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Research on Collaborative Mechanism for Emergency Medical Supplies Reserve and Supply Based on Scenario Analysis

Lijing Zhao[1], **Yi Zhang**[1], **Ting Pang**[2, 3*]

[1]*College of Health Management, Xinxiang Medical University, Xinxiang, China*

[2]*College of Medical Engineering, Xinxiang Medical University, Xinxiang, China*

[3]*Xinxiang High-performance-computing Medical Engineering Technology Research Center, Xinxiang, China*

**Corresponding Author.*

Abstract: Ensuring an adequate reserve, timely supply, and rational distribution of emergency medical supplies in the aftermath of public health emergencies is a critical factor in enhancing emergency response capabilities. To address this issue, this paper first establishes a scenario analysis model for emergency medical supply reserve and supply systems based on convolutional neural networks, using case attribute similarity. Subsequently, by analyzing the information sharing mechanism of reserve and supply entities, a multi-agent emergency medical supply reserve and supply system framework is constructed. Different scenarios such as material demand, entity responsibility, and emergency objectives are considered both vertically and horizontally to achieve resource balance and establish collaborative mechanisms for human, material, financial, and information resources. Taking the emergency medical supply reserve and supply during the COVID-19 pandemic as a case study, simulations are conducted using the Simpy platform. The results demonstrate that 1) scenario analysis models can ensure precise provisioning of emergency medical supplies; 2) the utilization of multi-agent technology promotes intelligent management of emergency medical supplies; 3) collaborative operational mechanisms reduce the risk of disruptions in the emergency medical supply chain. Finally, targeted measures are proposed for the assurance of emergency medical supply reserves and distribution to mitigate the impact of unforeseen events on societal stability.

Keywords: Emergency Medical Supplies; Public Health Emergencies; Scenario Analysis; Reserve and Supply; Collaborative Mechanisms

1. Introduction

Public health emergencies not only cause significant harm to the health of the general population but also have a profound impact on social stability. Rapid and timely emergency response is a fundamental requirement to minimize losses [1, 2]. Sufficient reserve, timely supply, and equitable distribution of emergency medical supplies are essential safeguards for enhancing emergency response capabilities [3, 4]. However, as evidenced by the outbreak of the novel coronavirus (COVID-19), issues persist in the management of emergency medical supplies, including insufficient reserves of critical medical equipment, delayed supply of essential protective gear, and uneven distribution. This has resulted in the inability of a majority of patients to receive timely medical treatment, leading to heightened tensions in doctor-patient relationships and strong public dissatisfaction. Therefore, the scientific and effective reserve and supply of emergency medical supplies following the outbreak of public health emergencies have become crucial research questions in the field of emergency management.

During public health emergencies, government agencies, hospitals, and other institutions are the primary procurers of emergency medical supplies. These supplies can be categorized as pre-event reserves, in-event reserves, physical reserves, contract reserves, and more. Guoli et al. explored procurement reserve models using two-way option contracts in cases of quality changes [5]. Li Zhenping et al. considering the uncertainty of major public health emergencies, studied the reserve and distribution of emergency medical supplies under random demand conditions [6]. Wei Jie et al. introduced the probability of epidemic occurrence and constructed a decision model for emergency medical supply reserves for contracted enterprises [7]. Ran et al. focused on the location selection of emergency supply facilities and constructed an Emergency Facility Location Problem (EFLP) model based on time series evidence reasoning under limited rationality [8]. The above-mentioned research discussed optimization models for emergency medical supply reserves but overlooked the critical technologies needed to ensure the continuous stability of these reserves.

Research on the supply of emergency medical supplies has primarily focused on production scheduling. Hu Xiaowei et al. constructed a dynamic allocation model for emergency medical supplies with the primary goal of maximizing the weighted demand satisfaction rate and the secondary goal of minimizing vehicle travel distance [9]. Su Qiang et al. considering the dynamic and time-varying nature of medical supply demands during sudden epidemics, built a multi-stage optimization model for dynamic allocation of emergency medical supplies, taking into account the relationship between medical supply ratios and recovery rates [10]. Zhu et al. investigated the decision-making process for selecting distribution paths and transport timing as disaster information continuously updates [11]. Bai Dong, in the context of sudden public health emergencies like epidemics, studied the distribution of emergency medical supplies and vehicle route planning [12]. However, these studies primarily discussed decision optimization through the supply structure of emergency medical supplies, with limited focus on rapid and accurate dynamic response methods.

