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A HYBRID GENETIC ALGORITHM TO DESIGN THE HYDROGEN SUPPLY CHAIN NETWORK WITH MULTI-TRANSPORTATION MODES

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Abstract. *Fossil fuel has faced with the problems such as constant growing of energy demand, imbalance of supply and demand, and global warming. To solve these problems, hydrogen is introduced with one of promising renewable energies. In this study, we consider to design a hydrogen supply chain network with multi-transportation modes (pipe-line, tank truck) for a future demand. The key decisions of the network design problem include the size and location of facilities (plant, storage), transportation modes, and the volume of hydrogen. To determine the decisions in the network design problem, a hybrid genetic algorithm with a local search heuristic is proposed and compared with a conventional genetic algorithm. For analyzing the algorithms, computational experiments are executed using randomly generated problem instances.*

Keywords: Hydrogen supply chain, Transportation modes, Location, Network, Genetic algorithm

1. **Introduction.** Hydrogen is recognized as one of promising alternative and renewable energies. A number of studies for using the hydrogen energy as vehicle fuel have been conducted. In forefront work, researchers determined the economic pathways from generation activities to consumption activities with considering various technologies [1-3]. Berry et al. [1] seem to have been the first to introduce the influence of hydrogen as an alternative energy for vehicle and describe various required techniques. Since then, many researchers have conducted a study to focus on using the hydrogen as future transportation fuel. Moore and Raman [2] described the technology for constructing hydrogen infrastructure and evaluated economic feasibility by analyzing the scenarios using specific technology. Ogden [3] gave full details of pathway for hydrogen supply chain and evaluated economic feasibility of pathways. Then, researches for designing hydrogen supply chain network using the pathways proven in the previous work [4-7] were performed. Kim et al. [4] and Almansoori and Shah [5] developed extended hydrogen supply chain network by considering multi-resource, multi-technology and conducted case studies in South Korea and England, respectively. Elia et al. [6] developed a hydrogen supply chain model and determined the market price of the hydrogen and the degree of carbon emission. Baufumé et al. [7] determined infrastructure for hydrogen supply chain using pipe-line transportation mode based on geographical information system.

To the best of our knowledge, no research has been found focusing on an effective and efficient algorithm to design hydrogen supply chain network under complex problem constraints i.e., multi-transportation modes. In this article, we propose a hybrid generic algorithm to design a hydrogen supply chain network with multi-transportation modes.

The organization of the article is as follows. Section 2 provides the problem statement on designing hydrogen supply chain network. Section 3 explains G&BF heuristic and a hybrid genetic algorithm with G&BF heuristic. Computational results are presented in Section 4, and finally Section 5 concludes the article.

2. **Problem Statement.**

In this study, a problem to design hydrogen supply chain network is addressed with considering regular replenishment cycle or multi-transportation modes using hydrogen tank truck and pipe-line. The hydrogen transportation network design is carried out for working days χ and the network includes nodes which indicate hydrogen generation plant, hydrogen storage facility, and hydrogen fuel filling station and links which indicate the volume of hydrogen by transportation modes. In this problem, there are n_I given locations $I = \{1, 2, \ldots, n_I\}$ which are not yet located hydrogen plants, n_J given locations $J = \{1, 2, \ldots, n_J\}$ which are not yet located hydrogen storages, and n_K given locations $K = \{1, 2, \ldots, n_K\}$ assigned to filling stations. Let Y_{ij} be a binary variable such that $Y_{ij} = 1$ if hydrogen plant at location $i \in I$ with size $j \in L$ is constructed. Note that $Y_{i0} = 1$ if a single sized hydrogen storage at location $i \in I$ is constructed. A transported volume of hydrogen is represented as X_{ij} on an annual basis, depending on a link in the chain between the corresponding locations $i \in I \cup J$ and $j \in J \cup K$ where $i \neq j$. T_{ij} represents transportation cycle between the locations $i \in I \cup J$ and $j \in J \cup K$ where $i \neq j$.

Hydrogen is transported from upstream nodes to downstream nodes in this network (i.e., plant-storage-filling station). Hydrogen plants generate a hydrogen within the daily capacity ω_i, depending on size $i \in L$ and convey hydrogen to storage. Hydrogen storages deliver hydrogen transported from plants to filling stations where we assume that the storages have sufficient storage-capacity. Hydrogen filling station should be delivered required volume of hydrogen from preceding nodes, storages, in order to satisfy the demand ρ_i which occurs daily, depending on filling station $i \in K$. In this study, transported volume and transportation mode must be simultaneously determined when the link between facilities is activated. There are two transportation modes. If the truck mode is selected, a number of replenishments χ/T_{ij} and a transported volume $X_{ij} \cdot T_{ij}/\chi$ are decided. If the pipe-line mode is selected, it is represented as $P_{ij} = 1$ and the pipe-line mode only decides daily transported volume of hydrogen as X_{ij}/χ.

