INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 48 (2023) 36223–36239

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

A web-based decision support system (DSS) for hydrogen refueling station location and supply chain optimization

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HIGHLIGHTS

- A decision support system is developed for hydrogen refueling station location and hydrogen supply chain optimization.
- Design requirements and features for DSS were obtained via interviews and literature reviews.
- The two-stage model finds the best HRS locations and HSC network.
- Nationwide HRS and HSC solutions for the years 2025 and 2030 in the Republic of Korea are demonstrated.

ARTICLE INFO

Article history:
Received 12 April 2023
Received in revised form
4 June 2023
Accepted 6 June 2023
Available online 20 June 2023

Keywords:
Hydrogen fuel cell vehicle
Hydrogen refueling station
Hydrogen supply chain optimization
Decision support system

ABSTRACT

This study presents a novel web-based decision support system (DSS) that optimizes the locations of hydrogen refueling stations (HRSs) and hydrogen supply chains (HSCs). The system is developed with a design science approach that identifies key design requirements and features through interviews and literature reviews. Based on the findings, a system architecture and data model were designed, incorporating scenario management, optimization model, visualization, and data management components. The DSS provides a two-stage solution model that links demand to HRSs and production facilities to HRSs. A prototype is demonstrated with a plan for 2025 and 2030 in the Republic of Korea, where 450 to 660 stations were deployed nationwide and linked to production facilities. User evaluation confirmed the effectiveness of the DSS in solving optimization problems and its potential to assist the government and municipalities in planning hydrogen infrastructure.

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https://doi.org/10.1016/j.ijhydene.2023.06.064

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Introduction

As the number of hydrogen fuel cell vehicles (HFCVs) is growing, planning hydrogen infrastructure has become essential to meet the fuel demand and hydrogen supply. Especially the location of the hydrogen refueling station (HRS) is critical for the accessibility of the drivers. Moreover, unlike electric vehicle refueling stations, HRS must be effectively linked to a hydrogen production facility (PF). This study proposed a two-step solution approach for nationwide hydrogen supply chain (HSC) design: deciding the HRS location considering the area demand and optimizing the HSC for sustainable operation of the stations. Significant studies have been conducted on the HRS location model [1–9] and HSC design [10–15].

The major challenge to solving HRS location and HSC design problems is considering various conditions and parameter values in the solution model and conducting multiple experiments. Traditional location models such as the covering model, *p*-median model, and flow-refueling location model (FRLM) are used [16]. The location selection results vary from the scope of the targeted area, the total number of candidate sites, and demand estimation. On the other hand, the HSC network design investigates the optimal selection of hydrogen production and delivery methods. The HSC optimization model determines the type of resource, production technologies, storage type, and mode of transportation [17]. Various options on each echelon differentiate supply volumes and the cost of hydrogen in the long term. Therefore, possible scenarios are created and compared to choose the best solutions for the location and optimization problems. However, it is difficult to conduct and review multiple scenarios for decision-making because designing a methodology to solve both HRS and HSC optimization problems is challenging, even for a single scenario.

In this context, a decision support system (DSS) can help planners to generate possible scenarios and compare them with visualized results. In general, DSS is an efficient tool that can analyze and demonstrate different schemes and designs in decision-making. Users can directly import data through a graphical interface, perform analysis, and visualize results. Spatial DSS (SDSS) with geographic information system (GIS) software is frequently used, particularly for solving facility location and logistics problems [18]. SDSS is characterized by its utilization of spatial information, including geographical coordinates, to analyze and visualize spatial relations such as proximity, overlap, containment, and distribution pattern [19]. Regarding HRS deployment, Kuby et al. [20] used the FRLM to determine the vehicle's driving range and the number of charging facilities. They integrated the network data in the model into GIS and presented the results in maps and graphs. With the same FRLM model, Kim [21] developed a DSS that allows users to calculate the origin-destination (OD) traffic based on the socioeconomic characteristics of the departure point. The system calculates the amount of traffic change at each site to show the best location of the refueling station. Moreover, the California Hydrogen Infrastructure Tool (CHIT) developed by the California Air Resources Board (CARB) provide HRS deployment scenarios with a comparison function between the operating HRS and newly proposed sites in the model, which could support business operators [22]. Related to the HSC, Dagdougui [23] developed a DSS to place an on-site production system in northern Italy. The possibility of producing hydrogen with renewable energy was measured by considering each region's potential wind and solar power. Similarly, Kim and Kim [24] analyzed and solved the hydrogen supply system with wind energy in Jeju Island, Republic of Korea. Wu et al. [25] examined the location of hydrogen storage with wind power in China. Baufume et al. [26] suggested GIS based scenario calculations for a nationwide hydrogen pipeline infrastructure in Germany. Several tools have been developed and aided actual planning, for example, the Spatially and Temporally Resolved Energy and Economy Tool (STREET) and the Scenario Evaluation and Regionalization Analysis (SERA) tool developed by the US Renewable Energy Laboratory. The STREET model targeted optimizing investments and minimizing the environmental effect of the hydrogen infrastructure development, therefore considering the hydrogen production aspect, such as resource and supply location and routes [27]. The SERA model provides both supply and demand models of the hydrogen market by integrating the cost variables and options of hydrogen production technology into the model [28,29]. These tools have been developed and utilized for scenario creation and analysis; nevertheless, user-centered DSS development related to HRS or HSC optimization is still limited [30].

More recently, there has been a growing preference for web-based DSS, allowing the integration of previous SDSS tools into mainstream IT decision support solutions [31]. The key advantage of web-based DSS is its easy accessibility, as the client user interfaces are independent of the actual processing of the DSS, which provides greater flexibility in targeting different user groups. In contrast to traditional GIS-based SDSS, which are complex systems requiring sophisticated hardware and infrastructure, web-based systems allow for multiple user access and increased computing capacity to handle large amounts of data, often in real-time [32].

Therefore, this study develops a novel web-based DSS for HRSs and supply chain optimization. We followed a design science research (DSR) approach, first to investigate the design requirements of DSS specific to HRS and HSC optimization. In the process, we aimed to develop a working system prototype that solves both HRS and HSC problems. We designed the system with actual user preferences by inviting the hydrogen experts for interviews and evaluation. The system provides GUI that allows users to customize input scenarios, configure optimization settings, analyze visualized results, and store examined scenarios into the database. Decision-makers can easily examine various scenarios on our web-based DSS without specialized knowledge of programming skills and optimization methodologies.

The design and demonstration of DSS are based on the national map of the Republic of Korea. The number of HFCVs in Korea reached 10,000 in 2020, the highest share of 29% among the countries [33]. The same year, the government announced a national roadmap that would supply 850,000 hydrogen cars by 2030 and 2.9 million by 2040 and build 660 HRSs by 2030 and 1200 by 2040 [34]. However, a comprehensive plan for the specific location and supply method for the HRS has not been presented. Thus, there is also a need for a suitable deployment strategy and methodology considering the existing government plans and HFCVs development trends.

The overall process of DSS development is presented in the following sections. Section 2 summarizes the design requirements and features extracted from the interview and literature. The optimization model is explained in Section 3. Section 4 and Section 5 illustrate the modeling and development of the DSS system, respectively. The demonstration of the system with test scenarios and user evaluation is in Section 6. The study concludes in Section 7, indicating DSS's effectiveness and some limitations.

Design requirements and features

Design science research approach

This study follows the design science research (DSR) approach from Peffers et al. [35], who suggested its application in information system research. The method originally creates and evaluates IT artifacts with a framework to solve organizational problems in product development [36]. The overall process follows design-and-evaluate iterations from identifying current issues to finding objectives of a solution, from designing and developing the artifact to showing the demonstration and evaluation. It ends with external communication [37]. This approach is widely used for DSS development [38]. In this study, the major objective of using the framework is to develop DSS by systematically analyzing the design requirements for locating HRSs and optimizing HSC. The overall research process is shown in Fig. 1.

We conducted a series of workshops with five hydrogen experts from representative public institutions for hydrogen to identify the key features of DSS and system preferences. Participating organizations, namely H2Korea (hydrogen-related consulting organization) and the Institute for Advanced Technology (a non-profit organization for industrial technology research and development) are in the hydrogen optimization research project group funded by the Ministry of Trade, Industry, and Energy of Korea.

Throughout a series of seven workshops, ideas were generated, prototypes were designed and developed, and feedback was incorporated. The initial workshop (session 1) focused on gathering basic requirements by brainstorming and open discussions on the necessary models, data, and visualization methods for the DSS. The ideas collected were then categorized as issues for further discussion and investigation. Subsequent workshops (sessions 2–6) involved presentations and discussions of survey findings along with the progress of system design and development with decisions on how to incorporate them into the DSS. The final session (session 7) concluded with finalizing the prototype design.