Managing the overall process of emergency medical supply reserve and supply is crucial for national stability and public safety. Peterson et al. suggested that the management of emergency supplies can be viewed as a supply chain model, allowing for planning, organization, and execution based on supply chain theory [13]. Zhu Xiaoyu proposed the use of blockchain technology, which offers advantages such as ensuring data authenticity, security, shareability, transaction transparency, and traceability, to optimize the regulatory system for emergency medical supply supply [14]. Mahmud et al. based on surveys of disaster management personnel, found that a lack of interaction between different organizations affected the effective implementation of the emergency supply chain [15]. Peng Yarui et al. discussed the pathways and methods for emergency supply management involving extensive participation from the government, society, businesses, and the public, considering both peacetime and wartime scenarios [16]. Despite the complexity and variability of emergency medical supply reserve and supply management, the aforementioned studies overlooked the complexity and self-interest of participating entities.Based on this, this paper considers the continuous and stable reserve and supply of emergency medical supplies by the government and hospitals during public health emergencies. It aims to address the contradiction between the rapid and dynamic response to societal needs and the complexity and self-interest of reserve and supply entities, providing a foundational reference and support for emergency management decision-making. Compared to existing research, this paper makes the following primary contributions: (1) it establishes a scenario analysis model for emergency medical supply reserve and supply systems based on convolutional neural networks, taking into account case attribute similarity; (2) it constructs a framework for a multi-agent (Agent) emergency medical supply reserve and supply system through an analysis of the information sharing mechanism among reserve and supply entities; (3) it focuses on different scenarios such as material demand, entity responsibility, and emergency objectives, considering resource balance both vertically and horizontally, and establishes collaborative mechanisms for human, material, financial, and information resources. In particular, the emergency decision-making method designed in this paper exhibits excellent scalability and can be adapted for emergency response to other public health emergencies.

2. Scenario Analysis Model

This model involves the following key steps:

(1) Scenario Element Clarification: Initially, it identifies the elements, states, responses, and outcomes related to the emergency medical supply reserve and supply scenarios during public health emergencies. The critical aspect is the utilization of convolutional neural networks to predict scenario states.

(2) Scenario Division through Case Analysis: Through the collection and analysis of historical cases, it divides the emergency medical supply reserve and supply into various scenarios. It constructs a scenario repository with multiple dimensions, multiple indicators, and multiple attribute properties.

(3) Scenario Matching using Attribute Similarity: It performs a retrieval of the initial scenario against the scenario repository. It uses attribute similarity to match the emergency medical supply storage and supply scenarios, identifying the scenario with the highest similarity. Subsequently, it develops a plan based on the decision-making processes observed in that matched scenario.

The specific model is depicted in Figure 1.

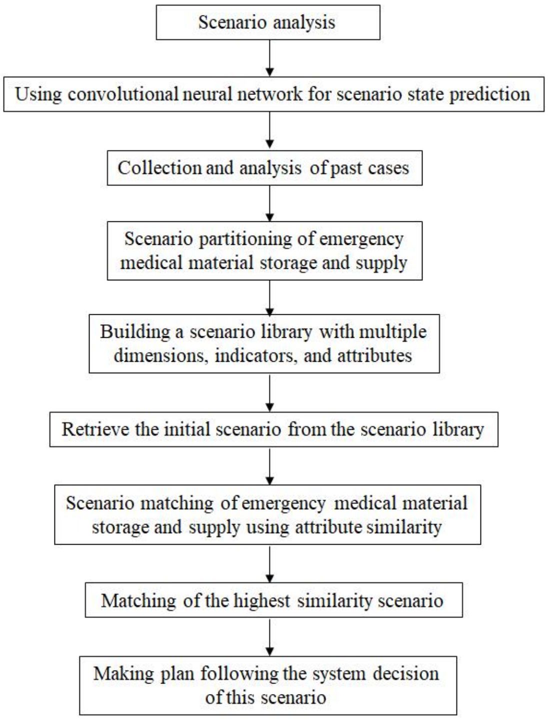

Figure 1. The Specific Model.

