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Design and implementation of an integrated safety management system for compressed natural gas stations using ubiquitous sensor network

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Abstract−To increase awareness of safety in facilities where hazards may exist, operators, managers, and executive officers on the site should be able to monitor such facilities. However, most compressed natural gas (CNG) service stations in Korea use only local-mode monitoring, with only on-site operators to monitor the facility. To complement this local-mode monitoring, an online safety management system called Ubiquitous-gas safety management system (U-GSMS) was developed. The U-GSMS consists largely of software and hardware. The software consists of systems that can manage safety and operations, while the hardware consists of sensors installed in the gas facility and wireless communication systems using a ubiquitous sensor network (USN) technology that facilitates communication between sensors as well as between sensors and other devices. As these systems are web-based, on-site operators as well as managers and executive officers at the headquarters can more effectively and efficiently perform monitoring and safety management.

Keywords: Safety Management System, Compressed Natural Gas (CNG), Ubiquitous Sensor Network (USN), Quantitative Risk Assessment (QRA), Emergency Response, Quantitative Management Assessment (QMA)

INTRODUCTION

In September 1999, the Ministry of Environment initiated a project to reduce emission gases, which are a significant cause of air pollution in metropolitan areas in Korea. This project includes converting local diesel buses to natural gas buses. Since 2006, the number of natural gas buses has been increasing, and by 2012, all metropolitan areas in Korea were operating natural gas buses for local transportation [1].

Most natural gas buses in Korea use compressed natural gas (CNG), which is produced in a charger by compressing natural gases under high pressure. Service stations for CNG are required to operate such natural gas buses. These gas-filling facilities are ideally situated near urban areas based on the characteristics of these buses [1].

As shown in Table 1, there were 366 CNG service stations throughout Korea in 2011. The Ministry of the Environment aims to increase the number of CNG stations to 400 and the number of natural gas public transportation vehicles to 20,000 in the future. Because of this policy, most transportation vehicles using CNG are local buses, and CNG service stations are located near downtown areas. These stations fill up the vehicles with CNG at 250 kPa. Low pressure natural gas (2.5-4 kPa) from a supply pipe is compressed with high-service pressure (250 kPa) in a four-step process. Table 2 shows the high-pressure operating conditions of the compressor at a CNG service station. Because of these high-pressure conditions, CNG service stations are vulnerable to safety problems such as released gases and explosions [2].

To prevent such accidents and minimize losses when such accidents do occur, the risk at each facility should be assessed, and detailed plans for accident response should be developed along with safety monitoring technologies [3,4].

This study discusses the development of a safety management system for CNG stations. We developed a risk assessment module to help operators and managers reduce the risk of accidents that may occur in CNG service stations, as well as an emergency response module that offers guidelines for when such accidents do occur. In

Table 1. CNG service stations in Korea

Type/region	Seoul metropolitan area	Gyeongsang-do	Jeolla-do	Chungcheong-do	Gangwon-do	Total
Stationary	85	43	16	8	5	157
Travelling	16	3	2	3	2	26
Total	101	46	18	11	7	183

Source: Korea Natural Gas Fueling Association, 2011

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Table 2. Operation conditions of compressor at CNG service stations

Location	Item		Unit	Rating	Warning level
Compressor package	Gas temperature	1st	ºC	129	165
		2nd	ºC	117	165
		3rd	ºC	103	165
		4th	ºC	117	165
	Gas pressure	Inlet	kPa	441	200-592
		1st	kPa	1,643	2,132
		2nd	kPa	4,134	5,224
		3rd	kPa	9,489	11,568
		4th	kPa	25,090	26,200
	Gas level		%LFL	20	20
	Oil temperature			78	4-92
Priority panel	Bypass pressure		kPa	26,200	26,540
Storage tank	Pilot pressure		kPa	25,000	26,540
Power	Main power supply		V	3 phase 380 V	

addition, we developed a monitoring module to help them monitor operational parameters in real time, a quantitative management assessment module to help them check and promote a safety-oriented culture, and an inspection history module to help them inspect facilities effectively using previous inspection data.

DESIGN OF U-GSMS

1. Status of CNG Service Stations

Various sensors were installed at CNG service stations to collect the data for this study. Main operating events and abnormal occurrences were monitored remotely by connecting the communication systems to the programmable logic controller (PLC). Currently, however, these facilities operate using local communications, which enable only on-site monitoring [5].

