Locomotive Scheduling Using Constraint Satisfaction Problems Programming Technique

Jong-Gyu Hwang*, Jong-Woo Lee* and Yong-Jin Park**

Abstract - Locomotive scheduling in railway systems experiences many difficulties because of the complex interrelations among resources, knowledge and various constraints. Artificial intelligence technology has been applied to solve these scheduling problems. These technologies have proved to be efficient in representing knowledge and rules for complex scheduling problems. In this paper, we have applied the CSP (Constraints Satisfaction Problems) programming technique, one of the AI techniques, to solve the problems associated with locomotive scheduling. This method is more effective at solving complex scheduling problems than available mathematical programming techniques. The advanced locomotive scheduling system using the CSP programming technique is realized based on the actual timetable of the Saemaul type train on the Kyong-bu line. In this paper, an overview of the CSP programming technique is described, the modeling of domain and constraints is represented and the experimental results are compared with the real-world existing schedule. It is verified that the scheduling results by CSP programming are superior to existing scheduling performed by human experts. The executing time for locomotive scheduling is remarkably reduced to within several decade seconds, something requiring several days in the case of locomotive scheduling by human experts.

Keywords: Train Scheduling, Locomotive Scheduling, Expert System, CSP Technique.

1. Introduction

One of the most difficult problems to overcome in railway transportation systems relates to operation planning such as timetable construction, vehicle and crew scheduling. These scheduling problems are very complex and difficult tasks to work out, taking up exorbitant amounts of time when performed manually. Railway scheduling problems still depend on the flexible decision-making abilities of experts, thus the resulting schedules may not be optimal.

In accordance with the increase in computer technology, a computer-based train scheduling system is introduced to overcome the above-described problems. Several approaches have been attempted to solve these scheduling problems [1-5]. The great part of these approaches involve mathematical techniques such as linear programming. However, the scheduling problems on railway transportation systems bring to conclusion as the nonlinear programming problems with the complexibility of the number of N!, it is difficult to express the knowledge and constraints as a mathematical model because most of the required knowledge or rules for these problems are obtained through the human expert's practical experiences [6].

The CSP program technique, one of the AI theniques, is able to solve these problems. This method is more effective at solving complex scheduling problems than available mathematical programming techniques [7-9]. In this paper, the searching technique and knowledge representation for locomotive scheduling are realized through the CSP technique. Furthermore, the comparison results are represented in the experimental results by proposed scheme and existing scheduling performed manually by human experts.

2. Conventional Data Link Protocol for Railway Signaling

2.1 Locomotive Linking Scheduling

Train scheduling generally consists of three parts: timetable construction, locomotive linking scheduling and vehicle rostering. Timetable construction is determined by the traffic demand and other significant factors. Basic locomotive scheduling problems involve finding a set of locomotives working as coverall trains within a particular timetable at minimum operating cost. This means the same sequence trains travel as locomotives. These results are available as basic data for vehicle and crew roster scheduling. Fig. 1 shows the configuration of train scheduling.

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* Dept. of Railway Electrical and Signaling Research, Korea Railroad Research Institute, Korea ({jghwang, jwlee}@krri.re.kr)