2.1 Scenario Analysis

(1) In the scenario analysis of emergency medical supply reserve and supply, the involved elements include the type of public health emergency, geographical location, time, types, and quantities of medical supplies, among others.

(2) Based on specific elements of the emergency event and medical supplies, along with historical data and critical factors of the current event, scenario states are determined to reflect the actual situation during the event. For example, this can include the severity of an outbreak or the urgency of supply shortages. This helps decision-makers prepare for medical supply reserves and supply in advance. In this context, convolutional neural networks (CNN) are used to predict scenario states, with detailed steps as follows:

1) Data Preparation and Preprocessing: Collect historical data and key elements of the current event and preprocess them using standardization to ensure data consistency.

2) Build CNN Model: Design the structure of the CNN model, including convolutional layers, pooling layers, and fully connected layers. Here, a pre-trained CNN model like VGG is used to learn useful features, considering that the task is to predict scenario states. The output layer uses the softmax activation function to output probabilities for each scenario state.

3) Data Splitting and Labeling: Split the data into training and testing sets, ensuring similar data distributions between the two. To label each data sample with the actual scenario state, historical data and event factors are considered.

4) Model Training: Train the CNN model using the training set, allowing it to learn patterns between historical data and event factors to predict scenario states. During training, a loss function is used to measure the difference between predicted results and actual scenario states.

5) Model Validation and Evaluation: Use the testing set to assess the performance of the trained model in predicting scenario states. Accuracy, precision, and recall are used to evaluate the model's accuracy.

6) Predict New Scenario States: When new emergency events and medical supply factors are input, these elements are passed into the trained CNN model to output the probability distribution of predicted scenario states.

(3) Take response measures for specific scenario states to implement scenario responses, which may involve the allocation of

medical supplies, personnel deployment, equipment scheduling, etc.

(4) Determine the effectiveness of specific scenario responses by measuring the adequacy of medical supply reserves, the coordination of personnel and equipment, and the effectiveness of response measures, which constitutes the scenario outcomes.

2.2 Building Scenario Repository

By collecting and analyzing past cases of similar events, the scenarios related to emergency medical supply reserve and supply are categorized into different classes. They are classified based on dimensions such as geographical region, event type, types of supplies, and detailed features and response strategies for each scenario are recorded.

2.3 Scenario Matching

When a sudden public health emergency occurs, the current event's characteristics are compared with the scenarios stored in the repository. The goal is to find the scenario in the repository that is most similar to the current event. This aids in developing more precise and effective response plans. Attribute similarity is used to calculate the degree of scenario matching. Here, two methods of calculating scenario similarity are used.

Jaccard Similarity: Applicable for describing set attributes in scenarios, such as event types, material types, etc. The formula is as follows.

$$Jaccard\ Similarity(A,B)=\frac{|A\cap B|}{|A\cup B|} \qquad (1)$$

Where A∩B represents the intersection of scenario A and scenario B, and A∪B represents the union of scenario A and scenario B.

Pearson Correlation Coefficient: Suitable for measuring the linear correlation between two numerical attributes. The formula is as follows.

$$Pearson\ Correlation\ Coefficient(A,B)=\frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2\sum(y_i-\bar{y})^2}} \qquad (2)$$

Where x_i and y_i represent the attribute values of scenario A and scenario B, $\bar{x}$ and $\bar{y}$ represent the means of the attributes, respectively.

3 Multi-Agent System Framework

Emergency medical supply reserve and supply can be divided into five key stages, including procurement, supply, centralization, transportation, and distribution of medical supplies. Throughout this entire process, multiple relevant entities are involved, such as command authorities, reserve agencies, suppliers, transporters, and distributors. To synergize and optimize the actions of these entities based on different stages and the involved parties, a multi-agent system framework is established. This framework employs agents to represent actual entities for interaction, facilitating collaborative efforts. Agents communicate and cooperate by sharing critical information, which plays a coordinating role throughout the process. Their control is managed by ontologies, ensuring the smooth flow of information coordination. The specific system framework is illustrated in Figure 2.