At a CNG service station, an interlock-type safety device is installed, which shuts down the service station without advance notice if the scope of the preset operation condition changes [5]. Hence, it is important to reduce losses, and minimize shutdowns by identifying and addressing potential breakdowns or abnormalities before they occur [6].

2. Design of U-GSMS

To meet Korean regulations, we designed the safety management system such that it helps identify hazardous factors in company safety management activities, analyze the characteristics of these hazards, and prepare measures to eliminate the root cause of such accidents.

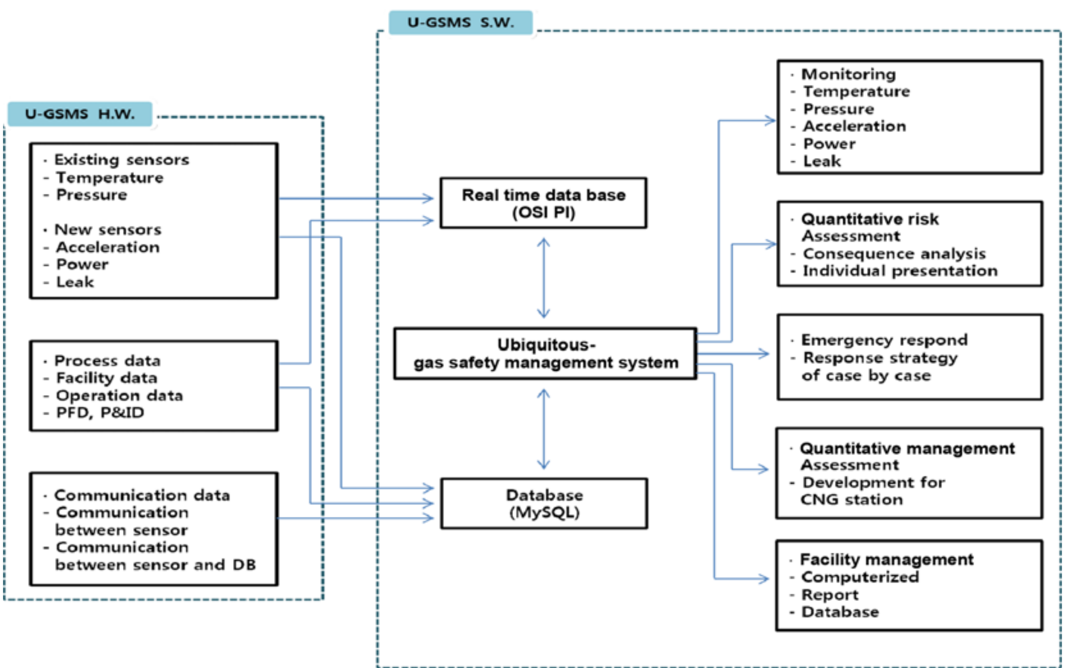


Fig. 1. System implementation.

The system consists of 12 main elements and 39 sub-elements [7]. The U-GSMS consists of modules that provide measures for items such as risk assessment and emergency procedures.

An overview of the U-GSMS is presented in Fig. 1. To identify the current status of CNG service stations, we ensured the U-GSMS satisfied the local requirements and then examined the most critical tasks by interviewing managers and operators on site. The results obtained through the interviews that were applied to the system fall into two categories: First, interlock-type blocking, used in the CNG service stations, was improved. Since an operation may shut down without any detected abnormalities, the operator may never know the cause of the shutdown. This result identifies the need to take action before such incidents occur. Second, to address the limitations of remote monitoring, the system was configured to be operable online by a manager or responsible personnel at the headquarters (HQ).

To suit the upgrade to the next-generation system, the U-GSMS included a quantitative management assessment (QMA) module. The QMA is a safety management method that complements a safety-oriented culture. It is an inspection system that aims to improve the current one initiated by the Korea Gas Safety Corporation (KGS). In 2012, a new application that can take action before an accident occurs was developed and added to this system.

SYSTEM CONFIGURATION AND APPLICATION

1. Safety Management Module

To prevent accidents that may occur at a CNG service station and minimize losses when an accident does occur, a system was developed to enable real-time monitoring of natural gas compressors that have high usage and high risk and enable quick and effective response to emergencies, based on risk inspection technology.

