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A review of hydrogen station location models

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HIGHLIGHTS

- The existing research efforts and works on hydrogen station location models are investigated.
- Detailed explanations, formulations and different constraints for these models are presented.
- Strengths, weaknesses and available solutions of these models are concluded

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ABSTRACT

Hydrogen is emerging as a zero-carbon energy source for the sustainable future. Hydrogen station plays the role of supplying hydrogen to fuel cell vehicles. However, the small number of hydrogen stations has become the biggest obstacle to the promotion of hydrogen energy. As an important infrastructure for the development of hydrogen energy industry, the hydrogen station will not be able to support the promotion and application of hydrogen fuel cell vehicles if it cannot form a large scale. In addition, the layout of the hydrogen station network should be reasonable to avoid waste of resources. The study of hydrogen station location models has significant economic, social and military implications. Considering these circumstances, this review investigates the existing research efforts and conducted a comprehensive overview of these works on hydrogen station location models. In this review, we divide the hydrogen station location models into several categories according to the spatial dimension of the facility, the structure of the planning area, and the number of objectives. We present detailed explanations, formulations and different constraints for these models. Finally, we conclude the strengths and weaknesses of these models and provide available solutions. To our best knowledge, this review might help researchers get a comprehensive understanding of related researches in the hydrogen station location.

Introduction

The layout of the hydrogen station network is critical to the commercial development of hydrogen energy and fuel cell vehicle industry. The facility location problem [1] refers to selecting the location of one or more facilities in the planning area to optimize the target, which is widely used in production, life, logistics, and military. This problem includes the locations of factories, warehouses, emergency centers, fire stations, garbage disposal centers, logistics centers, missile

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warehouses, etc. Site selection is one of the most important long-term decisions. The location of the facility directly influences the mode, quality, cost, and efficiency of the service [2]. The locations have definite impacts on the profit, market competitiveness, and fate of the enterprise. Therefore, the study of facility location has significant economic, social, and military implications.

According to the spatial dimension of the facility, the facility location problem mainly contains four categories [3]:

- Stereoscopic location.
- Plane location.
- Line location.
- Point location.

According to the structure of the planning area, this problem mainly contains three categories [4]:

- Continuous facility location.
- Discrete facility location.
- Grid facility location.

According to the number of objectives, this problem mainly contains two categories [5]:

- Single-objective facility location.
- Multi-objective facility location.

Hydrogen energy has a promising future for sustainable development. "Hydrogen Economy" has become a hot spot in recent years [6]. Compared to traditional energy sources such as petroleum, hydrogen has the advantages of high combustion value, rich in resources, and no pollution of combustion products [7]. Many researchers hold the view that the current large-scale commercial application of hydrogen energy requires the mastery of inexpensive and reliable hydrogen production, storage and transport technologies [8–11]. These technologies are the key to the development of hydrogen energy.

Many countries and regions are speeding up the construction of hydrogen stations nowadays. However, the promotion of hydrogen energy around the world has been blocked by the small-scale of the hydrogen station network [12]. High construction investment cost and operation cost make it difficult for hydrogen stations to achieve profitability without the government's policy support. The establishment of the hydrogen station network must precede the promotion of hydrogen fuel cell vehicles. Therefore, it is necessary to make reasonable plans for the locations of hydrogen stations. However, if the number of hydrogen stations is too little, the network would be inconvenient for the drivers. Otherwise, the cost of the refueling network would be prohibitive [13].

There are some unique constraints in selecting the potential locations compared to other usual facilities. Considering the characteristics of hydrogen, these potential locations for hydrogen stations should possess the characteristics of easy public access, high visibility, and safety. Therefore, most of the researchers consider the existing gasoline stations for potential locations of hydrogen stations [14–16], while some researchers consider open areas like public big-scale car parks for potential locations [17–19].

Model used

According to Section Introduction, the hydrogen station location models can be divided into several types according to the number of objectives, which can be seen from in Fig. 1.

From Fig. 1 we can clearly observe that the single-objective models include some basic facility location models. Flow-intercepting models associated with traffic flow are becoming more and more popular. Additionally, the multi-objective model involves several factors that affect the hydrogen station location, including economic cost, utilization rate, and safety risk, etc.

