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A Multi-Function Disaster Decision Support System Based on Multi-Source Dynamic Data

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Abstract

Disasters are unpredictable. However, occurrences follow a specific time sequence. Disaster management encompasses routine disaster reduction, pre-disaster preparation, mid-disaster response, post-disaster recovery, time management and allocating routine tasks over an extended period, and emergency response during highly stressful periods. Various response organizations rely on effective “integrated disaster management” to react to situations at different periods in time. In addition to making personnel and organization adjustments at different times, integration also requires systems for effective and fast communication and for providing first-hand supporting information to responders for data, manpower, organization, and resource integration. Based on design science theory, disaster decision support systems integrate internal and external data through (1) confirming problems and motivations, (2) defining solution objectives, (3) designing and developing a solution, (4) presenting the solution, (5) evaluating the solution, and (6) communicating protocols, and then consolidating the data into graphical or visual platforms and systems. These systems not only contain disaster prevention information, provide pre-disaster emergency response warnings, allocate supporting resources for mid-disaster response, evaluate the scale of disasters, and formulate response plans, but also simulate various disaster situations and scenarios during disaster-free periods for training and education purposes.

Keywords: Disaster Management, Disaster Decision Support Systems (D_DSS), Disaster Scenarios Tabletop Exercise, Interlink in Multi-Window

1. Introduction

Disasters continue to occur around the world every year as environments continue to evolve, as a result of climate change, or simply because of geographic location. Among these disasters, typhoons and typhoon-associated disasters are particularly devastating.

Taiwan is located in the Pacific Northwest, which is a region frequented by typhoons. The exacerbation of climate change has increased the frequency of typhoon rainfall and high rainfall accumulation instances in Taiwan. Statistics on heavy rainfall indicate an occurrence rate of once every three to four years between 1970 and 1999. After 2000, the frequency increased to once a year. Heavy rainfall causes the erosion of topsoil into rivers, reducing flood discharge and increasing the likeliness of embankment overflow, inundation, surface scouring, slope collapse, landslide, and river flow variance. These occurrences are devastating to surface facilities and structures. The frequency, impact, and scope of abnormal rainfall have increased in recent years, inducing fast-changing composite disasters that are increasingly more diverse and complex. Disasters not only endanger the lives of residents and visitors but also impact economic and infrastructure development. An increasing number of disasters have made news headlines with the advancement of information dissemination in recent years (Comfort & Kapucu, 2006; Matthew, 2005; Raschky, 2008; Comfort & Waugh, 2012; Yamamura, 2015; Wang, 2018). Disasters have increased public skepticism towards the competency of experts and decision makers. After a disaster, public concerns (e.g., “Why has this disaster happened?” “Why did we not see it coming?” “Why hasn't the disasterbeen handled?”) raises the pressure of disaster decision-making. Public skepticism on response time and performance exacerbates the stress of decisi on makers. Kocher et al. (2013) and Ordóñez and Benson III (1997) asserted that decision-makers tend to evade risk to minimize losses when they are pressured by time, and their decisions may have negative implications. Burnett (1998) examined the stress of decision makers during different decision-making stages in four constructs, namely, threat level, response options, time pressure, and degree of control. The researcher created a 16-item crisis matrix, allocating 16 crisis situations into five levels from Type 0 to Type 4. Type 4 situations are highly risky and urgent situations that are difficult to control.

Disasters progress in phases. Disaster responses encompass pre-disaster prevention and preparation, mid-disaster contingencies, and post-disaster recovery. These responses involve many organizations and departments. However, when a disaster occurs, a task-oriented organization is generally adopted to resolve all disaster crises. Subsequently, integration is a key aspect of the task-oriented organization. Integration refers to not only the adjustment of organizational personnel in response to different situations but also the systematic and effective communication for utilizing the manpower, organization, and resources and mitigating risk (Tushman & Nadler, 1978; Comfort & Kapucu, 2006).

Therefore, a integration decision support system developed to help disaster decision makers identify optimal solutions from complex data within stringent timeframes, make decisions, and mitigate uncertainty and instability.

A relationship diagram between the preceding phases of a typhoon and the stress of decision makers is illustrated in Figure 1. Figure 1 comprises two parts. The top part is a stress gradient corresponding to the route of the typhoon. The bottom part is the stress experienced by responders and decision makers. As illustrated in the figure, flow pressure increased concurrently with a decrease in the cross-section of the pressure pipe. Therefore, when the typhoon enters the gradient section of the pressure pipe, it enters the smallest area of the pressure pipe when the typhoon immediately after landfall. Referencing the bottom part of Figure 1, responders experience the greatest amount of stress. If the typhoon does not cause severe damage after landfall, the stress of the responders reduces rapidly. By comparison, if the typhoon causes severe damage, responders' stress increases until the restoration stage.

