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Effectiveness Analysis for Unmanned Emergency Supplies Delivery System of Systems Based on FDNA

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Rapid and effective disaster management is crucial following the occurrence of natural hazards, with emergency supplies delivery being a pivotal task that directly impacts the survival and safety of affected individuals. As unmanned systems are increasingly applied to emergency supplies delivery, it is essential to manage and allocate of various equipment from a systematic perspective to leverage the advantages of unmanned systems. One key research point is on evaluating the effectiveness of the emergency supplies delivery System of Systems (ESDSoS). This paper assessed the effectiveness of the ESDSoS using a functional dependency network analysis (FDNA) method and further analyzed potential directions in which unmanned systems could enhance the effectiveness of this system. Case studies are also provided to illustrate the points made in the paper.

Keywords: FDNA, disaster management, effectiveness analysis, unmanned system, System of Systems, supplies delivery.

1. General Appearance

As human society evolves, human activities have profoundly impacted the natural environment. Recent years have witnessed a marked increase in the frequency of natural hazards, resulting in substantial casualties and significant economic losses. Natural hazards are uncertain in terms of time and space, and their forms are unpredictable, making disasters relief operations challenging to conduct. To efficiently carry out relief work, it is necessary to rationally utilize various disaster relief equipment to maximize its effectiveness. Therefore, there is a need to establish an emergency relief equipment System of Systems, thereby forming robust emergency relief capabilities.

During disaster relief operations, to ensure the survival of affected individuals and the restoration of infrastructure in disaster areas, a significant amount of emergency supplies must be delivered to the disaster zone within a short period. Thus, establishing an emergency supplies delivery System of Systems (ESDSoS) is a crucial aspect of the construction of the emergency relief equipment System of Systems. After a disaster, infrastructure such as roads in the affected area is often destroyed, and adverse meteorological conditions may exist, posing numerous difficulties and risks for emergency supplies delivery. With the development and widespread application of autonomous systems such as unmanned aerial vehicle (UAV) and unmanned ground vehicles (UGV), the issues faced in emergency supplies delivery are gradually being addressed (Dukkanci et al. 2024). Autonomous systems have demonstrated good performance in this regard (Chai et al. 2024).

Emergency supplies delivery first requires the detection of disaster areas and the acquisition of material needs through communication. Subsequently, delivery task planning and allocation are carried out based on available supplies and transportation tools (Yu et al. 2024). Finally, the delivery tasks are executed. The detection and communication with disaster areas can be accomplished through satellites and UAVs. The planning and allocation of delivery tasks are generally handled by command center, or through distributed task planning by unmanned swarm. Ultimately, various autonomous systems are utilized to complete the emergency supplies delivery. Figure 1 illustrates a conceptual framework for the ESDSoS.

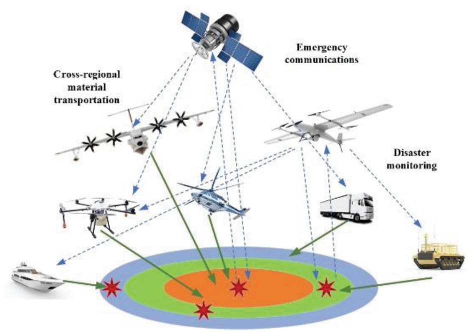

Fig. 1. Emergency supplies delivery System of Systems.

Currently, research on the application of autonomous systems in emergency suppliesdelivery primarily focuses on task allocation methods and delivery route planning. However, there is limited research on the effectiveness of ESDSoS and the contribution of unmanned systems to enhancing this effectiveness. Accurately assessing the effectiveness of ESDSoS and subsequently optimizing system design, while also providing direction for the application of unmanned systems in emergency supplies delivery, holds significant research importance. Therefore, this paper adopts the functional dependency network analysis (FDNA) method to evaluate and analyze the effectiveness of an emergency supplies delivery system, and examines an effective application approach for unmanned systems.

The focus of the study is evaluating the effectiveness of the ESDSoS and analyzing ways to enhance it. In section 1, the ESDSoS and the research status of unmanned systems' applications in the field of emergency supply delivery are introduced. In section 2, the modeling and analysis methods for ESDSoS, as well as the functional dependency network analysis method, are elaborated. In section 3, an effectiveness evaluation and result analysis are conducted based on a case study of an ESDSoS. In section 4, a conclusion of the entire paper is provided.

2. Modeling and analysis methods

The purpose of this paper's work is to conduct an effectiveness evaluation and analysis of the ESDSoS. In this section, research is conducted on the modeling methods for ESDSoS and the corresponding effectiveness evaluation methods..