Subsequently, three feedback sessions (sessions 8–10) were conducted, inviting users, including officials from public and private companies, to evaluate the system's effectiveness and identify areas for future improvement. The participants were recruited through H2Korea. After a brief showcase and demonstration of the DSS, open-ended questions were posed to gather their opinions. We provided these workshop results within the chapters of this study.

Key design requirements and features

Design requirements and features for the DSS were identified through expert interviews and literature surveys during the workshop. We have gathered expert opinions from multiple workshop discussions, which were summarized and categorized based on their similarities by the researchers into five major groups. Moreover, literature surveys were initially conducted during the workshop, searched with the combination of terms ‘hydrogen, refueling station, supply chain, optimization, DSS’ from Scopus and Web of Science, and also from Korea Citation Index and DBpia for domestic studies. The design requirements and features relevant to the final result of DSS are shown in Fig. 2.

First, the DSS is primarily used for long-term country-level planning. During the interview, potential users were identified

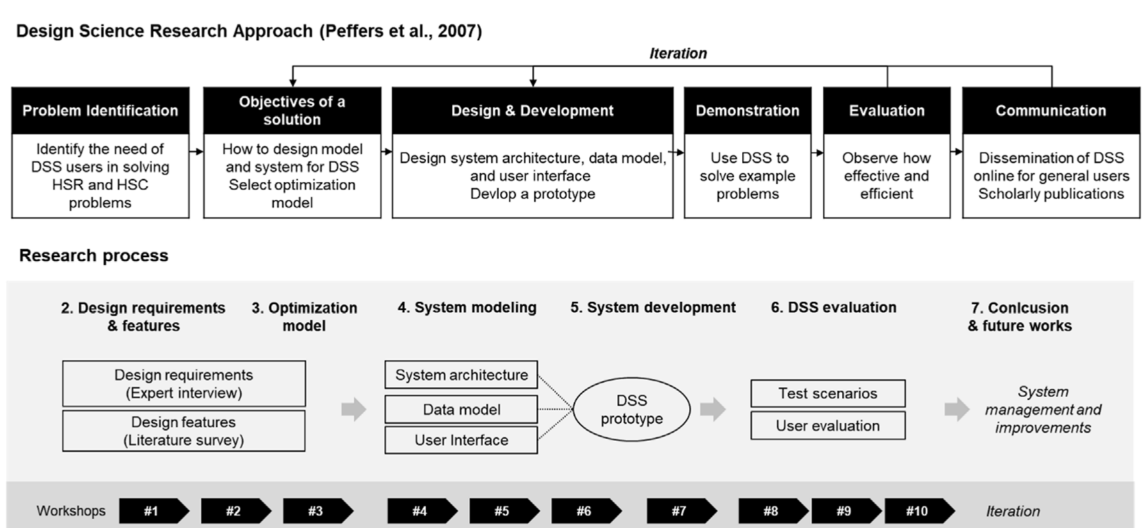

Fig. 1 – Design science research framework.

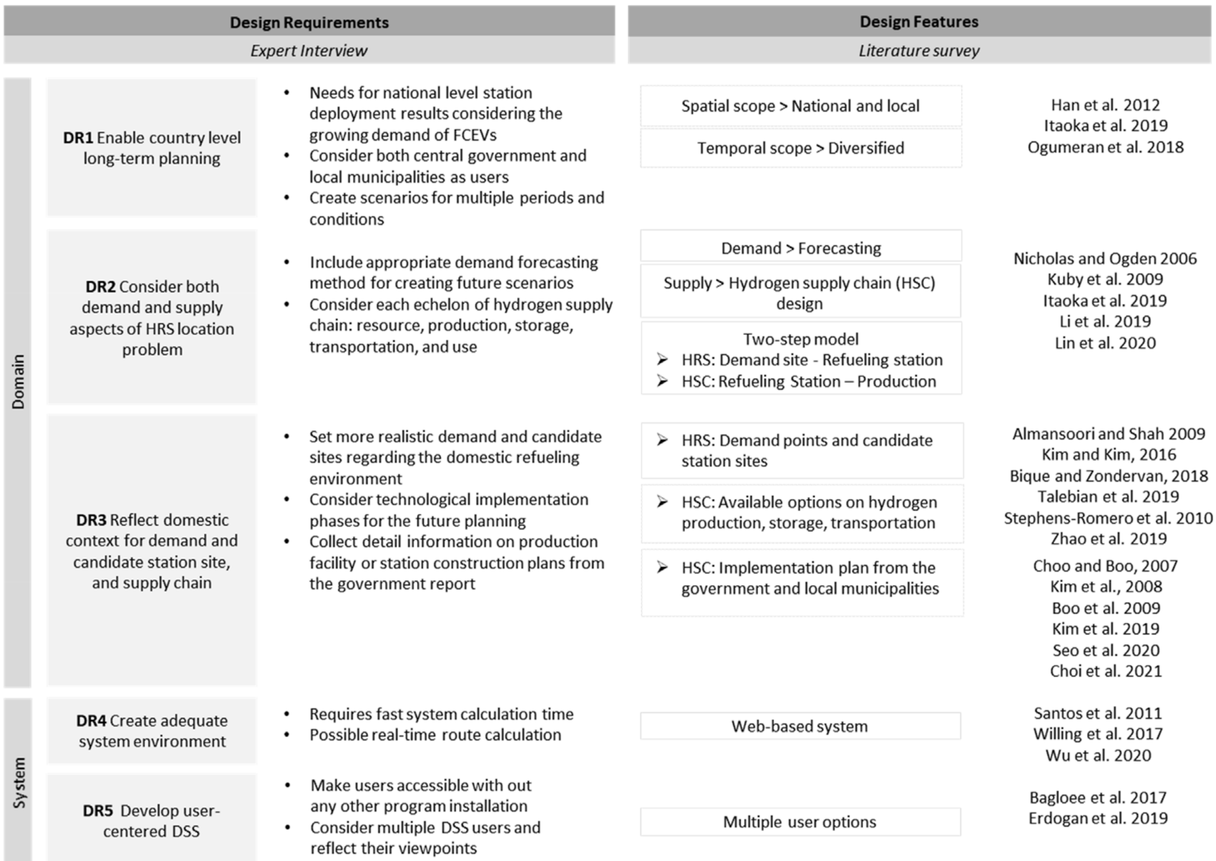

Fig. 2 – Design requirements and features identified from the interview and previous research.

as hydrogen-related national institutions, local governments, and related businesses. When utilizing a DSS, the spatial and temporal scope of the problem must be established first. In the case of HRS problems, the spatial scale is typically nationwide [39], within major cities [4], or both [5]. Additionally, users seek solutions from various temporal perspectives. For instance, the HRS problem may involve determining the next station location or analyzing long-term plans over 20–30 years, considering changes in demand. Similarly, HSC scenarios track conditional changes such as hydrogen production cost over the years [14,40]. Thus, a DSS must enable users to set national or local level analysis and diversify the temporal range in the scenario setting.

Secondly, it is necessary to reflect both demand and supply aspects in the HRS location model. The objectives of HRS and HSC problems are setting the optimal location of the stations for vehicle users and transporting sufficient hydrogen to the station. However, often it takes too much time to solve both demand and supply in the model all at once. Thus, a two-stage model should be employed in DSS, and each module should contain the most relevant variables and data. Various methods can be used to forecast and calculate regional hydrogen demand, with the number of the population [1], socioeconomic factors [7,41], car sales [5], or traffic volumes [2]. Also, hydrogen demand varies depending on the vehicle type, such as passenger cars, taxis, trucks, and buses [8,42]. Therefore, the demand module for DSS should include essential variables and data for users to calculate the demand in the targeted area. In addition, DSS should incorporate additional modules for HSC design. Various configurations include hydrogen production methods, hydrogen types, storage facilities, and transportation modes. The HSC network refers to the entire process of hydrogen raw material, production, storage, transportation, distribution, and use. It can be divided into hydrogen production and transport stages [17]. In the production stage, various technological production methods can be utilized using multiple energy sources, and the produced hydrogen can be converted into gas, liquid, solid, and other forms. In the transportation phase, the fuel type, either gas or liquid, determines the transportation modes and required refueling facilities.

