INFORMS Annual Meeting
RAS Problem

2020

A multi-objective railway freight timetable reschedule approach with extensive and stochastic delay

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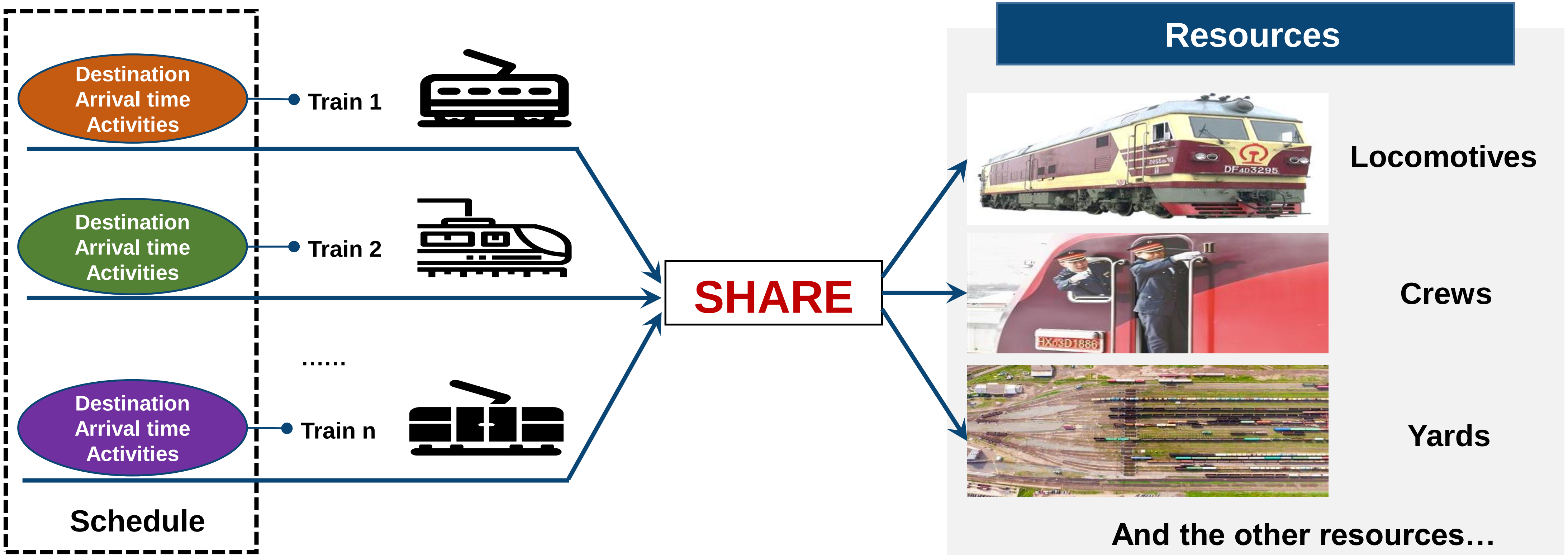
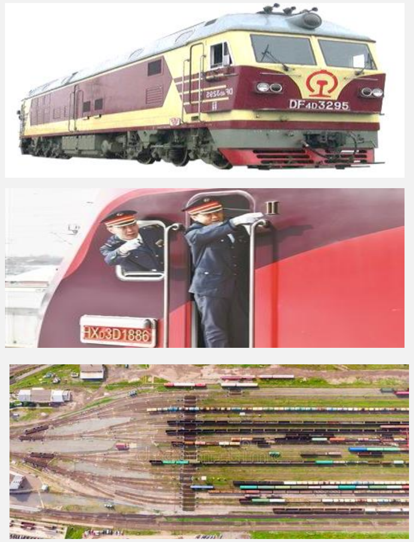
BACKGROUND

- Align three resources: **yards, crews, and locomotives.**
- The time-effectiveness of railway freight service is an important issue for the railway operation and shippers.



BACKGROUND

Resources



Unavailability

- **The delay from planned departure time at the point of origin**
- **The dwell time of a train at flagged stations for the crew change.**
- **The yard delay at flagged pickup and setoff points**

Our focus

Disturbances → **Reschedule timetable**

The arrival time of your delivery is Nov 3rd 15:00

Disruptions → Reschedule timetable + Change resource duties

- ☐ A more stable and precise timetable is an urgent need.
- ☐ **The predictive arrival time** based on the rescheduled timetable considering the extensive and stochastic delay is more suitable to inform the shippers.

PROBLEM STATEMENT

Difficulties for the railway freight timetable rescheduling

(1) The durations of disturbances are stochastic

- The departure delay resulting from the installing locomotive at the origin station. Fig. (a)
- The dwell time resulting from the crew change. Fig. (b)
- The delay of pick-up and set-off at the yard. Fig. (c)

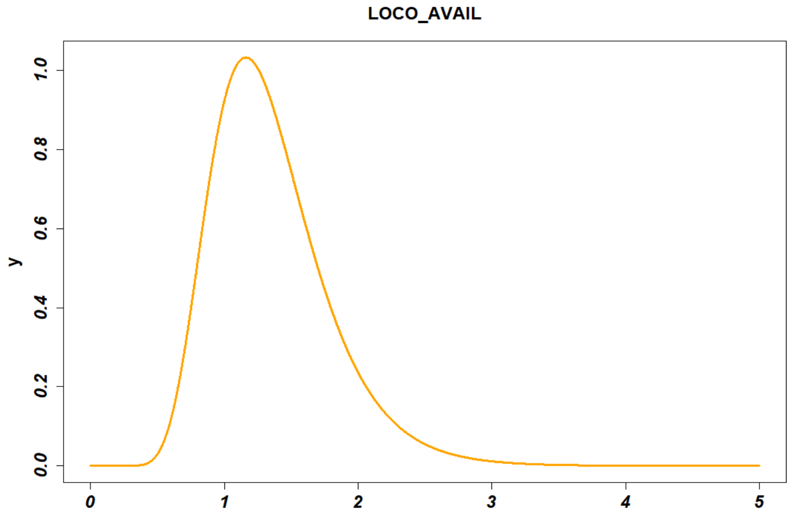


Fig. (a)