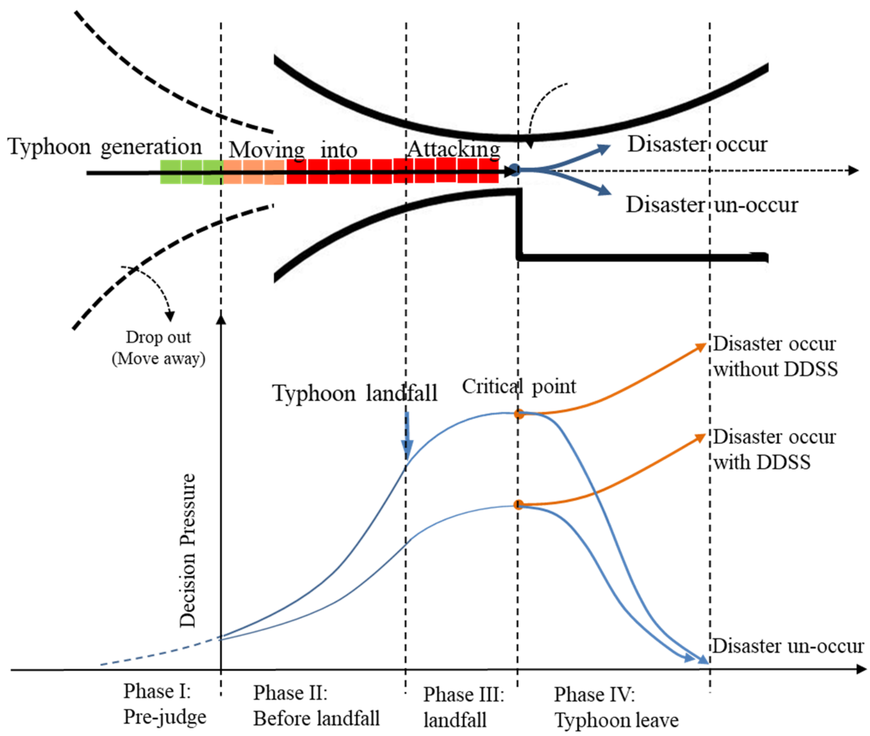

Figure 1. Decision pressure performance during the different disaster phases

Depending on organizational characteristics and content, decisions can be made by an individual or a group (Hackathorn & Keen, 1981). Decision support systems (DSS) help decision makers utilize data and modes through computerized conversations, enabling decision makers to resolve unstructured problems (Turban & Aronson, 1997). The consolidation and conversion of data and illustrating spatial data into diagrams help users of disaster prevention information and resources communicate and coordinate matters in disaster-prone regions, rapidly and accurately control disaster situations and resources, and allocation information and make decisions. The scope and content of network technologies in disaster prevention applications have consistently expanded in the past decade, and the research, development, and application of disaster prevention technologies have continued to advance (Hsu, 2005; Su et al., 2010; Merrett & Chen, 2010; Manfré, 2012). An immense amount of data has become available, including topographical, geological, hydrological, environmental, construction, and cadastral data, as well as data on sensitive locations and various types disaster trends and model predictions. They have become vital information in disaster prevention. Responders' and decision makers' demand for data at different stages of disaster response (i.e., dynamic weather data, data on the scope and scale disaster damage, resource distribution data, and evaluation data required for post-disaster recovery) are rising concurrently with the public's demand for faster and more accurate disaster management. Therefore, it is imperative that a disaster management information system be established that extracts, analyzes, and consolidates big data to provide dynamic, immediate, and accurate disaster data to facilitate decision making (Fika et al., 2016; Gottinger & Weimann, 1992).

2. Methodology

2.1 Design Science Research Methodology

Nunamaker et al. (1991) proposed a design science research framework that consolidated multiple theories.

User demand is a key element in the development of information systems. It is also the primary cause of failure. User demands can be categorized into macroscopic and microscopic demands. Macroscopic demands must be identified and validated during the demand analysis stage, while microscopic demands are typically only identified during system design. A favorable information system must be able to understand users' demands.

In this study, we adopted the design science research methodology (DSRM) proposed by Peffers et al. (2007) during the development of the theoretical model and methods. We followed six steps, namely, (1) confirming problems and motivations, (2) defining solution objectives, (3) designing and developing the solution, (4) presenting a solution, (5) evaluating the solution and (6) communicating, to create and implement a design science research-centered program model and a design science research-centered mental model suitable for information systems (Figure 2).

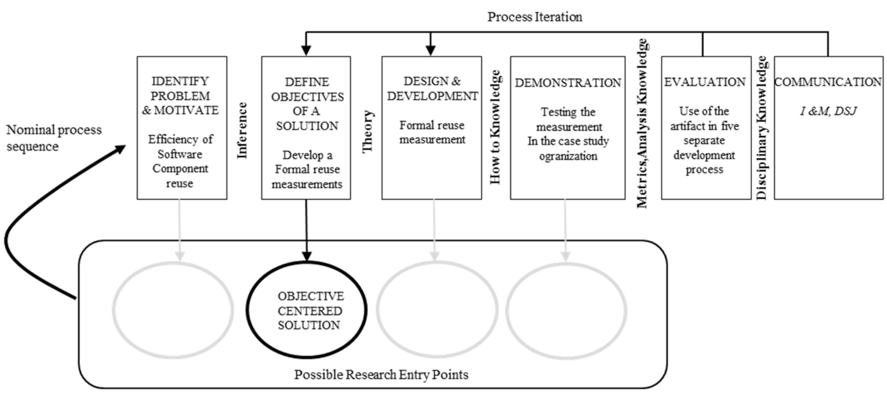

Figure 2. Design research process

2.2 Problem and Solution of D_DSS

(1) Disaster data consolidation and problem analysis

Disaster prevention decisions impact human life and property. Therefore, decisions makers require sufficient and accurate data to formulate decisions. Response data integration is a long-standing problem for the crisis response centers in various levels of government. In existing disaster prevention information systems of different organization and business authorities, disaster information collection and dissemination systems are established to serve as a platform for internal communication and external information announcement. When a disaster occurs, the decision makers first face large amounts of data in the form of reports. They then consolidate external information obtained from the websites of different administrative units and social media. These data are examined to form a preliminary disaster prevention agenda. Finally, the information is provided to the crisis commander as a reference for making decisions. Disaster updates are constantly received during the disaster response stage. A large amount of time is required to consolidate and analyze the data. Therefore, the information that decision-makers receive is usually not the latest and may be inadequate to meet disaster prevention needs. Moreover, independent information systems do not cover all organization operations and functions, and they may have different information formats and operating interfaces (Table 1). These problems highlight the importance of an information integration and support system to facilitate the communication and coordination between resource users and experts, thereby achieving organization integration (Tushman & Nadler, 1978).