Thirdly, the DSS should reflect domestic conditions to improve the solution accuracy. To do so, it is critical to identify the most suitable and realistic candidate sites, including gas stations, and utilize the existing liquefied natural gas (LNG) stations and compressed natural gas (CNG) stations. The model should consider these sites along with the safety inspection results. Moreover, the scenario should account for the timing of technological implementation. Prior studies conducted in Korea [43–48] suggest that strategic implementations of HSC be considered in line with introducing new technology and commercialization. Presently, hydrogen fuel can be produced in either liquid or gas form, utilizing reformation or by-product methods, with transportation possible through tube trailers or tank trucks. According to the interview, the proportion of renewable energy-based hydrogen usage is expected to increase, leading to decreased power generation prices and reduced water electrolysis production costs. Moreover, if domestic hydrogen production is insufficient, hydrogen can be imported from overseas. This information can be reflected in the DSS by providing input data on the arrangement condition at the time of technology introduction or by designing selection options in the scenario setting. Additionally, government and local municipality plans could serve as useful references, providing details on the construction of production facilities, transportation methods, and expected costs.

Lastly, the two system requirements are as follows. First, it is necessary to set the optimal system development conditions. Especially the solution model requires a system that can simultaneously reflect changes over time by considering the HSC and HRS. Also, the preference for route optimization considering real-time traffic was mentioned in the interview. These requests can be well managed with a web-based system [49–51]. Second, user-centered DSS development is required. Thus, the system should contain multiple options and easier access. In other words, DSS should incorporate the different viewpoints of users, such as system managers and general users [52], and provide access without installing any additional program [53].

Optimization models

DSS aims to provide optimized solutions for various scenarios of decision-makers. The solutions of DSS include optimized locations of HRSs, selection of proper PFs, and HSC network from PF to HRS and from HRS to demand points. The proposed DSS decomposes the entire problem of the HSC into several subproblems and uses mathematical models to solve the subproblems.

As Kim et al. [42] pointed out, solving the nationwide whole supply chain problem as one mathematical model is intractable. Therefore, as shown in Fig. 3, we determined to solve the design problem of HSC through two stages: demand and supply fulfillment stages. In the demand fulfillment stage, DSS decides the location of HRSs to maximize coverage of HFCVs and assign HFCVs to HRSs such that the total distance for refueling HFCVs can be minimized. Three subproblems for general roads, expressways, and hydrogen buses are solved in the demand fulfillment stage. The solutions for the subproblems are used in the supply fulfillment stage, as shown in Fig. 3. In the supply fulfillment stage, DSS decides the allocation between PFs and HRSs selected in the demand fulfillment stage to minimize the transportation cost. Note that the subproblems in the demand fulfillment stage can be solved in parallel because the HRSs are independent in general roads, expressways, and buses. However, the solutions of the subproblems must be integrated into the supply fulfillment stage because the HSC shares the supply with the HRSs for the three components.

Optimizing the location of HRSs belongs to the facility location problem. In general, most mathematical models solving facility location problems are classified into three categories: the covering model, the p-median model, and the flow-refueling location model (FRLM). The covering model, such as set covering and maximal covering (Max cover) problem [54], finds the optimal location of facilities to cover demand points. The p-median model finds the optimal location of facilities to minimize the distance between facilities and demand points [55]. The FRLM focuses on an origin-destination flow and finds the optimal location of facilities to maximize the flow that can be covered by deployed facilities [56]. For a more detailed review of the three models, see Kim et al. [42].

This study used Max cover and p-median models for each subproblem at the demand fulfillment stage. Given the number of HRSs to be installed, the Max cover model targets the maximum coverage for HFCVs. On the other hand, the p-median model in this study determines the deployment of HRSs and assignment HRSs and HFCVs to minimize the total distance for refueling HFCVs while the maximum coverage determined by the Max cover model is guaranteed. We used the framework and mathematical models proposed by Kim et al. [42] for the demand fulfillment stage. In this paper, we summarize the models briefly.

Max cover model

Objectives.

- Maximize number of HFCVs assigned to HRSs

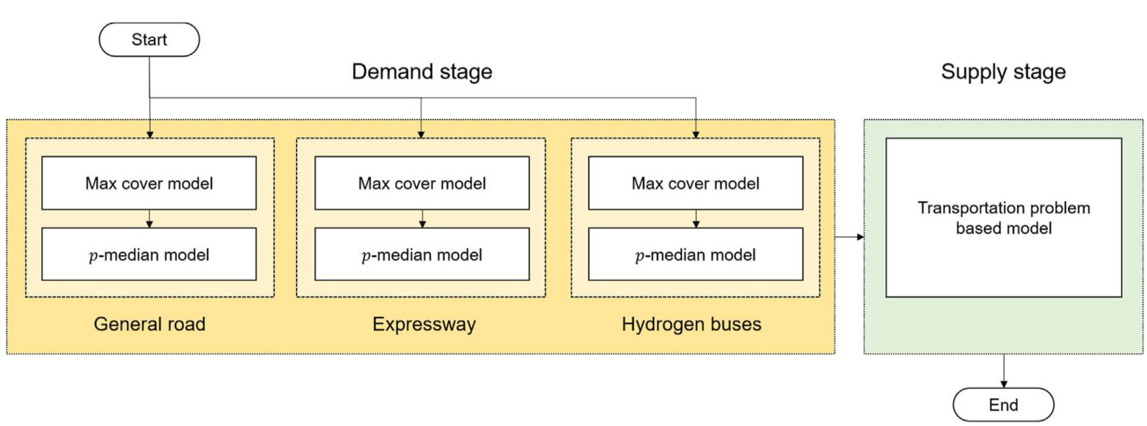

Fig. 3 – Optimization framework in DSS.

Constraints.

- Total number of installable gas and liquified HRSs is given
- Total number of installable gas and liquified hydrogen chargers is given
- Existing HRSs must be selected
- Eligibility constraints (e.g., distance restriction between demand point and HRS candidate site, availability of liquified hydrogen charger at HRS candidate site)
- Demand size at each demand point is given

p-*median model*

Objectives.

- Minimize the total distance between HRSs and demand points

Constraints.

- Same as the Max cover model
- The coverage of HFCVs demand obtained by the Max cover model must be guaranteed

After solving the demand fulfillment stage, the deployment plan of HRSs and assignment of demand points to HRSs are fixed. Therefore, the amount of hydrogen required for refueling HFCVs is determined for each selected HRS. Considering the given location of selected HRSs, the assignment of hydrogen amount from PF to HRS is determined in the supply fulfillment stage. In this stage, the total transportation and installation costs of additional PFs are minimized. The problem is a kind of transportation problem, a well-known model that minimizes transportation costs (e.g., travel time or distance) from supply points to demand points while the amount of supply and demand is satisfied [57]. The problem considered by DSS is a multi-commodity transportation problem because we deal with both gas and liquified hydrogen. In addition, the DSS can determine the locations and capacities of on-site HRSs when the total amount of hydrogen supply is less than the total amount of demand. On-site HRS is a HRS that can produce and transport hydrogen to nearby stations. Detailed mathematical models will be reported in another publication in the near future [58].

Transportation problem-based model

Objectives.

- Minimize the weighted sum of total transportation cost between PFs and HRSs and construction cost of additional on-site HRSs

Constraints.

- Existing PFs must be selected
- Production and transportation capacity of PFs must be satisfied
- Eligibility constraints (e.g., availability of gas and liquified hydrogen transportation between PFs and HRSs)
- Flow conservation constraints at each HRS (Incoming and outgoing flow amounts at HRS must be balanced)

Through these mathematical models, the DSS can determine the location of HRSs, assignments between HRSs and HFCVs, and assignments between HRSs and PFs, considering the construction of additional on-site HRSs to serve as PFs. The proposed models can optimize partial problems by configuring the options, such as only considering HRSs for general roads and assignment between HRSs and HFCVs. Users can set the maximum computation time. A nationwide HSC design problem considering general roads, expressways, and buses can be solved in a given time. More detailed and formal mathematical models and solution approaches are described in Lee et al. [58].