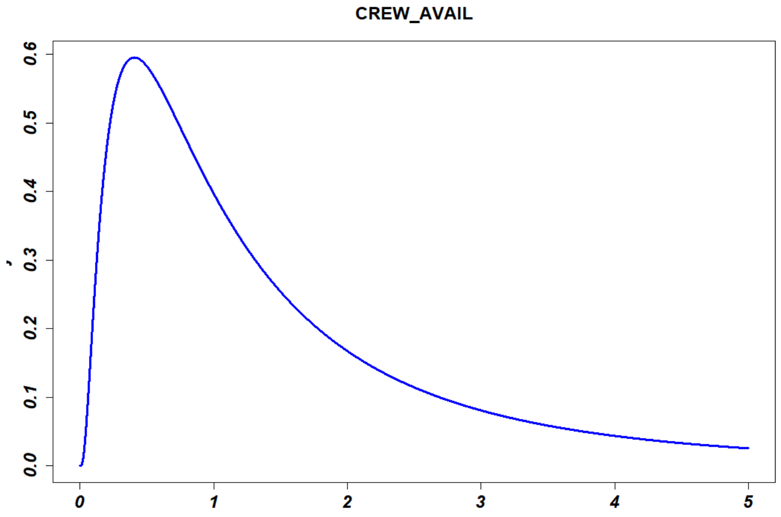


Fig.(b)

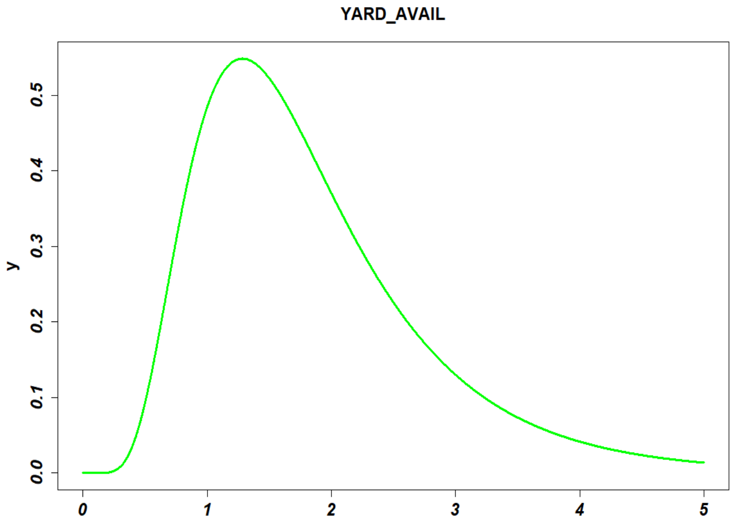
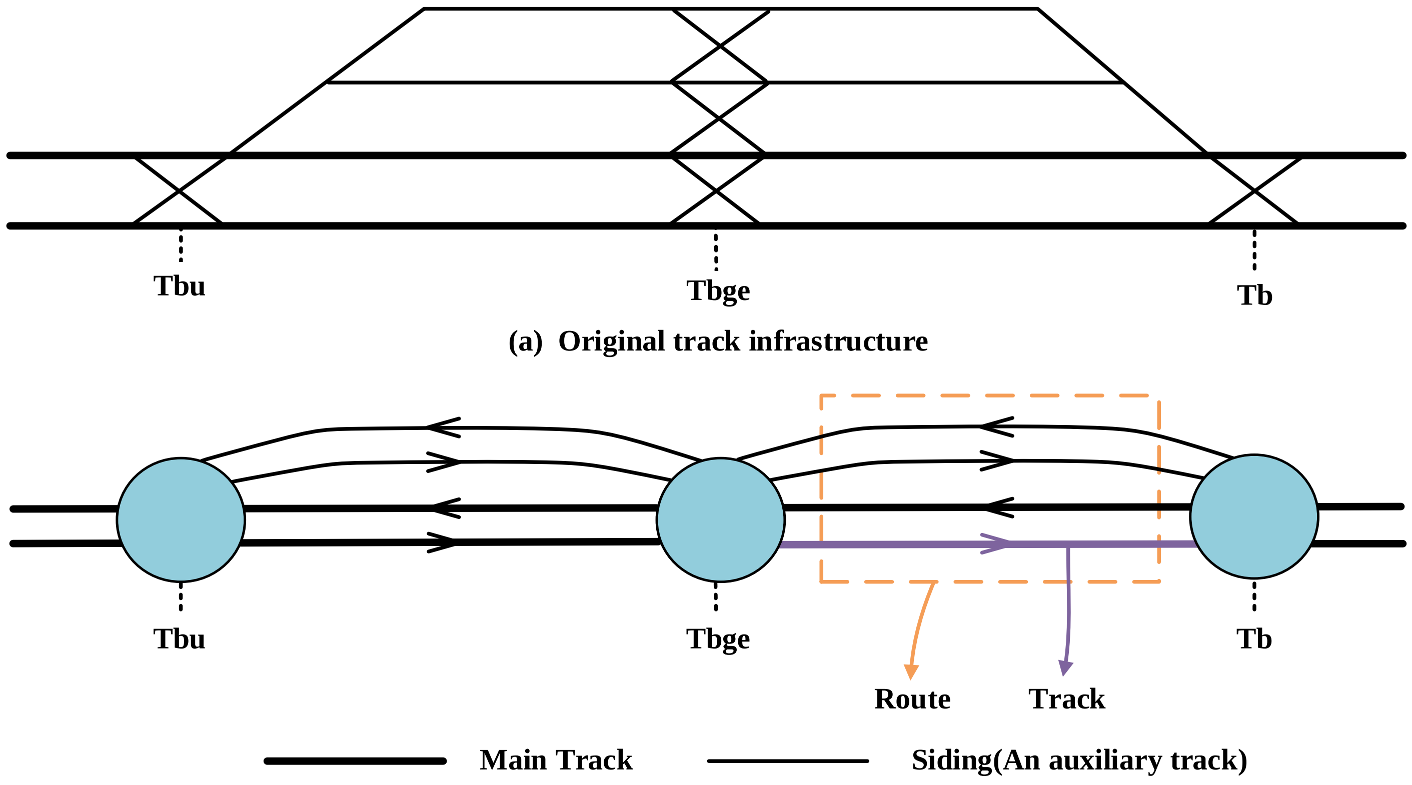


