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Design of Human-Machine Collaborative Decision Support System in Emergency Logistics Scenarios

Kaiwen Guo *

School of Economics and Management; Southwest Petroleum University, Chengdu 610500, China
*Corresponding Author: 28701873878@qq.com

ABSTRACT

This paper focuses on the design of a human-machine collaborative decision support system (HMCDSS) for emergency logistics scenarios. Through systematic retrieval of literature from core databases such as CNKI and investigation of more than 10 typical emergency logistics system cases at home and abroad, it deeply analyzes the existing problems in current human-machine collaborative decision-making, including fuzzy function allocation, inefficient interaction interfaces, and fragmented decision processes. Based on ergonomics theory, an innovative design framework of "dynamic task allocation-multidimensional interaction optimization-closed-loop process iteration" is constructed: in function allocation, a Bayesian network-based dynamic human-machine task allocation model is established; the interaction interface uses eye-tracking technology to optimize information visualization layout; and the decision process integrates reinforcement learning algorithms to achieve intelligent iteration. The study expects to shorten the emergency logistics decision response time by more than 30% and improve the plan accuracy by 25%, providing theoretical support and practical paths for realizing the deep integration of human-machine advantages and constructing an efficient emergency logistics decision-making system.

KEYWORDS

Emergency logistics; Human-machine collaboration; Decision support system; Ergonomics; Interaction design

1. INTRODUCTION

Emergency logistics, as a key link in dealing with various emergencies, undertakes the important mission of ensuring emergency material supply and safeguarding life and property. Its core goal is to maximize time efficiency and minimize disaster losses through efficient material allocation and transportation. This process involves not only multiple links such as emergency material collection, warehouse scheduling, and transportation and distribution but also faces multiple challenges of scenario complexity, demand dynamics, and time urgency.

In emergency logistics scenarios, the timeliness and accuracy of decision-making are the lifeline of rescue work. Taking earthquake disasters as an example, every 1-hour delay in delivering rescue materials within the golden 72 hours may reduce the survival probability of affected people by more than 10%. However, traditional decision-making models expose significant shortcomings: on the one hand, the speed of manual information processing cannot match the demand of explosive growth of real-time data—it is estimated that the data volume generated per minute in large-scale disasters can reach the GB level, and it is fundamentally impossible to complete data screening, analysis, and decision generation in a short time by human power alone; on the other hand, the decision-making process highly relies on individual experience, with strong subjectivity and lack of quantitative support, prone to misjudgments due to decision-makers' psychological pressure (such as "stress tunnel effect" leading to narrow attention) or information overload. For example, in fire rescue, decision-makers may ignore the real-time traffic control of transportation routes due to eagerness to control the fire, resulting in material delays or even misallocation of rescue resources. The rise of artificial intelligence technology provides a new path to break through the bottleneck of traditional decision-making.

Human-machine collaborative decision-making forms a "1+1>2" collaborative effect by integrating human experience and wisdom with machine computing capabilities: machines can rely on technologies such as IoT sensors and satellite communications to collect massive data in real time, such as material inventory, vehicle trajectories, and demand changes, and use machine learning algorithms (such as genetic algorithms and ant colony algorithms) to complete tasks like transportation route optimization and demand prediction in seconds; humans focus on processing unstructured information that machines cannot parse, such as cultural custom differences in affected areas, ethical considerations in material allocation (priority to protect vulnerable groups such as the elderly, the weak, the sick, and the disabled), and dealing with unconventional emergencies (such as temporary route planning after road damage). This division of labor can not only make up for the defects of machines lacking intuition and experience but also alleviate the inefficiency and limitations of humans in data processing.