1-1. Quantitative Risk Assessment System

Quantitative risk assessment (QRA) identifies problems and risks in processes based on the frequency of accidents and consequence of expected scenarios. This analysis quantitatively measures the effect of such accidents on humans and buildings [8]. Hence, in this study, case studies related to gas facility accidents were analyzed to obtain accident factors such as causes and mechanisms in order to develop a system for coping with accidents and resulting damages by simulating the consequences of accidents that can occur at CNG service stations [9].

In the U-GSMS, the dispersion model for consequence analysis (CA) was modified based on the guidelines of the Center for Chemical Process Safety (CCPS) and models from DNV's Phast industry hazard analysis software. In these cases, dispersion models were characterized using the CCPS's Gaussian distribution and dispersion equation for leakage through holes, and a combustion limit was applied using Le Chatelier's mixing rule. This safety management system was designed to be used by the administrators and operators of CNG service stations. The information needed for case studies is shown in Table 3 below. The material (methane) was chosen after selecting the evaluation process of the subject to proceed in the following order: input of atmospheric information (temperature, pressure, humidity, air volume, wind speed, and atmospheric stability); type of accident (VCE, jet fire, fireball, and flash fire); and accident information (pressure, volume, and height) [3,8,9].

The risk assessment phase applied to the system can be divided into leakage, diffusion, and accident impacts. Table 3 summarizes the application of the model to the system by phase [8,10,11].

Table 3. Information of QRA system

CNG leakage	CNG diffusion	CNG accident impacts
Instantaneous	Wind speed	Fireball
Gradual	Atmospheric stability	Vapor cloud explosion
	(Pasquill-gifford model)	Flash fire
	Plume	Jet fire
	Puff	

CNG Leakage: CNG leakage can occur instantaneously or gradually. If the CNG storage tank is damaged, CNG leakage takes place due to the physical characteristics of CNG (adiabatic expansion). In the event of CNG leakage, accidents (explosion and fire) occur due to the mixing of CNG with flammable fluids (air and gas). The leaked gas leads to a fireball, vapor cloud explosion, flash fire, or jet fire depending on how long it stays in the air and the presence of an ignition source [8,10,11].

CNG Diffusion: A mathematical model (Gaussian) was applied to the diffusion of CNG depending on the type of leakage by taking into consideration travel time and leakage time [8,10,11].

CNG Accident Impacts: Accident impacts were divided depending on the ignition time (instant or delayed) in the case of CNG leakage. We applied the worst-case scenario for accident impacts caused by CNG diffusion [8,10,11].

Fig. 2 below is a summary of the CNG diffusion model. CNG properties, facility information, leakage information, and weather information are used for application to the system.

It can be run easily by inputting simple information and using monitoring modules without requiring complex equations [10].

The QRA system developed in this study added individual risk (IR) and CA programs, taking into account the characteristics of CNG. A module was developed as a user-centered interface and applied to the analyzed data.

Table 4 shows the techniques applied to the safety management system and the required inputs and procedures for implementation. We based these techniques, inputs, and procedures on the guidelines of the CCPS [8,11], taking into account the chemical and physical properties of CNG.

1-2. Emergency Response System

Previous on-site emergency procedures were developed to ensure report-like planning complied with government regulations rather than to make planning efficient. Therefore, an emergency response

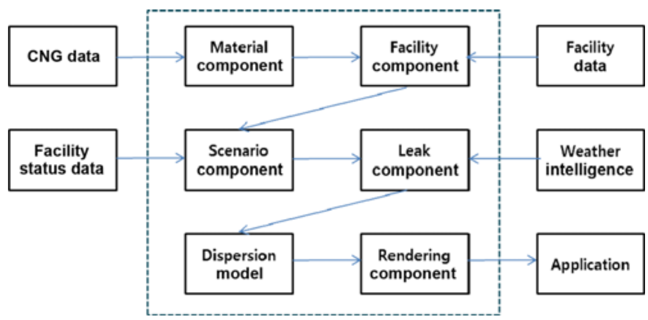


Fig. 2. Procedure of dispersion scenario.

Table 4. QRA system

QRA system	Technique	Input data and procedures
Consequence analysis	· Accident scenario analysis · Source model · Dispersion model · Effect model	· Selection of material · Weather conditions · Incident outcome · Incident outcome cases · Risk presentation
Individual risk	· Individual risk contour · Contour lines connecting points of equal risk superimposed over local map	Results of consequence analysis: · Selection of material · Weather conditions · Incident outcome · Incident outcome cases · Risk presentation

module that suggests accident scenarios that could occur frequently, generate a proactive response, and facilitate accident prevention is needed. To develop such an emergency response module, consequence data obtained from CA and data from the corresponding service station (material, process, specification, etc.) could be used.