Fig. (c)

PROBLEM STATEMENT

Difficulties for the railway freight timetable rescheduling

(2) Limited and congested track configuration



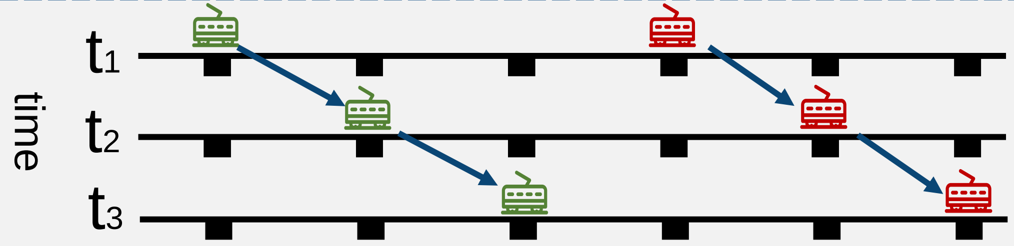
(b) Vertex-edge topology graph

- All directed edges are **one-way** for operation
- Occupying the siding or wyes should be delayed to some extent.

PROBLEM STATEMENT

Difficulties for the railway freight timetable rescheduling

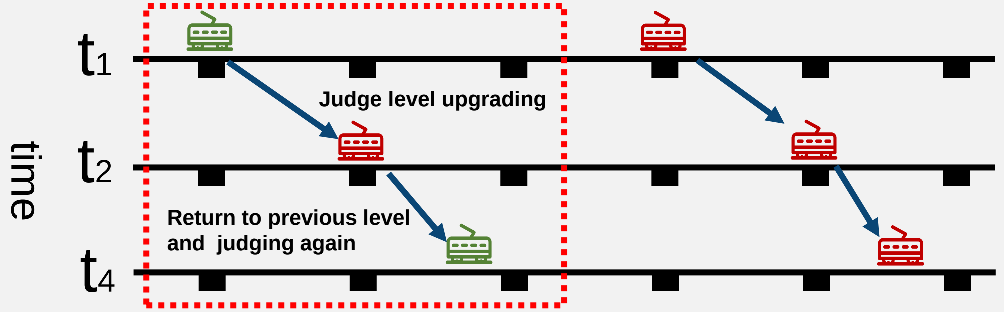
(3) The comprehensive level: static level + dynamic level



Static level

The cargo loaded on the train

Only consider static level



static level + **dynamic level** { 1 If dwell time>threshold; 0 Otherwise }

comprehensive train level

Comprehensive level

Train	Static level	Dynamic level	Comprehensive level
Train 1	1 (high)	-	1 (high)
Train 2	0 (low)	1 (high)	1 (high)
Train 3	0 (low)	0 (low)	0 (low)

Give the priority of departure order to the train with low static level.

■ station — The train with low level — The train with high level

PROBLEM STATEMENT

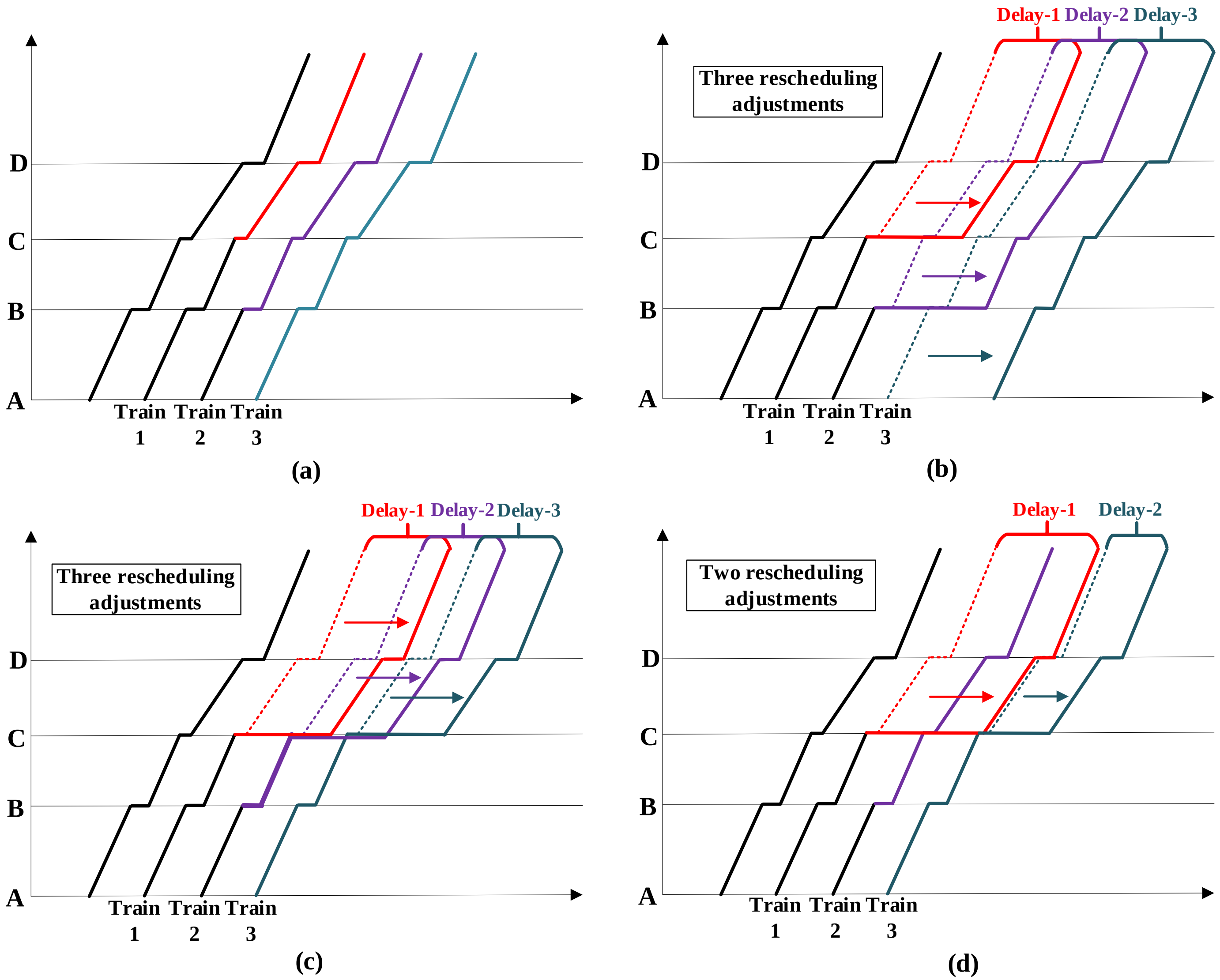
Difficulties for the railway freight timetable rescheduling