System modeling

System architecture

The architecture of the DSS system is shown in Fig. 4. The system consists of three layers: 1) presentation layer, 2) business logic layer, and 3) data storage layer [59]. The

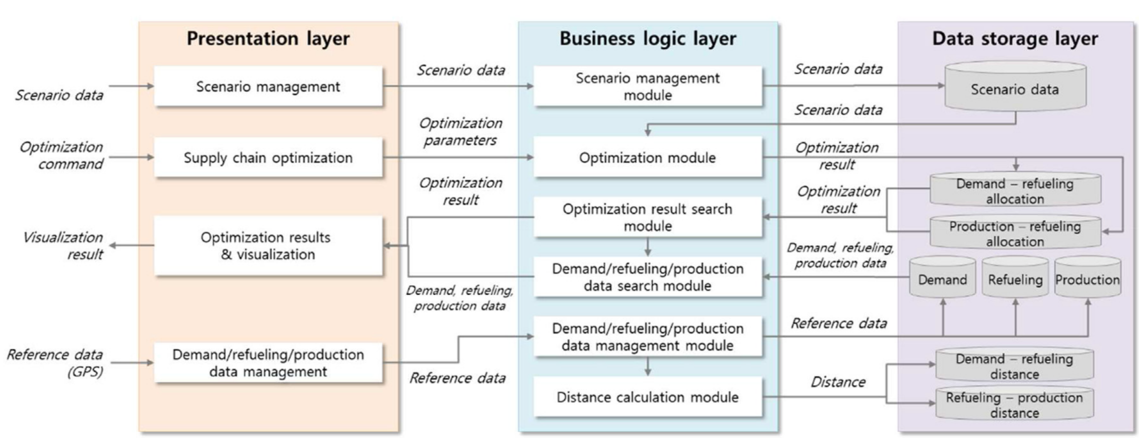

Fig. 4 – System architecture.

presentation layer receives commands from the user and transmits them to the business logic layer. It performs the role of visualizing and showing the obtained results from the business logic layer to the user. The business logic layer transfers the data passed from the presentation layer to the data storage layer and instructs it to be stored. Additionally, it communicates the output to the presentation layer. The data storage layer manages the data required to perform the DSS function, controls the data delivered from the presentation layer, or retrieves the retained data and delivers it to the business logic layer.

Presentation layer

The scenario management component receives scenario data (e.g., scenario name, scenario year, HRS candidate site, PFs, demand site) from the user and performs primary data verification. When verification is completed, the scenario data for which the first verification has been completed is merged and transferred to the business logic layer. The business logic layer provides error messages to the user in case of data errors.

The HSC optimization component receives the user's optimal deployment execution command, target scenario ID, and optimal deployment parameters (e.g., the number of HRS, the capacity of HRS, and transportation costs). Then, it is delivered to the business logic layer for optimization.

The HSC optimization results and visualization component receives detailed information on demand sites, HRS candidate sites, and PFs from the business logic layer and visualizes the information using a map.

The demand/refueling/production data management component plays a role in receiving the reference data information of the demand, HRS, and PF from the user and delivering it to the business logic layer. The reference data refers to the essential dataset users import when the information on demand, HRS, and PF sites is insufficient. The demand reference data compromises pre-generated data on the volume of hydrogen demand obtained from the Korean government's policy documents. The HRS reference data includes GPS coordinates, installation status and year, and capacity. Similarly, the reference data for PF contains GPS coordinates, production capacity, and hydrogen types such as gas and liquid.

Business logic layer

The scenario management module verifies the scenario data acquired from the presentation layer and reconfigures it into an appropriate format for storage. Subsequently, the module conveys the processed data to the data storage layer and directs it to be stored.

The optimization module is accountable for optimizing the placement of HRSs and the HSC plan under scenario data. Upon receiving optimization parameters from the user through the presentation layer, the module retrieves the relevant scenario data and applies the optimization logic to the retrieved data. Subsequently, the optimal arrangement is saved in the database for future use by the user.

The optimal result search module retrieves and provides the optimal results to the user. The module receives the scenario ID from the presentation layer as a key input. Leveraging the scenario ID, the module searches for the optimal arrangement result stored in the database. Then, the retrieved optimal arrangement outcomes are transmitted to the presentation layer. Additionally, the optimal result search module delivers the optimal result to the demand/refueling/production data search module, which allows the latter to provide detailed information regarding demand/refueling/production within the optimal result.

The demand, refueling, and production data search module searches the database for information on the relevant demand site, HRS candidate site, and PF and then delivers it to the presentation layer.

The demand/refueling/production data management module stores the reference data information received from the presentation layer in the database. The reference data information is transmitted to the distance calculation module, which calculates the distance between the stored data and newly added reference data. It includes information on the demand/refueling station candidate/production facility.

Lastly, the distance calculation module uses the received reference data information to calculate the distance and stores the result in the database.

Data storage layer

The entity relation diagram (ERD) in Fig. 5 shows a data structure of DSS. The ERD method is often used for modeling data using relationship information between entities [60]. The data model comprises eight entities: one scenario, three locations (hydrogen demand point, HRSs, and PFs), two distances (from demand to HRSs and PFs to HRSs), and two allocations for each optimization result. The scenario entity includes user-defined scenario information such as the name, year, and target region. The location entities represent the latitude and longitude reference data information where the demand occurs or the HRSs and PFs are located. Demand and HRS entities are divided into the general road, expressway, and bus. Sub-entities for each type are additionally configured. The distance entities manage the actual distance and travel time between two points and use this distance information for optimization. Lastly, the allocation entities manage the connection relationship derived from the optimization result.

System development

Development specification

Development specification is shown in Fig. 6. AngularJS which is a single page application (SPA) framework based on hypertext markup language (HTML), cascading style sheets (CSS), and JavaScript were used for presentation layer development. For the business logic layer, node. js and python were used. While node. js connects and manages the database, the hydrogen optimization engine developed in python was connected and executed, then the optimization results were displayed with node. js to the database. Additionally, the part developed with node. js and python was implemented as an application programming interface (API) so that data could be

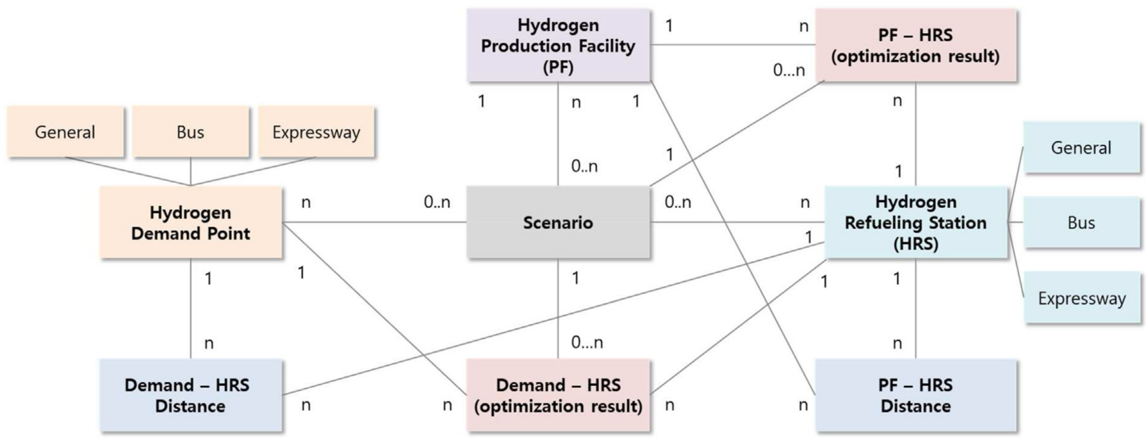

Fig. 5 – Data model.

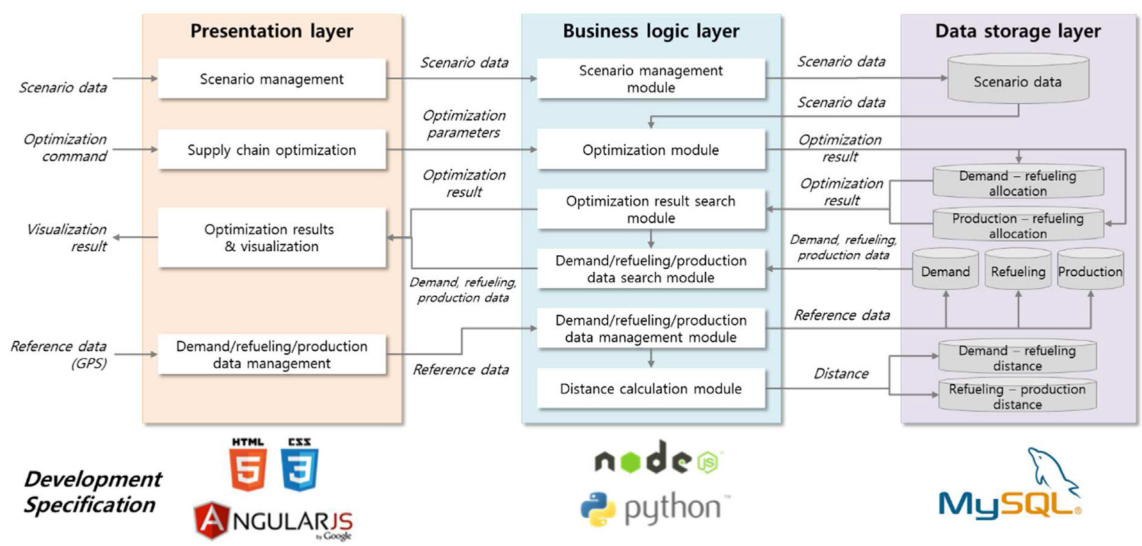

Fig. 6 – Development specification.

processed through hypertext transfer protocol (HTTP) request in the presentation layer. The database was built using MySQL.

