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Event-Driven Distributed Information Resource-Focusing Service for Emergency Response in Smart City with Cyber-Physical Infrastructures

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Abstract: The smart city has become a popular topic of investigation. How to focus large amounts of distributed information resources to efficiently cope with public emergencies and provide support for personalized decision-making is a vitally important issue in the construction of smart cities. In this paper, an event-driven focusing service (EDFS) method that uses cyber-physical infrastructures for emergency response in smart cities is proposed. The method consists of a focusing service model at the top level, an informational representation of the model and a focusing service process to operate the service model in emergency response. The focusing service method follows an event-driven mechanism that allows the focusing service process to be triggered by public emergencies sensed by wireless sensor networks (WSNs) and mobile crowd sensing, and it integrates the requirements of different societal entities with regard to response to emergencies and information resources, thereby providing comprehensive and personalized support for decision-making. Furthermore, an EDFS prototype system is designed and implemented based on the proposed method. An experiment using a real-world scenario—the gas leakage in August 2014 in Taiyuan, China—is presented demonstrating the feasibility of the proposed method for assisting various societal entities in coping with and efficiently responding to public emergencies.

Keywords: smart city; cyber-physical infrastructure; focusing service; geospatial information; mobile crowd sensing; event-driven mechanism; emergency response

1. Introduction

The smart city, one of the most popular topics and the most cutting-edge issues, has attracted widespread attention and has renovated the traditional city concept [1–5]. In analogy to a living organism, the intelligence of a smart city resides in its increasingly effective combination of digital telecommunication networks (the nerves), ubiquitously embedded intelligence (the brains), sensors and tags (the sensory organs), and software (the knowledge and cognitive competence) [6]. Moreover, from the perspective of a system, a smart city can also be regarded as a dynamic and complex system that evolves in space and time following trajectories that are hard to predict [7], mainly including a physical part and a cyber part, which is also called cyber-physical systems (CPS) [8–12]. Figure 1 presents a conceptual diagram of an operational smart city. As depicted in this figure, the sensing infrastructures belong to the physical component of the CPS and comprise various sensing devices such as diverse heterogeneous sensors (in situ/remote and fixed/mobile sensors, such as radio-frequency identification [RFID], the Moderate Resolution Imaging Spectroradiometer [MODIS], and the Global Positioning System [GPS] sensors in smart phones) [13,14]. The communication infrastructures (e.g., 3G/4G/ZigBee/Wi-Fi/WiMAX/WSN) and cloud computing infrastructures (e.g., Amazon EC2, Microsoft Azure, Xen Cloud Platform, Hadoop, HBase, Hive, Impala, Storm, Pig, and SPARK) belong to the cyber component of the CPS.

Figure 1. Conceptual diagram of an operational smart city.

The operational smart city is driven by various information resources, including both data and service resources. Data resources consist of archived data (e.g., basic geographic data, archived historical sensing data, remote sensing images, unmanned aerial vehicle images, RFID data, and video monitoring data) and real-time data streams (e.g., monitoring data for city water, electricity, fuel, and gas supplies) produced by sensing webs. Service resources include geospatial data services built on interoperable standards [15], e.g., the Web Feature Service (WFS) [16] for geographical features, the Web Map Service (WMS) [17] for geo-registered map images, the Web Coverage Service for raster data, the Sensor Observation Service (SOS) [18] for near-real-time sensor observations, the Web Processing Service (WPS) [19] for encapsulating analysis and decision models for smart cities, the Sensor Event Service (SES) [20] for filtering of and subscription to sensor observations (events), and the Web Notification Service (WNS) [21] for message notification. Meanwhile, various public emergencies, such as security incidents, transportation accidents, and accidents involving public facilities and equipment, occur frequently and can result in heavy casualties and economic losses [22]. These rich information resources can be utilized to assist smart-city decision-makers in coping with public emergencies and making decisions. However, these resources are overflowed and are geographically distributed on different network nodes. Thus, discovering proprietary information resources efficiently and focusing them on the effective handling of and personalized decision-making support for public emergencies is an urgent problem that must be solved for the smart city paradigm [2]. To help solve this problem, focusing service has been proposed in some studies.

Focusing service, in essence, focuses massive amounts of information resources on a specific task and provides personalized service to the various roles involved. Some preliminary work has been conducted in this area, primarily concerning its conceptual aspects. Yang et al. considered focusing service to be one of the main solutions to providing personal, accurate service of the intent information resources [23]. Huang et al. viewed information focusing as a new means of information service and presented the concept of and a mathematical model for semantic relatedness-based information focusing [24]. Zhu et al. proposed a hierarchical semantic constraint model for focusing remote sensing information services, in which constraints establish the connections among user semantics, the data service and processing services, and basic semantic reasoning toward service discovery, selection, and composition [25].

The combination of data and services on demand is one method of focusing the massive amounts of available information resources and thus realizing focusing service. Yue et al. developed a semantic-enhanced geospatial catalog service to satisfy the demands for the discovery and analysis of geospatial information (geospatial data, services/service chains) in a cyber infrastructure [26]. Yang et al. proposed a RESTFul-based workflow interoperation method to integrate heterogeneous workflows, e.g., one workflow to access sensor information and one to process it, into an interoperable unit [27]. Furthermore, Chen et al. used SensorML to construct a geoprocessing e-Science workflow model to internally integrate the sensor system, observation, and processes (physical and non-physical) under a sensor web environment [28]. Moreover, for operation in a cloud environment, an agent-based approach was proposed to support the execution of workflows that require large amounts of computational resources and expensive hardware in one or multiple clouds [29]. These works have primarily explored the technical possibilities and feasibility of various types of workflow design, implementation and execution. Additionally, these studies have paid considerable attention to remote sensing sensors for large-scale applications, such as province-scale normalized difference vegetation index (NDVI) calculations [28], rather than applications of in situ or mobile smart sensors, which are more relevant to the rapid operation of cities because of their low cost, relatively simple deployment, high accuracy, continuity and instantaneity.

Event-driven mechanism is critical for rapid public emergency response that has a minimum tolerance for time of reaction to events in smart cities. Yu et al. proposed a BPEL-based geoprocessing web service workflow that can be executed automatically upon the triggering of an event, such as the acquisition of a new observation at a new time, to perform the message-level coordination of sensors and earth science models in the Sensor Web environment [30]. Fan et al. considered both Observations & Measurements (O&M) information and the state changes of tasks as events and designed an active on-demand service method for geospatial data retrieval based on an event-driven architecture [31]. These studies have addressed micro and abstract events exceptionally well. However, they are somewhat unsuitable for macro urban public emergency scenarios. Thus, developing a new focusing service method driven by macro urban events for rapid emergency response in smart cities is a necessity.

To achieve the above goal, this paper proposes an urban macro event-driven distributed information resource-focusing service method for public emergency response in smart cities with cyber-physical infrastructures. It utilizes in situ sensors and sensors in smart phones to collect the context parameters of public emergencies and uses these parameters and other web-accessible data resources distributed on different network nodes as inputs to the analysis and decision-making models to produce analysis and decision results [32]. These results, with their necessary descriptions, can be further shared on the web for application by different societal entities. This study offers the following four contributions:

(1) An event-driven focusing service model is proposed. In the model, macro urban public emergencies trigger the focusing service process, and the requirements of handling urban public emergencies and urban information resources are integrated to assist different societal entities in their rapid response to public emergencies and making sensible decisions.

(2) An informational representation of the proposed focusing service model (IRFSM) is developed. It enables the focusing service model to operate in cyber infrastructures, seamlessly bridging public emergency and information resources.

(3) An event-driven focusing service process is established based on the IRFSM. It provides operational procedures for the execution of the focusing service throughout the entire lifecycle of public emergency response.

(4) A focusing service prototype system is developed based on the proposed focusing service model, its informational representation and the focusing service process. It is leveraged for public emergency response in a real-world scenario (the gas leakage in August 2014 in Taiyuan, China) to test its feasibility and effectiveness in assisting various societal entities to achieve personalized rapid response to public emergencies.

The remainder of the paper is organized as follows. In Section 2, the proposed method is detailed, including the focusing service model, its informational representation and the focusing service process. In Section 3, an experiment to test the proposed method is presented, considering the gas leakage event that occurred in August 2014 in Taiyuan, China, as a study case. Section 4 provides discussions of the proposed method, including its feasibility, advantages, scope and limitations. Finally, in Section 5, several conclusions are provided, including possible directions for future work.

2. Methods

This paper proposes an event-driven distributed information resource-focusing service method for public emergency response in smart cities. The proposed method, from a macro perspective, consists of a focusing service model that provides an in-depth analysis of the focusing service provision process, offering guidance for rapid response to public emergencies. To make the model operate smoothly and to seamlessly integrate the requirements of public emergency handling, rich urban information resources, and decision-making, a bridge between public emergencies and urban information resources—an informational representation of the focusing service model—is established.

2.1. Focusing Service Model

The focusing service model, as depicted in Figure 2, is based on the object and process models introduced by Governance Enterprise Architecture (GEA) [33,34] with the addition of event-driven concepts and features. In the proposed service model, the focusing service is triggered by public emergency events in smart cities and serves various societal entities, including governments, enterprises and citizens. Being a generic model, the service description covers many different areas of application in public emergency response, making it highly flexible for use in different cases of focusing service provision. Public Administration Entities are a type of Governance Entities that participate in service provision, fulfilling one of the following roles during the focusing service provision phase:

- Service Provider that provides the focusing service to Societal Entities, i.e., government decision-makers, enterprises, and citizens.
- Evidence Provider that provides Service Providers with the necessary Evidence to execute the Focusing Service.
- Consequence Receiver that should be informed following the execution of the Focusing Service.
- Service Collaborator that participates in providing the focusing service.