Covering model

As shown in Fig. 1, the covering model is divided into two categories [20]. This model focuses on the coverage of the station. Whether a point can be covered by a station is evaluated by the distance between them.

Set covering model

This model is to reduce the station needed [21]. Suppose that P represents the demand points set, C_p represents the stations set that can cover demand point p, and D represents the alternative stations set. This model can be raised below.

$$min \sum_{d \in D} x_d \tag{1}$$

$$subject\ \ to: \sum_{d \in C_p} x_d \ \geq \ 1, \forall p \in P \tag{2}$$

$$x_d \in \ \{0, 1\}, \forall d \in D \tag{3}$$

Equation (1) is intended to minimize the number of stations. x_d represents the decision variable. If $x_d = 1$, then station d can be built. In Equation (2), every point is served by a station or more. Equation (3) ensures that x_d can only be 0 or 1.

For hydrogen station location in the Irvine community, Kang and Recker [22] combined the set covering model with the routine selection of each driver. They simplified this case by assuming that a specific vehicle driver only refuels once a day. The experimental results show that the converging time of the solution is effectively lowered.

Toregas [23] considered this model for the site selection of the typical emergency facilities, including the hospitals, fire facilities, etc. In addition, he applied an integer programming method to speed up the calculation process.

Similarly, Gleason and John [24] applied the set covering model to locate the bus stations. They developed a zero-one integer programming method to generate the solution. Simulation results show that their station location plan would be convenient to the passengers, which can reduce the time spent on their way to the stations nearby.

Maximal covering location model

This model is presented by Church and Velle [25], which maximizes the covered demand when the number of stations is given. The demand of a certain point in the network can be calculated through the population, income, family size, vehicle ownership, etc [26]. This model can be raised below.

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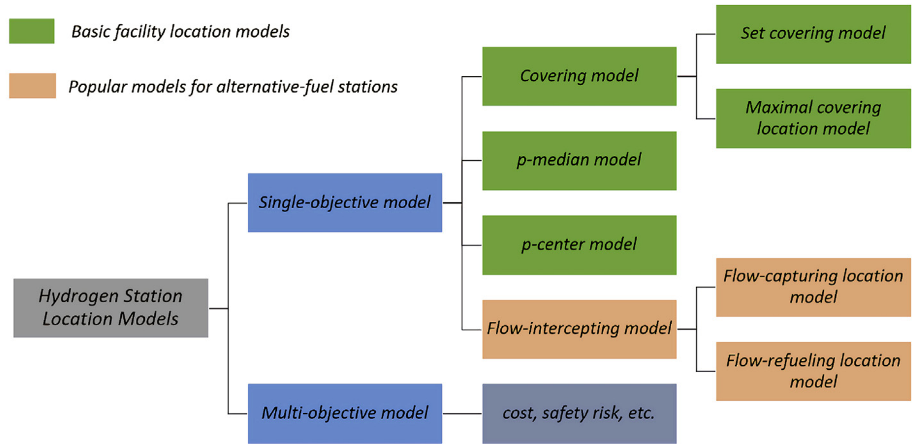

Fig. 1 — Hydrogen station location models.

$$max\sum_{p\in P} m_p e_p \tag{4}$$

$$subject\ \ to: \sum_{d\in C_p} x_d \geq e_p,\ \forall p\in P \tag{5}$$

$$\sum_{d\in D} x_d = a \tag{6}$$

$$x_d, e_p \in \{0,1\},\ \forall d \in D, p\in P \tag{7}$$

Equation (4) maximizes the covered demand. m_p represents the demand of point p. x_d and e_p represent the decision variables. If $e_p = 1$, then the demand point p is covered. Equation (5) means that if one available station is built, then it can serve a demand point nearby. Equation (6) indicates that the number of stations to be built is a. Equation (7) ensures that x_d and e_p can only be 0 or 1.

Daskin [27] extended this model to handle the situation of serving a real-time incoming demand point. He applied an integer programming method to this problem. The proposed method has been compared with other heuristic algorithms like a genetic algorithm.

In addition, ReVelle and Hogan [28] enhanced the maximal covering location model by combining with a certain degree of reliability. The proposed model can search for an available station for a demand point with specific reliability in a certain period of time.