(4) High standard of **solving time and the solution quality**

- Ensure the handover of dispatcher responsibility to the next shift and timely operation.

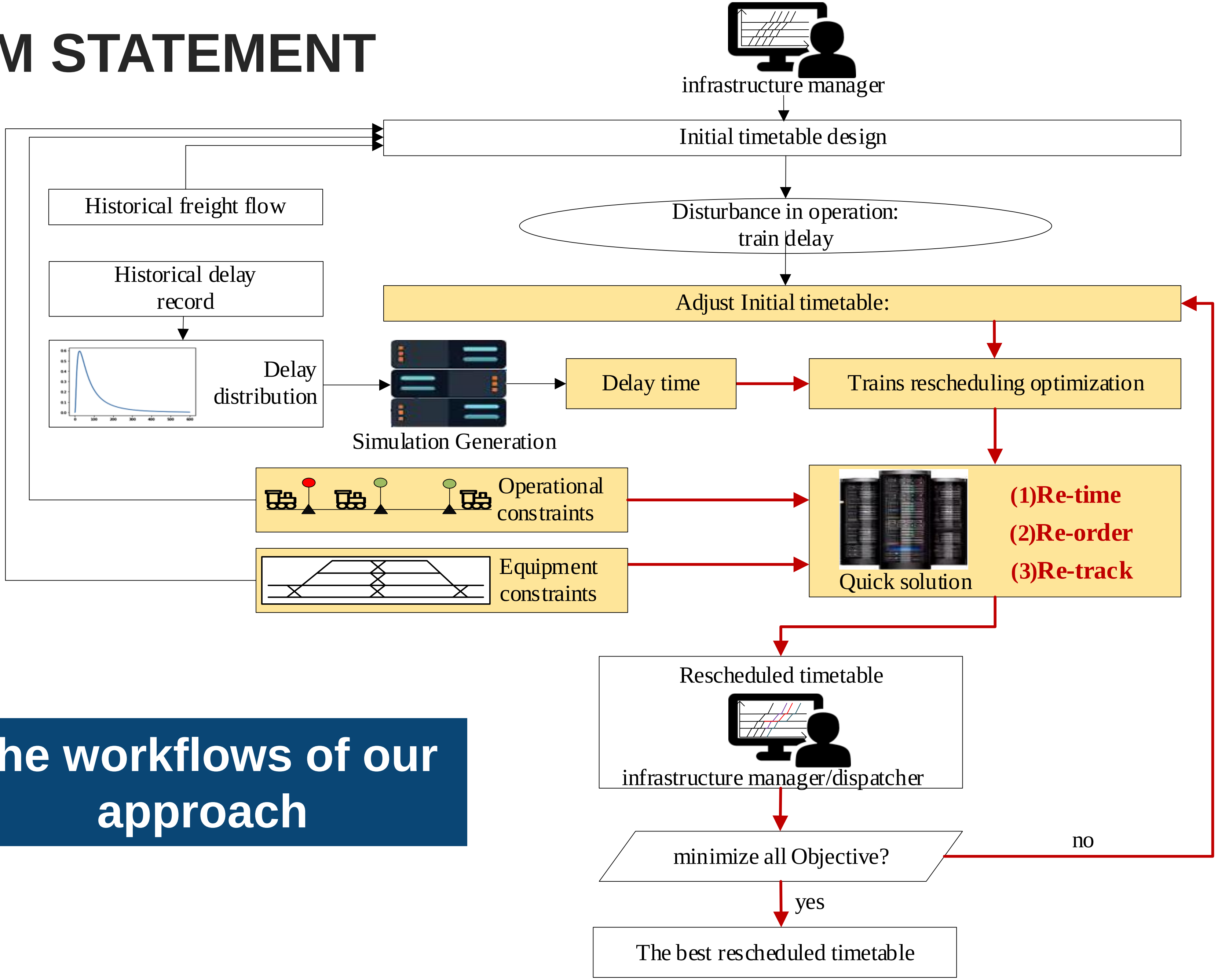
PROBLEM STATEMENT

A simple example to describe the dispatching scenes.



- **Case1 Fig. (b)**
  - ✓ One track is available in station C.
  - ✓ Comprehensive level: 1st train > 2nd train.
  - ✓ At least three delays and three adjustments.
- **Case2 Fig. (c)**
  - ✓ Two tracks are available in station C.
  - ✓ Comprehensive level: 1st train > 2nd train.
  - ✓ No delayed effects when the 3rd train runs between station A and station C.
- **Case3 Fig. (d)**
  - ✓ Two tracks are available in station C.
  - ✓ Comprehensive level: 1st train < 2nd train.
  - ✓ At least two delays and two adjustments.