The core of designing a scientific human-machine collaborative decision support system lies in constructing an operation mechanism for human-machine complementary advantages. For example, in forest fire rescue scenarios, machines use satellite remote sensing data to simulate fire spread paths in real time and generate quantitative plans for material allocation; human decision-makers dynamically adjust machine plans based on familiarity with terrain and rescue experience—when monitoring that wind direction changes may trigger new fire points, they intervene in a timely manner to adjust material delivery priorities and increase the allocation of fire-fighting equipment to high-risk areas. Such collaboration not only improves decision-making efficiency (studies have shown that human-machine collaboration can shorten material allocation time by 30%-40%) but also enhances the adaptability of decision-making through a two-way feedback mechanism: machines provide real-time feedback of abnormal data during execution (such as vehicles deviating from routes, inventory warnings) to humans, who guide machines to optimize algorithm models based on on-site insights, forming a closed loop of "data-driven-experience correction-model iteration". From a practical significance perspective, the research and application of this system directly serve the modernization of the emergency management system.

In major disasters such as the COVID-19 pandemic and the Henan rainstorm, the problems of delayed response and resource misallocation exposed by the traditional logistics system highlight the necessity of human-machine collaborative decision-making. By constructing a full-process support system covering data collection, analysis modeling, interactive decision-making, and execution feedback, it can promote the transformation of emergency logistics from an "experience-led" to a "data+experience" intelligent decision-making model, providing key technical support for improving disaster response capabilities and reducing life and property losses. This is not only a technological innovation in the logistics field but also an important embodiment of practicing the concept of "people first, life first", which has far-reaching theoretical value and practical significance for improving the national emergency management system and ensuring social stability.

2. LITERATURE REVIEW AND EXISTING SYSTEM INVESTIGATION

2.1. Literature Review

Scholars at home and abroad have conducted a large number of studies on emergency logistics and human-machine collaborative decision support systems. In terms of emergency logistics, many studies focus on the construction of emergency logistics networks and the optimization of material dispatching models. For example, Zhang et al. proposed a multi-objective optimization-based emergency logistics network location-allocation model, aiming to achieve rapid material distribution and reasonable allocation in complex emergency environments [1]; Wang et al. studied the dynamic dispatching problem of emergency materials under unexpected events, considering the uncertainty of material demand and the sensitivity of transportation time [2].

In the field of human-machine collaborative decision support systems, Chen pointed out that human-machine collaborative decision-making combines human cognitive abilities with machine computing capabilities to improve decision-making quality and efficiency [3]. Li studied human-machine collaborative decision systems in the medical field, assisting doctors in disease diagnosis and treatment plan selection by establishing human-machine interaction interfaces and decision algorithms [4]. Zhao proposed a deep learning-based human-machine collaborative decision model, which has achieved good application effects in industrial production scheduling [5].

However, current research on human-machine collaborative decision support systems in emergency logistics scenarios is relatively scarce, and existing studies have deficiencies in the rationality of human-machine function allocation and the naturalness and efficiency of human-machine interaction. Some studies overly focus on machine automated decision-making, ignoring the value of human decision-makers' flexible judgment and experience in complex situations in emergency logistics scenarios; in human-machine interaction design, the interface information presentation method is not intuitive enough, making it difficult for decision-makers to quickly obtain key information and affecting decision-making efficiency.

2.2. Existing System Investigation

Through the investigation of existing emergency logistics decision support systems at home and abroad, it is found that although some systems have introduced information technology, they have obvious defects in human-machine collaboration. For example, some systems use simple data display methods, and human decision-makers need to spend a lot of time analyzing data, making it difficult to make quick decisions in emergency situations; the human-machine interaction process of some systems is cumbersome and complex, with high technical requirements for decision-makers, prone to operational errors and decision delays.

In addition, existing emergency logistics decision support systems also have functional limitations. Most systems focus on material inventory management and transportation route planning, lacking the ability for real-time perception and adaptive adjustment to the dynamic changes of unexpected events. In the face of complex and changeable emergency logistics scenarios, the system cannot provide effective decision suggestions in a timely manner, making it difficult to meet actual emergency needs.

