is significantly higher than the cost of ambulance transport, which is only 1 thousand US dollars. P. Udekwu et al. (2019) suggest that ambulance transport can result in significant cost savings without increasing mortality, as long as certain criteria are met. These criteria include the patient being aged between 16 and 70, having a closed injury, no motor impairments according to the GCS scale, SBP above 90 mm Hg, pulse between 60 and 120 bpm, and respiratory rate between 10 and 29 per minute

3.2. Modelling planning

Anticipating issues related to patient flow logistics during the planning stage is crucial to avoid problems during everyday operations. One effective approach to achieve this is through simulation modelling using modern computer simulators, which can provide a more convenient, informative, and often visual representation. In this work, we utilized FlexSim HealthCare. In addition to supporting basic technologies for creating simulation models, this software product offers comparable accuracy to similar programs and provides visual clarity. This is crucial when applied by non-specialised users without technical education. FlexSim HealthCare's graphical interface, tools, and libraries contain models for creating production processes specifically for healthcare organizations (Figure 1).

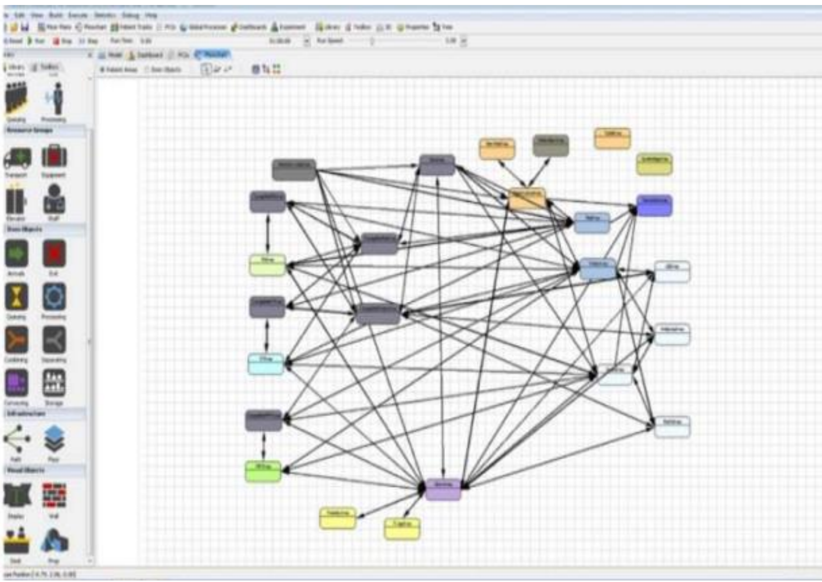

Figure 1 The FlexSimHC software working screen showing the logistics chain modelling scheme.

Based on our modelling, we propose a mathematical model to construct logistic routes more effectively by performing engineering and technological functions. It is necessary to create a set of routes and determine the evacuation period and time (Wernecke et al., 2019) to minimize total costs and increase efficiency (Williams et al., 2017). Evacuation takes place from point

0 to points 1…n. We assume the number of composed routes as p (p≤n). The parameter Xkij (i=0..n, j=0..n, k=1…p) is assigned a value of 1 when re-transport occurs on the k-route, and 0 otherwise. This parameter determines the order of bypass.

Constraints (1,2) are in place to ensure that each evacuation point is visited once by a transport vehicle and departs from it:

$$\sum_{k=1}^{p}\sum_{i=1}^{n} X_{i,j}^{k} = 1, j = 1 \dots n \quad (1)$$

$$\sum_{k=1}^{p}\sum_{j=1}^{n} X_{i,j}^{k} = 1, i = 1 \dots n \quad (2)$$

Constraint (3) - Route connectivity requires that each point on the route is entered and exited by a vehicle:

$$\sum_{j=0}^{n} X_{i,j}^{k} = \sum_{l=0}^{n} X_{i,l}^{k} \quad k = 1 \dots p, i = 1 \dots n \quad (3)$$