PROBLEM STATEMENT



The workflows of our approach

PROBLEM STATEMENT

Assumptions

- (1) The section **running time is fixed** and depends on the planned timetable;
- (2) The **transition of trains** between segments would be instantaneous;
- (3) Passing through the siding, wye, or industrial spur can be regarded as instantaneous movement but need to **add the penalty of time**;
- (4) **Any route can only be occupied by one train** at the same time;
- (5) The **acceleration/deceleration of the train should be instantaneous**;
- (6) There is **no interference coming from passenger trains** on the same rail line;
- (7) There is **no change in the stations and stations order** of train's passing.

OPTIMIZATION MODEL Train Timetable Rescheduling Model (TTR)

Decision variables

m_{ispk}

The train i takes the track k from the station s to the station p.

t_{ispk}^{d} (arriving at station s).

The time of the train i departing from the track k between station s and station p

t_{ispk}^{a} (departing from station s).

The time of the train i arriving at the track k between station s and station p

$stop_i^s$

The actual dwell time of the train i at the station s(regular station).

y_{ijsp}

The departure order of train i, j in the section (s, p)

z_{isb_s}

The train i occupies line b at station s.

Intermediate variables

$$t_{is}^{A} = \sum_{p \in S} \sum_{k_{ps} \in K_{ps}} t_{ipsk_{ps}}^{d}$$

Arrival time of the train i at station s.

$$t_{is}^{D} = \sum_{p \in S} \sum_{k_{sp} \in K_{sp}} t_{ispk_{sp}}^{a}$$

Departure time of the train i at station s

pdl_{is}

The dynamic priority of the train i at station s.

$$m_{is} = psl_i + pdl_{is}$$

The comprehensive priority of the train i at station s.

OPTIMIZATION MODEL

Train Timetable Rescheduling Model (TTR)

- departure time constraints

1 $$\sum_{p\in S}\sum_{k_{sp}\in K_{sp}} t^{a}_{ispk_{sp}} \geq \bar{t}^{D}_{is} \quad (\forall i\in I; \forall (s,p)\in S(s,p))$$

2 $$\Pr\Big(\big(\sum_{p\in S}\sum_{k_{sp}\in K_{sp}} t^{a}_{io(i)pk_{sp}}\big) - \bar{t}^{D}_{io(i)} \geq tdl_i\Big) \geq \alpha \quad (\forall i\in I; \forall (s,p)\in S(s,p))$$

Departure time at the origin station

3 $$\Pr\Big(\big(\sum_{p\in S}\sum_{k_{sp}\in K_{sp}} t^{a}_{ispk_{sp}} - \sum_{p\in S}\sum_{k_{sp}\in K_{sp}} t^{d}_{ispk_{sp}} - stop^{s}_{i}\big) \geq tdp^{s}_{i}\Big) \geq \beta \quad (\forall i\in I; \forall s,(s,p)\in S^{ps}_{l}, S(s,p))$$

Departure time at stations with pick-up and set-off flags

- dwell time constraints

4 $$stop^{s}_{i} \geq \overline{ts}^{s}_{i} \quad (\forall i\in I; \forall s\in S)$$

5 $$\Pr(stop^{s}_{i} \geq tsc^{s}_{i}) \geq \gamma \quad (\forall i\in I; \forall s\in S^{crew}_{l})$$

Prolonged dwell time due to crew changes

- running time on sidings constraint

6 $$\sum_{k_{sp}\in K_{sp}} t^{d}_{ispk_{sp}} - \sum_{k_{sp}\in K_{sp}} t^{a}_{ispk_{sp}} = t_{sp} + t_{r}\cdot \sum_{k_{sp}\in K^{-}_{sp}} m_{ispk_{sp}} \quad (\forall i\in I; \forall (s,p)\in S(s,p))$$

OPTIMIZATION MODEL Train Timetable Rescheduling Model (TTR)

- section route selection constraint

7 $$\sum_{k_{sp}\in K_{sp}} m_{ispk_{sp}} = r_{isp} \quad (\forall i \in I; \forall (s,p) \in S(s,p))$$

- section route occupation constraints

8 $$t^a_{jspk_{sp}} - t^d_{ispk_{sp}} \geq M \cdot (1 - y_{ijsp}) \quad (\forall i, j \in I \text{ and } i \neq j, \forall k_{sp}, (s,p) \in K_{sp}, S(s,p))$$

Aims to the consecutive trains running in the same direction

9 $$t^a_{jpsk_{ps}} - t^d_{ispk_{sp}} \geq M \cdot (1 - y_{ijsp}) \quad (\forall i, j \in I \text{ and } i \neq j, \forall k_{sp}, (s,p) \in K_{sp}, S(s,p))$$

Aims to the consecutive trains running in the opposite direction

- trains level adjustment constraints

10 $$t^D_{is} - \bar{t}^D_{is} - t_r < M \cdot pdl_{is} \quad (\forall i \in I^-, \forall s \in S)$$

Not upgrading to high level

11 $$t^D_{is} - \bar{t}^D_{is} - t_r \geq M \cdot (pdl_{is} - 1) \quad (\forall i \in I^-, \forall s \in S)$$

upgrading to high level

- station track constraints

12 $$\sum_{b_s\in B_s^+} z_{isb_s} = 1 \text{ and } \sum_{b_s\in B_s^+} z_{jsb_s} = 1 \quad (\forall i \in I, \forall s \in \frac{S}{o(i)})$$

13 $$\sum_p \sum_{k_{sp}} t^a_{ispk_{sp}} - \sum_p \sum_{k_{sp}} t^d_{jspk_{sp}} \geq h_{fd} - M \cdot (3 - y_{ijsp} - z_{isb_s} - z_{jsb_s}) \quad (\forall i \in I, i \neq j, \forall s \in S)$$