The proposed hydrogen supply chain network design problem should be solved to minimize the complex nonlinear total network cost (TNC) function comprised of ordering cost (ODC), transportation cost (TPC), inventory handling cost (IHC), pipe-line installation cost (PIC), facility investment cost (FIC), and operating cost (OPC). Furthermore, hard constraints exist (i.e., transportation mode selection constraints, transported volume constraints, capacity constraints).

3. **Heuristics.**

In this section, a hybrid genetic algorithm (HGA), which incorporates a heuristic using well-known greedy and best-fit heuristics as the one of chromosomes of initial population in HGA, has been presented to design an effective hydrogen supply chain.

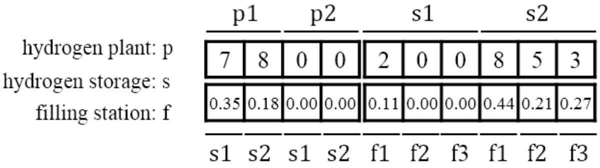
3.1. **G&BF heuristic.**

Greedy heuristic selects one of the most promising alternatives for local search heuristics [8]. In this study, we propose a combination of two well-known greedy heuristic and bin-packing heuristic named *greedy and best-fit* (G&BF) heuristic. In the heuristic, a *greedy heuristic* to determine an assignment of the volume of hydrogen with the shortest distance to given links and a *best-fit heuristic* to determine the capacity of the corresponding facilities with positive volume given from the greedy heuristic are sequentially applied.

The procedure of G&BF heuristic in the hydrogen network design problem is described in three stages. In the first stage, greedy algorithm sorts an order of the link related to hydrogen storage location $j \in J$ and filling station $k \in K$ by distance and assigns the annual hydrogen demand of filling station k for the link which is close to j for all k. Then, the link related to hydrogen plant $i \in I$ and hydrogen storage $j \in J$ is also listed. The volume of hydrogen required for the hydrogen storage j related the links are ordered to relate plant i in order. To assure feasibility of a solution, the portion of hydrogen required (or the whole quantity) is added to the accumulated order quantity of the plant i by comparing the accumulated order of related plant i to the maximum capacity of the hydrogen plant. In the second stage, the transportation mode incurred the lowest cost is selected per link by calculating the objective function terms (i.e., *ODC*, *TPC*, *IHC*, and *PIC*) for every transportation mode with the volume of hydrogen. In the last stage, the capacity of facilities in each location with positive volume is determined by best-fit heuristic because the problem is a simple well-known knapsack problem.

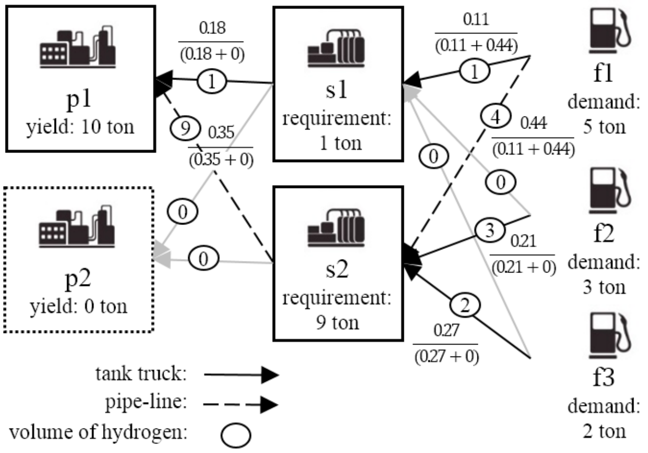
3.2. **HGA with G&BF heuristic.** Genetic algorithms (GAs), which are introduced by Holland [9], are an effective and efficient approach that applied the evolution theory as one of meta-heuristics. GAs are known to find a near-optimal solution for combinatorial optimization problems in a relatively short time. In this study, we propose HGA with G&BF heuristic for effectively solving the network design problem.