2.1.*Method for modeling System of Systems*

System of Systems (SoS) modeling involves describing the key characteristics of a SoS through a certain degree of abstraction and simplification, representing the various components of the SoS and their relationships in the form of a model.

2.1.1. *System of Systems*

A system of systems (SOS) is a collection of multiple systems organized according to specific mission. Within an SOS, systems with different functions are integrated, cooperating through the sharing of resources and information, to achieve capabilities that are not possessed at the individual system level.

ESDSoS should possess the capability to rapidly and flexibly deliver emergency supplies in disaster areas. The demand for emergency supplies in disaster areas is concentrated temporally and dispersed spatially, and transportation condition in disaster areas is poor. Therefore, ESDSoS must swiftly and accurately perceive the demand for emergency supplies, reasonably plan delivery schemes, and overcome geographical limitations to achieve supply delivery. When constructing ESDSoS, it is necessary to integrate the functional characteristics of individual systems according to the aforementioned requirements, in order to fulfill the mission requirements.

2.1.2. *System of Systems modelling*

The purpose of SoS modeling is to describe the characteristics of the SoS and to solve corresponding problems based on the constructed model. Currently, SoS modeling methods primarily include SoS modeling based on SoS architecture framework, SoS modeling based on network models, and SoS modeling based on multi-agent theory.

SoS modeling based on SoS architecture framework describes system architecture and behavior through various views. Within the SoS modeling domain, extensively utilized architectural frameworks encompass standardized modeling methodologies such as the Department of Defense Architecture Framework (DoDAF) and the Unified Architecture Framework (UAF). These modeling frameworks provide a set of common terminology, model views, and modeling rules, enabling a clear representation of interactions and dependencies among different levels and categories of elements within the system. This modeling approach offers high flexibility and extensibility and is typically used in system design and development work.

SoS modeling based on network models views the SoS as a network structure composed of multiple interconnected nodes, with these connections describing SoS behavior and characteristics. The nodes in the network model can represent SoS components, basic functions, or operations. The edges in the network model can represent interactions among SoS components or actual information flow, energy flow, material flow, etc. Using this method, we can gain insight into the generation of SoS capabilities, resilience, robustness, and other features by simulating and analyzing the nodes and connections in the network (Wang et al. 2021).

SoS modeling based on multi-agent theory views the SoS as a cluster composed of multiple autonomous agents and conducts modeling by studying the interactions and cooperation among these agents. This method fully considers the interactions and coordination among agents and can describe the impact of the environment on SoS behavior. With the increasing level of SoS intelligence and the application of autonomous systems, this method demonstrates good applicability.

This study aims to evaluate the effectiveness of ESDSoS and analyze potential measures for enhancing its performance. To construct a SoS model, it is necessary to describe the process of aggregating the functions of various systems within ESDSoS to generate SoS-level capabilities. Therefore, ESDSoS is modeled based on network model. Figure 2 presents the multi-layer network capability aggregation model of ESDSoS.

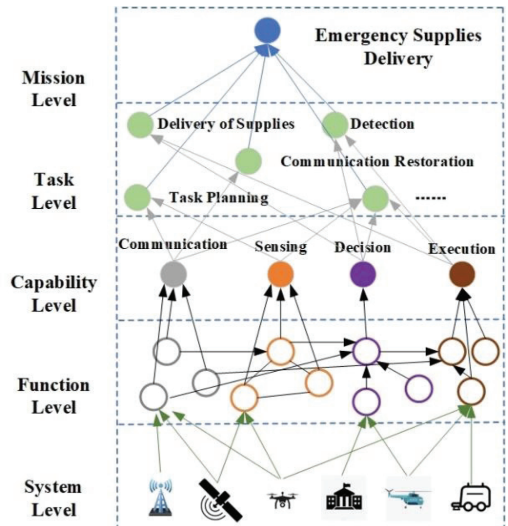

Fig. 2. Multi-layer network capability aggregation model of ESDSoS.

In Figure 2, the Emergency Service Delivery System of Systems (ESDSoS) model is constructed with five hierarchical levels: mission level, task level, capability level, function level, and system level. The mission of ESDSoS is emergency supply delivery, which can be divided into multiple tasks such as detection, task planning, and supplies delivery. To accomplish the tasks outlined in the task level, a combination of four capabilities in the capability level—communication, sensing, decision-making, and execution—is required. Each capability in the capability level corresponds to specific functions in the function level. Since systems within ESDSoS often possess multiple functions, there exists a many-to-one mapping relationship between the functions in the function level and the systems in the system level.