In the emergency response module developed in this study, scenarios that are likely to occur were organized based on real accidents, a database was developed using details of emergency response procedures, and guidelines were applied so that emergency response could be user-configured.

In addition, accident scenarios were selected and checked through QRA based on information on the facility, material, and operating conditions.

The emergency response scenarios derived through this study were divided into six kinds based on the accidents that can occur at the CNG station. Fig. 3 shows the procedure for configuring this

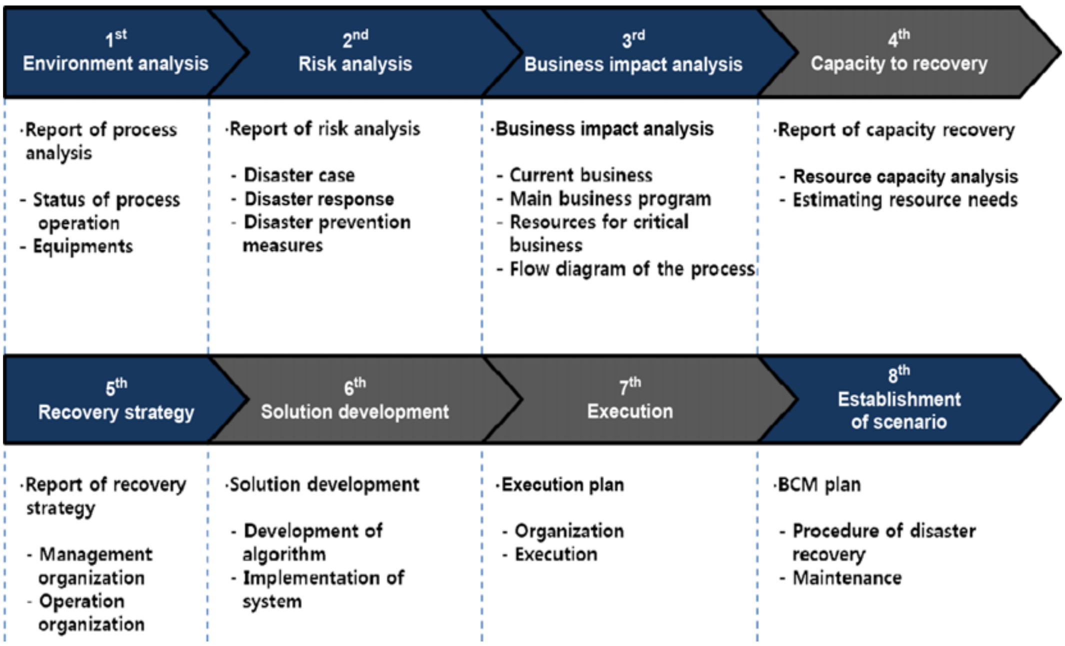


Fig. 3. Procedure of emergency response scenario.

Table 5. Procedure of emergency response scenario

No.	Scenario name	Action tips by phase	Content of scenario composition
1	A conflagration in the area near a CNG station	Phase 1: State of emergency situation notified	- Time and order
2	Dispenser collision accident	Phase 2: First aid	- Actions
3	Traffic accident in the CNG station	Phase 3: Restoration work	- Detailed action tips
4	Explosion of CNG storage container in the CNG station	Phase 4: Accident investigation and report	- Responsible person(s)
5	Gas leakage of medium pressure pipeline in the CNG station		
6	Collapse of CNG station		

study's emergency response scenarios as listed in Table 5. The response scenarios were configured in a way that they reviewed the risk assessment, selected the accident scenario, and complemented the existing emergency action plan. Table 5 lists the systems applied to this system, and each scenario was configured based on the guidelines presented in CCPS [6,15].

Based on the QRA results, scenarios were organized, and response strategies, interactive support systems, and response facilities were checked in order to develop an accident report hierarchy. Furthermore, this accident report hierarchy was presented as a diagram that can be used to improve training and education.

1-3. Monitoring System

The process monitoring technology can detect unexpected operational changes and abnormalities early and identify and remove the root cause of such abnormalities, thereby ensuring stable and safe operations [11].