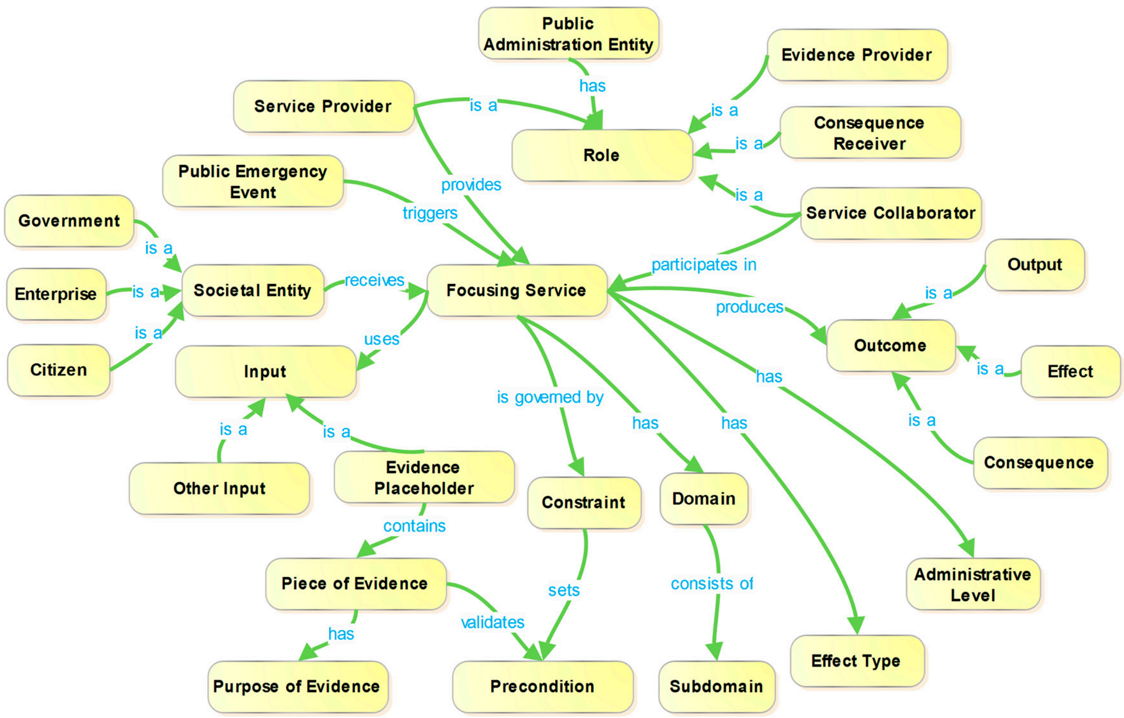

Figure 2. Event-driven focusing service model for city information resources.

Preconditions set the general framework in which the focusing service should be performed and the underlying business rules that should be fulfilled for its successful execution. Preconditions can be formally expressed as a set of clauses (or rules) and are validated by a Piece of Evidence serving a Purpose. Because Evidence is pure information, it is stored in Evidence Placeholders (e.g., an administrative document).

The Outcome refers to the different types of results that a focusing service may have. The focusing service model defines three types of Outcomes:

- Output, which is the documented decision of the Service Provider regarding the service requested by a Societal Entity. This is currently embedded and reaches the client in the form of an Evidence Placeholder.
- Effect, which is the change in the state of the real world that is caused by the execution of a service. In public administration, the service Effect is the actual permission, certificate, restriction or punishment to which a citizen is entitled. In cases in which public administration refuses the provision of a service, there is no effect.
- Consequence, which is information regarding the executed focusing service that needs to be forwarded to interested parties, i.e., other public agencies (Consequence Receivers).

2.2. Informational Representation of the Focusing Service Model

The focusing service model is an abstract conceptual model that depicts the roles of the participants in the focusing service, the constraints of the focusing service, the inputs and outcomes of the focusing service, the service object of the focusing service and the service mechanism (event-driven), ultimately providing high-level guidance for the focusing service for public emergency response. To allow the focusing service model to operate in cyber infrastructures, it is necessary to establish an informational representation of the focusing service model, bridging public emergency and information resources.

The IRFSM is specific to the event type and event stage. Put another way, it is a prearranged plan for a certain type of public emergency at a certain stage. From an information service perspective, it is also an abstract service chain for retrieving and processing information resources and producing results for assistance in decision-making. Figure 3 presents a UML diagram of the proposed IRFSM.

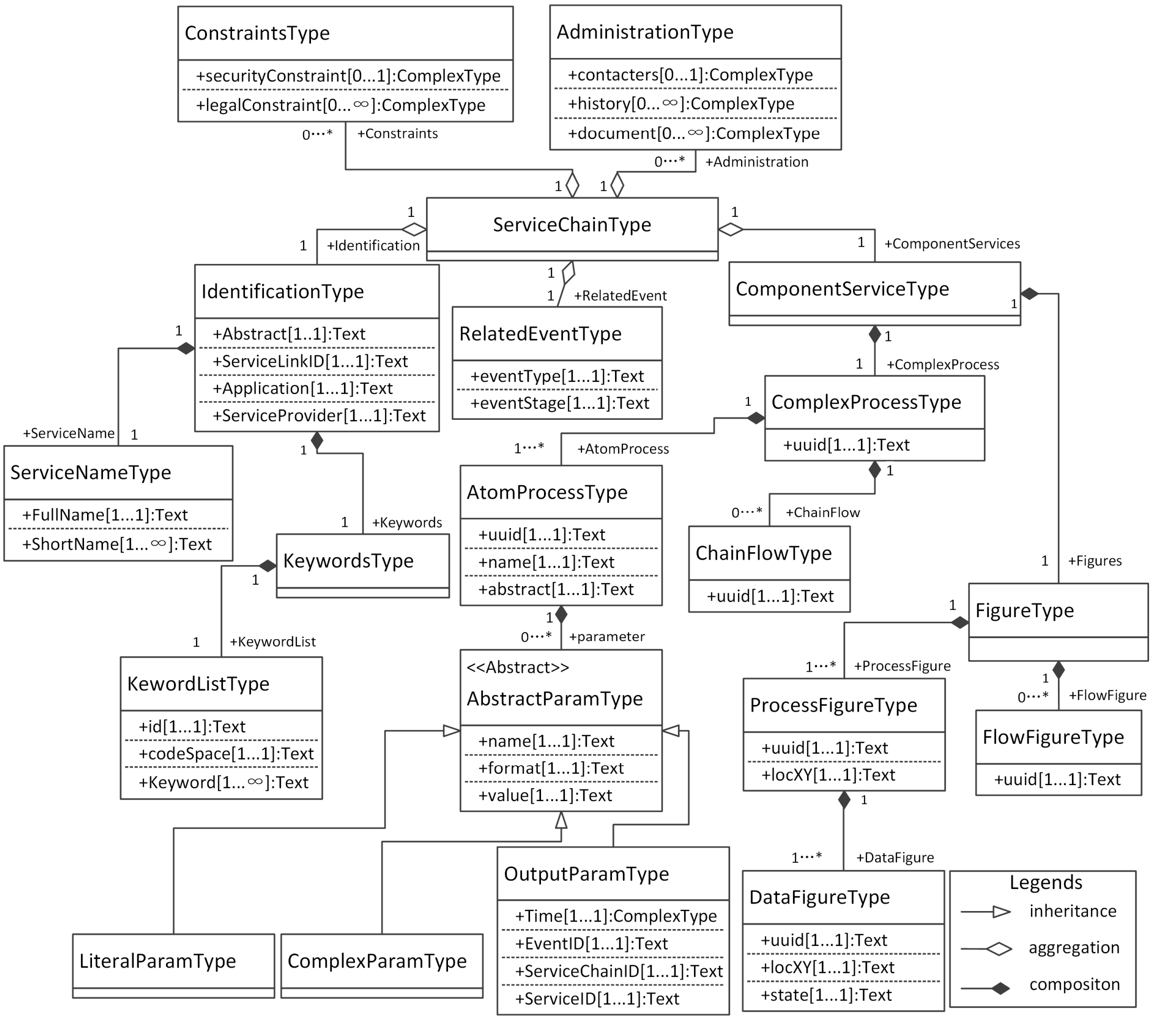

Figure 3. UML diagram of the IRFSM.

2.2.1. Metadata

The proposed IRFSM consists of five aspects of information, in accordance with the focusing service model, which can be expressed as IRFSM = {$IRFSM^I$, $IRFSM^{RE}$, $IRFSM^{CS}$, $IRFSM^A$, $IRFSM^C$}, where the individual items represent "Identification", "Related Event", "Component Service", "Administrative" and "Constraints" information, respectively.

(1) *Identification*. The Identification information specifies the basic information regarding the IRFSM for its discovery, including the name, abstract, keywords, identification, applications and provider of the abstract focusing service chain. The identification of each service chain in the registration center is unique. The remaining information is useful for the discovery of a desired abstract focusing service chain.