** Div. of Electronic Engineering, Hanyang University, Korea (park@hyuee.hyu.ac.kr)

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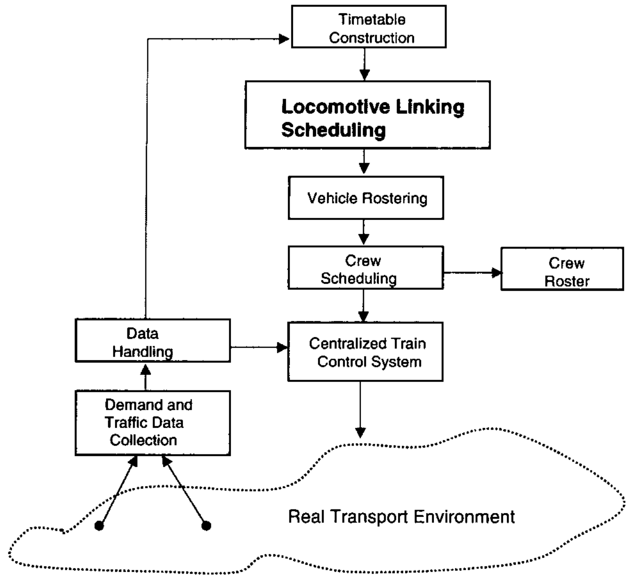
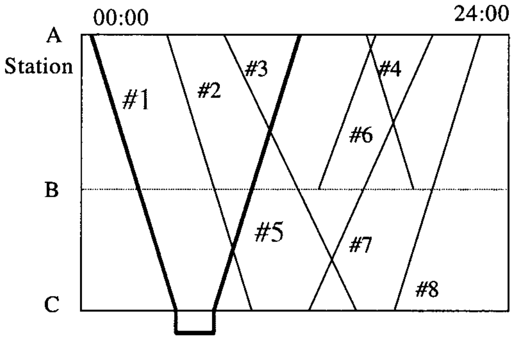


Fig. 1 Configuration of train scheduling.

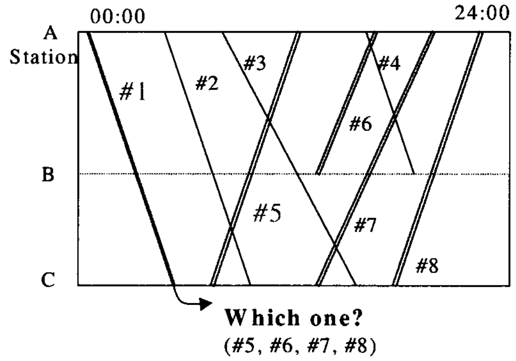
From among these, it is locomotive linking scheduling problems that are studied in this paper. Vehicle roster scheduling involves actual vehicles being allocated in correspondingly to the prescheduled locomotive schedule. Fig. 2 (a) describes the concept of locomotive scheduling and Fig. 2 (b) shows the optimization problems of scheduling. A locomotive linking DIA (train DIAgram) is formulized by the connection of sequential trains. For example, subsequent trains #5, #6, # 7, and #8 in Fig. 2 (b) are able to connect with the previous train #1. If trains #1 and #6 are set as a DIA, a light running between station C and station B is needed. Therefore, it is important that any train be connected as a next train in the case of a DIA. Optimization problems begin from this point. To solve these optimization problems, objectives must be determined. A conceptual approach, such as minimization of train operation costs, is introduced in this paper. That is, the basic objectives are to find the set of locomotive DIAs that covered all trains in the timetable with minimum operating costs. To implement these approaches, the train operating costs must be adjusted properly.

Costs affecting locomotive scheduling problems consist of locomotive capital costs and operational expenditure costs. The capital costs are simply determined in proportion to the number of available locomotives. However, the operational expending costs are somewhat complex to estimate. They include power consumption costs, labor costs, maintenance costs and indirect costs such as the absorbed rate of railway lines or facilities.

To simplify these problems, a modified objective omitting the minor expending costs, is considered in this paper. The objective cost function was deduced from this procedure, and composed of two cost variables, which are the waiting time cost between the arrival time of train i and subsequent departure time of train j, and the light running time cost between train i and train j. Light running signifies no customer-service operation. The objectives with this cost function can be expressed as follows:



(a) Locomotive scheduling



(b) Optimization of scheduling

Fig. 2 Optimization of locomotive scheduling.

$$Min\left(\sum_{i,j} A_t \cdot LT_{ij} + B_t \cdot WT_{ij}\right) \qquad (1)$$

where A_t, B_t *: The cost function coefficients (costs per minute)*

LT_{ij} *: The light running cost between train i and j*

WT_{ij} *: The waiting time cost between the arrival time of train i and the departure time of train j*

2.2 Locomotive Schedule of Kyong-bu Line

The actual schedule of the Saemaul type train on the Kyong-bu line of the KNR (Korea National Railway) is used for our study. This actual schedule is compared with the experimental results using our proposed algorithm.