3.2.1. *Chromosome.* In GAs, the performance of the algorithm primarily is influenced by the representation of a solution, which is a chromosome. In this study, we represent the chromosome based on two single dimensional arrays. Each array has a number of genes, such as the number of links (i.e., $n_I \cdot n_J + n_J \cdot n_K$). The first array is expressed by digits from 0 to 8 and the numbers indicate transportation modes under replenishment cycle in each link (e.g., '0': nothing used, '1'-'7': replenishment cycle using tank truck, and '8': pipe-line), and the second array is expressed by real number from 0 to 1. Real number



	p1		p2		s1			s2		
hydrogen plant: p hydrogen storage: s	7	8	0	0	2	0	0	8	5	3
filling station: f	0.35	0.18	0.00	0.00	0.11	0.00	0.00	0.44	0.21	0.27
	s1	s2	s1	s2	f1	f2	f3	f1	f2	f3

(a) Chromosome



(b) Corresponding hydrogen supply chain network

Figure 1. Chromosome representation and corresponding hydrogen supply chain network

is used to calculate the portion of the volume of hydrogen in the each link. Figure 1 illustrates a chromosome and corresponding hydrogen supply chain network. Figure 1(a) describes a chromosome in the case of 2 plants, 2 storages, and 3 filling stations. The first row of the chromosome simultaneously indicates transportation mode and replenishment cycle. For example, '7' in the first gene indicates 7 day replenishment cycle using 'tanker truck' mode from p1 to s1 and '8' in the second gene indicates continuous flow using 'pipe-line' mode from p1 to s2. '0' in the third gene indicates 'nothing used' in the link from p2 to s1. The second row of the chromosome indicates the portion of a required hydrogen demand. For example, two receiving portions of a required amount of hydrogen demand with 5 ton in f1 are calculated from s1 and s2 as 0.11 and 0.44, respectively. The corresponding hydrogen supply chain network of the chromosome representation is described in Figure 1(b).

3.2.2. *Initialization using G&BF heuristic.* For improving the solution quality and computing time, the solution obtained by G&BF heuristic local in Section 3.1 is adapted as the one of solutions in an initial population.

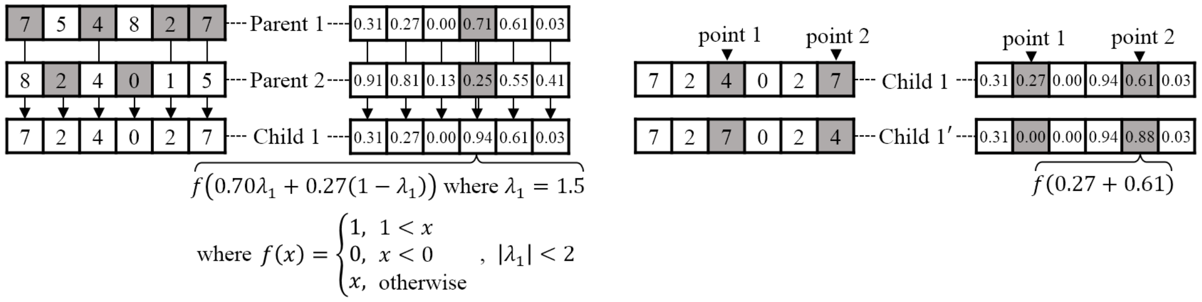
3.2.3. *Fitness function.* The fitness of a solution obtained by decoding of the chromosome is measured by the fitness function. The fitness value is a measure of the goodness of a solution and is used when selecting a parent to generate the next generation. Fitness function of the chromosome i is expressed by Equation (1) using TNC of the solution $i(TNC_i)$ and the maximum TNC in the current generation ($TNC_{\max}$).

$$F_i = TNC_{\max} - TNC_i \tag{1}$$

3.2.4. *Genetic operators.* Figure 2 is illustrated with crossover and mutation operators of HGA in this study. We suggest two types of crossovers and two types of mutations for each chromosome because it simultaneously represents the transportation modes and the volumes. In Figure 2(a), *uniform crossover* is used for the first array representing transportation mode and *convex crossover* is used for the second array representing the volume of hydrogen. In Figure 2(b), *Swap mutation* is used for transportation mode and *shifting mutation* is used for the volume of hydrogen in which a value of gene randomly selected is removed and adds it to the value of another gene randomly selected.

The selection of parent chromosomes for generating a child chromosome utilizes a probabilistic method for selecting an object in a *roulette wheel* with a fitness value for the current generation. And the best and the second best chromosome are *cloned* for the next generation.

4. **Computational Results.** In this section, HGA is compared with a conventional genetic algorithm (GA). Extensive computational experiments are implemented to evaluate HGA and GA which has not applied G&BF heuristic to generating initial-solution. The



(a) *Uniform crossover* and *convex crossover*

(b) *Swap mutation* and *shifting mutation*

FIGURE 2. Crossover and mutation operators

test data is set to less than 20 plant locations, 40 storage locations, and 100 filling stations, locations of facilities are randomly generated in each problem instance space set by 200×200 km^2, a distance of each link is calculated by *Euclidean distance*, and a hydrogen demand of each filling station is determined in the range between 1 and 3 tons/day. The input parameters to calculate *TNC* are given in Table 1 [4,10].