Table 1. Challenges concerning disaster prevention data during the response stage

Existing problem	Description
● Different and inconsistent data formats	A universal format should be established for different data sources to facilitate consolidation and analysis
● Inaccurate data	Optimal decisions can only be made with accurate information
● Complex system operations	Increased traffic or delay during a disaster and system crashes impact data consolidation and application
● High operator turnover and lack of operation familiarity	No dedicated team or high turnover
● Failure to fulfill notification responsibilities	Local governments at all levels fail to fulfill inspection responsibilities and upload disaster-related information
● Unintegrated data	Ministries establish their own disaster prevention information system. These systems have not been consolidated.

(2) The need for D_DSS

The Taiwanese Government increased the application of disaster prevention technologies and improved the performance of its disaster response centers by establishing a disaster prevention system, conducting potential disaster surveys, collecting disaster prevention data, and providing disaster prevention and rescue training and education over the last ten years. These efforts evidenced Taiwan's gradual improvement in disaster prevention and rescue. Disaster information systems not only provide sufficient data to predict disaster development but also effectively and rapidly disseminate data to response teams, facilitating preparation and response efforts and minimizing the impact of disasters. Integrated disaster decision-making information systems are effective tools for enhancing disaster response performance.

The content of disaster data includes disaster response organizations, laws and regulations, pre-disaster risk and trend analysis, disaster outcome determination, warning data, decision risk, information dissemination, data source extraction and analysis, and data integration and application. Fu (2017) interviewed experts who were members of response teams during Typhoon Morakot in 2009 and Typhoon Nibble in 2016 and compared the application of D_DSS data. Among the various applications, the integration of disaster situation notification, establishment of network support systems, and incorporation of disaster information from social media allowed responders to obtain first-hand information concerning the situation and formulate effective response measures (Figure 3). The results in Figure 3 not only show improvement in information and communication equipment and hardware but also highlight the completeness and effective utilization of supplementary data. Although disaster prevention performance improved, data lacked integration. The problems tabulated in Table 1 remained evident.

(3) Design and develop solutions

Design and development solutions must be able to create artifacts, including determining the artifact's desired functionality and its architecture. When presenting a solution, the use of the artifact to solve one or more instances of the problem must be demonstrated. Finally, when evaluating the solution, the degree of support of the artifact on problem-solving must be observable and measurable (Hevner et al., 2004). The development of a D_DSS must resolve the problems listed in Table 1 and integrate big data. Data are analyzed, converted, and provided to users at various decision-making levels (Figure 4). To satisfy the information service function illustrated in Figure 4, the fuzzy theory and case-based reasoning theory (Wang et al., 2014; Kuo et al., 2005) are conducted to consolidate several internal and external data sources, such as meteorological data, geographical data, disaster trends, disaster risk assessments, and historical data from existing databases. Then, we applied information processing (MDBS), statistical analysis, and data mining techniques to create a decision-making system suitable for responders and decision makers at all levels (Figure 4). The decision-making analysis results were finally presented as graphics, which served as supportive information for making disaster-related decisions.

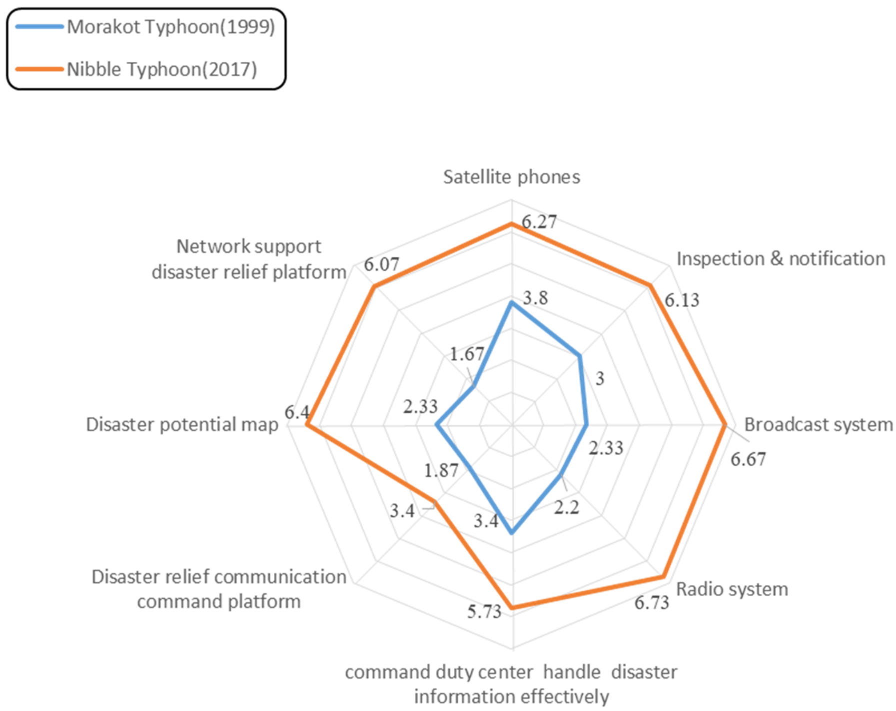

Figure 3. Expert Questionnaire results for disaster information performance during typhoon Morakot (1999) and Nibble (2016)