(2) *Related Event*. The Related Event information describes the related event type and stage to which the abstract focusing service chain is applicable. It can be used to quickly discover the most suitable abstract focusing service chain when a public emergency occurs.

(3) *Component Service*. The Component Service information consists of a complex process and a figure. The complex process consists of one or more atom processes and the control flows between them. Each atom process can be regarded as a model that performs a specific function. The figure is

further composed of process figures and flow figures for the visualization of the abstract service chain. The Outcome is also part of the Component Service information and is represented by *OutputParam*.

(4) *Administration*. The Administration information includes contact, history, and document features that are important for administrative management of the abstract focusing service chain. In particular, the history information records the update history of the abstract focusing service chain.

(5) *Constraints.* The Constraints information includes legal constraint and security constraints that affect the accessibility of the abstract service chain.

2.2.2. Input and Output

Input and output are both critical for the IRFSM, describing what it requires and what it can produce.

(1) *Input*: The entire IRFSM is registered in a registration center in advance and is managed by the registration center through functional interfaces. Inputs for the discovery of the IRFSM are event information (event type and event stage).

(2) *Output:* Basically, an output consists of an output name, output format (which is helpful for later use; commonly used formats are GeoTIFF, TIFF, and Shape), output value (this can be a literal value or a reference to a web-accessible resource, e.g., a GetFeature request or a Map request indicating a reference to an interoperable result published as a WFS or WMS service), and output generation time (this should be in a standard date and time format, such as ISO 8601 [e.g., 2004-04-18T12:03:04.6Z], which is an information interchange representation of dates and times) as well as the ID of the event, service, and service chain that produced the output. Using this information, the origins of the output (provenance information) can be readily identified. Because focusing service is, in essence, a personalized service, the output differs for different Societal Entities (government, enterprise and citizen users):

- *Government users*: Government users, the administrators of a smart city, are concerned about rescue information and the reduction and evaluation of losses caused by public emergencies. Thus, the shortest paths to a public emergency site and the nearest available facilities that can be immediately used for rescue and alleviation should be output, as should casualties and economic losses.
- *Enterprise users*: Enterprise users may be more concerned with the losses caused, such as the degrees of damage to natural gas pipelines and power grids. This information can help companies to evaluate their losses and determine the compensation required from insurance companies or for other societal entities.
- *Citizen users*: Citizen users usually pay more attention to their own ranges of activity, i.e., where they can go and where they cannot, their escape routes, their ability to receive alerts when an emergency occurs, and information regarding the evolution of an emergency over time. Thus, for citizens, timely alerts and warnings should be provided, and detailed information about the evolution of emergencies should also be provided in a timely manner.

2.2.3. Formalization

XML Schema is a language for defining the structure of XML document instances that belong to a specific document type. The UML of the IRFSM can be mapped to an XML Schema; thereafter, XML representations of the IRFSM can be established based on the constraints provided by the established XML Schema. Such XML representations are registered in the registration center, and the XML Schema can be used to validate these XML representations.

2.3. Focusing Service Process

The process of focusing service is sophisticated and systematic, as is shown in Figure 4. Many entities with different roles are involved in the interactions that are necessary for focusing service, typically including the registration center, public emergency events, information resources, focusing service software and societal entities.

The registration center, which is the core of the focusing service, registers public emergency event information, the data resources of the smart city, the analysis and decision-making model services available in the smart city, the available abstract focusing service chains (the IRFSM), and the analysis and handling results for public emergencies. Considering different characteristics and other possible applications of these resources, the registration center also provides other operation interfaces, which generally include query and updating interfaces.

Entities with the five roles listed above interact with each other directly or indirectly, with the registration center as the pivot, to form the overall process of the event-driven focusing service:

(1) *Registration of information resources*. To make information resources more easily manageable and discoverable, these resources are first registered in the registration center, thereby laying a solid resource foundation for the event-driven focusing service.

(2) *Triggering by events.* The entire process of the focusing service is triggered by the initiation or phase transformation of a public emergency. Once triggered, the focusing service software initiates the focusing service process.

(3) *Query and retrieval of abstract focusing service chain(s).* The focusing service software queries and retrieves the abstract focusing service chain(s) that are related to the type and specified stage of the event through the query interfaces provided by the registration center.

(4) *Service instance binding and data linking*. Because the abstract focusing service chain is not executable, it must be instantiated before it can be executed. This process involves binding every model in the service chain to a service instance that resides in a certain web server and linking data resources as inputs to these models. For data linking, an SOS can provide open spatio-temporal sensor observations through the GetObservation interface with the specified filters, e.g., eventTime, procedure, observedProperty, and featureOfInterest. A WFS can provide geographical features through the GetFeature interface, and a WMS can provide geo-registered map images through the Map interface with spatio-temporal filters [35] specified.

(5) *Execution of the focusing service chain instance and establishment of a description of the analysis results.* The instantiated service chain is executed by a workflow engine, such as Apache ODE, to obtain the intermediate results (results of executing a sub-service chain) and final results (results of executing the entire service chain). The proposed method establishes a description that relates every result, including both intermediate and final results, to a public emergency, a service chain, and models in the service chain, thus facilitating the provenance of results.

(6) *Registration and sharing of analysis results.* The focusing service software publishes the analysis results, making them accessible through the web. Meanwhile, a description of the analysis results (stored in the OutputParam element of OutputParamType, as depicted in Figure 3) is registered through an interface provided by the registration center, making these results discoverable and reusable by different societal entities.

(7) *Retrieval of analysis results.* Societal entities retrieve the analysis results of public emergencies from the registration center through the discovery interfaces provided.

(8) *Decision-making.* Societal entities make their own decisions in response to public emergencies based on the analysis results retrieved in step 7.

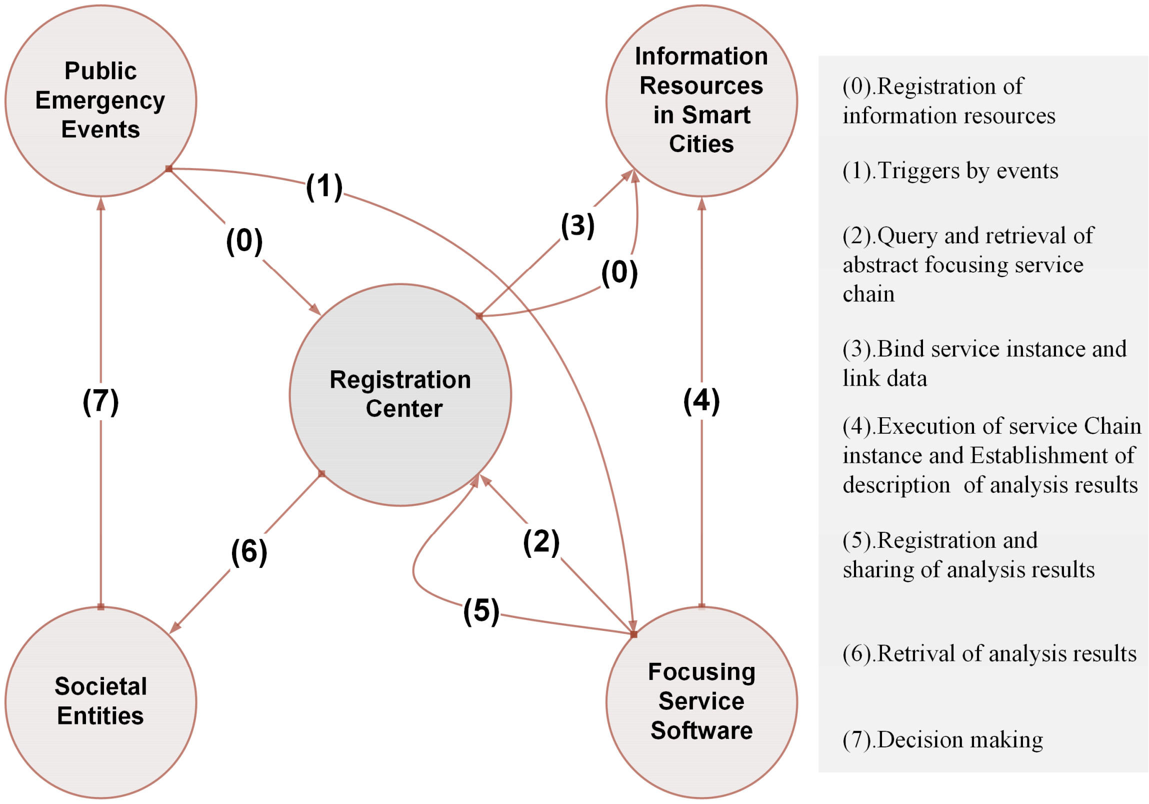

Figure 4. Event-driven focusing service process.

The focusing service process described above can be utilized throughout the entire lifecycle of public emergency response because the preregistered abstract focusing service chains already consider the various phases of emergencies.

3. System Implementation and Experiment

3.1. System Implementation

To test the proposed method, a focusing service prototype system is developed based on the proposed focusing service model, its informational representation, and the focusing service process. The architecture of the prototype system is illustrated in Figure 5, including four layers: a resource layer, a component layer, a business layer and a representation layer. In particular, the resource layer manages distributed information resources through the CSW (an implementation of the registration center) in a unified manner. The prototype system assists in decision-making for public emergencies through the collaborative application of networked and distributed information resources.