User interface and functions

The main screen of the DSS and the user functions are shown in Fig. 7.

In the scenario management window (1), users can create a new scenario or select an existing one previously saved. To create a new scenario (1-1), the user can enter the scenario title and choose the year, type, and problem. The type includes general roads, expressways, and buses, then select two-step solutions for demand to station and station to supply. Also, scenarios can be loaded and deleted. At the demand estimation (1–2) stage, the user can either upload the existing data file or use system calculation. The input of data is required, such as population statistics by administrative district, the number of HFCVs planned by the state, and annual hydrogen consumption data by transportation vehicle type. These data are provided as comma-separated values (CSV) files with the location of demand points. Users can also select the target area at the state level. For HRS options (1–3), the user can input the location of station candidate sites and pick the target area at the state level. For supply information (1–4), the user can input the location of the PF. Additionally, the user can decide whether to include on-site HRS as PF if the amount of hydrogen is insufficient from the existing PF.

Optimization (2) is automatically calculated in the system. The users can check the processing status through the progress bar. Prior to calculation, users can also type in or edit the value of optimization parameters (2–1) relevant to station, vehicle, road, optimization, and experiment conditions. The values are initially provided with default data.

The visualization section displays the scenario results (3). The quantities of demand estimations and selected HRSs on the map (3–1) are provided as heat maps. Other functions, such as blur or zoom in and out, are provided for user convenience. The user can change the visual settings through the icon options (3–2), which display settings show the result for each type and problem. The icons of the stations and the connection links will be shown on the map when selected.

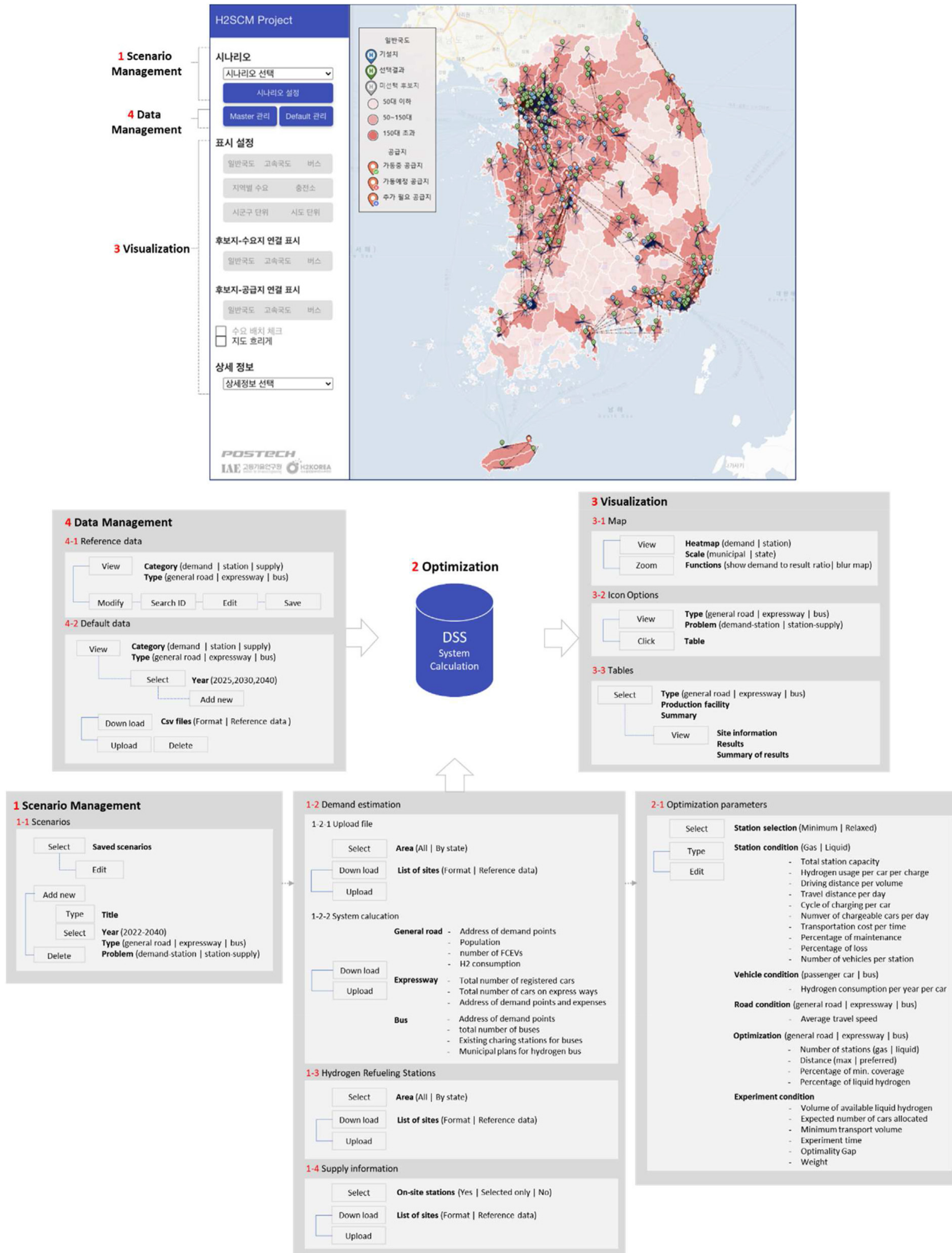

Fig. 7 – User interface and functions.

Users can obtain detailed information and results from the summary tables (3-3). For example, the station information includes the name of the station, location of the administrative district or highway direction, hydrogen form such as gas and liquid, and maximum number of vehicles and hydrogen capacity. The information on the production site includes the year of construction, minimum and maximum production level, construction cost, annual operating cost, unit production cost, production method, and manufacturing method. Users can also check the summarized result of the links between HRSs and production, such as the total number of operating units, the total number of allocated vehicles, and the percentage of utilization.

In addition to user input, the administrator can manage reference and default data through data management options (4). Reference data (4–1) can be updated to reflect changes by managing IDs of demand points, HRS candidate sites, and PF lists. For example, administrators can add new IDs in case additional stations are constructed. Moreover, administrators can change the default data (4–2) provided in each designated year, as demand and supply can change over time.

DSS evaluation

Demonstration

Two scenarios were established and demonstrated to evaluate the performance of the DSS, as shown in Table 1. We have selected these scenarios to effectively demonstrate the functionality of the DSS, considering the current availability of data. The model inputs include hydrogen demand, supply, and station configuration. In scenario A, projected for 2025, the total hydrogen demand for 200,000 passenger cars, 4600 buses, 100 taxis, and 900 trucks was estimated at 79,201 tons per day. In Scenario B, projected for 2030, the demand would increase to 377,350 tons per day to satisfy the fuel needs of 835,000 cars, 20,000 buses, 10,000 taxis, and 10,000 trucks. Hydrogen production can be either a by-product or steam reforming. The production facility includes existing 20 to 21 PFs and on-site HRSs serving as small hydrogen production bases which the number will depend on the HRS selection prior to HSC optimization. Initially, 750 HRSs possible for on-site production if hydrogen is insufficient from the existing PFs. The hydrogen type is gas or liquid, and the transport methods are tube trailers and tank trucks. Transportation costs 1 Korean Won (KRW) for gas and 1.527 KRW for liquid hydrogen. In 2025, 450 HRSs will be installed, with 660 planned for 2030. The maximum number of stations by type is 450 for gas and 170 for liquid in 2025, which means that some candidate sites cannot install liquid hydrogen chargers. The default capacity per station is set at 0.5 tons per day, which the experiment will determine the total hydrogen volume for refueling and the actual capacity per station.

Results

The results of the DSS demonstration are presented in Figs. 8–10. Figs. 8 and 9 display the nationwide solution for general roads, expressways, and buses for Scenarios A and B. It provides an overview of the changes between the two scenarios. Additionally, a detailed depiction of the changes in demand-to-stations is in Fig. 10, focusing on the Seoul metropolitan region. Finally, Fig. 11 shows the results of station-to-supply with the selected PFs near the Seoul metropolitan region.

Fig. 8 displays the results of Scenarios A and B, the selected candidate sites and hydrogen supply to the stations. The detailed optimization results appear in summary tables (see Fig. 9).

In Scenario A, out of 7599 candidate sites, 224 stations were installed, comprising 157 for gas and 67 for liquid. Thus, 98.4% of the total 230,199 HFCVs can be charged, and the total transported hydrogen is 34 tons. The average travel time per vehicle is 13.24 min, and the average travel distance is 9.13 km. Among the sites on expressways, 128 stations were installed, meeting the demand of 99.6% of the total vehicles. As for the buses, 98 stations were established, reaching 95.7% of the total demand. The existing 20 PFs cover 98.7% of the total hydrogen demand from the HRSs, with a capacity of 245 tons for 320,412 vehicle units.