The existing monitoring system used in a CNG service station collects operational data from a PLC and provides the data to an operator in real time through an application program [5].

The structure of the monitoring system developed in the study is a real-time, database-grounded monitoring system that can analyze historical data in the controller and transmit the values obtained from the current controller to the abnormal detection and inspection system.

Fig. 4 shows the characteristics of the developed monitoring module. The module was designed based on actual processes. The sensor information was indicated in the drawings of a CNG service station so that abnormal signals could be displayed in the drawings [12,13].

Trend analysis was performed based on past operation data to verify that operation inspection could be done [13,14]. Furthermore, vibration and electric sensors were added to the existing monitoring method, which depended only on temperature and pressure data, to increase the reliability of the monitoring of facilities.

2. Operation Management Module

The management system currently used at CNG service stations consists of monitoring the operation of the gas filling system and point of sales for sales management. The scope of the system was limited to a local system that was only operated within a service station with monitoring of the operation of the devices and facilities and did not provide a control room or managers at the HQ with monitoring information.

Due to this limitation, miscommunication between operators on site and managers at the HQ occur, negatively affecting the safety management, and consequently, the overall operations of a service station. To overcome this limitation, we developed a QMA system that measures safety levels and promotes a safety-oriented culture.

A CNG service station is a facility that requires strict regulation management where inspection is mandatory. Currently, inspection results for a gas service station are recorded by hand on paper. A system was developed so that facility inspection history could be computerized to enable efficient utilization of the inspection history.

2-1. Quantitative Management Assessment System

Since gas-related facilities handle harmful and hazardous materials, they face the risk of major industrial accidents. The safety levels at these hazardous facilities can be improved by better decision-making and rectifications by the business owner. To this end, there is a need to identify a safety level for these facilities and then manage that level objectively and continuously [16].

A measurement model for the safety level of a CNG service station was developed and applied through a survey that aimed to improve safety awareness according to factors that influence safety levels and designs that can measure the safety level of operators. Moreover, the system simultaneously performs assessment and education and takes into account the required regulatory elements.

Through the system, safety management activities, regulations, and procedures (which are conducted currently) can be assessed. Since the system provides a logical basis to assess safety, a manager can now monitor objective data and all safety procedures in order to establish a direction for the improvement of operation safety.

2-2. Inspection History System

Inspection operation at a CNG service station is conducted frequently and periodically and by hand, which makes sharing the facility inspection data and utilization of past data difficult. In this study, an inspection history system was developed. The workload related to the inspection operation was reduced via automation and computerization, and inspection-related data was stored in a database that could be accessed online. Accordingly, data utilization improved and workflow documentation and reporting could be produced electronically to facilitate a smooth workflow.