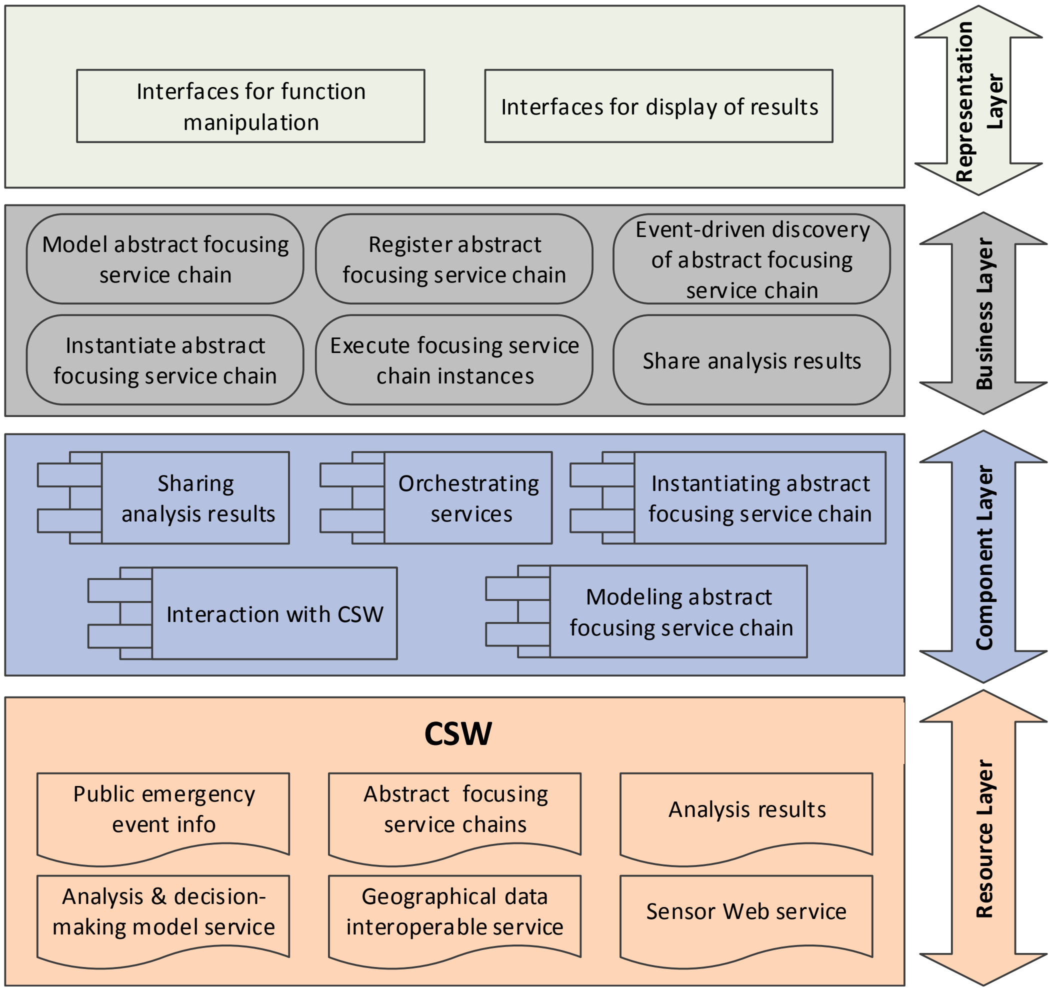

Figure 5. Architecture of focusing service prototype system.

The prototype system performs three main functions: (1) the modeling and registration of abstract focusing service chains, which is realized by the component for modeling abstract focusing service chains and the component for interacting with the CSW; (2) the discovery and instantiation of abstract focusing service chains, which is realized by the component for instantiating abstract focusing service chains and the component for interacting with the CSW; and (3) the execution of focusing service chain instances and the sharing of analysis results, which is realized by the component for orchestrating services, the component for sharing analysis results, and the component for interacting with the CSW. Communication among the system modules is achieved through three types of interfaces: (1) interfaces for interacting with the CSW, (2) interfaces for interacting with the workflow engine, and (3) interfaces for utilizing information resources.

3.2. Gas Leakage Scenario

Types of public emergency events that frequently occur in cities include gas leakages, pipe breakages, and utility outages etc. Gas leakage is the most dangerous to the general public for that it may explode when exposed to flame or sparks if not handled correctly or in time. In addition to causing fire and explosion hazards, leaking flammable gases can kill vegetation, including large trees, and release powerful greenhouse gases into the atmosphere [36]. To help alleviate this problem, Google Earth Outreach and the Environmental Defense Foundation (EDF) are now working together, utilizing Google Street View cars mounted with mobile methane sensors to find and assess leaks under streets and sidewalks and publishing interactive thematic maps of leakage in certain US cities.

Gas leakage is also a serious problem in China, particularly in cities with decades-old gas pipelines that may suffer from aging and erosion. Taiyuan, the capital of Shanxi Province, uses coal gas and natural gas as its two main energy sources and is therefore one such city. Currently, the total length of the city's gas pipelines is more than 2700 kilometers, making effective management of the pipelines and monitoring and addressing gas leaks vitally important. With the smart city building boom, Taiyuan has become one of the pilot smart cities of the Ministry of Housing and Urban-Rural Development (MoHURD) of China. One major goal of the construction of smart Taiyuan is to achieve real-time/near-real-time monitoring and effective management of gas pipelines by adopting Internet of Things (IoT) technologies.

On 15 August 2014, a truck crashed into a pipeline, leading to a gas leakage event at the intersection of Xuefu Road and Changzhi Road. It was reported by nearby citizens through smart phones, and various parameters of the leakage were gathered by in situ sensors and transmitted to the Smart City Intelligent Decision Making Center (SCIDMC) in Taiyuan in near real time. At the SCIDMC, a cloud platform was deployed that ran a CSW instance to register and manage diverse information resources, multiple WPS instances to serve analysis and decision models, multiple instances of MongoSOS (an SOS implementation for serving sensors and live sensor observations that was developed by our team and is suitable for distributed environments), and multiple GeoServer instances to serve basic geographical data. Figure 6 depicts the scenario.

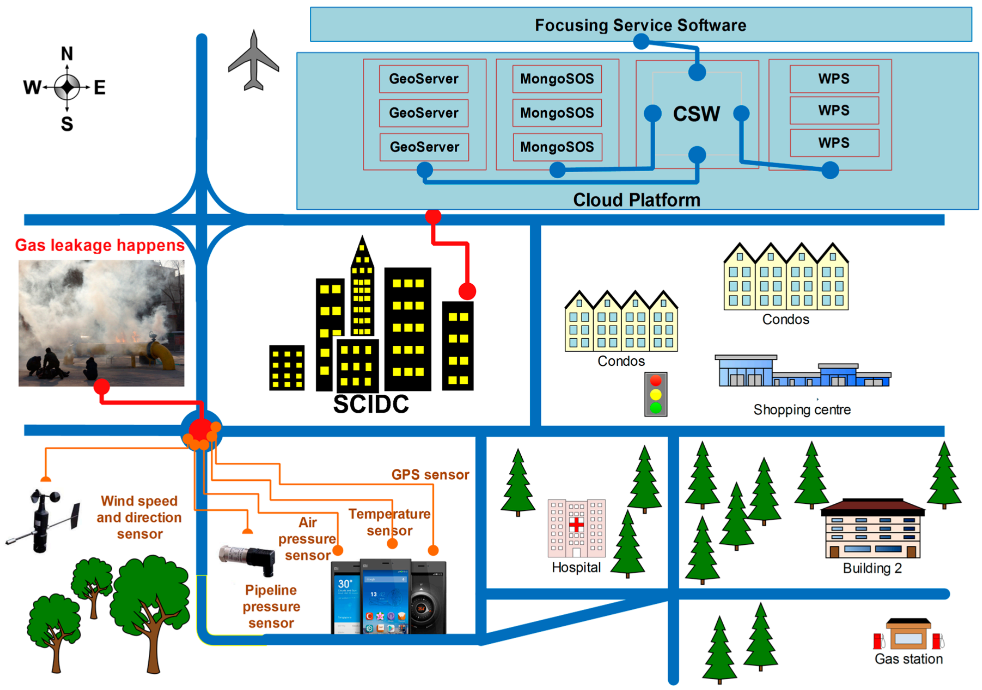

Figure 6. The gas leakage scenario and platform deployment at the Smart City Intelligent Decision Making Center (SCIDMC).

3.2.1. Model Service

The severity of the consequences caused by a gas leakage depends on the amount and extent of expansion of the leakage. The amount of leakage further depends on the intensity of the leakage source and its duration. Analysis and prediction of the amount and expansion extent of the leakage are of fundamental importance for severity evaluation and emergency response. Because the gas in this scenario was natural gas, whose density is approximately 0.7174 kg/m^3, equivalent to a fraction of 0.5548 relative to that of air at 0 °C and 101.325 kPa, the Gaussian plume model is suitable for calculating the expansion of the leakage. The Gaussian plume model has ten input parameters: pipeline pressure, atmospheric pressure, environmental temperature, leak diameter, leak duration, pipeline height, wind direction, wind speed, latitude of the leak, and longitude of the leak. The output of the model is the mass concentration of gas at every specified location. To allow the model to be used online in an interoperable manner, the Gaussian plume model is encapsulated as a WPS process and invoked through the standard interfaces.