Frade et al. [29] conducted research on the site selection of the hydrogen station in Avenidas. The proposed model is also performed in Lisbon. Evaluation of the location plan is also provided. However, they could not make further precise calculations of the demand.

P-median model

This model is developed by Hakimi [30], which is to reduce the distance with demand as weight. It is considered to be a "min-sum" problem [31]. This model can be raised below.

$$min\sum_{p\in P}\sum_{d\in D} m_p d_{pd} y_{pd} \tag{8}$$

$$subject\ \ to: y_{pd} \leq x_d,\ \forall d\in D, p\in P \tag{9}$$

$$\sum_{d\in D} y_{pd} = 1,\ \forall p\in P \tag{10}$$

$$\sum_{d\in D} x_d = a \tag{11}$$

$$x_d, y_{pd} \in \{0,1\},\ \forall d \in D, p\in P \tag{12}$$

Equation (8) is to reduce the distance with demand as weight. In Equation (8), d_{pd} is the distance between point p and station d. m_p is the demand of point p. x_d and y_{pd} represent the decision variables. If $y_{pd} = 1$, then station d can serve demand point p. Equation (9) ensures that if one available station d is built, then it can serve a demand point p nearby. Equation (10) indicates that there can only be one station serves for each demand point. Equation (11) expresses the same meaning as Equation (6). Equation (12) ensures that x_d and y_{pd} can only be 0 or 1.

This problem is considered to be NP-hard, which means the analytical solution cannot be obtained in polynomial time. Therefore, applications of heuristic algorithms during the computing process are necessary. Mladenović et al. [32] conducted a survey and provided a review for heuristic methods that have been used for this problem. Besides, ReVelle et al. [33] presented an integer linear programming method for this problem.

Nicholas et al. [34] combined the p-median model with the geographic information system and applied them to the site selection of the hydrogen station in California. The driving time during the trip is applied to evaluate the travel cost in their proposed model. Finally, the simulation results show that the existing network layout of gasoline stations can still be optimized.

P-center model

This model is to reduce the maximum distance between a point (or a node) and the station that covers it. Therefore, it is considered to be a "min-max" problem [35]. This model can be raised below.

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$$min \quad r \tag{13}$$

$$subject \quad to: \sum_{d\in D} d_{pd} y_{pd} \le r \tag{14}$$

$$\sum_{d\in D} x_d = a \tag{15}$$

$$y_{pd} \le x_d, \forall d\in D, p\in P \tag{16}$$

$$\sum_{d\in D} y_{pd} = 1, \forall p\in P \tag{17}$$

$$x_d, y_{pd} \in \{0,1\}, \forall d \in D, p\in P \tag{18}$$

Equations (13) and (14) are intended to reduce the maximum distance. In Equations (13) and (14), r represents the maximum distance. x_d and y_{pd} represent the decision variables. Equation (15) expresses the same meaning as Equation (6). Equation (16) expresses the same meaning as Equation (9). Equation (17) expresses the same meaning as Equation (10). Equation (18) expresses the same meaning as Equation (12).

From Equations (13)–(18) we can infer that this model is not directly linked to the demand calculation. Therefore, this model is more likely applied to the location of emergency facilities since the service accessibility for these demand points is the primary consideration [36].

Suzuki and Drezner [37] combined the graphical calculation with the p-center model. Therefore, each station in the network can be viewed as a circle with a certain radius. These circles should maintain a certain distance from each other to ensure the service accessibility for these demand points. They discussed the reasonable range of radiation radius among the stations. They also presented heuristic algorithms for this problem.

Marcus [38] applied a grid search method for searching the optimal combination of parameters that affect the p-center problem. Different combinations of parameters have been tested in their experiments. Finally, they have provided reasonable suggestions for the selection of p-center model parameters.

Flow-intercepting model

Unlike other models, the flow-intercepting models [39] calculate the demand through a dynamic way.