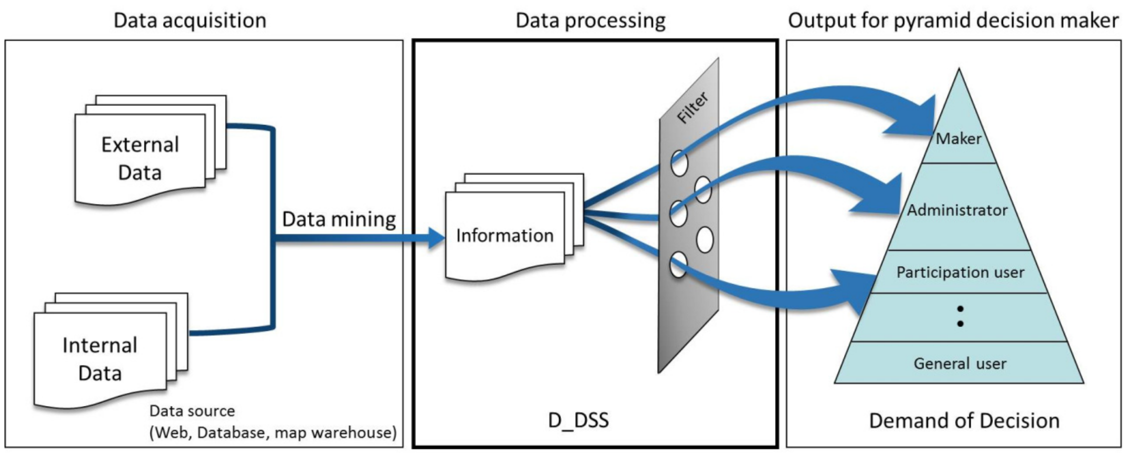

Figure 4. D_DSS Solution

2.3 D_DSS Solution

The D_DSS was developed based on the decision-making support required in the four stages of disaster development, namely mitigation, preparedness, response, and recovery (Altay & Green, 2006) development. The system was to receive the latest weather reports in real-time. Fuzzy theory was applied to cross-reference the typhoon with previous typhoons to formulate pre-disaster warning information. This information helps responders and decision makers make decisions or formulate strategies early, such as pre-disaster prevention measures, resource and medical supply storage, and information and communication equipment maintenance. In addition, the data can be used to predict the influence of disaster damage and formulate evacuation plans. The D_DSS also provides response units with the latest disaster situations, such as road and bridge outages, resource and medical supply shortage, and damage to information and communication equipment.

The D_DSS not only provides support for making tangible decisions during the disaster response period, such as determining disaster and trends, disaster timelines, and response measures but also serves as a disaster situation simulator and an information platform for routine disaster prevention and rescue training. Furthermore, the assessment module of the system can be used to evaluate the efficacy of the situation simulations. The system framework is illustrated in Figure 5. The development of the multifunctional DSS aims to satisfy four major objectives:

(1) Information relevancy

The D_DSS provide instantaneous dynamic disaster information and allows users to rapidly reference various historical disasters and events or rainfall simulation data to determine disaster situations. Data are presented in graphic form to enhance responders' and decision makers' comprehension and reduce their time constraints in making decisions.

(2) Sequential warning

Relative to immediate disaster situation information, the D_DSS offers a referencing function for historical disaster data to help decision makers predict disaster settings in the near future. The proposed system uses historical data as the source of reference for current disaster situations. Using the typhoon path prediction data released by the Central Weather Bureau, users can freely set future parameters and select historical data for reference, such as the reference icons and data for various disaster situations eight hours before landfall, two hours before landfall, during landfall, and during departure. These icons and data serve as supporting information to help responders, rescuers, and decision makers with planning and forming decisions.

(3) Situation simulation and prevention and rescue resource scheduling

Disaster situation simulation entails disaster trends, disaster scope setting and validation, and relevant population and key facilities. The EMIC resources of the Ministry of the Interior were incorporated to build a rescue and prevention resource information database with spatial location and layout display functionality. By evaluating the site and scale of the disaster, the system can rapidly transfer prevention and rescue resources, identify resource inadequacy, and coordinate resource allocation.

(4) Situation setting, education, training, and disaster evaluation

Historical events can be set as the desired situation for routine education and training. The proposed system offers a function to evaluate the resource requirements for the situational deduction of disasters, allowing users to allocate resources accurately. The efficacy of situational exercises can be ensured through assessment (Figure 5).