It is not sufficient to simply calculate the expansion extent of gas leakage; it is also important to know which buildings, facilities and populations are or will be affected by the gas leakage and its expansion. Thus, overlay analysis is a necessity; in such an analysis, the expansion of the gas leakage is overlaid on basic geographical data, such as maps of buildings and populations. There are many open-source implementations of overlay analysis models, which can also be encapsulated as a WPS process and invoked through the web.

Knowledge of the shortest paths that relevant staff can take to reach the leakage site is also critical for rescue and urgent repair, both of which are time-sensitive tasks. A shortest-path analysis model can facilitate the acquisition of this information. Similar to overlay analysis models, there are many open-source implementations of such models available in a variety of programming languages, which can also be encapsulated as a WPS process and invoked through the web.

3.2.2. Sensors and Data

As stated in Section 3.2.1, the Gaussian plume model requires ten input parameters. Among these parameters, the pipeline pressure can be measured by a pressure sensor mounted on the pipeline; the atmospheric pressure, environmental temperature, and leak position (latitude, longitude) can be measured by sensors embedded in smart phones, supposing that a personal mobile sensor web (PMSW) app (Figure 7) is installed on each to publish sensor observations to MongoSOS in a timely fashion; the wind speed and wind direction can be obtained by looking up the MongoSOS to obtain observations from the wind sensors placed by the Weather Bureau that are located nearest to the leak; the diameter of the leak can be estimated from prior knowledge of the pipeline; and the height of the pipeline can be obtained from construction records.

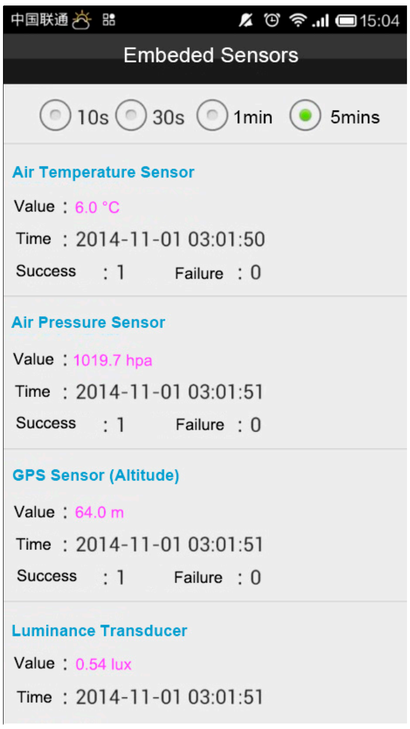

Figure 7. A screenshot of the personal mobile sensor web app.

Basic geographical data, including base map data, administrative division data, road net data, gazetteer data, building data, and population and juridical person information data, are necessary for evaluating and predicting the impact on and harm to nearby human activities caused by the leakage and expansion of the gas through overlay analysis and for determining the shortest paths to the emergency site through shortest-path analysis. These data can be retrieved from GeoServer, which provides a standard and interoperable WFS and WMS service for basic geographical features and map images.

3.3. Experimental Process and Results

Figure 8 illustrates the process for gas leakage emergency response in Taiyuan. A public emergency evolves in four phases: the monitoring phase, the warning phase, the response phase, and the recovery and evaluation phase. Government departments, enterprises, and citizens focus on different tasks in different phases, and the focusing service provides different outcomes and decision-making support for each of them during these phases.

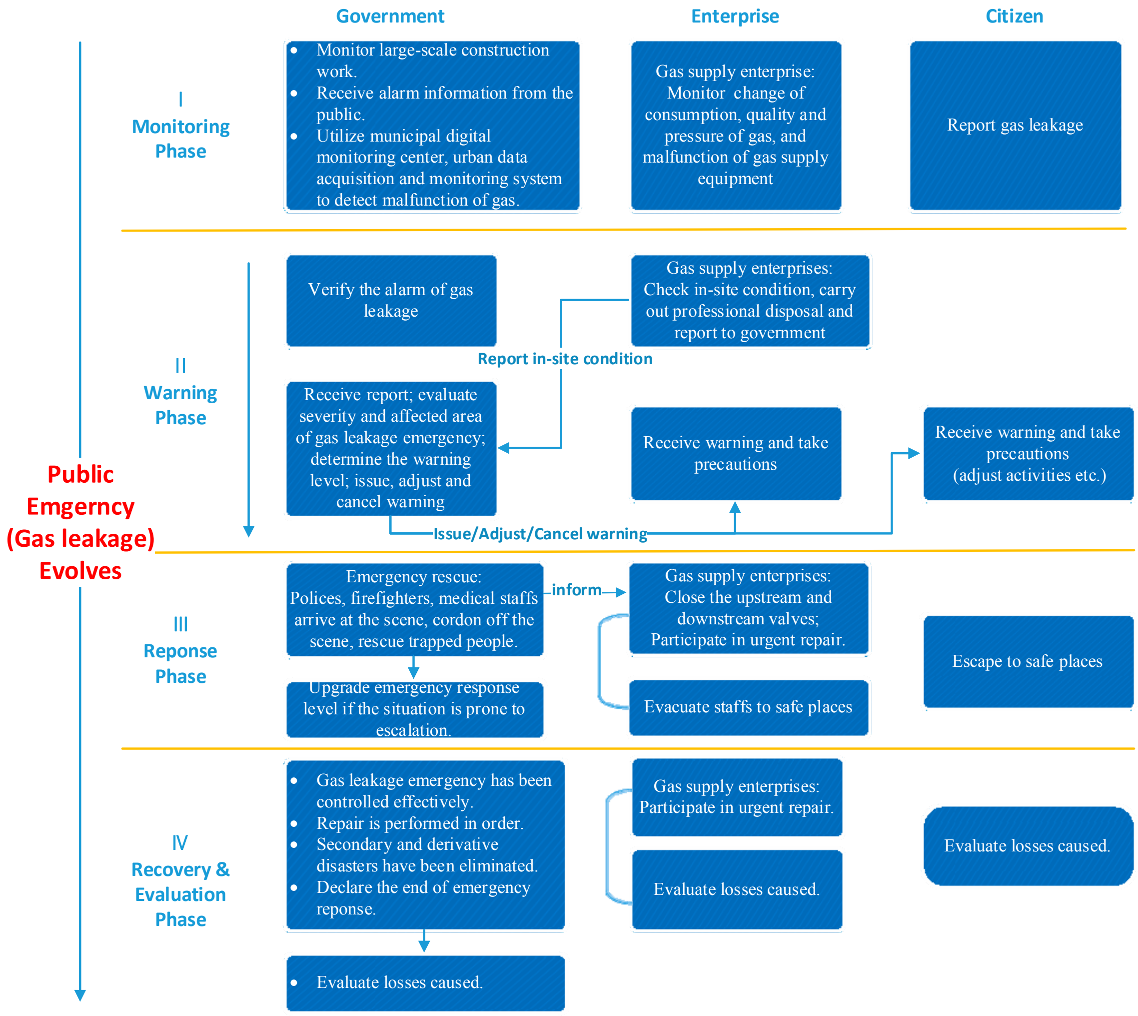

Figure 8. Gas leakage emergency response process.

3.3.1. Monitoring Phase

In the monitoring phase, gas pipelines are monitored by various sensors, such as gas detectors, smoke alarms, fire detectors, and video sensors. Citizens and inspectors can also report malfunctions of gas pipelines or gas leakages to government departments. Once an abnormality is monitored or reported, the monitoring phase evolves into the warning phase, and the focusing service is triggered and begins operation.

3.3.2. Warning Phase

As stated in Figure 8, the most important task for government departments is to determine the severity of and the area affected by the gas leakage and expansion; based on this information, the government issues a suitable level of warning. As discussed in Section 3.2.1, the Gaussian plume model and overlay analysis model can be used together to perform this task. In step 0 of the proposed focusing service process, an abstract focusing service chain containing these two models for the warning phase of the gas leakage emergency has been registered in the CSW in advance. The abnormality monitored or reported in the monitoring phase triggers the focusing service prototype system to retrieve this registered abstract service chain and instantiate it by binding model service instances (WPS processes) and linking data (real-time sensor data from MongoSOS and archived WFS/WMS data service from GeoServer). Figure 9 shows a service chain instance for evaluating the impact of gas leakage and expansion. The intermediate and final results are contained in the proposed informational representation of the focusing service model and registered in the CSW. These results can be obtained from the CSW through the web and displayed on various platforms, including 3D desktop platforms and 2D mobile platforms, as shown in Figure 10. Based on these results, the warning level, time, message type, message content, area, and extent of the alert are determined by the government and issued to enterprises and citizens to inform them to take the appropriate precautions.