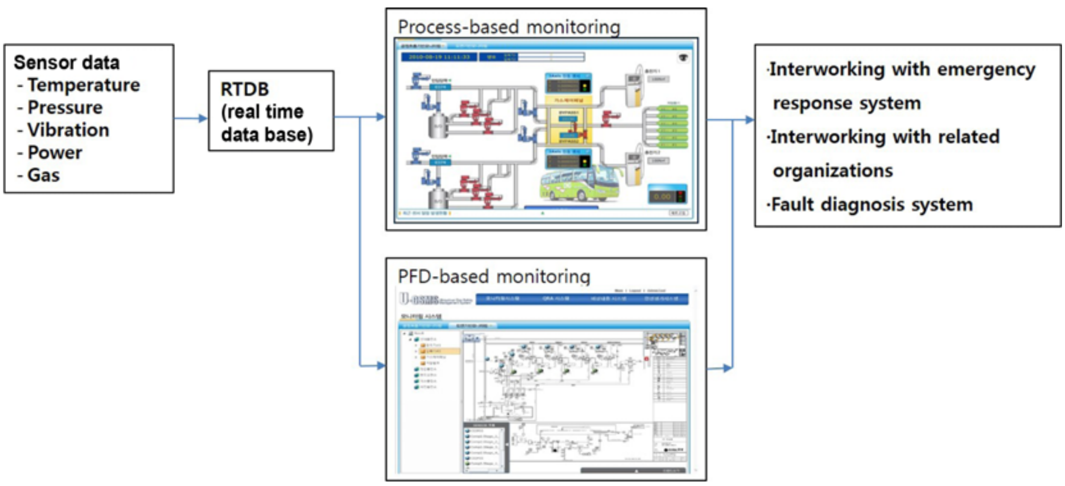
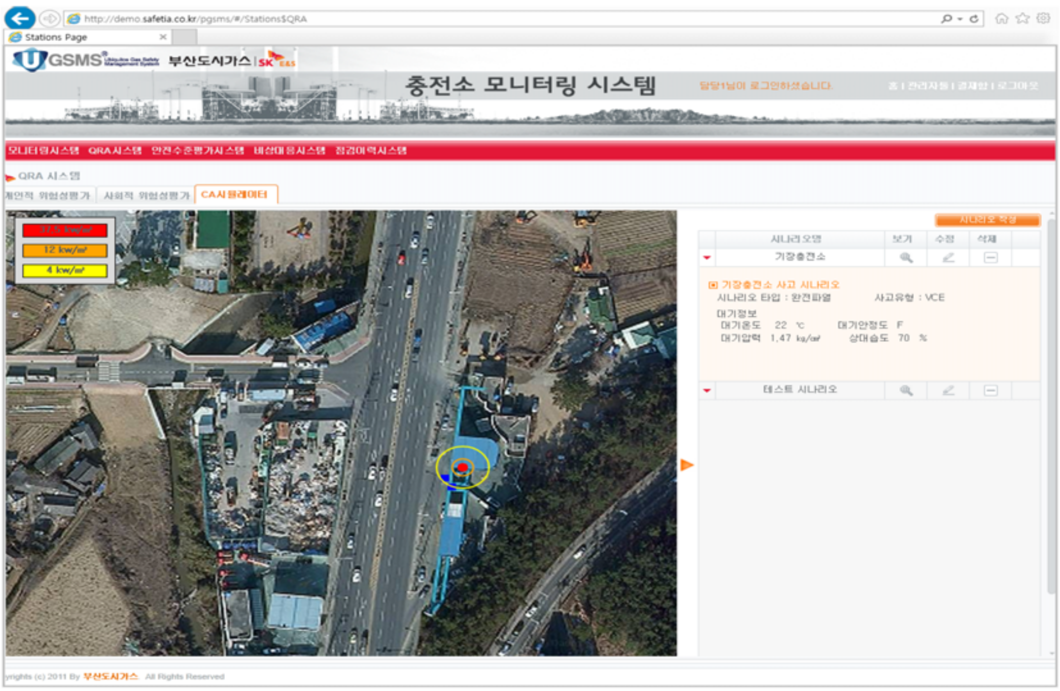


Fig. 4. Flowchart of monitoring.

(a)



(b)

Fig. 5. (a) System application - system main. (b) System application - QRA module. (c) System application - ERP module. (d) System application - monitoring module. (e) System application - QRA module. (f) System application - QRA module.

Due to the standardization and computerization of the inspection work, the system increased the reliability of the inspection data recording and promoted data sharing, thereby improving the overall level of data utilization and response to accidents.

3. System Application

The system was tested at CNG service stations operated by companies Y and S via two-stage tests. The criterion for the selection of the demonstration service station was to provide sufficient operation for a test. Fig. 5 shows the system after the first stage of the test at a CNG service station of Company S. Fig. 5(a) shows the system's main screen. Using the geographic information function, the system displays the location of the CNG service station of Company S. Upon the selection of the service station, the system displays the information and status of the selected station. Fig. 5(b) shows