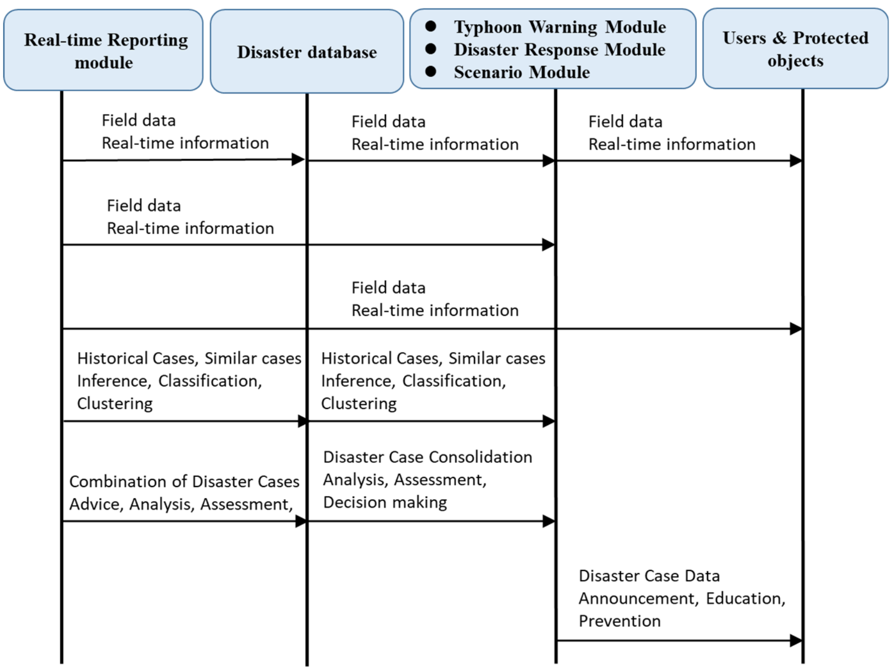

Figure 5. Architecture of D_DSS with relevance to typhoons

3. Design and Development Solution

3.1 Data and Sources for D_DSS

(1) Big data

Due to climate change, disasters are coupled with landslides and mudslides. Heavy rainfall has become a causal factor of disasters. The Central Weather Bureau has recorded 426 typhoon between 1958 and 2017 which with content 22 types of meteorological data such as typhoon warning sheet, weather overviews, satellite images, oblique temperature diagrams, regional rainfall diagrams, radar maps, typhoon path predictions, rainfall and wind diagrams, typhoon path diagrams, weather station data, typhoon survey reports, cumulative rainfall map, typhoon warnings, typhoon hourly movement maps, hourly changes in the meteorological elements at each station, wind field maps at each stage, pressure field maps, bar graphs of maximum average wind and maximum gust at each station, bar graphs of overall rainfall at each station, bar graphs of cumulative rainfall over 24 hours at each station, and overall typhoon data. Most of the data are presented as diagrams.

(2) External data: online data mining

Data were collected from online disaster rescue and prevention databases using keyword searches and data extraction. The main sites were:

Central Weather Bureau: http://www.cwb.gov.tw/

Japan Meteorological Agency: http://www.jma.go.jp/jma/index.html

Soil and Water Conservation Bureau: http://www.swcb.gov.tw/

National Science and Technology Center for Disaster Reduction: http://ncdr.nat.gov.tw/

Taiwan Typhoon and Flood Research Institute: http://www.ttfri.narl.org.tw/

Water Resources Agency: http://www.wra.gov.tw/

(3) Internal data: existing databases

Internal data is refers to a self-compiled database. Data includes disaster trend evaluations, disaster-prone regions, meteorological hazard factors, digital terrain model (DTM), traffic, key facilities, scale and spatial properties of various typhoons, and prevention and rescue resources such as material resources, shelters, evacuation routes, and equipment. In addition, rescue construction projects were also incorporated. Internal data serve as a source of operating data for the proposed system.

3.2 Application of Fuzzy Theory in Comparing Historical Typhoon Data

Most disaster data have spatial attributes and temporal associative properties (e.g., typhoon data are updated every 15min). Such data should be stored in an easily accessible part of the system for future use. The internal and external data acquired through data mining must be cross-referenced with past events. Fuzzy case-based reasoning is required (Wang, 2014) to identify similar historical events or disasters.

Fuzzy theory uses experience and relevant knowledge to identify rules. The rules are then converted into "IF-THEN" principles. Therefore, fuzzy theory is the science of inferring rules (Schmucker, 1984; Takagi, 1985). These rules subsequently express the knowledge principles of fuzzy theory. A number of different inference rules have been proposed in the past, such as Mamdani's min-min-max fuzzy inference method (Mandani, 1974), Larsen's min-product-max fuzzy inference method, Sugeno's fuzzy inference method (Sugeno, 1985; Takagi & Sugeno, 1993) and Tsukamoto's fuzzy inference method (Sari et al., 2016). In this study, we adopted the min-min-max fuzzy inference method show in Figure 6. This inference process comprises of three steps.

(1) Use min (logical product) to calculate the member functions (W_i) of the various preconditions.

$$W_i = \min\left\{\max_{x_1}\left[\min\left(A_i, A^{'}\right)\right], \max_{x_2}\left[\min\left(B_i, B^{'}\right)\right]\right\} \tag{1}$$

where, i represents the rule code, and $A^{'}$ $B^{'}$ represent input values for Input Variable x_1 and x_2. If the input values for Input Variable x_1 and x_2 are fuzzy single values ($x_1^{'}$ and $x_2^{'}$), then the preceding equation can be simplified to:

$$W_i = \min\left\{\min\left(A_i, x_1^{'}\right), \min\left(B_i, x_2^{'}\right)\right\} \tag{2}$$

(2) Use min (logical product) to calculate the conclusion section for the precondition member functions.

$$C_i = \min\left(\widetilde{W}_i, u_{C_i}(y)\right) \tag{3}$$

(3) Use max (logical product) to consolidate all the triggered rules, where *n* represents the triggered rules.

$$C^* = \max_{i=1}^{n} \widetilde{C}_i \tag{4}$$

The preceding inference steps are illustrated in Figure 6.