Similarly, in Scenario B, 326 of the 7615 potential refueling stations were installed, 315 for gas and 11 for liquid. Of the 1,220,720 vehicles, 67.9% can be charged, and the total transported hydrogen is 124.3 tons. The average travel time per vehicle is reduced to 2.9 min, and the average travel distance is 2.35 km. Moreover, 188 stations were installed on the expressways, covering 77.5% of the vehicle demand, while 146 stations accounted for bus demand, covering 40.5%. The existing 21 PFs cover 70.2% of hydrogen demand, totaling 703.7 tons for 1,205,704 vehicle units.

Table 1 – Test scenarios.

Options		Scenario A		Scenario B	
Year		2025		2030	
Demand Estimation	Passenger Cars	200,000 (car)	30,000 (ton)	835,000 (car)	125,250 (ton)
	Bus	4600 (car)	44,620 (ton)	20,000 (car)	194,000 (ton)
	Taxi	100 (car)	81 (ton)	10,000 (car)	8100 (ton)
	Truck	900 (car)	4500 (ton)	10,000 (car)	50,000 (ton)
	Total	79,201 (ton)		377,350 (ton)	
Hydrogen Supply Chain (HSC)	Production method	By-product/Steam reforming		By-product/Steam reforming	
	Production facility (PF)	20		21	
	Possible on-site HRSs	750		750	
	Hydrogen type	Gas	Liquid	Gas	Liquid
	Transportation mode	Tube trailer	Tank truck	Tube trailer	Tank truck
	Transportation cost	1 (KRW)	1.527 (KRW)	1 (KRW)	1.527 (KRW)
Hydrogen Refueling Station (HRS)	Max. Number of stations by type	450	170	660	70
	Default capacity per station	0.5 (ton/day)	0.5 (ton/day)	0.5 (ton/day)	0.5 (ton/day)
	Total number of stations	450		660	

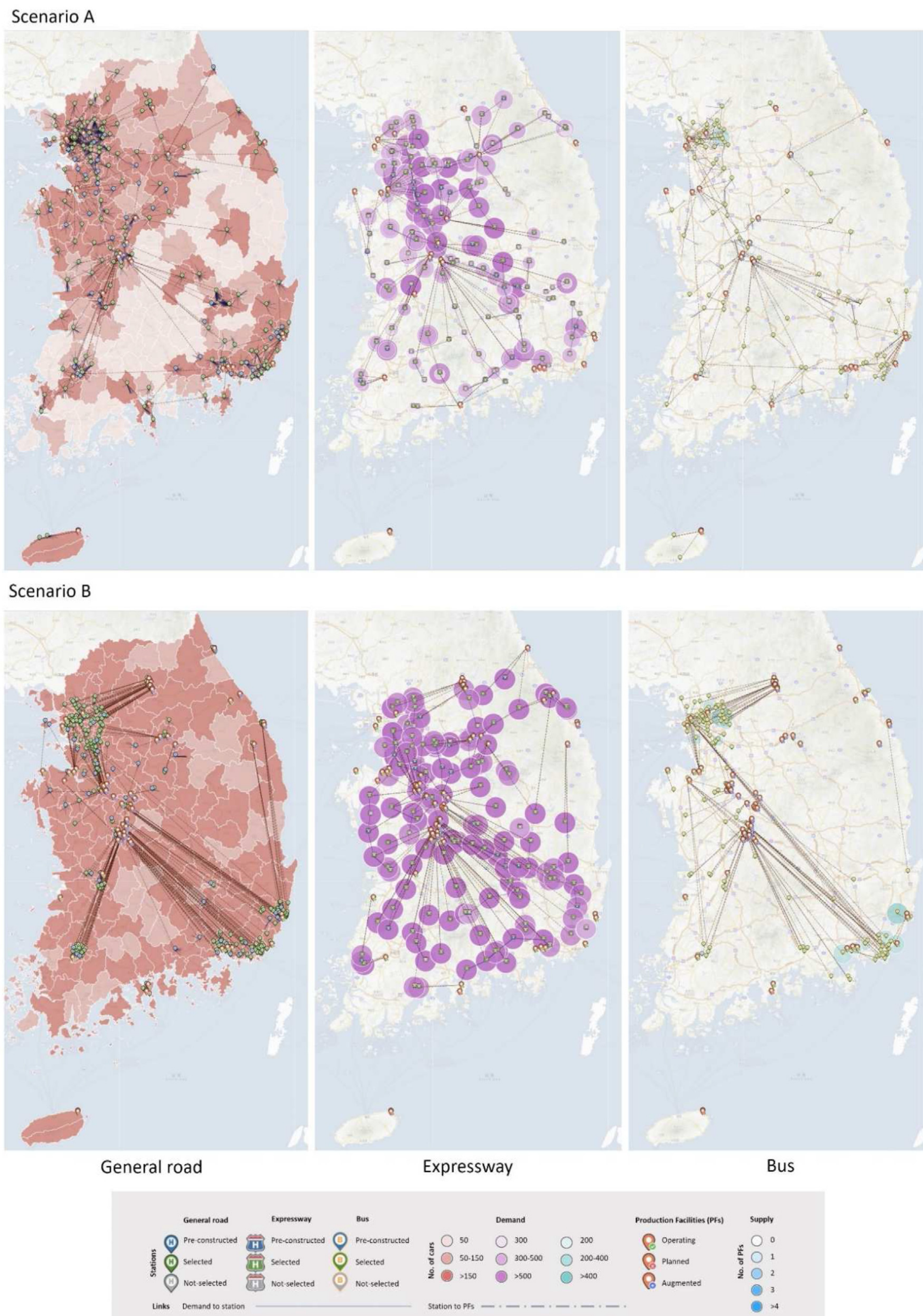

Fig. 8 — Results of test scenarios by general road, express way, and bus.

Fig. 10 illustrates the differences in demand points to stations between two scenarios in the Seoul metropolitan area. The allocated vehicles increased from 23,834 to 37,605. By 2030, the number of HRSs will grow from 14 to 18 stations, and the charging units, which can be installed in multiples, will increase from 60 to 180. The average utilization rate of HRSs rose from 88% to 100%, with a maximum of 100% and a minimum ranging from 50.3% to 99.7%. These results imply that

(Scenario A) HRS deployment and HSC optimization in 2025, national-level

	General road	Expressway	Bus	Production facility
No. of demand points	3,434	206	352	-
No. of candidate sites	7,599	206	416	8 (onsite)
No. of production facility	-	-	-	20
Total no. of charging facility	450			-
Total no. of selected stations	450			-
No. of selected stations	224	128	98	-
No. of gas stations	157	128	80	-
No. of liquid stations	67	0	18	-
Total no. of cars allocated	230,199	89,745	4,600	324,544
No. of covered demand (cars)	226,586	89,426	4,400	320,412
Ratio of covered demand	98.4%	99.6%	95.7%	98.7%
Total hydrogen transported (ton/day)	34	13.4	42.2	245
Travel time per car (min)	13.24	11.93	5.03	29.3
Travel distance per car (km)	9.13	11.93	3.84	48.9

(Scenario B) HRS deployment and HSC optimization in 2030, national-level

	General road	Expressway	Bus	Production facility
No. of demand points	3,452	210	368	-
No. of candidate sites	7,615	210	425	57 (onsite)
No. of production facility	-	-	-	21
Total no. of charging facility	660			-
Total no. of selected stations	660			-
No. of selected stations	326	188	146	-
No. of gas stations	315	188	97	-
No. of liquid stations	11	0	49	-
Total no. of cars allocated	1,220,720	476,171	20,000	1,716,891
No. of covered demand (cars)	828,675	368,927	8,102	1,205,704
Ratio of covered demand	67.9%	77.5%	40.5%	70.2%
Total hydrogen transported (ton/day)	124.3	55.3	77.8	703.7
Travel time per car (min)	2.9	3.66	0	50.4
Travel distance per car (km)	2.35	3.66	0	84

Fig. 9 – Summary tables of scenario results.

the stations not selected in 2025 were chosen in 2030 with an increased operation rate. For example, in 2025, a pre-constructed station (B0011416) had one gas-type charging unit allocated to 1317 vehicles, with a 100% utilization rate covering the entire demand in the area. By 2030, three additional stations were selected nearby, each with two gas charging units capable of serving 2439 vehicles per station.