Twenty-seven Saemaul type trains are scheduled at the down-line of the Kyong-bu line (Seoul station is the first departure station) and the same number of trains is planned up-line (Seoul station is last arrival station). Therefore, the total number of Saemaul trains is 54 trains at present. All of the trains travel between Seoul and Taegu stations but some trains travel to a different O-D section. This means that the starting station of trains for Pusan is Seoul station, but their final destination is different stations, such as Masan, Pohan, Haehndae, Ulsan, Jinju and Taedu, Conversely, the starting station of trains for Seoul is different respectively.

Each of the fifty-four trains must be connected as several sequence trains in the DIA. This procedure is part of locomotive scheduling. For example, DIA9601 is expressed in Fig. 3. This graphical DIA of a locomotive traveling sequence is produced following locomotive scheduling. As shown in Fig. 3, any locomotive starts at 07:20 at Yong-san station, the yard station, for the starting of customer-service operation from Seoul station. This locomotive then waits until 08:00 at Seoul station because of passengers arriving at the platform. It then runs to Pusan station as a prescheduled #3 train and departs to the original station from Pusan station after nearly 4 hours of waiting time. The above procedure is a DIA that any locomotive travels and operates.

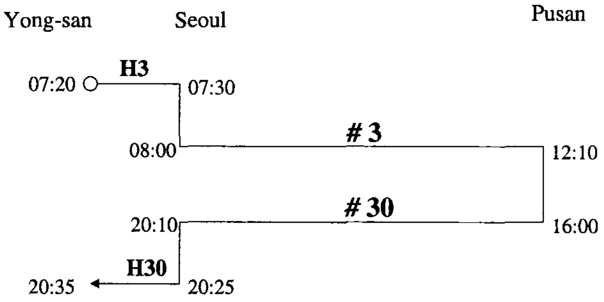


Fig. 3 Locomotive schedule DIA.

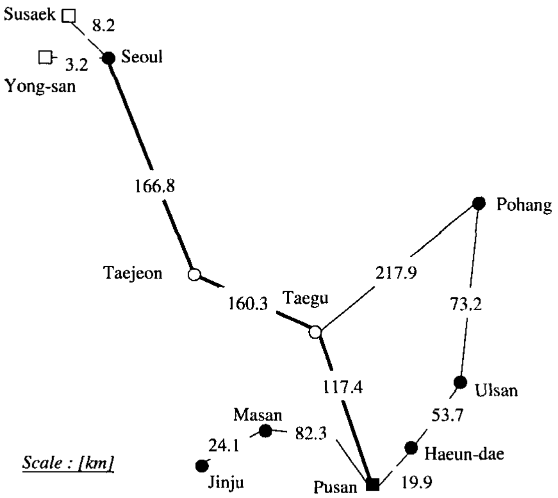


Fig. 4 Geographical diagram of the Kyong-bu line.

In the case of the locomotive schedule for the Saemaul trains of the Kyong-bu line, the waiting time between the arrival time of a train and the departure time of a successive train is broadly scattered. That is, the minimum time is about three hours but the maximum time is nearly twenty-two hours. For example, train #19 arrived at Pusan station at 17:47 but the successive train #28 departs the next day at 15:30 after nearly twenty-two hours. This clearly demonstrates that locomotive utilization is not fruitful.

The next factor for consideration is that light running, or operation without customers, is not used effectively when the next successive train in the sequence is connected. Fig. 4 shows a geographical diagram of the Kyong-bu line. This figure illustrates that the distance between Pusan, Haeundae, Ulsan and other stations is not far away respectively, and therefore some of the light only operation is possible between these stations.

3. Modeling by CSP Programming

3.1 Overviews of CSP Programming Technique

Several approaches have been attempted to solve the various complex scheduling problems. In particular, researchers have tried using mathematical techniques such as linear programming. However, the scheduling problems on railway system are NP problems with the complexity of the number of $N!$. As such, if the scale of problems is increased, then the complexity for solving them is steeply increased. Therefore, a more effective solution is needed. It is also difficult to express entirely the domain knowledge and constraints as a mathematical model. As a result, the inference mechanism is required to solve these scheduling problems.