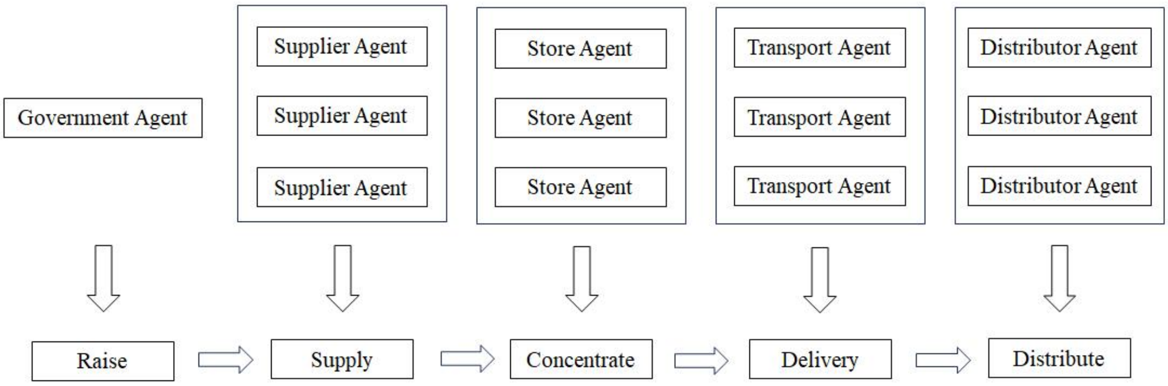

Figure 2. The Specific System Framework.

This architecture consists of the following agents, with each module serving a specific function:

(1) Government Agent (Main Control): Responsible for procuring emergency supplies and overseeing their distribution.

(2) Store Agent: Establishes safety stock and reserves emergency supplies.
(3) Supplier Agent: Produces emergency supplies based on demand.
(4) Transport Agent: Distributes emergency supplies to the required locations.
(5) Distributor Agent: Allocates emergency supplies to individual recipients in need.

4. Collaborative Mechanisms

In the construction of the emergency medical supply reserve and supply system, collaborative strategies are developed among the various agents, guided by material demand, entity responsibility, and emergency objectives. These strategies aim to facilitate the coordinated utilization of resources such as manpower, materials, finances, and information, establishing an organized and efficient emergency medical supply organization. To ensure the smooth operation of the entire process, detailed operational standards and rules are formulated. Under the concept of multi-entity collaborative management, a set of systematic collaborative operating mechanisms is established. These mechanisms include rule-based coordination, planning coordination, information coordination, and risk coordination mechanisms, et al. Through these mechanisms, strong interrelationships and cooperation are established to achieve the goal of collaborative operation. The specific operation of these collaborative mechanisms is depicted in Figure 3.