Flow-capturing location model

In these basic location models, the demand is usually considered as the weight of a specified point or a specified node in a given network, which is calculated through a static perspective [40]. While for other situations, the demand is associated with the traffic flow, which can be calculated through a dynamic way. Therefore, the demand point covering problem can be turned into the traffic flow capturing problem. Under these circumstances, Hodgson [41] presented this model, which can be raised below.

$$max \sum_{o\in O} f_o y_o \tag{19}$$

$$subject \quad to: \sum_{d\in D} x_d = a \tag{20}$$

$$\sum_{d\in C_o} x_d \ge y_o, \forall o\in O \tag{21}$$

$$x_d, y_o \in \{0,1\}, \forall d \in D, o\in O \tag{22}$$

Equation (19) maximizes the captured flow. x_d and y_o represent the decision variables. In Equation (19), O represents all origin-destination (OD) pairs. f_o stands for the traffic volume between OD pair o. If $y_o = 1$, then f_o is captured. Equation (20) expresses the same meaning as Equation (6). Equation (21) ensures that if there is one station available on path o, then it can capture the flow on path o. In Equation (21), C_o represents the alternative stations set that can capture o. Equation (22) ensures that x_d and y_o can only be 0 or 1.

In addition, Hodgson et al. [42] combined the FCLM with a greedy algorithm to locate the hydrogen station in Canada. They applied the peak-hour traffic flow in the morning to simulate the all-day traffic flow. However, the traffic flow information would be hard to acquire. Using the peak traffic flow only to simulate the traffic flow throughout the day will cause some deviations.

Riemann et al. [43] took the drivers' path-selection behavior during their daily travel into consideration. They applied the FCLM to the charging station siting. Simulation results imply that combining the driver's path-selection behavior with the traffic flow can generate more affordable location plans. This might be able to find the global optimal solution quickly.

Cruz-Zambrano [44] applied the FCLM to search for the charging stations' sites in Barcelona. The target is to reduce the economic cost of the stations. The experimental results show that the total economic cost is reduced while the service availability of these stations remains stable, which can bring certain economic benefits.

Flow-refueling location model

The FCLM does not consider the situation that when the drivers have to refuel their vehicle more than once during their long journey. Kuby and Lim [45] addressed the defect in FCLM and developed the FRLM to meet the new requirements.

Similar to FCLM, this model maximizes the refueled traffic flow. Besides, the FRLM considers some additional factors, including the average driving speed and the maximum driving range [46]. The FRLM can be raised below.

$$max \sum_{o\in O} f_o y_o \tag{23}$$

$$subject \quad to: \sum_{m\in M} b_{om} n_m \ge y_o, \forall o\in O \tag{24}$$

$$a_{md} x_d \ge n_m, \forall m \in M; d | a_{md} = 1 \tag{25}$$

$$\sum_{d\in D} x_d = a \tag{26}$$

$$x_d, n_m, y_o \in \{0,1\}, \forall d \in D, m \in M, o\in O \tag{27}$$

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Equation (23) expresses the same meaning as Equation (19). Equation (24) indicates that at least one station in combination m should be built on path o. In Equation (24), M represents the alternative stations combinations set and m represents its index. x_d, n_m and y_o represent the decision variables. If $n_m = 1$, then all stations in combination m are built. Equation (25) ensures that if there is one station in combination m is built on path o, then it can refuel the flow on path o. In Equation (25), if $a_{md} = 1$, then station d is in combination m. If $b_{om} = 1$, then the station combination m can refuel OD pair o. Equation (26) expresses the same meaning as Equation (6). Equation (27) ensures that x_d, n_m and y_o can only be 0 or 1.

From Equations (23)−(27) we can infer that the FRLM calculation process includes generating the combinations of all alternative stations. The combinations are more and more difficult to traverse in a constant time once the number of stations is becoming larger and larger. Like other models, heuristic algorithms are necessary in order to speed up the calculation process. Reviewing this situation, Capar and Kuby [47] applied a mixed-binary-integer programming method in FRLM. They performed experiments in different sizes of networks. Results show that their model can generate better location plans faster than the customized greedy algorithm.

In addition, Kuby et al. [48] also applied the FRLM to locate the hydrogen station in Florida. Build on previous researches on the characteristics of hydrogen stations, they made a few improvements by adding some extra factors to the FRLM, including the cross-regional routines and drivers' multiple path-selections during their trips.

Other model

However, these models mentioned above cannot cover all the situations in the hydrogen station location. Some other models derived from these models are applied to other situations, including demand uncertainty situation, capacitated refueling situation, traffic deviation situation, etc.