To solve the problem, HGA and GA run with a population size of ${n_J}^2$, the generation size of 500 is fixed, and crossover and mutation rates are set with 0.3 and 0.005, which are predetermined by extensive preliminary experiments. GAs are executed on a PC with 3.40 GHz and 4 GB RAM.

Table 1. Input parameters

Parameter	Value
working days per year (day)	250
maximum capacity of hydrogen tank truck (ton/unit)	4
productive capacity of hydrogen plant (ton/day)	$\{30, 50\}$
ordering cost at hydrogen storage ($)	220
ordering cost at filling station ($)	300
shipping cost for tank truck ($)	25
shipping cost for pipe-line ($)	4
inventory carrying cost at hydrogen storage ($)	10
inventory carrying cost at filling station ($)	15
investment cost for hydrogen plant (1,000$/year)	$\{340, 470\}$
investment cost for hydrogen storage (1,000$/year)	50
investment cost for hydrogen pipe-line ($/year)	4080
operating cost for hydrogen plant ($)	130
operating cost for hydrogen storage ($)	2

Table 2. Test data sets and results of the problems

No.	Data set			GA			HGA			Gap
	n_I	n_J	n_K	RPD (%)	MAD (%)	CPU time	RPD (%)	MAD (%)	CPU time	RPD (%)
1	3	6	15	12.8	0.7	0.7	1.0	0.4	0.7	11.9
2	4	8	20	12.0	0.9	2.3	0.4	0.3	2.3	11.6
3	5	10	25	10.5	0.6	5.3	0.6	0.3	5.3	9.9
4	6	12	30	13.6	0.7	11.2	1.2	1.2	10.9	12.5
5	7	14	35	14.7	0.8	20.3	0.5	0.2	20.1	14.2
6	8	16	40	17.4	0.8	35.0	0.4	0.3	34.4	17.1
7	9	18	45	13.7	0.4	56.6	0.3	0.2	55.6	13.5
8	10	20	50	17.5	0.8	85.8	2.0	0.6	83.8	15.5
9	11	22	55	16.4	0.6	126.5	0.8	0.4	123.4	15.6
10	12	24	60	24.9	0.5	179.9	1.4	0.4	177.4	23.5
11	13	26	65	26.4	0.9	252.0	0.3	0.1	242.4	26.1
12	14	28	70	39.9	1.1	333.3	0.7	0.5	322.5	39.2
13	15	30	75	46.1	0.8	449.3	0.3	0.2	427.6	45.8
14	16	32	80	56.4	0.8	575.0	0.7	0.3	565.6	55.7
15	17	34	85	68.5	0.6	724.5	2.0	1.0	700.9	66.5
16	18	36	90	83.3	0.8	904.1	1.1	0.8	881.2	82.1
17	19	38	95	93.1	0.9	1,180.2	1.2	0.8	1,113.2	92.0
18	20	40	100	104.2	0.9	1,429.0	0.6	0.4	1,355.4	103.6
	Average			37.3	0.8	354.0	0.9	0.5	340.2	36.4

Table 2 summarizes the problem instances and computational results of GA and HGA. In each problem instance, both GAs are repetitively tested 10 times; the results incorporate the average of objective value and the best objective value. The relative percentage deviation (RPD) and mean absolute deviation (MAD) were used as measure for evaluating the performance of a GA where RPD is percentage deviation from best objective value for the value obtained in all replications of each problem instance. The RPD and MAD of HGA are significantly smaller than GA as the problem size is increased. Furthermore, the average computational (CPU) time of HGA is smaller than average CPU time of GA recorded as 354.0 (sec.) and 340.2 (sec.), respectively. This means that HGA is an effective and efficient algorithm with a low variation for large size network design problem.

5. **Conclusion.** In this study, we developed a hydrogen supply chain network design problem with considering multi-transportation modes, which consist of hydrogen tank truck modes with a different transportation cycle and pipe-line mode. The objective of the study is to assign the volume of hydrogen from upstream nodes to downstream nodes and determine the transportation mode for each link. To solve the network problem, HGA with G&BF heuristic is proposed and compared with a conventional GA which has not applied G&BF heuristic. HGA showed the good quality performance given testing problem environment.

Extensions of the paper may consider the case study using the proposed current model because the current model does not apply real problems. For future estimating hydrogen demand in Korea, we should design hydrogen supply chain based on the proposed model. Also, other meta-heuristics should be applied as another extension of the paper for real-sized problems.

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