14 $$\sum_p \sum_{k_{sp}} t^a_{jspk_{sp}} - \sum_p \sum_{k_{sp}} t^d_{ispk_{sp}} \geq h_{fd} - M \cdot (3 - y_{jisp} - z_{isb_s} - z_{jsb_s}) \quad (\forall i \in I, i \neq j, \forall s \in S)$$

OPTIMIZATION MODEL Train Timetable Rescheduling Model (TTR)

Objective function

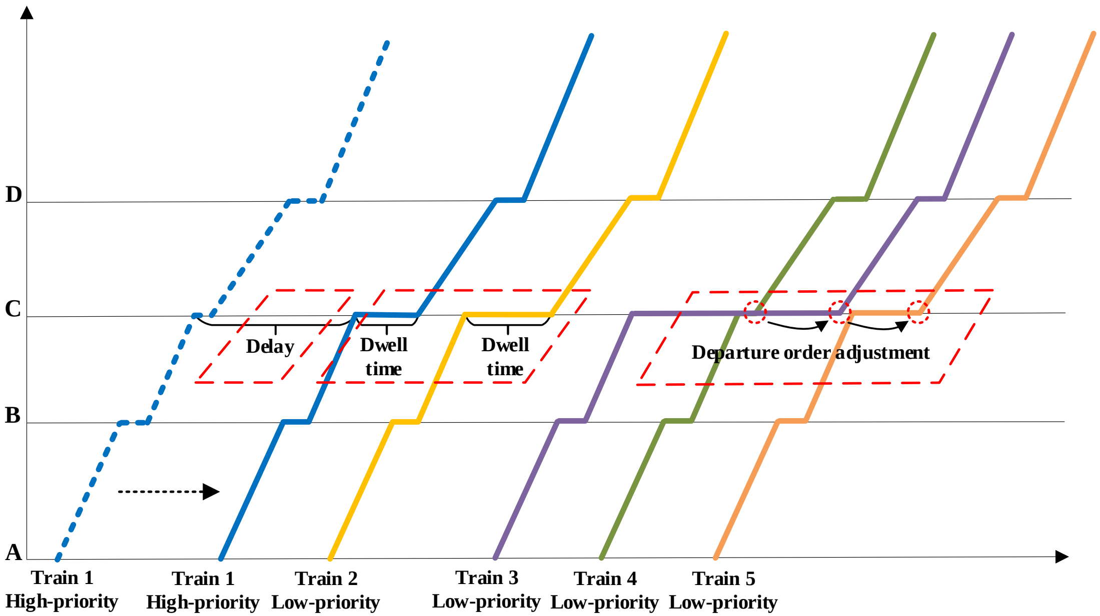
Type1:Minimize direct effects of disturbances

- (1) Minimize the total arrival deviation at the stations with flags

$$\min\ Z_1 = \sum_{i \in I} (t_{is}^{A} - \bar{t}_{is}^{A}) \quad (s \in S_l^{crew} \cup S_l^{ps})$$

- (2) Minimize the total weighted dwell time of all trains

$$\min\ Z_2 = \sum_{i \in I} \sum_{s \in S} ((t_{is}^{D} - t_{is}^{A}) \tau_{is})$$



Type2:Minimize indirect effects of disturbances

- (3) Minimize adjustment number of departure order

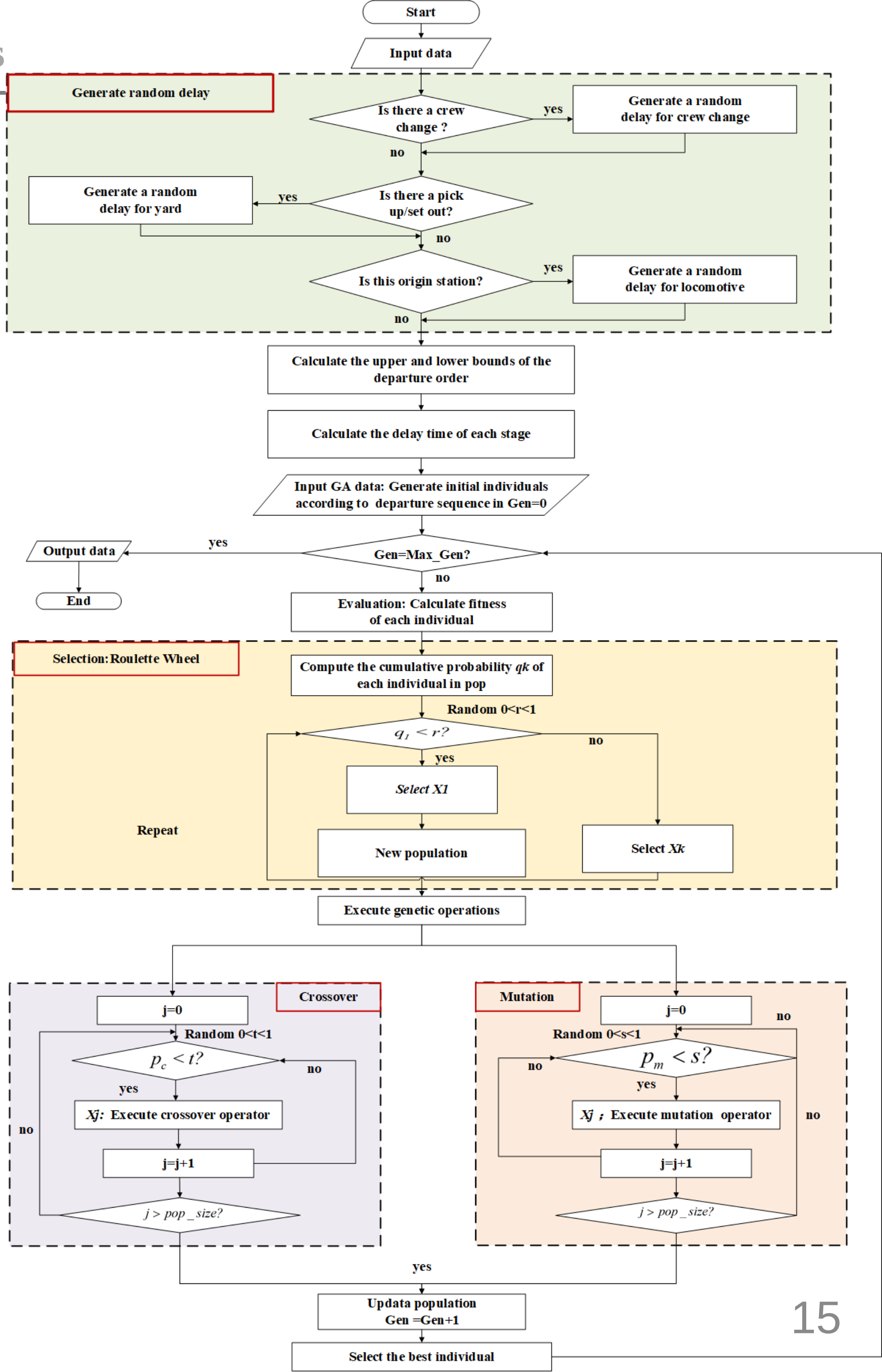
$$\min\ Z_3 = \sum_{i \in I} \sum_{j \in I} \sum_{s \in S} \sum_{p \in S} | y_{ijsp} - y_{ijsp}^{*} | \quad (i \neq j, (s,p) \in S(s,p))$$