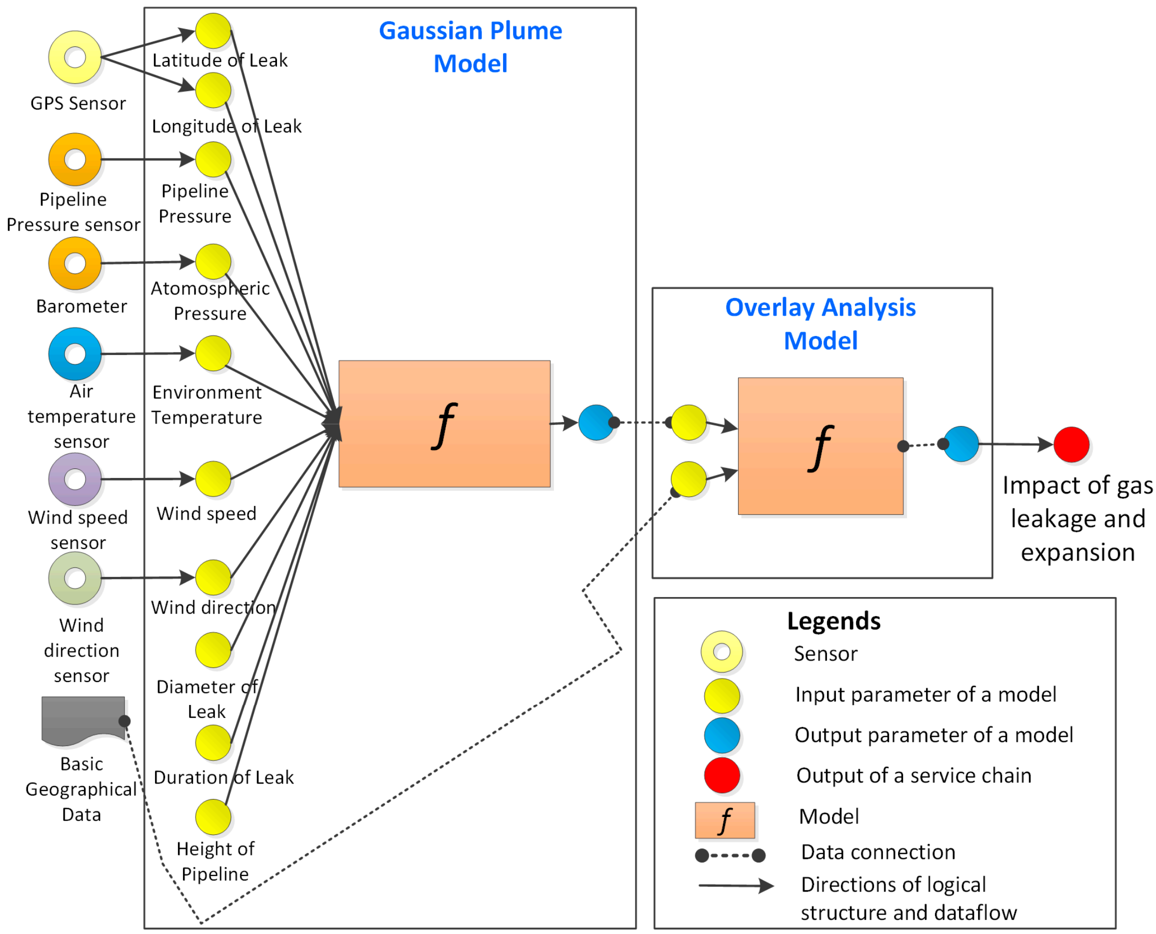

Figure 9. A service chain instance for evaluating the impact of gas leakage and expansion.

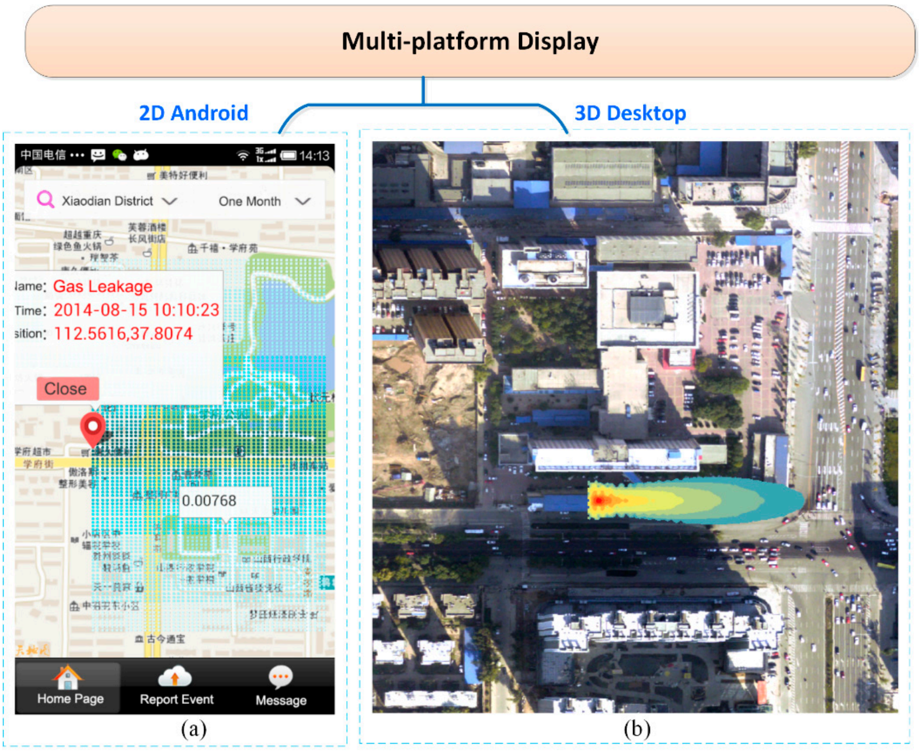

Figure 10. Gas expansion area shown on: (**a**) an Android 2D platform; (**b**) the Gaea 3D GIS platform.

3.3.3. Response Phase

Emergency rescue and urgent repair are the two main tasks in this phase. Thus, the police stations, fire stations, hospitals, and other public facilities nearest to the scene of the gas leakage emergency and the shortest paths for them to reach the scene should be determined. As explained in Section 3.2.1, the overlay analysis model and shortest-path analysis model can be utilized together to perform this task. In step 0 of the proposed focusing service process, an abstract focusing service chain containing these two models for the response phase of the gas leakage emergency has been registered in the CSW in advance. The evolution from the warning phase to the response phase triggers the focusing service prototype system to retrieve this registered abstract service chain and instantiate it through binding model service instances (WPS processes) and linking data (archived WFS/WMS data service). Figure 11 illustrates a service chain instance for finding the shortest paths along which relevant staff can reach the emergency scene in the shortest amount of time. The results are contained in the proposed IRFSM and registered in CSW. These results can be obtained from the CSW through the web and displayed on various platforms, including 3D desktop platforms and 2D mobile platforms. Figure 12 shows the shortest paths (red and blue solid lines) displayed on Gaea (a 3D GIS platform). Based on these results, rescue staff and urgent repair staff (from both government departments and gas enterprises) can perform their duties (as shown in Figure 13) in the shortest possible time and thus reduce losses to the greatest possible extent. Similarly, the shortest paths for rapid evacuation from the dangerous gas leakage area are also determined and provided to enterprises and citizens, thus ensuring the safety of their lives and property.

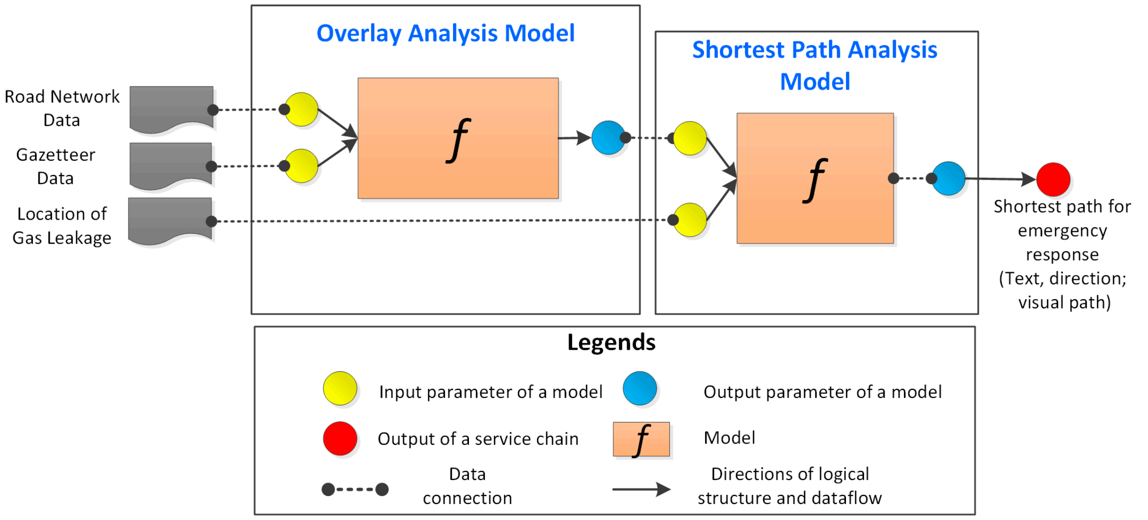

Figure 11. A service chain instance for determining the shortest paths to the emergency site.