Demand uncertainty model

Kitamura and Sperling [49] discovered that a lot of refueling behaviors take place near people's home or workplace. Inspired by their research, Lin et al. [50] proposed a new model considering the situation that people always want to reduce the time spent for refueling. The target is to reduce the time for refueling. The model is applied to derive an optimal station roll-out scheme for Southern California. The target of the proposed model can be raised below.

$$\min \quad ARTT \cdot FUEL \tag{28}$$

In Equation (28), $ARTT$ is the average time for refueling. Such a fuel-travel- back problem is in nature a typical transportation problem and they applied a mix-integer programming method to this model.

Similar to this, Jia et al. [51] used the number of vehicles and delay time to calculate the demand, which can be raised by Equation (29).

$$Demand = N \cdot t \tag{29}$$

In Equation (29), N means the number of vehicles, t means the delay time. The larger the product, the greater the demand. They implemented this model for the site selection of the hydrogen station. Their experiments show that the economic cost of the hydrogen station is effectively reduced.

For those demand-associated location models, the demand of a certain point or a certain node is usually fixed. However, when meeting the situation of demand uncertainty, it is necessary to improve the existing models. Lou et al. [52] considered the situation of demand uncertainty in flow capturing models. They calculated the demand of OD pair with dynamic value. Averbakh and Berman [53] enhanced the p-center model so that the demand of each point in the network can be uncertain. They presented the polynomial algorithms for this demand uncertainty situation with acceptable time complexity.

Besides, Miralinaghi et al. [54] presented a model which can not only handle the situation of demand uncertainty but also deal with the situation of the drivers' deviation on their way to refueling. The target is to reduce the economic cost and the time spent in refueling. An enhanced genetic algorithm is implemented as the solution. This proposed model can generate reliable location plans compared to other models.

Capacitated refueling and traffic deviation model

For capacitated refueling situation, Geoffrion and Bride [55] proposed the Lagrangean relaxation solution, which can improve the performance of the location model. Upchurch et al. [56] presented the capacitated FRLM for hydrogen station location in Arizona. They turned the target into maximizing the driving distance other than maximizing the refueled traffic flow. Miralinaghi et al. [57] aimed at reducing the driver's time consumption and proposed a capacitated location model considering the driver's route selection. A mixed-integer linear programming method is deployed in their model. They tested this model in different networks. Results show that the proposed solution can generate satisfactory solutions and the computing time is reduced effectively.

Traffic deviation situation is usually associated with capacitated refueling situation. Kim and Kuby [58] applied the deviation FRLM to handle the deviations that happened in refueling trips. A mixed-integer linear programming method combined with punishment function is proposed. Simulation results show that this model can generate optimal location plans for hydrogen stations.

Multi-objective model

Most studies focused on single-objective optimization problem for the hydrogen network, but few account for the multi-objective optimization problem. The multi-objective model involves several factors that affect the hydrogen station location. These factors include economic cost, utilization rate, and safety risk, etc.

Yunqiang et al. [59] focused on the economic cost in the hydrogen station location. The objective function is to reduce the economic cost. The proposed methodology for the multi-objective optimization of hydrogen network considers flow rate constraints, pressure constraints, purity constraints, impurity constraints, payback period, etc. This multi-objective problem can be raised below.

$$min \quad f = w_1 f_1 + w_2 f_2 \tag{30}$$

$$subject\ to : min \quad f_1, f_2 \tag{31}$$

$$f_1 = \frac{C_1(x) - C_1^{min}}{C_1^{max} - C_1^{min}} \tag{32}$$

$$f_2 = \frac{C_2(x) - C_2^{min}}{C_2^{max} - C_2^{min}} \tag{33}$$

$$w_1 + w_2 = 1 \tag{34}$$

Equations (30) and (31) indicate that the target is to reduce the operational cost and investment cost. In Equation (30), w_1 and w_2 are the corresponding weight coefficients. The objective function is turned into Equations (32) and (33). In Equation (32) and Equation (33), C_1^{max} and C_2^{max} are the maximum values of operational cost and investment cost. C_1^{min} and C_2^{min} are their minimum values. Equation (34) indicates that w_1 and w_2 satisfy the condition $w_1 + w_2 = 1$.