SOLUTION

Stochastic delay generating combined with Multiple Objectives GA(S-MOGA) Solution

GA: Genetic Algorithm

- (1) Stochastically simulate the delay
- (2) Calculate the lower and upper bound of departure order adjustment based on the delay time
- (3) Generated the two-dimension initial chromosome
- (4) Repeat
- (5) Terminate



SOLUTION

Certain Transformation of uncertain inequalities constraints

Locomotives | **Crews** | **Yards**

(1) $\Pr(x_i \geq \xi_i) \geq \alpha_i$

(2) $\xi_i \sim \log \mathrm{N}(\mu, \sigma^2)$ (3) $Y = \mathrm{LN}(\xi_i) \sim \mathrm{N}(\mu, \sigma^2)$

(4) $\Pr(x_i \geq K_a) = \alpha_i$

(5) $K_a = \sigma_i \cdot \Phi^{-1}(1-\alpha_i) + \mu_i$

(6) $\Pr(h(y) \geq Y) = F_1(h(y)) = \Phi[\frac{h(y)-\mu}{\sigma}] \geq \alpha$

(7) $h(y) \geq K_a = \sigma_i \cdot \Phi^{-1}(1-\alpha_i) + \mu_i$

Multiple objectives

$$Eva = \lambda_1 \cdot Z_1 + \lambda_2 \cdot Z_2 + \lambda_3 \cdot Z_3 \quad (\lambda_1 + \lambda_2 + \lambda_3 = 1)$$

OPTIMIZATION MODEL — Train Timetable Rescheduling Model (TTR)

- departure time constraints

$$\sum_{p \in S} \sum_{k_{sp} \in K_{sp}} t^a_{ispk_{sp}} \geq \overset{-D}{t_{is}} \quad (\forall i \in I; \forall (s,p) \in S(s,p))$$

$$\Pr((\sum_{p \in S} \sum_{k_{sp} \in K_{sp}} t^a_{io(i)pk_{sp}}) - \overset{-D}{t_{io(i)}} \geq tdl_i) \geq \alpha \quad (\forall i \in I; \forall (s,p) \in S(s,p))$$

$$\Pr((\sum_{p \in S} \sum_{k_{sp} \in K_{sp}} t^a_{ispk_{sp}} - \sum_{p \in S} \sum_{k_{sp} \in K_{sp}} t^d_{ispk_{sp}} - stop^s_i) \geq tdp^s_i) \geq \beta \quad (\forall i \in I; \forall s, (s,p) \in S^{ps}_l, S(s,p))$$

- dwell time constraints

$$stop^s_i \geq \overline{ts}^s_i \quad (\forall i \in I; \forall s \in S)$$

$$\Pr(stop^s_i \geq tsc^s_i) \geq \gamma \quad (\forall i \in I; \forall s \in S^{crew}_l)$$

- running time on sidings constrain

$$\sum_{k_{sp} \in K^-_{sp}} t^d_{ispk_{sp}} - \sum_{k_{sp} \in K^-_{sp}} t^a_{ispk_{sp}} = t_{sp} + t_r \cdot \sum_{k_{sp} \in K^-_{sp}} m_{ispk_{sp}} \quad (\forall i \in I; \forall (s,p) \in S(s,p))$$

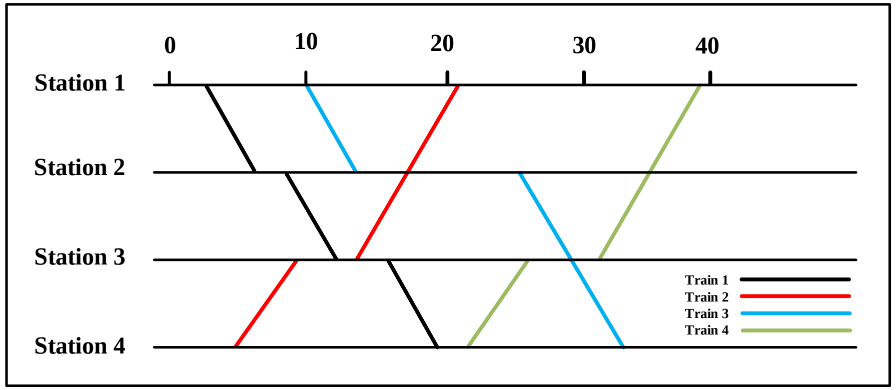
- Standard form
- Set it as an equation
- Calculated by the formula
- Transform into deterministic inequality

Reference: Liu B. Uncertain planning and application [M]. Beijing: Tsinghua University Press, 2003.