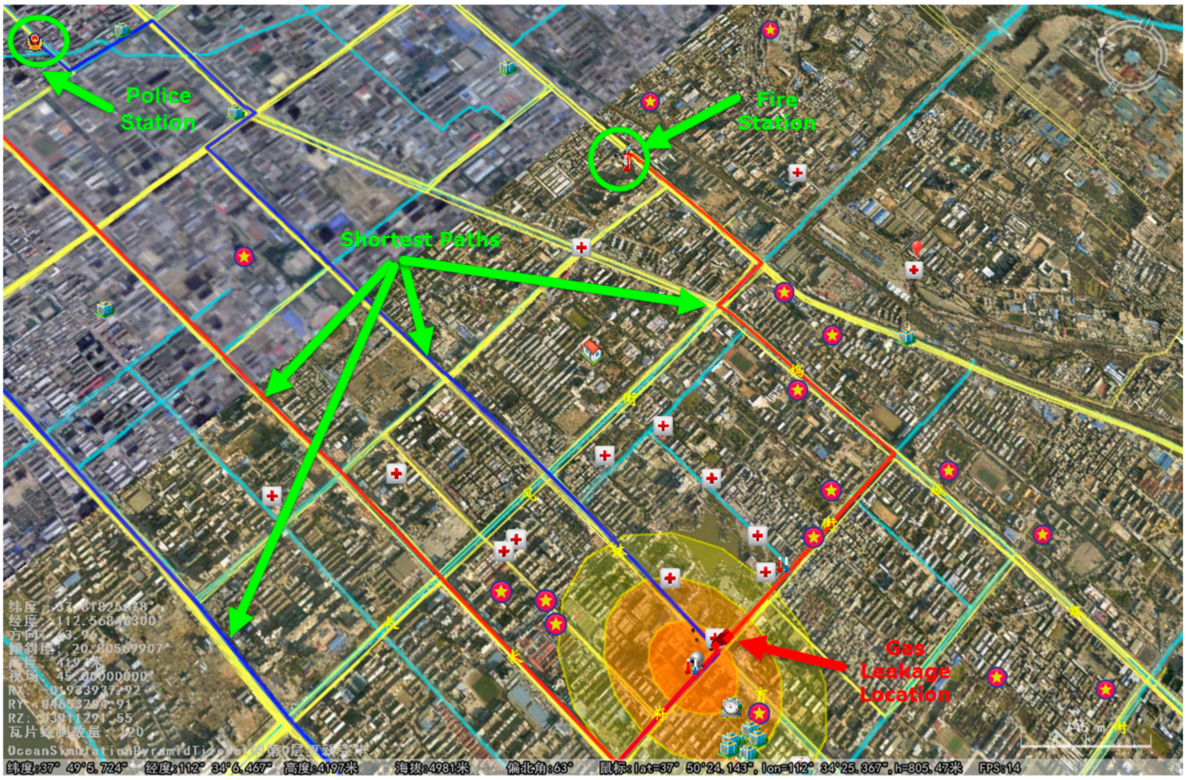

Figure 12. Gaea displaying the shortest rescue paths (red and blue solid lines) in a 3D scenario.

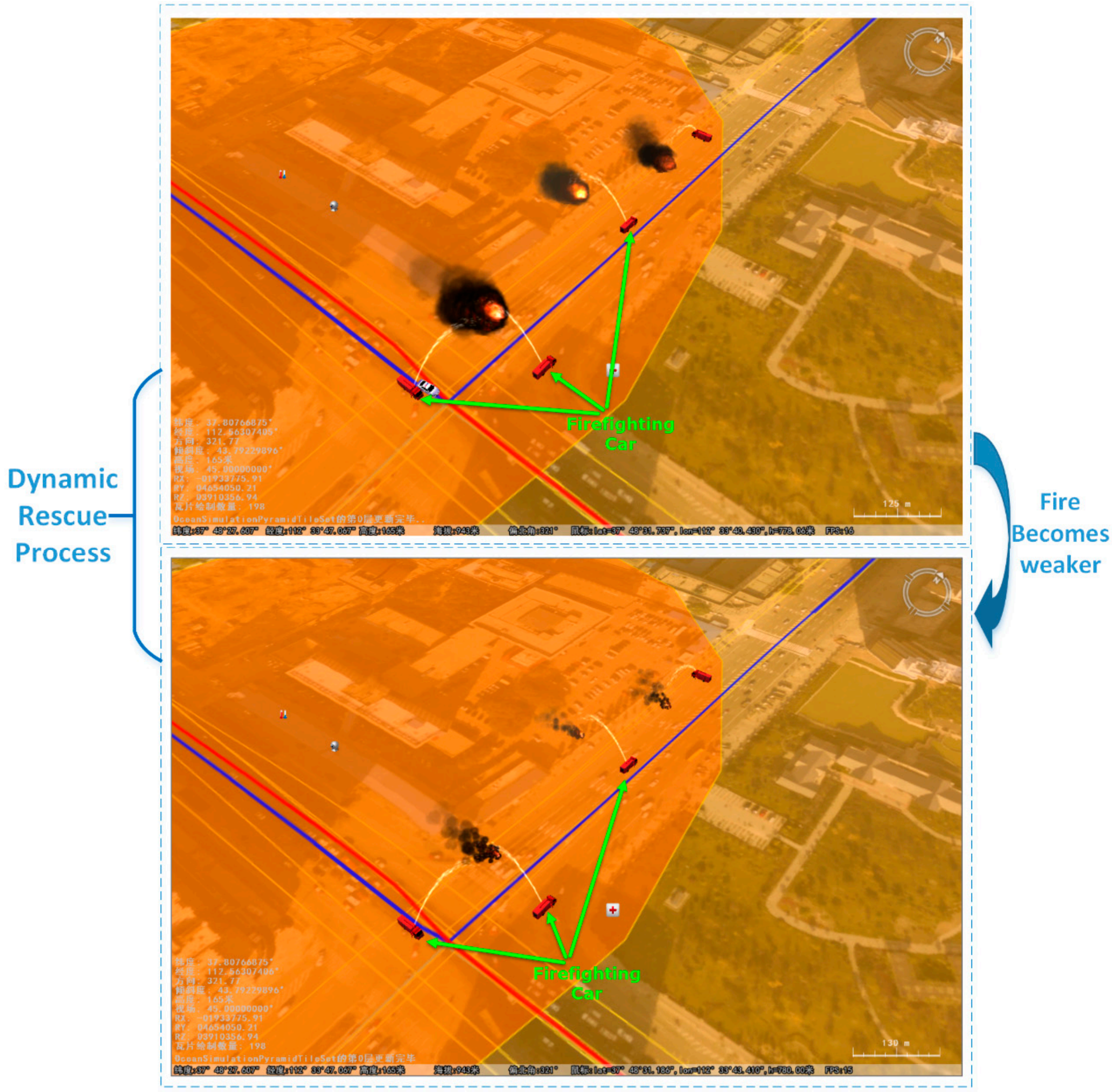

Figure 13. Gaea displaying the dynamic rescue process in a 3D scenario.

Once a gas leakage emergency has been effectively controlled, the repair work is in order, and any secondary and derivative disasters have been eliminated, the response phase ends and evolves into the next phase, the recovery and evaluation phase.

3.3.4. Recovery and Evaluation Phase

In this phase, the gas leakage emergency is under effective control, those wounded are being treated, and any damaged facilities are under urgent repair. The main task to be executed in this phase is to recover from and evaluate the losses caused by the gas emergency.

This objective can be achieved through the orchestration of the Gaussian plume model and overlay analysis model. Although this combination of models is the same as that used in the warning phase, a separate abstract focusing service chain containing these two models for gas leakage emergencies, but for the recovery and evaluation phase thereof, is registered. One difference between the focusing service process applied in this phase and that executed in the warning phase is the geographical data used. In the warning phase, base map data, road network data, building data and population data are used as inputs to the overlay analysis model to predict the possible extent of the area affected by the gas leakage, based on which the warning information is determined. However, in the recovery and evaluation phase, the primary task is to evaluate the losses that have already been incurred because of the gas emergency; therefore, economic data are used in addition to the data used in the warning phase.

The main results of the focusing service for this phase are loss reports, including casualties, facility damage, and economic losses, as shown in Figure 14. These reports are output and distributed to government departments in the form of documents (Evidence Placeholders in the proposed focusing service model) or published to the public as news items.