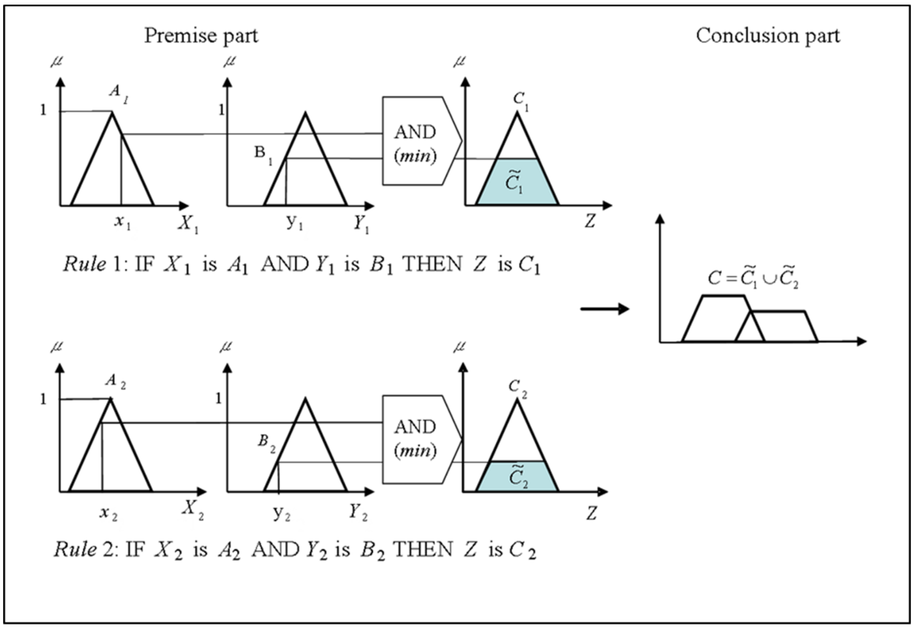

Figure 6. Illustrated diagram of min-max-fuzzy inference method

4. System Realization

4.1 Functional Framework Analysis

To achieve the pre-established system development objectives, including information immediacy, sequential disaster warning, disaster situation simulation, prevention and rescue resource scheduling, and situation setting and provision, and disaster situation education and exercise evaluation, the functional framework of the proposed D_DSS are tabulated in Figure 7.

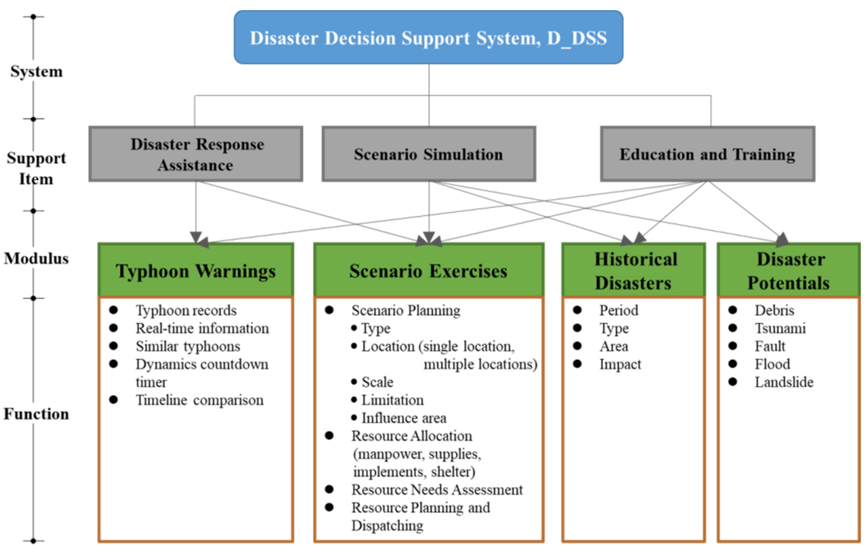

Figure 7. D_DSS function frame structure

4.2 System Information and Application Procedure

(1) System information procedure

To maintain data sharing, prevent logical distress in data application, and clarify various data content, the Yourdon Symbol Set was applied in system development to illustrate data flow diagrams (DFD), as illustrated in Figure 8. A grid structure was used to express process conversion, the flow of data into and out of various processes, and the flow of data in connecting different processes. The DFD components are as follows:

A. Process: Converts input data flow to output data flow; expressed as a circle.

B. Data flow: Expresses flow data sets; expressed as an arrow in the data flow direction.

C. Data storage: Symbolizes static data in storage; expressed as two parallel lines with a name in the middle.

D. Terminator: External entities connected to the system; expressed as an individual, a group, or a department; expressed as a rectangle.

E.