Recently, AI techniques have been used in an attempt to solve the scheduling problems. Recently, there have been several efforts to resolve these scheduling problems using the CSP technique, one of the AI techniques. In the CSP technique, the complex problems are modeled as a set of constraints and finite discrete domains, and then solved by consistency checking and heuristic search algorithm. This employs use of the scheduling problems, circuit design and graph problems.

All constraint satisfaction problems are composed of variables ($V_i, i = 1, 2, ..., n$), with finite discrete domains ($D_i, i = 1, 2, ..., n$) corresponding to each variable and constraint ($C_i, i = 1, 2, ..., n$). These models perform the searching activity of a solution with satisfaction of all constraints in domains corresponding to each variable. An effective scheme of the CSP technique is domain filtering. This domain filtering scheme is the filtering of unnecessary domains by the given constraints so that the searching space becomes reduced. This searching reduction is realized by the constraint consistency check scheme. The constraints for domain filtering are optional constraints. As the variables and domains become more numerous, the searching time and necessary space for a solution is increased. As such, a more effective searching technique is needed. The procedure for determining the solution using the CSP technique is as follows.

1) Problems arise.

2) Modeling of variables, domains and constraints corresponding to given problems.

3) Reduction of searching space by the constraint consistency process. The purpose of this phase is the reduction of searching space using a domain filtering technique by given constraints. Consequently, the inference time can be considerably reduced.

4) Finding the solution by general inference techniques.

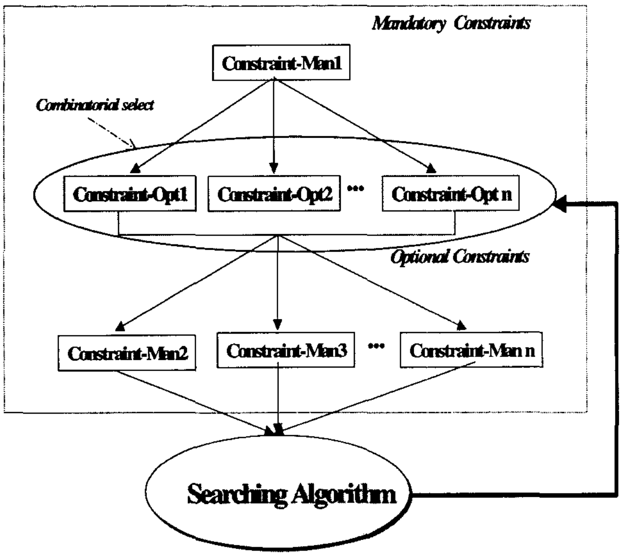


Fig. 5 Constraints processing procedure.

Recently, there have been some languages used to describe and to process the logical constraints and variable domains, etc. The CHIP (Constraint Handling In Prolog) and the ILOG Solver are examples of these tools. In this research the ILOG Solver, the ILOG Scheduler and the ILOG View are used as CSP development tools.

In this study, the constraints and rules are represented and processed by the logical language for effective scheduling by the CSP technique. These methods are efficient in representing knowledge and solving the locomotive scheduling problems. Using these techniques, the searching space can be reduced and the speed for solution finding can be enhanced.

3.2 Modeling by CSP

Domains and Variables

The domains and variables are modeled for solving the locomotive linking scheduling problems. Some of them are described in this section.