Through constructing the ESDSoS model, it can be observed that there is a clear dependency between the effectiveness of ESDSoS and the functions of its constituent systems. Therefore, a method that can describe the dependency relationships among different functions and perform quantitative analysis can be selected for evaluating the effectiveness of ESDSoS, namely Functional Dependency Network Analysis (FDNA) (Wang et al. 2024).

2.2. *Functional dependency network analysis*

The FDNA method models the complex dependency relationships within a SoS and among systems within a SoS through the Functional Dependency Network (FDN) model. It then calculates the effectiveness using dependency parameters and piecewise linear functions (Huan et al. 2022).

2.2.1. *FDNA method*

The FDNA method examines the impact of systems within a System of Systems (SoS) on each other and on the whole from the perspective of dependencies (Luo et al. 2020). In the FDNA method, nodes represent system functions within the SoS, while edges represent dependency relationships. Nodes are classified into receiver nodes and feeder nodes, where the operability of a receiver node depends on the operability of the feeder node. A typical FDN (Functional Dependency Network) is shown in Figure 3.

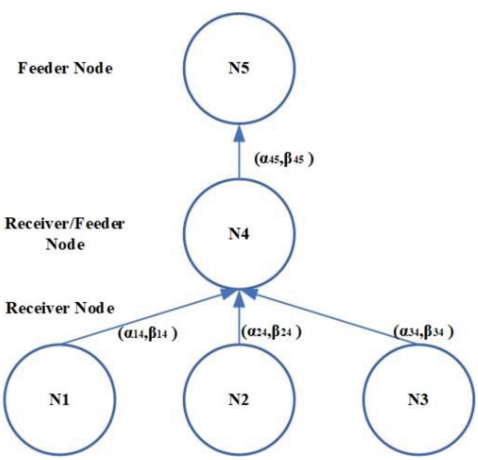

Fig. 3. Functional Dependency Network.

The FDNA method defines the Dependency Relation (DR) between receiver nodes and feeder nodes using two parameters: Strength of Dependency (SOD) and Criticality of Dependency (COD). SOD represents the contribution of a feeder node to enhancing the effectiveness of a receiver node under the dependency relation, denoted by the parameter α_{ij}, where i is the identifier for the feeder node and j is the identifier for the receiver node. The value of α_{ij} ranges from [0,1], with a higher α_{ij} indicating a greater contribution from the feeder node to the receiver node, and thus a stronger dependency of the receiver node on the feeder node. COD represents the extent to which the effectiveness level of a dependent node is constrained by the effectiveness level of a supplying node, denoted by the parameter β_{ij}, with a value range of [0,100]. β_{ij} represents the residual effectiveness of a receiver node when its corresponding feeder node completely fails. A smaller value indicates that the feeder node is more critical to the receiver node (Wang et al. 2014).

2.2.1. *Effectiveness assessment*

Assuming that the feeder node is represented by the symbol $i = 1,2,\dots,h$, the receiver node by the symbol j, the effectiveness of the supply node by O_i, and the effectiveness of the receiving node by O_j, the node aggregation model based on the principle of the constrained average weakest link is shown in Eq.(1)-(3) (Qiu et al. 2022):

$$O_j = \min\left(SOD_j, COD_j\right) \tag{1}$$

$$SOD_j = \frac{\sum_{i=1}^{h}(\alpha_{ij}O_i + 100(1-\alpha_{ij}))}{h} \tag{2}$$

$$COD_j = \min\{O_i + \beta_{ij}\}, i = 1,2,\dots,h \tag{3}$$

In these equations：

$$0 \le \alpha_{ij} \le 1, 0 \le \beta_{ij} \le 100, 0 \le O_i \le 100$$

In Eq.(2), when α_{ij} equals 0, SOD_j equals 100, which implies that the receiver node has an effectiveness of 100 when there is no dependency between it with the feeder node. This is obviously unreasonable, so an self effectiveness parameter

SE_i is introduced to improve Eq.(2) The improved form is as Eq.(4)

$$SOD_j = \frac{\sum_{i=1}^{h} SE_i(\alpha_{ij}O_i + 100(1 - \alpha_{ij}))}{100h} \quad (4)$$

3. Case study

In this section, we evaluate and analyze an ESDSoS case, which includes satellites, UAVs, UGVs, task management center (TMC), and supply points (SP), using a functional dependency network analysis method.