Constraint (4) aims to ensure consistent traversal of points:

$$y_i - y_j + (n+1)\sum_{k=1}^{p} X_{i,j}^{k} \leq n \quad yi = Zo, i \ j = 1 \dots n, i \leftrightarrow j \quad (4)$$

To minimize the total time spent during the evacuation period Tk (i=0...n, j=0...n, k=1...p) when transporting seriously ill patients, it is necessary to find the optimal logistics route:

$$\sum_{k=1}^{p}\frac{1}{T_k}\sum_{i=0}^{n}\left(\sum_{j=0}^{n} C_{i,j}\, X_{i,j}^{k} + \sum_{j=1}^{n} \alpha_j\, X_{i,j}^{k}\right) + \sum_{k=1}^{p}\frac{T_k}{2}\sum_{i=1}^{n}\sum_{j=0}^{n} h_i\, w_i X_{i,j}^{k} \rightarrow min, (5)$$

A comparison was made between solutions obtained by computational algorithms using different ratios of transport time costs for travel to the incident scene and transportation to evacuation and storage locations. The simulation model used was FlexSimHC. The comparison was conducted for points using computational algorithms with an accuracy of 12=n (full enumeration). The PRH algorithm is more efficient but requires more computations. Under certain ratios of the number of different landing places, the data obtained by these algorithms are close. This allows for the determination of the zones of effective use of the algorithms.

The overall model is divided into several sub-models, enabling the design of practical economic evacuation systems by stepwise solving individual tasks of optimizing the logistic chain. The models presented in this work are intended for developing software complexes for evacuation and for dealing with theoretical research in the field of logistic transportation.

4. Discussion

Specialized medical transport, primarily by air, addresses the challenges of transporting patients in critical condition over long distances while maintaining high-quality medical care. It is important to establish logistical chains and routes to reduce delivery time. Increasing the fleet of aircraft and helicopters equipped with portable medical modules (PMM and PMV) also leads to greater variability.

Aviation medical modules facilitate the evacuation of casualties, significantly improving the accessibility and quality of medical support for the wounded, sick, and affected individuals. However, it is important to note that these modules are not designed for evacuating casualties from sanitary loss centres and can only be used to a limited extent during wartime and emergencies. Recently, the optimization of medical evacuation has involved the creation of autonomous medical evacuation transport devices. These devices are equipped with portable monitoring systems to assess the functional status and life support of patients (Bazaluk et al., 2020).

The design features of these devices enable a significant reduction in the time required for 'intermediate' patient evacuation to a medical vehicle. This facilitates long-distance evacuation without the need to transfer the patient or disconnect life support systems during medical evacuation.

5. Conclusion

Evacuating casualties from the incident site via medical aviation helicopters can significantly reduce mortality rates in cases of severe injuries (ISS ≥ 16 points). This is achieved by decreasing the pre-hospital period and transporting patients directly to high-level trauma centres. Constructing models of a rapid logistical system using computer and mathematical methods enables the utilization of medical aviation helicopters with significantly lower risks to the crew's lives and requires much less funding for expenses and specialized equipment. The noise, vibration, and low air temperatures in the helicopter cabin complicate the provision of assistance and adversely affect the patient during flight.

The main criteria for using helicopters in medical evacuation are the inability to transport the patient to the trauma centre within 45–60 minutes by ambulance. The effectiveness of medical helicopter usage depends on geographical and demographic factors, the condition of the road network in the region, the proximity of emergency stations, and the degree of interaction between rescue services and logisticians. Modern information technologies such as geospatial analysis, mathematical modelling, telemetric collision warning systems for vehicles, and video communication systems can improve the efficiency of using helicopters for medical aviation evacuation of casualties.

Ethical considerations

Not applicable.

Conflict of Interest

The authors declare no conflicts of interest.

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