- Domain of departure time for each train $i : L_i$
  Domain of arrival time for each train $i : A_i$
  Domain of running time for each train i :
  $DT = \{\, i \mid (A_i - L_i), 0 \le i \le m \}$
- Domain of station: X
  $X = \{Seoul, Taegu, Pusan, Haeundae, Ulsan,$
  $Pohang, Masan, Jinju\}$
- Domain set of each DIA: $TD = \{TD_1, TD_2, ..., TD_n\}$
- Domain of a locomotive length: *Length*( )
  $Length(TD_1) = Length(TD_2) = Length(TD_3)$
  $= Length(TD_4) = 8$
  $Length(TD_5) = Length(TD_6) = ... = Length(TD_{27}) = 16$
- In the case of train i that is running from departure station (X_i) with departure time (L_i) to arrival at station (X_i') with arrival time (A_i), the expression is follows:

$$TB = \{\, i \mid (X_i, L_i) R_{DT_i} (X_i', A_i), 1 \le i \le n \,\}$$

where i : The number of trains,
n : The number of DIAs
m : The number of train numbers

Constraints

In this section, the constraints for the locomotive scheduling are represented. Two types of constraints, the mandatory and optional constraints, are required in the CSP technique. The mandatory constraints must be satisfied during the scheduling process. If these constraints are violated, then the solutions are no longer valid. The optional constraints can be violated in a specific environment. During scheduling, the optional constraints are checked, and these constraints can be relaxed to reduce the searching space by the domain filtering scheme.

The significant constraints for our task are presented. Among them, the [Constraints 1~2] are defined as mandatory constraints and the others are considered as optional constraints.

[Constraint-1]: $TB_i(L_i) \ge TB_{i-1}(A_{i-1}) + 180$

A DIA number has at least 2 trains. The TB is defined as a set of train numbers for a DIA. $DIA = \{ i \mid TB_i, TB_{i+1}, \ldots \}$.

The connecting time for linking as a sequence DIA must be limited to 3 hours. This time for two trains connecting is influenced by several factors such as typical maintenance, passenger riding, coach cleaning, reallocation of the train onto proper track and others. The approximate time was obtained from KNR employees. If the DIA_1 consists of TB_1 and TB_2, then these are able to be expressed as $TB_1 = (X_1, L_1) R_{DT_1} (X_1', A_1)$ and $TB_2 = (X_2, L_2)$ $R_{DT_2}(X_2', A_2)$.

Generally, if the departure time of TB_i is $TB_i(L_i)$ and the arrival time is $TB_i(A_i)$, then [Constraint-1] can be expressed as follows:

$TB_i(L_i) \geq TB_{i-1}(A_{i-1}) + 180$

[Constraint-2]: $|\ DIA_k\ | \geq 2$

All trains must be used for effective locomotive scheduling. In addition, if possible, a DIA should be composed of more than two trains.

[Constraint-3]: $TB_j(X'_j) = TB_{j+1}(X_{j+1})$

The arrival station of the previous train $TB_j(X'_j)$ must be the same as the departure station of the next successive train $TB_{j+1}(X_{j+1})$ at a DIA. This constraint is only an optional constraint.

[Constraint-4]: $Length\ (DIA_k) = Length\ (TB_i)$

Every train in the same DIA is assigned to a locomotive of the same type. In the actual Korean railway system, this is a valid practical constraint. However, this constraint needs to be relaxed for further effective and/or optimal results. So this is an example of optional constraints in our study.

[Constraint-5]: $\overline{TD}_{am} = Minimum\ (\overline{TD}_a\ (LT_m))$

The previous [Constraint-3] may have a certain degree of inefficiency. If this constraint were relaxed in any case, then a higher utilization of the locomotives would be expected. It is possible to identify that the distance between Pusan, Haedundae, Ulsan and other stations in the Kyong-bu line of the KNR is not far away respectively, and therefore some light running time is possible between these stations. That being the case, the light running of a locomotive, operating without customers on it, should occur. This is able to expressed follows:

$\overline{TD}_{am} = Minimum\ (\overline{TD}_a\ (LT_m))$

where $\overline{TD}_a = \{TD_1, TD_1, \ldots\}$: The set of trains located at different stations