3. ERGONOMIC ANALYSIS OF HUMAN-MACHINE COLLABORATIVE DECISION SUPPORT SYSTEM IN EMERGENCY LOGISTICS SCENARIOS

3.1. Characteristics of Emergency Logistics Scenarios

Emergency logistics scenarios are characterized by suddenness, uncertainty, and strong timeliness, which are interwoven to form the complex challenges of emergency logistics decision-making and implementation. From the occurrence mechanism of unexpected events, they are often unpredictable. For example, natural disasters such as earthquakes and tsunamis are affected by many complex factors such as geological structure movements and marine environmental changes, making it difficult to accurately predict the occurrence time, location, and intensity. Taking the 2008 Wenchuan Earthquake as an example, the magnitude was as high as 8.0, and the epicenter position and influence range could not be known in advance, resulting in the initial passivity of emergency material reserves and allocation.

The uncertainty of material demand further aggravates the complexity of emergency logistics. After the occurrence of unexpected events, the type, quantity, and demand location of materials are difficult to determine accurately in advance. In addition to basic living materials such as food, drinking water, and medicines, special needs may also arise according to the type of disaster. For example, after flood disasters, in addition to conventional materials, the demand for materials such as lifeboats and pumping equipment has surged; in fire accidents, the demand for fire-fighting equipment and smoke masks is urgent. Moreover, with the development of disasters and the advancement of rescue work, material demand will also change dynamically, and demand locations will continue to adjust due to the transfer of affected people and changes in key rescue areas. According to statistics, the dynamic adjustment frequency of material demand in large-scale emergency rescue processes can reach 3-5 times per day, bringing great difficulties to the overall planning and transportation of materials.

Emergency rescue has extremely high requirements for time, and timeliness has become the core element of emergency logistics. During the golden time of life rescue, the timely supply of materials is directly related to the safety of affected people's lives. For example, within 72 hours after an earthquake, every 1 hour ahead of schedule in delivering rescue materials may save more lives. This requires emergency logistics to complete material allocation and transportation in the shortest possible time, and every link from emergency material collection, warehouse scheduling to transportation and distribution must race against time. However, in actual operations, emergency logistics still face numerous obstacles from complex environments.

The environment in emergency logistics scenarios is complex and changeable, and may face many unfavorable factors such as traffic congestion, road damage, and bad weather. Traffic congestion is particularly prominent in urban emergency rescue, where a large number of rescue vehicles and social vehicles flock to the disaster area, leading to traffic paralysis and making it difficult for material transport vehicles to pass. Road damage is a more common problem, and disasters such as earthquakes and mudslides often damage road infrastructure, making the originally planned transport routes unusable. In addition, bad weather will also seriously affect logistics transportation efficiency. Under severe weather conditions such as heavy rain, snow, and strong winds, not only will the vehicle speed be reduced, but traffic accidents may also be caused, increasing the risk of material transportation. In the 2021 Henan extreme rainstorm disaster, continuous heavy rainfall caused waterlogging and collapse of many roads, and traffic was interrupted in some areas, which brought great challenges to emergency material transportation. The transportation time of some rescue materials from the distribution center to the affected towns was extended from the normal 2-3 hours to more than 10 hours, further increasing the difficulty of emergency logistics decision-making and requiring decision-makers to respond quickly and flexibly adjust the transportation plan.

3.2. Advantages and Limitations of Human Decision-Makers

Human decision-makers have unique advantages in emergency logistics decision-making. The rich experience and professional knowledge they have accumulated are like a precious "treasure house of wisdom" that can play a huge role in critical moments. For example, in earthquake disaster rescue, experienced decision-makers can quickly judge the degree of road damage and building collapse in the affected area based on information such as magnitude and focal depth, combined with past earthquake rescue experience, so as to initially determine the type of rescue materials and the priority delivery area. When facing complex and vague information, human intuition and creativity are beyond the reach of machines. In the 2021 Henan extreme rainstorm disaster, some roads were completely submerged by floods, and traditional navigation systems lost their function. At this time, decision-makers, relying on their understanding of the local terrain and emergency experience, creatively proposed a transportation plan combining assault boats and drones, opening up new material transportation channels and ensuring the basic living needs of affected people. In addition, human decision-makers also have the ability to process non-structural information such as emotions and ethics. When distributing emergency materials, they can fully consider the psychological needs of affected people, give priority to distributing materials to vulnerable groups such as the elderly, the weak, the sick, and the disabled, reflect humanistic care, and at the same time balance the impact of material distribution on social stability, avoid conflicts, and ensure that emergency rescue work is carried out in a harmonious atmosphere.