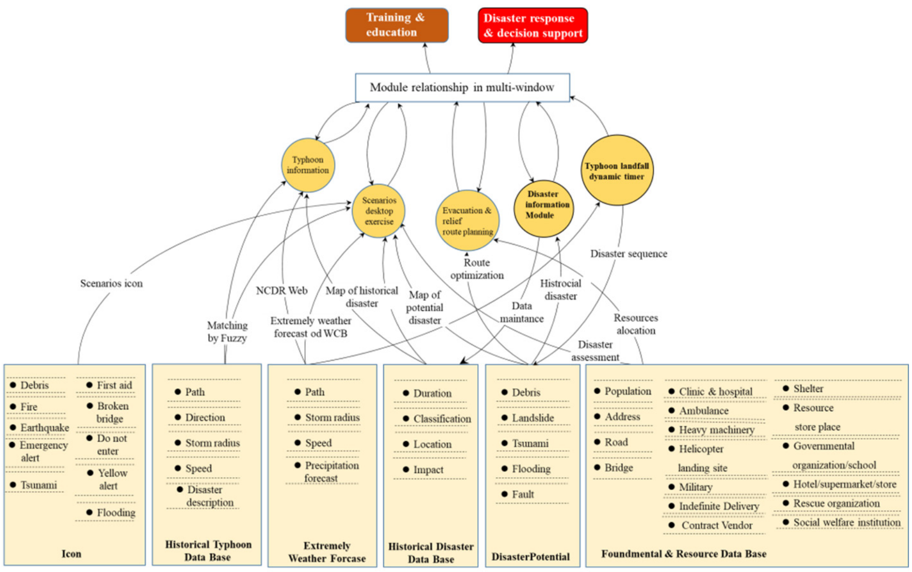

Figure 8. Data flow diagram of D_DSS

(2) Human-machine interaction of D_DSS

D_DSS is an interactive disaster prevention DSS. The system enables users (single users or group participants) to propose contingency measures or directly implement solutions depending on the disaster situation. After receiving a command, the system activates the database management system (DBMS) through the model-based management system (MBMS). Once connected to the resource database, data analysis commences, and outcomes for the command are generated via the dialog generation and management system (DGMS). Human-machine interactions comprise the following four states:

State 1: User asks system for assistance

State 2: Result output

State 3: User to user

State 4: System to system

Response decision and actions generally change depending on the disaster situation. Demands also change as disaster advance into different stages. Therefore, the proposed D_DSS enters different states depending on the user's needs. A human-machine interaction diagram is illustrated in Figure 9. The solid line (-) represents the reliance of the D_DSS during decision making. A solid line with an outlined arrow ( ) represents a user issuing a support request in the system and inputting his/her demands or solution content. This communication state is State 1. Once a request is made, the system provides supporting content. The user determines whether the content satisfies his/her needs. This process is State 2. A solid line with a solid arrow ( ) represents the generation of decision-making data after system analysis and data extraction. The data is presented on the screen, which the user can use to support his/her decision. This communication state is State 2. After State 2, the user determines whether another support request is necessary. The primary extrinsic functions of the D_DSS manifest in the interactive processes of State 1 and State 2.

Once the supportable functions of the system achieve their objectives, the response decisions proposed by the participants for the disaster situation are manually validated. The implementation of the response decision and actions are converted into interpersonal relationships. Through evaluation, the decision maker ultimately decides on a prevention and rescue strategy. In this state, the DSS no longer serves a decision support function. This communication state is State 3 (user to user). In this state, human-machine relationships no longer exist. The dotted line (----) in Figure 9 represents the absence of human-machine connections in the decision-making stage.

State 4 (system to system) is the core intrinsic function of the D_DSS. To satisfy the multi-faceted demands of disaster prevention and rescue and consolidate various source data into a single system, the proposed system must be able to rapidly process big data collected internally and externally once it receives a user request, and then extract, analyze, and present useful information. The system only terminates its interactive processes when a final decision has been made.

4.3 Module Interlink in Multi-Window Development and Application

The D_DSS system is composed of several modules. The system architecture is based on a modular design. This design was adopted primarily to enhance the expandability of the D_DSS in the future. The formulation of disaster prevention decisions requires multi-source and diverse data to serve as supporting data for determining disaster conditions. Typically, single windows are unable to satisfy decision makers' need for diversified information. Therefore, we developed a technique to interlink modules into multiple windows. Different from network applications, the module interlink in multi-window is presented on a single display (Figure 10). Multiple, interlinking windows, each with independent data, can be opened simultaneously. When operations cause data variance or influence outcomes, the system changes the data according to the variance and displays the new data in the corresponding windows, thereby maintaining data consistency.