3.1. *Construction of Functional Dependency Network*

By analyzing the systems and their functions within this ESDSoS, we obtain the nodes for the functional dependency network. The specific node information is shown in Table1. The node types include sensing nodes (S), decision-making nodes (D), support nodes (A), execution nodes (I), and effectiveness nodes (E).

Table 1. Nodes information

No.	Node Name	Description	Node Type
1	TMC-S	Situational awareness function	S
2	TMC-D	Delivery task command function	D
3	SP-A	Material and energy supply function	A
4	SAT-S	Satellite Detection Function	S
5	UAV-S	UAV Detection Function	S
6~8	UAV-I(1~3)	No.1~3 UAV material delivery function	I
9~11	UGV-I(1~3)	No.1~3 UGV material delivery function	I
12	ESDSoS	Emergency supplies delivery function	E

The dependency relationships between the various nodes are illustrated in Figure 4.

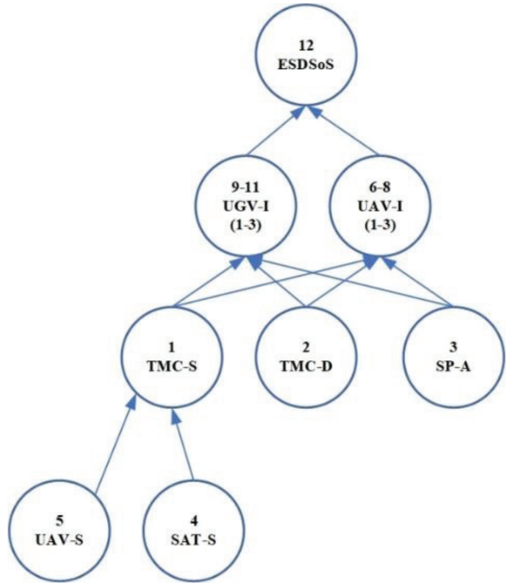

Fig. 4. Functional Dependency Network of ESDSoS.

3.2. *ESDSoS effectiveness assessment*

After determining the parameters α_{ij} related to dependency strength, β_{ij} related to dependency criticality, and the self-effectiveness parameter SE_i based on historical data and expert experience, the effectiveness of the ESDSoS is obtained through calculation.

3.3. *ESDSoS effectiveness analysis*

3.3.1 *Analysis of the impact of single-system effectiveness on ESDSoS effectiveness*

To analyze the impact of changes in the effectiveness of a single system on the overall effectiveness of the ESDSoS, we vary the effectiveness of one system from 0 to 100 while keeping the effectiveness of other systems constant (both 60). This allows us to calculate the corresponding changes in the overall effectiveness of the ESDSoS. Figure 5 is the result of effectiveness calculation.

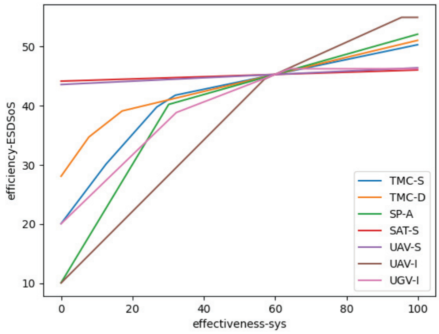

Fig. 5. The impact of single-system effectiveness on ESDSoS effectiveness.

As can be seen from Figure 5, the changes in the effectiveness of UGV-I, TMC-S, TMC-D, and SP-A have a significant impact on the changes in the effectiveness of ESDSoS.

3.3.2 *Analysis of the impact of autonomous capabilities of unmanned systems on the effectiveness of ESDSoS*

Currently, the execution of delivery tasks by ESDSoS heavily relies on the situation awareness and task management functions of the task management center. With the increasing intelligence of unmanned systems, autonomous systems such as UAVs have gained the ability to autonomously execute delivery tasks. In this study, controlled variable experiments were conducted, with the results presented in Figure 6 and Figure 7 . It can be observed from the figure that as the parameter α_{ij}, which correlates with the degree of UAV-I's dependence on TMC-S and TMC-D, decreases, the effectiveness of ESDSoS increases. This indicates that enhancement of autonomous capabilities of unmanned systems are beneficial for enhancing the overall effectiveness of the SoS.