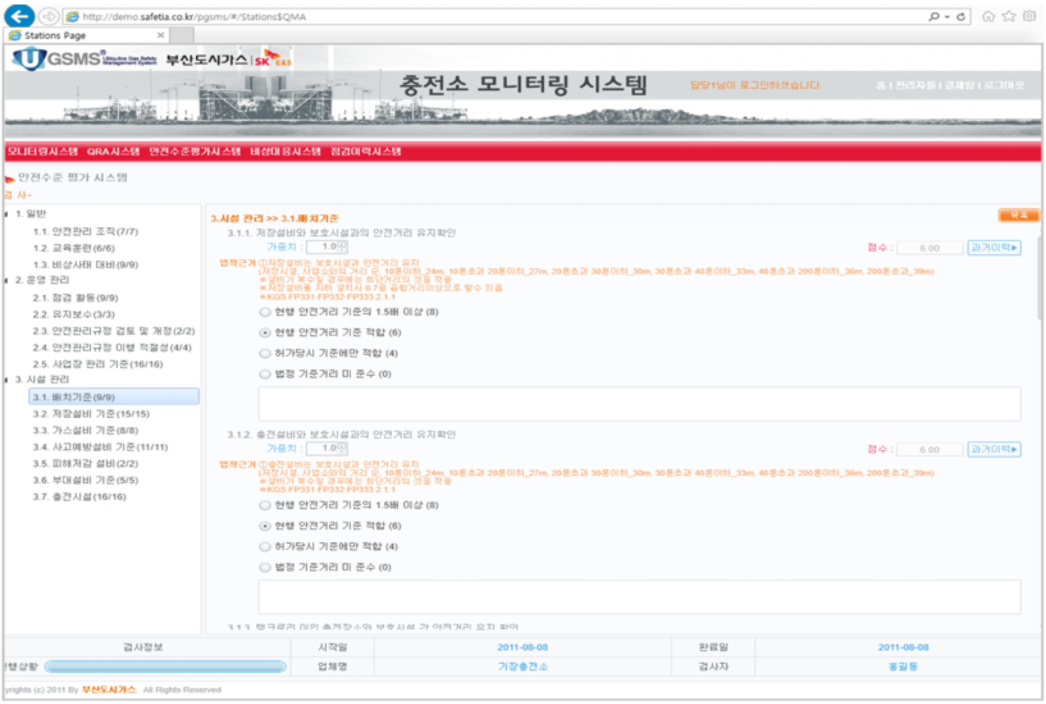
(c)

(d)

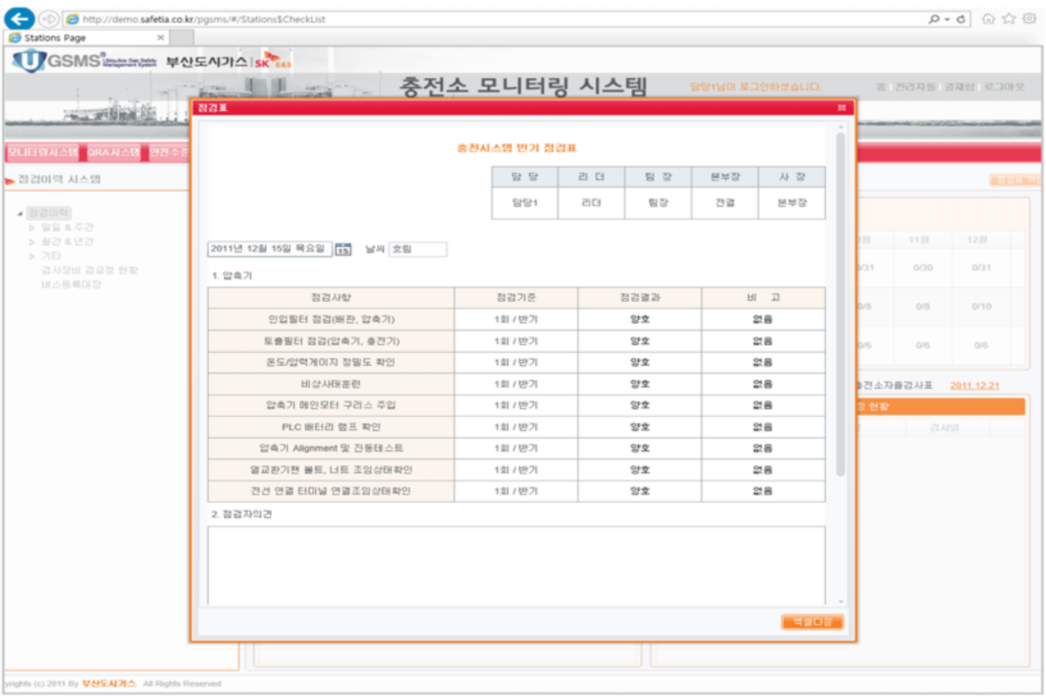
Fig. 5. Continued.

the risk analysis module of the selected service station. It was developed for beginner usage, using a combination of radio buttons indicating parts of the CNG service station where accidents could occur. By assigning the supervisor separately, a user or supervisor can modify information on the distribution of the population around the service station, thereby addressing the need to configure environmental changes around the service station. Fig. 5(c) shows the emergency response module. The scenarios are organized based on actual accidents at the CNG service station. Since the accident response guidelines were configured using diagrams, operators could respond to an accident instinctively. In particular, since the number of CNG service stations in a region is limited depending on local bus operations, the system made sure that local bus operations are not interrupted due to an accident.