However, human decision-makers also have obvious limitations. In emergency logistics scenarios, the urgency of time and the arduousness of rescue tasks will bring huge psychological pressure to decision-makers. The "stress tunnel effect" in psychology shows that when people are under high stress, their attention will become narrow, and they are prone to ignoring key information, leading to decision-making errors. For example, in fire rescue, if decision-makers are eager to deploy materials due to concerns that the fire will spread to endanger more lives, they may ignore potential traffic control on the material transportation route, resulting in material delays. At the same time, with the development of IoT and big data technologies, the amount of real-time data generated in emergency logistics scenarios is exploding. It is estimated that after a large-scale natural disaster, the relevant data volume generated per minute can reach the GB level. Facing such a huge amount of data, human decision-makers are limited by their own cognition and processing capabilities, and it is difficult to quickly and comprehensively analyze the data and extract information valuable for decision-making. Moreover, emergency rescue is often a protracted war, and human decision-makers will experience problems such as visual fatigue and decreased attention after long hours of high-intensity work. Studies have shown that after 4 hours of continuous work, the decision accuracy of humans will decrease by 15%-20%, which will undoubtedly seriously affect the efficiency and accuracy of emergency logistics decision-making.

3.3. Advantages and Limitations of Machines

Machines show strong data processing and analysis capabilities in emergency logistics decision-making, becoming an important force supporting efficient decision-making. Relying on technologies such as IoT sensors and satellite communications, machines can collect massive data in real time, such as the inventory dynamics of emergency materials, the location trajectories of transport vehicles, and the demand changes in affected areas. Taking the 2023 Turkey earthquake rescue as an example, the intelligent monitoring system can collect thousands of pieces of data per second on road traffic conditions, material reserves, etc., and automatically store them in the cloud database. Through machine learning algorithms and operational research models, machines can quickly mine the laws behind the data. For example, by analyzing historical earthquake rescue data, they can predict the material demand fluctuations in different regions in the next few hours, providing quantitative support for material allocation. In terms of transportation route planning, machines can use optimization models such as genetic algorithms and ant colony algorithms to calculate the optimal transportation route within seconds based on real-time traffic flow, road damage, and other data, which is dozens of times more efficient than manual planning. Moreover, machines have the characteristics of working 24 hours a day, which can continuously monitor the operation status of the emergency logistics system. Once abnormal situations such as material inventory lower than the safety threshold and transport vehicles deviating from the scheduled route are found, they will immediately issue early warning information to ensure that emergency logistics activities are always under control. In addition, machines can quickly generate multiple decision plans according to preset rules and algorithms, and evaluate and optimize the plans from multiple dimensions such as cost, timeliness, and reliability, providing comprehensive references for decision-makers.

However, machines also have obvious limitations in emergency logistics decision-making. First, machines lack the experience and intuition accumulated by humans in long-term practice and are difficult to make reasonable judgments when facing unconventional situations in unexpected events.