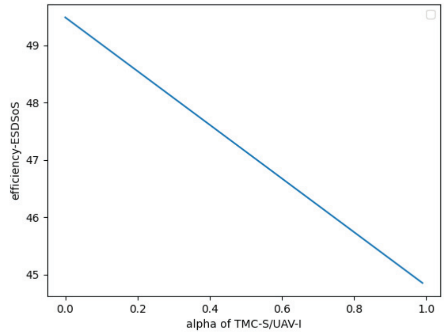

Fig. 6. The impact of autonomous capabilities of unmanned systems on the effectiveness of ESDSoS.(1)

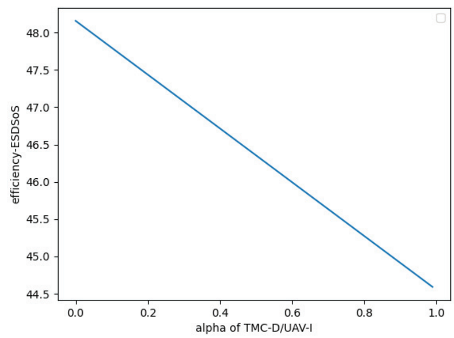

Fig. 7. The impact of autonomous capabilities of unmanned systems on the effectiveness of ESDSoS.(2)

3.3.3 *Analysis of the impact of cooperation between unmanned systems on the effectiveness of ESDSoS*

Another characteristic of unmanned systems is their ability to complete tasks through cooperation among systems. In the context of emergency supplies delivery tasks, there has been extensive research on the cooperation between UAVs and UGVs. In this paper, by introducing a functional dependency relationship of UAV-I on UGV-I, we simulate behaviors such as relay supplies delivery by UGVs and UAVs, as well as UGVs charging UAVs (Chen et al. 2024), as illustrated in the Figure 8。

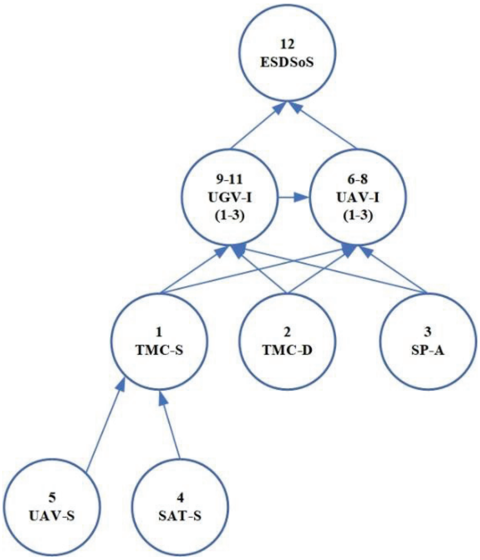

Fig. 8. Functional dependency network with added dependency relationships.

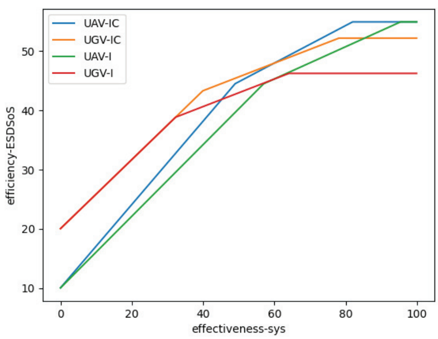

Fig. 9. The impact of cooperation between unmanned systems on the effectiveness of ESDSoS.

After effectiveness calculations, the results are as shown in Figure 9. When the effectiveness values of UAVs and UGVs fall within the range of 40-80, the effectiveness value of the ESDSoS (UAV-IC, UGV-IC) with cooperative behaviors is higher than that of the scenario without cooperation (UAV-I, UGV-I). This indicates that cooperation among unmanned systems contributes to the improvement of SoS effectiveness.

4. Conclusion

Emergency supplies delivery plays a crucial role in disasters relief efforts, directly impacting the survival of affected individuals, hence the necessity to establish a highly effective ESDSoS. Meanwhile, the application of unmanned systems offers a new direction for enhancing the effectiveness of this system. This paper first analyzes the capability generation model of the ESDSoS. Based on this analysis, a functional dependency network model is constructed to represent the functional dependencies among the constituent systems of the ESDSoS, which is then used to evaluate the system's effectiveness.

Based on the system effectiveness evaluation, this paper further analyzes the sensitivity of the ESDSoS's effectiveness to changes in the effectiveness of individual systems. The results indicate that functions such as task management and supplies replenishment have a significant impact on the system's overall effectiveness. Additionally, the impact of unmanned systems' autonomy and cooperative behavior on the effectiveness of the ESDSoS is analyzed. The results demonstrate that the autonomy and cooperative behavior of unmanned systems can effectively enhance the system's effectiveness.

Future research should consider potential internal and external disturbances within the ESDSoS and provide more accurate system effectiveness evaluation methods by incorporating specific mission scenarios and unmanned system cooperation strategies.

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