$LT = \{LT_1, LT_2, \ldots\}$: The set of light running time

$\overline{TD}_a\ (LT_m)$: The light running time of each $\overline{TD}_a$

<u>GOAL Function</u>

The objective of locomotive scheduling is to find a set of locomotive coverall trains within a particular timetable at minimum operating costs. In this case, WT_a is the waiting time of a locomotive at a station X_a and LT_a is the light running time of a locomotive. The cost function for this scheduling can be represented as follows:

$$C_a = A_t \cdot LT_a + B_t \cdot WT_a \tag{2}$$

The selection of coefficients for the objective cost function is very important. One method to decide the coefficients is to use the ratio between the straight-line depreciation of locomotives, labor costs and power consumption costs, etc. In a rough estimation of the Korean railway system, the coefficients $A_t : B_t$ are able to estimate about 4:1.

$$A_t : B_t = 4 : 1 \tag{3}$$

This cost function must be applied to all locomotive linking problems.

$$\sum_{i,j}^{m} 4 \cdot LT_{ij} + WT_{ij} \tag{4}$$

where i, j : a locomotive,

m : The number of DIAs.

The objectives of locomotive linking scheduling with cost function can be expressed as follows:

$$Min\left(\sum_{i,j} A_t \cdot LT_{ij} + B_t \cdot WT_{ij}\right) \tag{5}$$

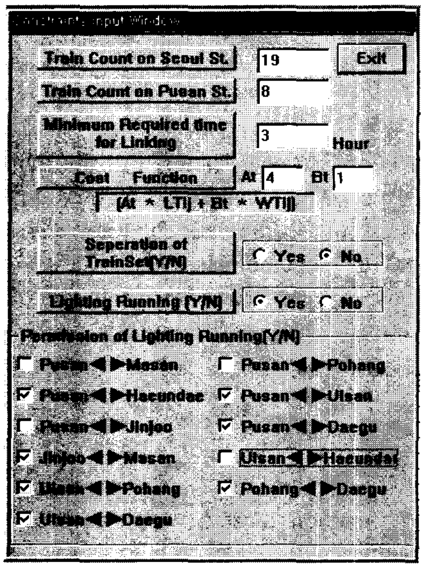
And another objective is to consider minimizing the number of DIAs with the fixed locomotives. Therefore, the coal function for scheduling can be represented by equations (5) and (6).

$$Min\ (|\ DIA\ |) \tag{6}$$

4. Experiment and Results Analysis

For the above clause modeling experiments performed using the CSP technique, we selected the actual timetable of the Saemaul type trains on the Kyong-bu line. The program is developed to achieve appropriate locomotive scheduling based on this timetable. The ILog scheduler and ILog Solver were used for the CSP programming tool, and the operational system environment was the personal computer with Pentium IV 1.7 GHz and RAM 256 Mbyte.

The window for constraints input is shown in Fig. 6. This interactive program is developed for the analysis of influence of constraints. The coefficients of equation (5)



Train Count on Seoul St. 19

Train Count on Pusan St. 8

Minimum Required time for Linking 3 Hour

Cost Function At 4 Bt 1

(At * LTij + Bt * WTij)

Seperation of TrainSet(Y/N) ○ Yes ● No

Lighting Running (Y/N) ● Yes ○ No

Permission of Lighting Running(Y/N)

☐ Pusan◀ ▶Masan ☐ Pusan◀ ▶Pohang
☑ Pusan◀ ▶Haeundae ☑ Pusan◀ ▶Ulsan
☐ Pusan◀ ▶Jinjoo ☑ Pusan◀ ▶Daegu
☑ Jinjoo◀ ▶Masan ☐ Ulsan◀ ▶Haeundae
☑ Ulsan◀ ▶Pohang ☑ Pohang◀ ▶Daegu
☑ Ulsan◀ ▶Daegu

Fig. 6 Window for constraints editing.

can be modified through this, and permit light running scheduling. Fig. 7 displays the total scheduling result by Gantt chart form, parts of which are shown in Fig. 8. According to the output of this Gantt chart form, the scheduling results can be easily acknowledged. From Fig. 8, the DIAs with light running can be set up.