The HSC network is presented in Fig. 11. In 2025, there will be three production bases in the vicinity of Seoul: the Sangam on-site HRS (P13), Incheon A utilizing the reforming method (P6), and Incheon B producing by-product hydrogen (P16). The production volume of the largest P16 ranges between 41 and 82 tons per day, providing gaseous hydrogen to 97 HRSs, consisting of 58 public roads, nine expressways, and 30 buses. With a 100% utilization rate of 82,003 vehicle units, the supplied amount equals the total production of 200,000 tons. P6 can provide gaseous hydrogen for two bus charging stations, with a total production of 3171 tons. In the case of the P13 Sangam on-site station, gaseous hydrogen will be supplied with a 100% operation rate on 9366 tons of 3840 vehicle units transporting to 5 HRSs, including four general roads and one bus station. In 2030, these PFs will operate at full capacity, and more PFs should be developed to meet the area demand. The primary supplier to the stations in Seoul metropolitan area will be in the east Gangwon region, where nine on-site stations should be augmented to cover the area demand. As the minimum production of 4.36 tons per day exceeds the 0.5 tons per day capacity as an on-site HRSs, the location should have additional large-scale production facilities to cover the area demand.

The DSS demonstration has shown that the system is fully functional in solving 2025 and 2030 scenarios in the Republic of Korea. Users can create and compare the change between the two scenarios, optimize nationwide solutions with regional-level analysis, and check the result on each point of interest. The results can be displayed in two steps: from demand to the station for HRS selection and from stations to the PFs for HSC optimization. The DSS also enables individual analysis of general roads, expressways, and buses.

User evaluation

We conducted user evaluations with the five experts who participated in the interview from the beginning of the DSS development. Checklists were provided to evaluate DSS and confirm the fulfillment of design requirements (see Fig. 12). Each feature is reflected in four categories of DSS layer components: scenario management, optimization, visualization, and data management. Users also evaluated the DSS qualitatively by answering open-ended questions regarding their experiences using the system. The results are as follows.

The DSS provides user convenience, scenarios and parameter versatility, and excellent visualization. The system allows for testing HRS locations, which can be checked directly on a map through visualization. This convenience is highly valued, as selecting station sites can be challenging.

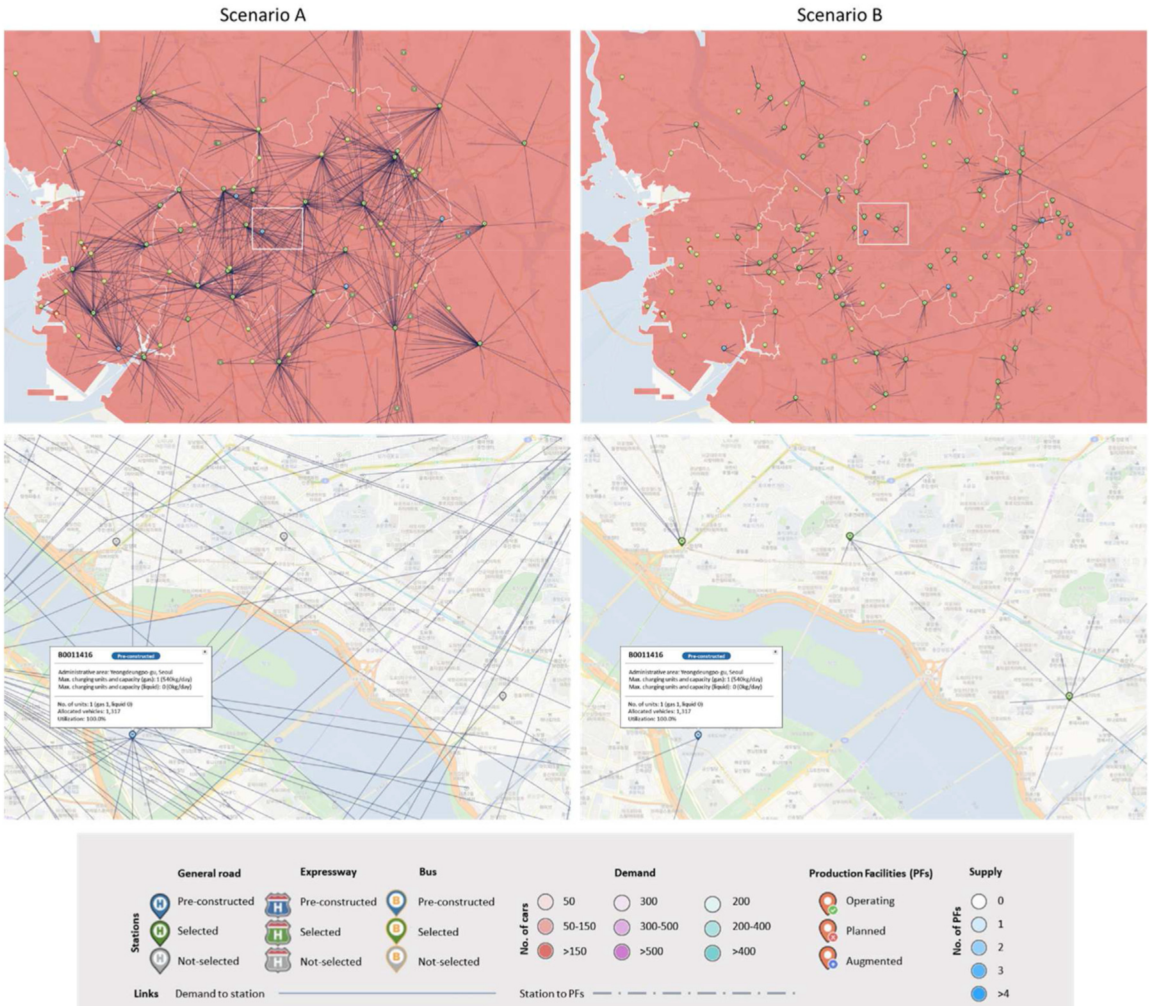

Fig. 10 – Results of demand point to stations in the Seoul metropolitan region.

Additionally, the DSS is suitable for deploying HRS, as users can create multiple scenarios and reflect various parameters. The detailed estimation of demand and supply and the diverse variable options allow for more accurate results in site selection. Lastly, the select function of the displays is convenient and useful.

However, the complexity and the need to supplement user experience were identified as disadvantages. With the versatility, the system becomes more complex for users. For example, the scenario-setting process requires several data inputs. However, too many options for changing various parameters make it difficult for general users, such as local government officials or business operators, to utilize the system. In addition, evaluators requested improvement in the process that detects and notices scenario input errors and provide information on the estimated time required while waiting for calculation processing.

Additionally, we held three feedback sessions with general users, including officials from private and public companies related to hydrogen. There were five municipal officers from the provinces; three experts from private and public companies in the hydrogen industry, six officials from the Korea Institute of Energy Technology Evaluation and Planning. H2Korea recruited these interviewees since they provide a major platform for connecting hydrogen experts in industry and academia in South Korea.

During the feedback session, the DSS prototype was briefly introduced and demonstrated; then, users had the opportunity to create scenarios hands-on and provide their opinions through open-ended questions. As a result, users pointed out five major points for the future development of DSS.

Firstly, users expressed the expectation for the DSS to offer a wider range of options for hydrogen supply. Specifically, they inquired about enhancing the DSS model to align with the direction of commercialization technology, considering the market's preference for liquefied hydrogen and pipeline supply. Additionally, users suggested that the DSS should be capable of calculating self-sufficiency options within the region for local vehicles. For example, in case of a production shortage, the DSS could suggest on-site hydrogen refueling stations using water electrolysis or extraction methods rather than moving toward the neighboring province.

Secondly, users requested additional information regarding HRSs. They mentioned including hydrogen price information and specifying the type of hydrogen, such as green hydrogen produced from renewable energy sources.