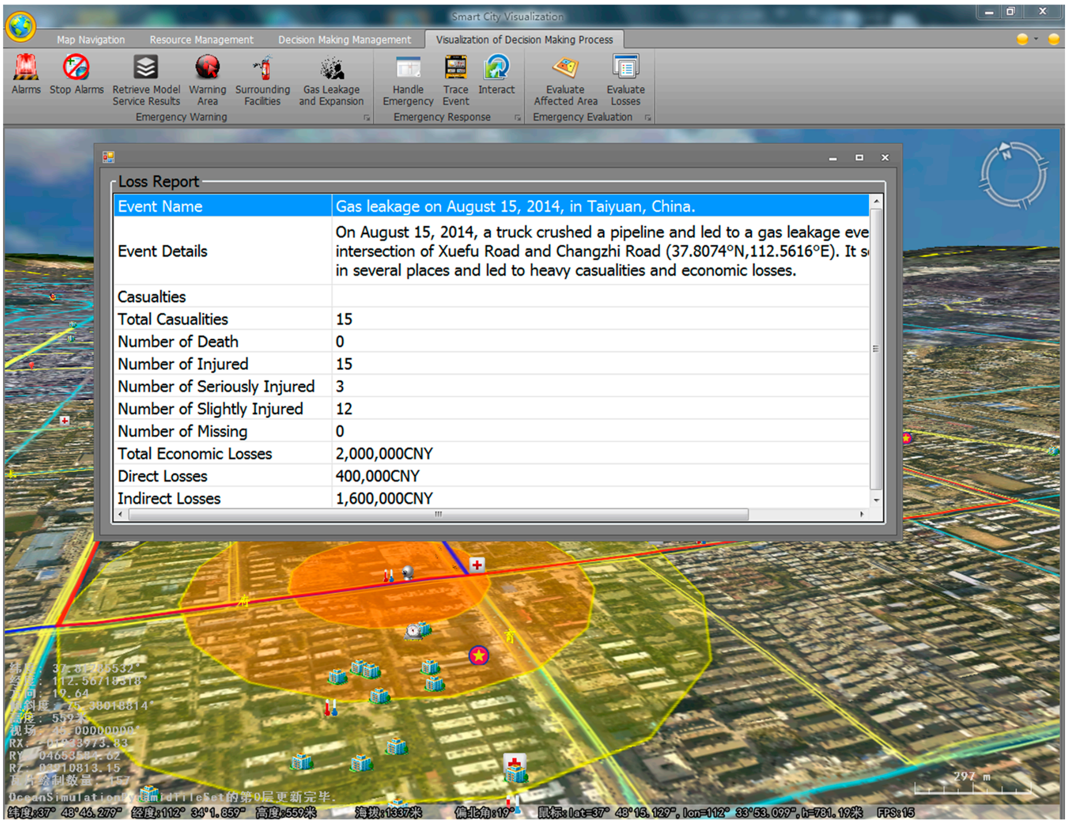

Figure 14. Gaea displaying a loss report generated by the focusing service during the recovery and evaluation phase.

4. Discussion

The experiments carried out in four different phases of a real-world scenario—a gas leakage emergency that occurred in 2014 in Taiyuan, China—demonstrate that the proposed focusing service method is feasible for application in assisting with emergency response in smart cities and also offers certain unique features and advantages over the existing methods, as is discussed below in detail.

4.1. *Feasibility of the Proposed Focusing Service Method*

Based on considerations of the overwhelming amount of available information resources and the types of public emergencies that most frequently occur, the proposed method adopts an event-driven mechanism to actuate the focusing service process. It prefabricates processing flows (abstract focusing service chains) related to both the types and phases of public emergencies, based on practical historical experience. When a public emergency occurs, suitable processing flows can thus be made available in a relatively short period of time, using the event type and event phase as query filters. These processing flows can be instantiated to be executable by binding the appropriate service instances and linking data with the assistance of the registration center (e.g., the CSW in the experimental scenario) and can thus produce personalized outputs for various societal entities, e.g., government users, enterprise users and citizens, in accordance with their knowledge requirements in response to an emergency. Taking the warning phase of the gas leakage emergency considered in the experiment as an example, the process flow orchestrating the Gaussian plume model and overlay analysis model predicts the expansion area of the gas and provides this information to government departments to allow them to determine a suitable warning level. Further warning information is issued and pushed to enterprise and citizen users so that they can take necessary precautions in a timely manner. Therefore, the proposed focusing service method can feasibly provide personalized service support throughout the entire lifecycle of public emergencies to various users to facilitate their effective and efficient response to public emergencies. However, an important premise of the feasibility of the proposed method is that the communication infrastructure is not damaged in the emergency cases, namely the sensing devices can still function well and sensing data can be transmitted back normally.

4.2. Advantages of the Proposed Focusing Service Method

4.2.1. Efficient Urban Event-Driven Emergency Response in Smart Cities

The event-driven mechanism is vitally important for efficient emergency response in smart cities. However, studies to date have focused primarily on micro events [31], such as sensor observation events, which are difficult to adapt to macro urban public emergency scenarios. By contrast, the method proposed in this paper is oriented toward macro urban public emergencies. IRFSMs specific to the various types and stages of public emergencies are registered in and managed by the registration center and are retrieved through interoperable web service interfaces by the focusing service software when an urban emergency event occurs or when such an event evolves to another phase. Thus, it can apply to the whole life-cycle of an event which, however, is not supported by some of the state-of-the-art methods [25,31]. This urban event-driven mechanism for focusing service implementation contributes to providing greater suitability and efficiency in response to macro urban emergencies. Table 1 details the comparison between the proposed method with some state-of-the-art methods.

Table 1. Comparison of the proposed method with others.

Method	Event-Driven	Event Type	Suitable for the Life-Cycle of Events	Efficiency	Real-Time	Dynamic
The proposed method	Yes	Macro	Yes	High	High	High
Zhu et al. [25]	Yes	Macro	No	Medium	Medium	Medium
Yu et al. [30]	Yes	Micro	No	Medium	High	Medium
Fan et al. [31]	Yes	Micro	No	Medium	High	Medium
Yang et al. [23]	No	- [1]	-	Medium	Medium	Medium
Huang et al. [24]	No	-	-	Not known	Medium	Medium

[1] "-" means that the comparison item does not apply to a method in that row.

4.2.2. Cyber-Physical Infrastructures for Near-Real-Time Location-Based Sensing and Handling of Emergencies

In the proposed method, cyber-physical infrastructures (as shown in Figure 1) are utilized rather than cyber infrastructures alone, as in the traditional methods: (1) Sensing Infrastructures: various sensors (static in situ sensors and dynamic mobile sensors embedded in smart phones) to acquire comprehensive data regarding the emergency conditions, including geo-location information, which is particularly important for emergency response; (2) Communication Infrastructures: communication fabrics (e.g., wireless/wired communication; 3G/4G/Wi-Fi/WSN; email/SMS) to transmit emergency states (measurements of the surrounding context) and emergency response messages (e.g., issuance/cancellation of warnings and warning level adjustments); and (3) Cloud Computing Infrastructures: storage and computation facilities (e.g., the cloud platform deploying the MongoSOS, WPS, and GeoServer instances at the SCIDMC in the experimental scenario) for the analysis of, decision-making in, and efficient handling of emergency scenarios utilizing service chains comprising analysis and decision-making models with near-real-time and archived data services as inputs. These cyber-physical infrastructures form extensive networks of sensing-transmission-computation links to realize the near-real-time location-based sensing of emergencies, thereby contributing to the efficient handling of emergencies and reducing losses to the greatest possible extent.

4.2.3. Mobile Crowd Sensing for Dynamic Comprehensive Monitoring of Emergencies in Smart Cities

Traditional sensing techniques such as wireless sensor networks (WSNs), in which distributed sensors are leveraged to acquire real-time measures of emergency conditions, rely on static sensing, which suffers from several disadvantages, such as insufficient node coverage, high installation/maintenance costs, and lack of scalability. As a consequence, these traditional sensing techniques have been established only in specific areas and are generally not adopted on the large scale; the necessary support may be lacking throughout most of or even an entire city, thus reducing the utility and practicability in effective monitoring of emergencies, which occur randomly in time and space. To overcome these limitations, in addition to traditional sensing techniques (e.g., wind speed/direction sensors and atmospheric sensors), the proposed method leverages the increasingly popular mobile crowd sensing technique [11], which represents a new sensing paradigm based on the power of various mobile devices/objects, such as the smart phones considered in the experiment using the PMSW app (Figure 7) for the near-real-time publishing and sharing of measurements by a large pool of mobile sensors and sensor-equipped vehicles. The huge number of users with sensor-enhanced mobile devices and their inherent mobility and geographical distribution enables more comprehensive sensing of city dynamics, ensuring that occurrences of public emergencies are identified and reported in the shortest possible time and in reasonable detail (e.g., when and where it occurred and parameters of the surrounding context), thereby aiding in timely sensing, decision-making and handling of public emergencies and contributes to safer and smarter cities.

4.3. Limitations of the Proposed Focusing Service Method

Despite the advantages of the proposed method discussed above, it still suffers certain drawbacks and limitations:

(1) Static event-driven mechanism: In the proposed method, abstract focusing service chains for different types and phases of public emergencies must be established in advance. Thus, it is a static event-driven process that involves human labor.

(2) Semi-automatic focusing service process: The proposed method is not a fully automatic but rather a semi-automatic focusing service process. The procedure for the retrieval and instantiation of abstract processing flows involves human interaction with the focusing service software, which requires that the users involved possess certain prior knowledge concerning public emergencies, the abstract processing flows, and manipulation of the software, thereby reducing the usability of the system for non-expert users.

5. Conclusions and Outlook

This paper proposes an event-driven focusing service method to focus the overwhelming amounts of available distributed information resources to efficiently respond to the types of public emergencies that occur most frequently in smart cities. The method consists of a focusing service model, an informational representation of the model, and a focusing service process. Mobile crowd sensing and cyber-physical infrastructures are utilized to comprehensively monitor and sense emergencies, to perform near-real-time analysis of emergencies and to help respond to emergencies in the shortest possible time. The proposed method can focus a rich variety of information resources on public emergencies and provide personalized service to three different types of societal entities—government users, enterprise users, and citizen users—to assist them in their efficient responses and decision-making with respect to public emergencies, ultimately contributing to the establishment of safer and smarter cities.

However, the proposed focusing service method still needs human interaction. To further improve the efficiency and utility of the proposed method, the development of a dynamic event-driven fully automatic focusing service process will be addressed in our future work. Besides, how to assist decision-making and emergency response in extraordinary serious disasters during which communication infrastructures may be heavily damaged should be further investigated.

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