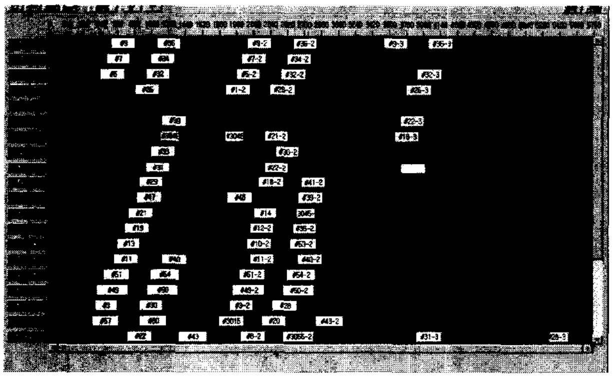


Fig. 7 Scheduling result.

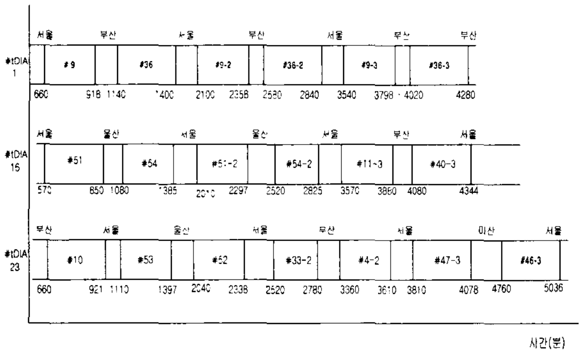


Fig. 8 Several examples of scheduling results.

By comparison with the operating costs between the existing schedule performed manually by human experts and simulated scheduling results performed by the proposed scheme presented in this paper, it is verified that the operating costs were reduced from 17,996 to 10,247. This signifies that the performance of locomotive scheduling is greatly improved. Furthermore, the executing time for the scheduling is about 16.5 sec. If human experts are scheduling under the same constraints and conditions, it is expected to take around 2 ~ 3 days, and therefore the cost of results is much higher than the scheduling results using the proposed CSP programming. From these results, it is possible to identify that the application of the CSP programming technique to scheduling problems can remarkably reduce human scheduling errors and scheduling times. In addition, more advanced scheduling results can be obtained by comparison with manual scheduling performed by human experts. It is anticipated that the CSP programming technique proposed in this paper will be effective not only in the case of locomotive scheduling but also in timetable construction, crew roster scheduling, train control systems and etc.

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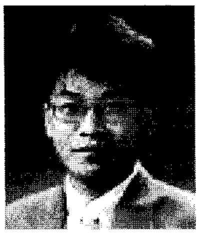

Jong-Gyu Hwang
He received his B.S. and M.S. degrees in Electrical Engineering from Konkuk University, Korea in 1994 and 1996, respectively. He has been working towards his Ph.D. in the Division of Electrical and Computer Engineering, Hanyang University since the year 2000. As of 1995, he has been a Senior Researcher with the Dept. of Railway Electrical and Signaling Research of the Korea Railroad Research Institute. His research interests are in the areas of protocol for railway signaling systems, communication network technology and train scheduling.

Jong-Woo Lee
He has been working as a Principal Investigator at the Korea Railroad Research Institute since 1994. He received his B.S. in Mechanical Engineering from Hanyang University, M.S. in System Control from Ecole Centrale de Nantes and Ph.D. in Electronic Engineering from the University of Paris VI, France in 1983, 1986 and 1993, respectively. His research interests are in the areas of the theoretical aspect of systems engineering, controller design, system engineering in the railway system, fault tolerant and fail safe systems on computerized train control systems and theoretical train control systems.

Yong-Jin Park
He received his B.S., M.S. and Ph.D. degrees in Electronics Engineering from Waseda University, Tokyo, Japan in 1969, 1971 and 1978, respectively. In 1978, he joined Hanyang University in Korea where he is currently a Professor in the Division of Electrical and Computer Engineering. He was a Visiting Professor at the University of Illinois in the USA, University of Kent in the UK and Chuo University in 1984, 1992 and 1998 respectively. Presently, he is President of the Korea Information Science Society and Secretary of IEEE Region 10. His main research interest is advanced networking technology.