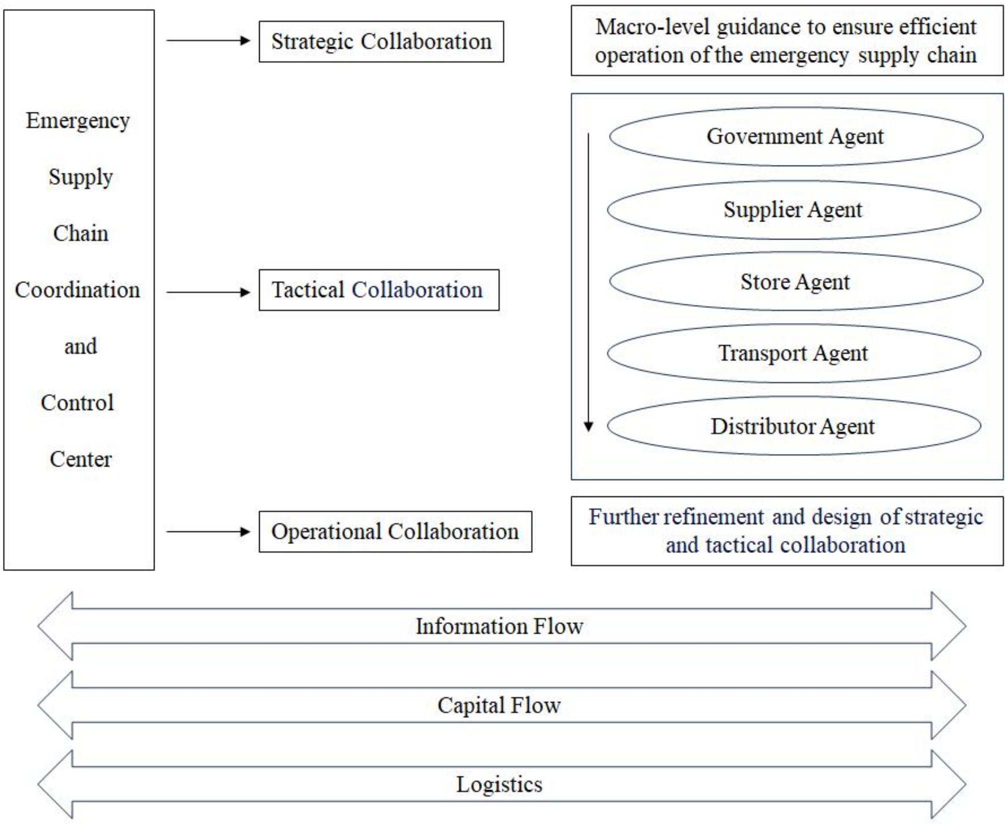

Figure 3. The Specific Operation of These Collaborative Mechanisms

5 Simulation and Analysis

The Emergency Medical Supplies Reserve and Supply Rule Coordination Mechanism refers to a series of coordinated management systems. These management systems serve as guidelines for coordinated actions during the emergency medical supply reserve and supply process, providing common principles for organizational management and collaborative progress of teams. The Planning Coordination Mechanism aims to achieve overall objectives, encompassing planning and management activities from material procurement to distribution to disaster-affected populations. The Information Coordination Mechanism is designed to facilitate the extensive sharing of various supply-related information, enabling the organic integration and network transmission of information flows. Supply entities can adjust their work promptly based on shared information, effectively addressing errors and delays in information transmission, thereby enhancing the responsiveness of emergency medical supply distribution. The Risk Coordination Mechanism involves all relevant entities jointly shouldering environmental, social, and interest-related risks that may affect supply during emergencies, ensuring the normal operation of the supply chain.

Taking the construction of the emergency medical supplies reserve and supply system during the COVID-19 pandemic as an example, simulation and modeling are conducted using the Simpy platform. This aims to verify the effectiveness and feasibility of the technology and propose measures to ensure the construction of the emergency medical supplies reserve and supply system.

5.1 Simulation Using Simpy

Simpy is a process-based discrete event simulation framework, which is suitable for fields requiring process optimization such as system design [13]. It provides the following four core components to help developers build simulation systems: 1) Environment provides the initial simulation environment that manages the simulation time, the creation and deletion of processes, and the scheduling and handling of events in the process. 2) Process is used to describe the activities to be carried out by the simulation object, implemented by the python generator, the model can be encapsulated through the process for scheduling. 3) Event is generated by the process and waiting to be triggered. A more important event in the simulation process is the timeout event. The timeout event in the process is set in advance, and the activities carried out in the real system are simulated in the environment in the way of countdown, so as to reflect the operation law of the model in time. 4) In the form of a queue to simulate the real system with common attributes of resources, entities through the application method to represent the occupation of resources, by calling specific subclasses can achieve priority queues.

According to the above steps, 10 disaster scenarios are generated, including 4 emergency medical supplies demand points. Some scenarios are shown in Table 1.

Table 1. Scenario of Emergency Medical Supplies Reserve and Supply Generation (Part)

No.	Type	Daily demand quantity	Geographical location	Outbreak Severity	Lack of urgency
1	Mask	9038	Northwest of China	not so serious	not so lacking
	Protective clothing	683			
	Anti-fog goggles	362			
2	Mask	52620	Coastal of China	very serious	very short
	Protective clothing	6934			
	Anti-fog goggles	4870			
3	Mask	29193	Central plains of China	very serious	very short
	Protective clothing	2494			
	Anti-fog goggles	1517			
4	Mask	19302	Northeast of China	more serious	shortage

According to the corresponding scenario, the quantity of emergency medical supplies to be distributed (as shown in Table 2), the time to be distributed (as shown in Table 3), and the distribution in the case area without coordination mechanism were obtained (as shown in Table 4).