Fig. 5(d) shows the monitoring module. The points on the figure indicate the locations of the installed sensors. Through these sen-



(e)



(f)

Fig. 5. Continued.

sors, current operation information can be monitored in real time. Once a sensor is selected, its location can be seen in the diagram along with past operation information. Furthermore, upon the detection of an abnormality, an alarm goes off to prompt action. Fig. 5(e) shows the QMA module. It is configured so that regulation requirements for CNG service stations are reviewed against a checklist. The history of the assessment results is stored so that the safety awareness level of an individual and category are checked continuously. Furthermore, the system was designed to check individual safety levels and all safety levels through category assessment results. Fig. 5(f) shows the facility management module. This module systemizes all the inspections performed at the CNG service station. The required periodic inspection is scheduled, and the sensor value is input automatically in connection with the sensor database. This module was developed to reflect the operator's suggestions, creating a report and workflow system that could be used by both operators and managers.

Through the demonstration process, which entailed surveys and interviews with experts and users, the system was improved. The main questionnaire survey aimed to verify how useful the system was for managers and operators. Meanwhile, the expert survey was conducted to verify how the U-GSMS could be used as a specialized system for CNG service stations. The survey was conducted for information input, editing of modules, data search, reports of view, statistical analysis, and graphics and system suitability of each module. The system was revised by referring to the answer proposed for each item.

CONCLUSIONS

The U-GSMS developed here is a system for the efficient management of safety and operations at CNG service stations. Since the system is web-based, remote managers and executive officers, in addition to on-site operators, can monitor operations at the service stations, thereby improving the effectiveness and efficiency of safety management. The online system does not require client program distribution or additional installation procedures. It also enables convenient program revisions and functional improvements in terms of system management. The system is convenient and user-friendly, allowing early adoption based on a service station's environment and usage without additional training. In the future, an abnormality detection model will be added to the process-monitoring module to increase the system's reliability by conducting demonstration tests continuously at the selected service stations.

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REFERENCES

1. S. M. Jun, *A study on propulsion for CNG bus expanding supply*, Korea Research Institute of Transportation Industries (KRITI) (2007).
2. J.-W. Choi, *Journal of the Korean Institute of Gas (KIGAS)*, **4**(3), 53 (2000).
3. D. A. Crowl and J. F. Louvar, *Chemical process safety: Fundamental with applications*, 2nd Ed., Prentice-Hall, NJ (2011).
4. Korea Occupational Safety & Health Agency (KOSHA) R&D Center, *Incident cause analysis based on major accident database*, R&D Center 2005-15-33 (2005).
5. Hyosung Corporation, *CNG compressor package manual*, Version 1.03.
6. Center for Chemical Process Safety (CCPS), *Continuous monitoring for hazardous material release*, WILEY (2009).
7. http://www.kgs.or.kr/kgsmain/informationdb/law/law_information02.jsp.
8. Center for Chemical Process Safety (CCPS), *Guidelines for chemical process quantitative risk analysis*, 2nd Ed., American Institute of Chemical Engineers (2000).
9. S. Chamberlain and M. Modarres, *Risk Analysis*, **25**(2), 377 (2005).
10. J. H. Yoo, H. S. Lee, J. W. Choi, J. M. Seo and J. W. Ko, *Korean Chem. Eng. Res. (HWAHAK KONGHAK)*, **46**(1), 156 (2008).
11. Center for Chemical Process Safety (CCPS), *Guidelines for hazard evaluation procedures*, 3rd Ed., Wiley (2008).
12. K. S. Kim and J. W. Ko, *Korean J. Chem. Eng.*, **22**(1), 26 (2005).
13. J. H. Yoo, H. S. Lee and J. W. Ko, *Korean J. Chem. Eng.*, **28**(2), 323 (2011).
14. C. K. Yoo, S. W. Choi and I. B. Lee, *Korean Chem. Eng. Res. (HWAHAK KONGHAK)*, **46**(1), 233 (2008).
15. J. W. Lee, D. Shin, J. H. Yoo, H. S. Lee and J. W. Ko, *Korean J. Chem. Eng.*, **25**(6), 1267 (2008).
16. J. B. Baek, *J. KOSOS*, **21**(4), 127 (2006).