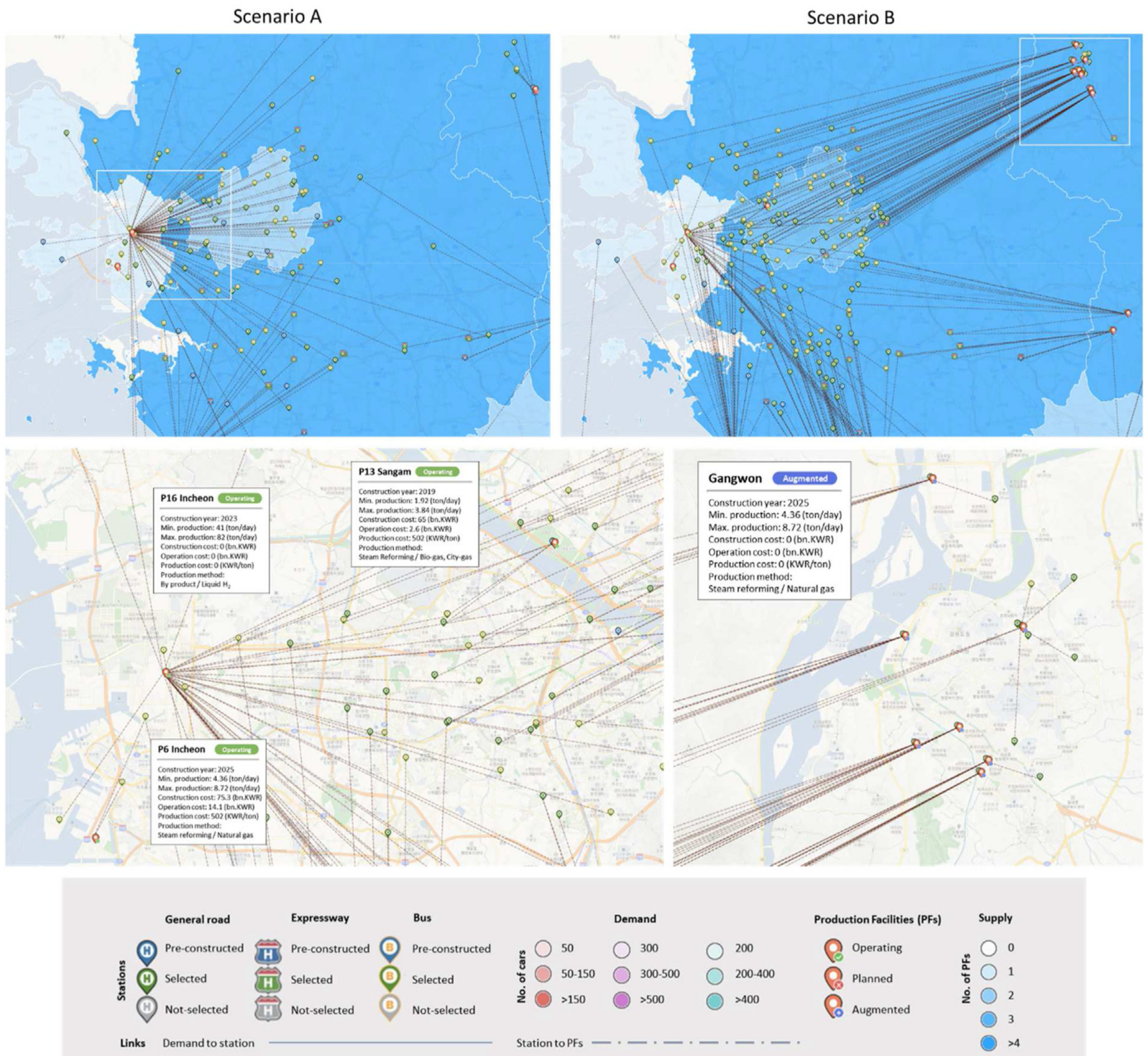

Fig. 11 – Result of HRSs to PFs in the Seoul metropolitan region.

Furthermore, when selecting candidate station sites, users emphasized the importance of considering factors beyond the existing safety review criteria, such as nearby civil complaints.

Thirdly, users emphasized the need for fast and updated data management within the DSS. They highlighted the importance of periodically updating the database to ensure system reliability, as accurate parameter inputs are essential. Users also expressed the desire for real-time data synchronization in further development of the DSS.

Fourthly, users recognized the potential of the DSS for business model determination and stressed the need for additional empirical evidence on business viability. They suggested that different supply prices for each supply base could assist decision-making processes for HRS construction agencies. Furthermore, gathering data on the number of hydrogen vehicles supplied near the station and the volume of vehicle traffic could provide insights into business feasibility, supporting policy establishment and station operation. However, users cautioned that the information disclosure level should be adjusted to avoid overly unfavorable exposure for business operators.

Lastly, the scalability of future scenarios was emphasized. Users discussed extending the time range of the DSS to 2050 and suggested including simulation capabilities for not only HRS site selection but also station operations.

Discussion

The developed DSS for HRS and HSC problems is a valuable tool for future hydrogen infrastructure development and offers several advantages to stakeholders. Firstly, the system is highly flexible, allowing users to create, modify, and compare scenarios easily. Users can generate an extensive range of scenarios to solve HRS and HSC problems and conduct experiments for decision-making under various conditions. Secondly, the DSS uses a holistic supply chain design process, which allows users a more systematic approach to hydrogen supply and demand estimation when deploying stations. The system also visualizes the locations of stations and production networks simultaneously. Lastly, the DSS offers a user-friendly interface, default data, and information obtained from the government plan until 2040. Users can customize the

Design Requirements	Design Features	Scenario management	Optimization	Visualization	Data management
DR1 Enable country level long-term planning	Spatial scope > National and local	☑ Designed to select scope of regions for problem solving		☑ Offered regional level heatmap and zoom in functions	☑ Included categories of the region based on the address
	Temporal scope > Diversified	☑ Offered default target years between 2020-2040 and options to type in values			☑ Offered default data by year
DR2 Consider both demand and supply aspects of HRS location problem	Demand > Forecasting	☑ Included demand calcuation module and estimated values	☑ Considered estimated demand as an input for HRS model	☑ Showed heatmap for demand	
	Supply > Hydrogen supply chain (HSC) design	☑ Included location and information of production facilities	☑ Considered stations to HSC model	☑ Showed heatmap for station deployment	
	Two-step model HRS: Demand site - Refueling station HSC: Refueling Station – Production	☑ Designed select function for problem solving	☑ Separated two different modules in system	☑ Designed two different linkages for showing result	☑ Managed two data modules for distance calculation
DR3 Reflect domestic context for demand and candidate station site, and supply chain	HRS: Demand points and candidate station sites	☑ Included exisitng gas stations and CNG supply chain as candidate sites	☑ Divided general road, expressway, bus	☑ Designed icons and functions in each category	☑ Divided pathways and entities in data model
	HSC: Available options on hydrogen production, storage, transportation	☑ Considered on-site station as production faciltiies and included options to choose in or out		☑ Offered detail information with icon tables	☑ Included production method, type of hydrogen, and capacity
	HSC: Implementation plan from the government and local municipalities				☑ Included construction year of facilities and future options
DR4 Create adequate system environment	Web-based system		☑ Utilized both node.js and python for fast processing in business logic layer	☑ Considered real-time base map and http request in presentation layer	☑ Used MySQL for data storage layer
DR5 Develop user-centered DSS	Multiple user options	☑ Offered upload and download functions for CSV files for easier user modification		☑ Created various map visualization and selection options	☑ Offered master data management for system managers

Fig. 12 – Checklist for user evaluation.

scenario with the updated data and plans, ensuring the system remains relevant and useful over time.

However, the user evaluation revealed that the DSS has become more complex to reflect various conditions. Therefore, it was necessary to improve the user interface according to its complexity. This problem was later supplemented by providing user guidance for scenario creation with a brief explanation of the background of DSS development. Still, the system can be updated in basic or advanced mode, differentiating the level of user-created options and selecting functions to allow easier access for general users.

The evaluation conducted with general users highlighted the importance of the practical usability of the DSS. Feedback from private and public companies involved in the hydrogen sector emphasized the need for the model to reflect real-world conditions accurately. There was also an expressed interest in demonstrating business viability and station operations. Additionally, the management of the DSS, particularly in terms of timely data updates, emerged as a key consideration for future development.

Conclusion and future developments

This study developed a web-based DSS that offers a convenient solution to the complexity of HRS and HSC problems. The DSS was designed through interviews and literature, resulting in an optimization model and system that delivers the necessary functions. The developed DSS provides a two-step solution model for analyzing long-term HRS and HSC problems at the country level. It enables users to create scenarios with variables and data that best fit domestic conditions and calculate demand and supply with various spatial and temporal range options. Furthermore, the web-based systems provide users with easier access and faster route calculation in real-time, distinguishing it from previous spatial DSS for hydrogen or location models primarily based on GIS. The findings from the interview and literature contributed to the improvement of the DSS design specific to HRS and HSC. The developed DSS has been pilot tested by several domain experts.

To further enhance the DSS, we plan to broaden our user base to include a more diverse range of opinions. Although five experts and 14 officials from hydrogen-related institutions were involved in the development and evaluation process, we recognize the need for a more extensive user base. Additionally, we intend to include more optimization factors, such as infrastructure scale and environmental considerations, including renewable energy use and carbon emissions. These features can be supplemented by future model improvement and scenario-setting function design to make the DSS more effective and efficient for solving HRS and HSC problems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (No. 20203020040050) and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2022R1A4A1019071).

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