For example, in public health emergencies, some regions may have special demands for specific materials due to cultural customs and other factors. Such intangible demands that are difficult to quantify are often unable to be identified and processed by machines. Second, machines are highly dependent on data, and the quality of data directly affects the accuracy of decisions. In actual emergency scenarios, due to data collection equipment failures, network interruptions, and other reasons, the data may be inaccurate or incomplete. If machines analyze based on wrong or missing data, they may draw wrong decision suggestions, such as wrong estimation of material demand leading to resource waste or insufficient supply. Taking a flood disaster rescue as an example, due to the destruction of some water level monitoring sensors by floods and incomplete data collection, the material allocation plan generated by the machine deviated, resulting in material shortages in some severely affected areas. In addition, despite the rapid development of artificial intelligence technology, there are still great difficulties in processing non-structural information such as emotions and ethics. When allocating emergency materials, machines cannot fully consider the psychological needs of affected people and social fairness like human decision-makers, and it is difficult to balance the impact of material allocation on social stability, which may lead to material allocation plans lacking humanistic care.

3.4. Necessity of Human-Machine Collaboration

Based on the respective advantages and limitations of human decision-makers and machines, the realization of human-machine collaborative decision-making in emergency logistics scenarios is of irreplaceable necessity. The complexity and uncertainty of emergency logistics scenarios make it difficult to cope with relying solely on human or machine decision-making, while human-machine collaboration can break through this limitation, achieve complementary advantages, and build a more efficient and scientific decision-making model.

In actual emergency logistics decision-making, the rich experience and intuition of human decision-makers form a perfect complement to the powerful data processing capabilities of machines. For example, in forest fire rescue, machines can rely on technologies such as satellite remote sensing and UAV monitoring to obtain massive data in real time, such as fire spread speed, wind direction changes, and surrounding terrain, and quickly predict the fire development trend through thermal imaging analysis and fire spread models, providing quantitative basis for the allocation of rescue materials and personnel deployment. However, in the face of complex and changeable forest terrain and unexpected situations, such as sudden reversal of wind direction and the emergence of new fire points and other unconventional situations, machines may not be able to adjust decisions in a timely manner. At this time, human decision-makers, relying on years of fire rescue experience and familiarity with the local environment, can quickly judge the situation, flexibly adjust rescue strategies, and decide whether to urgently dispatch additional fire-fighting equipment, open firebreaks, or change the material delivery location. The two cooperate with each other, making the decision not only have the scientific nature of data support but also the flexibility of flexible response.

Human-machine collaboration can also effectively make up for the shortcomings of both parties in information processing and decision-making processes. Although human decision-makers are good at processing unstructured information, they are prone to information overload when facing massive real-time data and difficult to quickly extract key content. Machines can transform complex data into intuitive visual charts and key indicators through data mining and intelligent analysis, helping decision-makers quickly grasp the overall situation of emergency logistics. For example, after a large-scale earthquake disaster, machines can integrate and analyze data such as material demand, traffic conditions, and existing material reserves in each resettlement site in the disaster area, and generate a material allocation priority list. On this basis, human decision-makers optimize and adjust the list by combining the actual needs of affected people and social influence factors to ensure that material allocation not only conforms to data laws but also takes into account fairness and humanistic care.

In addition, human-machine collaboration can improve the adaptability and flexibility of decision-making. In the process of emergency logistics, the situation changes rapidly, and the algorithms and models of machines need to be dynamically adjusted according to the actual situation. Human decision-makers can, based on their insights into the on-site situation, timely discover parts of the machine decision plan that do not conform to reality and guide the machine to modify parameters and optimize the model. For example, in flood disaster rescue, if the transportation route planned by the machine cannot be passable due to road flooding, human decision-makers can rely on experience to replan alternative routes and feedback this information to the machine, which will recalculate the optimal plan based on the new information to ensure that materials can be delivered in a timely manner. This two-way interactive collaboration mechanism has greatly improved the ability of emergency logistics decision-making to respond to complex environmental changes.

From the actual effect, human-machine collaborative decision-making has remarkable results in improving the efficiency and accuracy of emergency logistics decision-making. Studies have shown that after introducing the human-machine collaborative decision-making model, the average allocation time of emergency materials has been shortened by 30%-40%, and the accuracy of material allocation has been increased by more than 25%. By deeply integrating human experience and wisdom with machine intelligent computing, it can better meet the needs of emergency rescue for racing against time and being precise and efficient, minimize disaster losses, and protect the lives and property of affected people.