Girardin [60] applied a multi-objective optimization model to optimize the hydrogen station construction and the compatible units' selection. He presented a mixed-integer programming method and an evolutionary algorithm for this problem. Pareto surface during the calculation is analyzed. Results show that the construction plans generated by this model can reduce the hydrogen consumption effectively.

Sabio et al. [61] considered the environmental factors for hydrogen station network construction in Spain. They presented a framework to optimize the hydrogen supply chains based on these factors. They showed that this framework can optimize multiple environmental factors that have significant impacts on supply chains.

Similar to this, Almaraz et al. [62] involved the cost, hydrogen recovery rate, and safety factors into the hydrogen station supply chain construction. The multi-objective solution is analyzed through a mixed-integer linear programming method. The proposed model is applied to supply chain design in England. Besides, they also focused on the development of a methodological framework for the design of a five-echelon hydrogen supply chain (HSC) (energy source, production, storage, transportation and fueling station) with the assistance of the geographic information system [63]. Considering these objectives, they applied the proposed framework to optimize supply chain construction in France. They provided comparisons of the construction plans for areas of different sizes.

Model comparison

There is no uniform criterion regarding which model is better than the others because it depends considerably upon how we measure the effectiveness of facility location. The performance of a specific location model depends on the measurement method [64]. Based on existing applications and works, we can draw the conclusion that greedy and genetic heuristic algorithms are commonly applied to the covering model. Additionally, the integer programming method is commonly applied to other models, including the zero-one integer programming method and the mixed-integer linear programming method. Comparison between these models for hydrogen station location is shown in Table 1.

He et al. [65] compared the location plans for electric vehicles generated by three location models. Based on the population and economic data, the formula for calculating the demand is provided. The experimental results show that the solution generated by the p-median model is closer to these high-demand areas compared to the other two models.

Hodgson et al. [66] compared the FCLM with the p-median model in a small-scale network. They observed from the comparison results that the solution of the p-median model is more unstable. Besides, they proposed a model using two different ways for demand calculation. Therefore, the proposed model can be applicable to the larger road network.

MirHassani and Ebrazi [67] applied two types of covering models to the site selection of alternative fuel station in a large-scale network. It is necessary to combine the calculation process with heuristic algorithms. Therefore, they presented a mixed-integer linear programming method. Results show that the computing process is speeded up finally.

For Florida hydrogen station network construction, Upchurch et al. [68] compared the FRLM with the p-median model by evaluating one model with the other model's objective function. By performing the experiments, they pointed out that the FRLM solution is more stable. The

Table 1 – Comparison between models for hydrogen station location.

Model	Data Needed	Strength	Weakness	Common-used Solution
Set covering model Maximal covering location model	Demand points set Potential locations set Distance matrix	Emergency facility location Demand is primary consideration	Distance calculation is not related to the model	Greedy and genetic heuristic algorithms/Integer programming
p-median model		Service convenience guarantee	Demand usually not associated with traffic flow	Integer programming
p-center model		Service distance guarantee	Level of demand is not primary consideration	
Flow-intercepting model	Origin-Destination (OD) flow volumes Potential locations set	Based on traffic flow	Rely on OD traffic matrix	

differences between the two models are growing with the network size and the station's number.

Conclusion

Hydrogen is considered to be the most promising clean energy source in the future. Since hydrogen station plays the role of an infrastructure to supply hydrogen to fuel cell vehicles. Construction of hydrogen station is the key to the development of hydrogen energy and fuel cell vehicle industry. The lack of hydrogen stations is a major barrier to the introduction of hydrogen vehicles. Given the high cost of constructing hydrogen stations, it is desirable to build as few stations as possible while still adequately serving consumers. Most studies focused on the specific location problems for the hydrogen stations, but few account for the review of hydrogen stations location models.

In this paper, we present an extensive overview of hydrogen station location models, applications, and works in over 60 representative publications. During our literature collecting, we set up a tree diagram that includes major models for hydrogen station location, which can be observed from Fig. 1.

According to the spatial dimension of the facility, the structure of the planning area, and the number of objectives, we can divide the hydrogen station location models into several categories. For these hydrogen station location models, we also present formulations and different constraints in this review.

Finally, we conclude the strength and weakness of each model for hydrogen station location and provide available solutions for each model based on existing researches. After all, this review might help researchers get a comprehensive understanding of related researches in the hydrogen station location.

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