Table 2. The Quantity of Emergency Medical Supplies Distributed in the Case Area

No.	Type	Quantity of supplies allocated
1	Mask	9246
	Protective clothing	656
	Anti-fog goggles	394

2	Mask	50765
	Protective clothing	6900
	Anti-fog goggles	5008
3	Mask	28852
	Protective clothing	2387
	Anti-fog goggles	1500
4	Mask	18991
	Protective clothing	2603
	Anti-fog goggles	805

Table 3. The Time of Emergency Medical Supplies Distributed in the Case Area.

No.	Type	Acquisition time of supplies（h）
1	Mask	5.1
	Protective clothing	5.8
	Anti-fog goggles	6.3
2	Mask	12.6
	Protective clothing	13.9
	Anti-fog goggles	8.9
3	Mask	7. 5
	Protective clothing	6.8
	Anti-fog goggles	8.9
4	Mask	9.8
	Protective clothing	9.7
	Anti-fog goggles	8.5

Table 4. The Distribution of Emergency Medical Supplies in the Case Area Without Coordination Mechanism

No.	Type	Quantity of supplies allocated	Acquisition time of supplies（h）
1	Mask	7569	6.3
	Protective clothing	509	7.9
	Anti-fog goggles	189	9.9
2	Mask	39810	15.2
	Protective clothing	5077	25.8
	Anti-fog goggles	3693	14.8
3	Mask	20491	16.2
	Protective clothing	1966	11. 0
	Anti-fog goggles	1185	12.6
4	Mask	11947	8.85
	Protective clothing	1632	10.5
	Anti-fog goggles	816	9.7

From the above results, it can be seen that the amount of distributed supplies at the demand point of emergency medical supplies is moderate, indicating that the scenario analysis model can ensure the accurate support of emergency medical supplies. The distribution time of emergency medical materials at the demand point is shortened, indicating that multi-agent technology can promote the intelligent management of emergency medical materials. In the case of no collaborative operation mechanism, the distribution of emergency medical supplies at demand points is poor, indicating that the collaborative operation mechanism can maintain the stability of the supply chain and reduce the risk of interruption of the emergency medical supplies supply chain.

5.2 Optimization Measures

Based on the above simulation results, the following measures are proposed for the construction of an emergency medical supplies reserve and supply system to mitigate the impact of unforeseen events on societal stability.

(1) Data Collection and Analysis: Establish a comprehensive data collection system to gather

historical pandemic data, population statistics, and medical supplies inventory data. Utilize data analysis and predictive models to proactively identify potential pandemic outbreak risks and prepare for reserve and supply.

(2) Diversified Supply Chain: Establish collaborative relationships with multiple suppliers to diversify risks and ensure an adequate supply of medical resources. Create emergency procurement channels for swift resource allocation in urgent situations.

(3) Warehouse and Inventory Management: Equip modern warehousing facilities and implement automated systems for inventory management. Enforce strict policies for supply distribution and recovery to ensure the efficient utilization and recycling of resources.

(4) Personnel Training and Drills: Provide training to medical personnel and warehouse management staff to enable efficient collaboration during emergency situations. Conduct regular simulation drills to test emergency response capabilities.

(5) Policy and Regulatory Framework: Develop regulations and policies that outline responsibilities and procedures for medical supplies reserve and supply. Establish a cooperative mechanism between government agencies and healthcare institutions to ensure the coordinated allocation of resources.

6. Conclusion

In this study, by establishing a scenario analysis model for the emergency medical supplies reserve and supply system, we have addressed the complexity and uncertainty of responding to sudden public events, ensuring the precise provisioning of emergency medical supplies. Through the construction of a multi-agent emergency medical supplies reserve and supply system framework, we have connected with modern artificial intelligence technology, creating a dynamic supply-demand network for rapid response and intelligent management of emergency medical supplies. By building a collaborative operating mechanism for the emergency medical supplies reserve and supply system, we have effectively supported the supply of emergency medical supplies, ensuring preparedness and orderliness and reducing the risk of interruptions in the emergency medical supply chain. Through simulation and analysis of real-world cases, we have clarified the feasibility and effectiveness of key technologies such as scenario analysis, multi-agent systems, and collaboration in the emergency medical supplies reserve and supply system. While this study has introduced coordination in emergency capacity and decision-making, further research is needed to delve into the factors influencing emergency medical supplies reserve and supply. Additionally, exploring the problems and reasons underlying emergency medical supplies management is a direction for future research.

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