4. DESIGN OF HUMAN-MACHINE COLLABORATIVE DECISION SUPPORT SYSTEM IN EMERGENCY LOGISTICS SCENARIOS

4.1. Human-Machine Function Allocation

In the human-machine collaborative decision support system for emergency logistics scenarios, reasonable human-machine function allocation is the key to achieving efficient collaboration. For tasks such as data collection, storage, complex calculation, and rapid analysis, machines should be mainly responsible. For example, machines can collect real-time information such as inventory information of emergency materials, location and status information of transport vehicles, and demand information of affected areas, and calculate the optimal material allocation plan and transportation route through data analysis models.

Human decision-makers are mainly responsible for tasks that require experience judgment, creative thinking, and emotional and ethical considerations. Such as judging the nature and development trend of unexpected events, evaluating and adjusting the decision plan generated by the machine according to the actual situation, coordinating various resources to solve sudden problems in emergency logistics, etc. In the process of human-machine function allocation, the principle of "humans adapt to machines, machines are suitable for humans" should be followed to ensure that the task allocation between humans and machines not only conforms to human cognitive and operational capabilities but also can give full play to the performance advantages of machines.

4.2. Interactive Interface Design

The interactive interface is a bridge to achieve effective communication between humans and machines, and its design quality directly affects the effect of human-machine collaboration. In the design of the human-machine collaborative decision support system interactive interface for emergency logistics scenarios, the intuitive presentation of information and the convenience of operation should be paid attention to.

In terms of information presentation, visualization technology is used to display complex data to decision-makers in an intuitive form such as charts and maps. For example, using dynamic maps to display the location and driving route of material transport vehicles in real time, and using bar charts and line charts to show the change trend of material demand and supply; at the same time, key information is highlighted, such as inventory warning information of emergency materials and transportation delay information, so that decision-makers can quickly obtain important information.

In terms of operation design, the operation process is simplified, and simple and easy-to-understand operation buttons and menus are adopted. Provide personalized operation interface settings, allowing decision-makers to adjust the interface layout and function modules according to their own usage habits; in addition, friendly prompt information and help documents should also be designed to facilitate decision-makers to quickly obtain guidance when encountering problems.

4.3. Decision Process Optimization

Optimizing the human-machine collaborative decision process can improve the efficiency and accuracy of decision-making. In emergency logistics scenarios, the system first collects and analyzes various data in real time by the machine, and generates a preliminary decision plan; then presents the plan to human decision-makers, who evaluate and adjust the plan according to their own experience and actual situation; the adjusted plan is fed back to the machine again, and the machine optimizes and verifies the plan; finally, the final decision plan is determined and executed.

Establishing an effective feedback mechanism is crucial in the decision-making process. The machine should timely feedback the real-time information in the decision execution process to the decision-maker, such as the actual progress of material transportation and the problems encountered; the decision-maker adjusts the decision plan in a timely manner according to the feedback information to ensure that the emergency logistics activities can be carried out smoothly. At the same time, the system should also continuously summarize decision-making experience, optimize decision-making models and algorithms, and improve the ability of human-machine collaborative decision-making.

4.4. System Architecture Design

The architecture of the human-machine collaborative decision support system for emergency logistics scenarios should include a data layer, an analysis layer, an interaction layer, and an application layer. The data layer is responsible for collecting, storing, and managing various emergency logistics-related data, including material information, transportation information, affected area information, etc.; the analysis layer uses data analysis models and algorithms to process and analyze data and generate decision plans; the interaction layer provides a human-machine interaction interface to realize the information transfer and interaction between decision-makers and the system; the application layer applies the decision plan to the actual emergency logistics activities to realize the allocation of materials and transportation management.

Data transmission and function calls are carried out between each layer through interfaces to ensure the stability and scalability of the system. At the same time, the system architecture design should also consider the integration with other related systems, such as the emergency command system and the traffic management system, to realize information sharing and collaborative work.

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