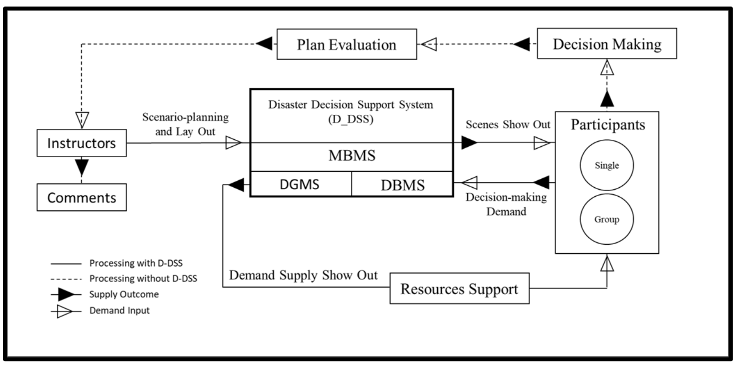

Figure 9. Illustrate of D_DSS human-machine interaction

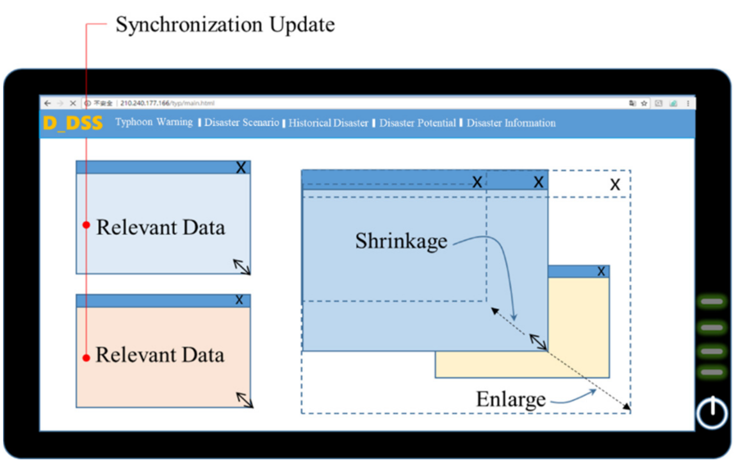

Figure 10. Illustrate of data interlink with multi-window

5. D_DSS Application

The D_DSS, which is based on disaster management, provides responders with the functions to form disaster reduction strategies, preparation plans, and risk assessments during the calm stage, as well as form response strategies during the disaster stage. Figure 11 shows the functions of the D_DSS and the available applications. The D_DSS provides system-to-system functions, such as basic database establishment, system integration, and risk assessment, in the form of a smartphone app, providing an application platform for disaster response, industrial disaster prevention, disaster training, and disaster prevention education. Ensuring disaster prevention ultimately relies on people. Disaster prevention is a long-term task. Therefore, the system only serves as a supportive measure for decision makers (system to people). Fostering disaster prevention skill and mastering the application of information systems require self-implementation and interpersonal communication and encouragement within the organization (people to people).

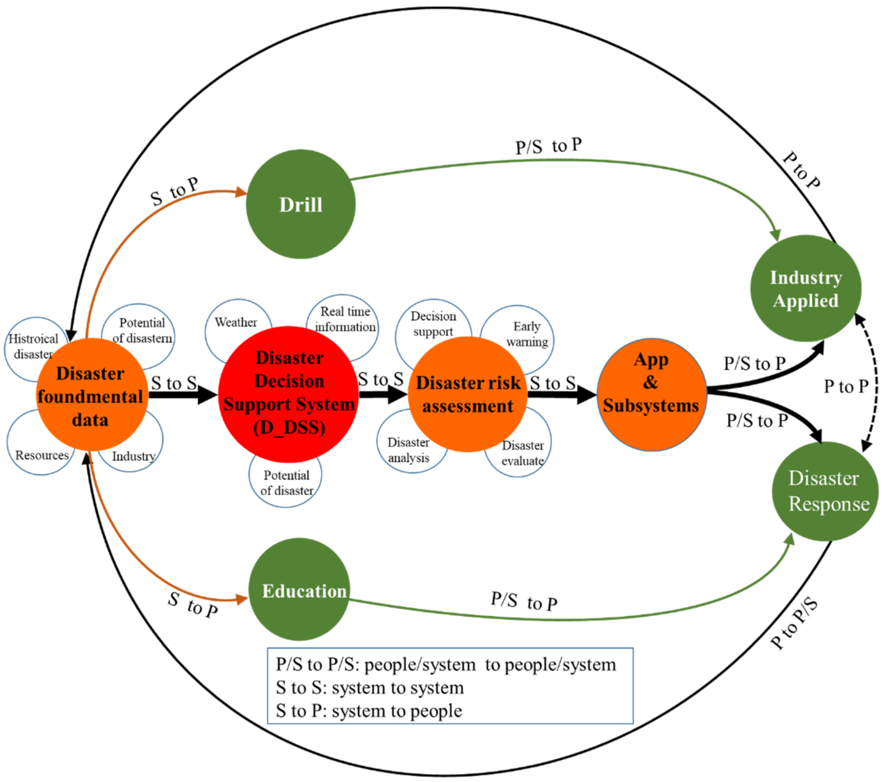

Figure 11. Function and application Path of D_DSS

6. Conclusion

The D_DSS features the module interlink in multi-window technology. This technology allows users to flexibly display supportive data on a single display or multiple displays. The various windows are interlinked to provide consistent data to decision makers. The data used by the system derive from the resource databases managed by various disaster prevention units. The main functions of the system are as follows:

(1) An internal database is created using real-time survey resources. The system serves as a reference for deductions and assessments and provides the necessary resources and information to make accurate decisions in different disaster situations.

(2) The system using data mining technology to integrate the dynamic resources of external databases into a simple system. It updates the data stored in the internal database concurrently with those of external databases.

(3) The system provides a graphical interface for single points (single regions) more multiple points (multiple regions) and different disaster situation settings, including disaster type, disaster location, disaster status, and scope of influence.

(4) The system automatically assesses the disaster prevention and rescue resources that decision makers may require and the available resources. When resources are inadequate, the system can allocate resources from other target sources.

(5) The module interlink in multi-window technology provides diverse data for the prediction of disaster situations.

(6) During non-disaster periods, the system can serve as a disaster prevention and rescue training and education platform. It can also assess training outcomes, transforming past active training systems into a desktop, self-administered training platform.

(7) The inference system can automatically engage in path planning. During congestion, the system can calculate the ideal rescue routes.

(8) The system comprises various functional modules and reserves the capacity for future expansion.

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Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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