SOLUTION

Two-dimensional chromosome coding strategy

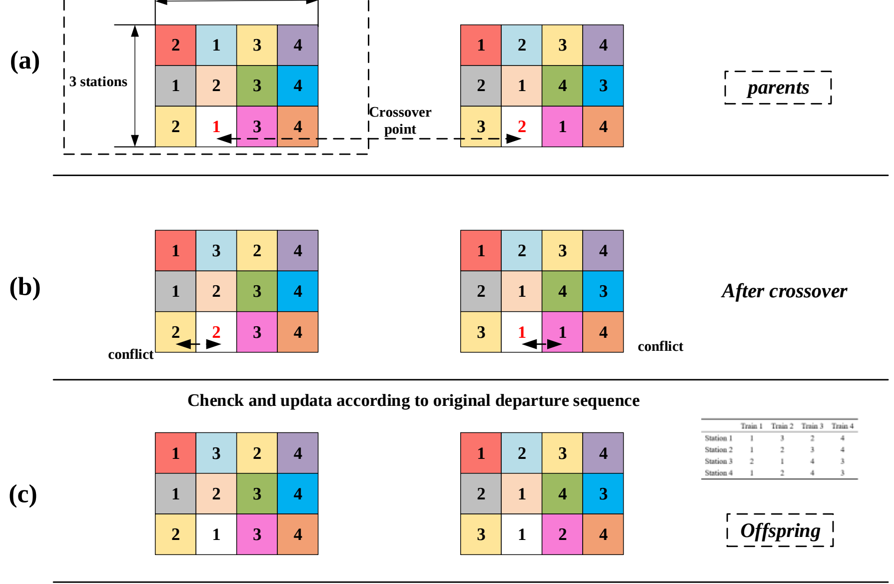
train timetable



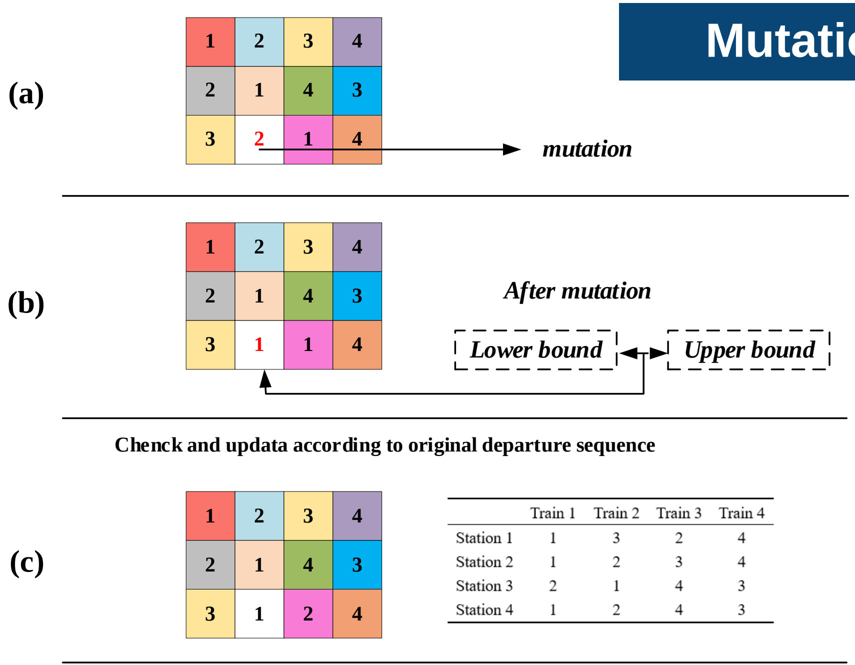
train departure order

	Train 1	Train 2	Train 3	Train 4
Station 1	1	3	2	4
Station 2	1	2	3	4
Station 3	2	1	4	3
Station 4	1	2	4	3

Crossover



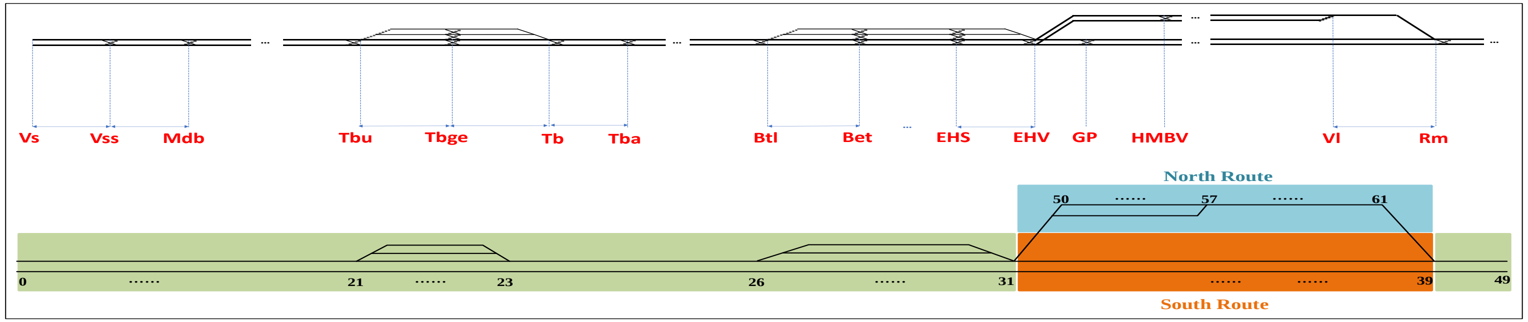
Mutation



CASE STUDY

Line description and Parameter settings

(1)



(2)

A time penalty: 5min.

- 62 stations, 254.9 km in length.

(3)

Random variable	Distribution function (unit: h)	Lower bound of delay K_a ($\alpha=\beta=\gamma=90\%$)(unit: min)
CREW_AVAIL	$X_1 \sim \log N(0.1,1)$	18.40
LOCO_AVAIL	$X_2 \sim \log N(0.25,0.1)$	51.37
YARD_AVAIL	$X_3 \sim \log N(0.5,0.25)$	52.12

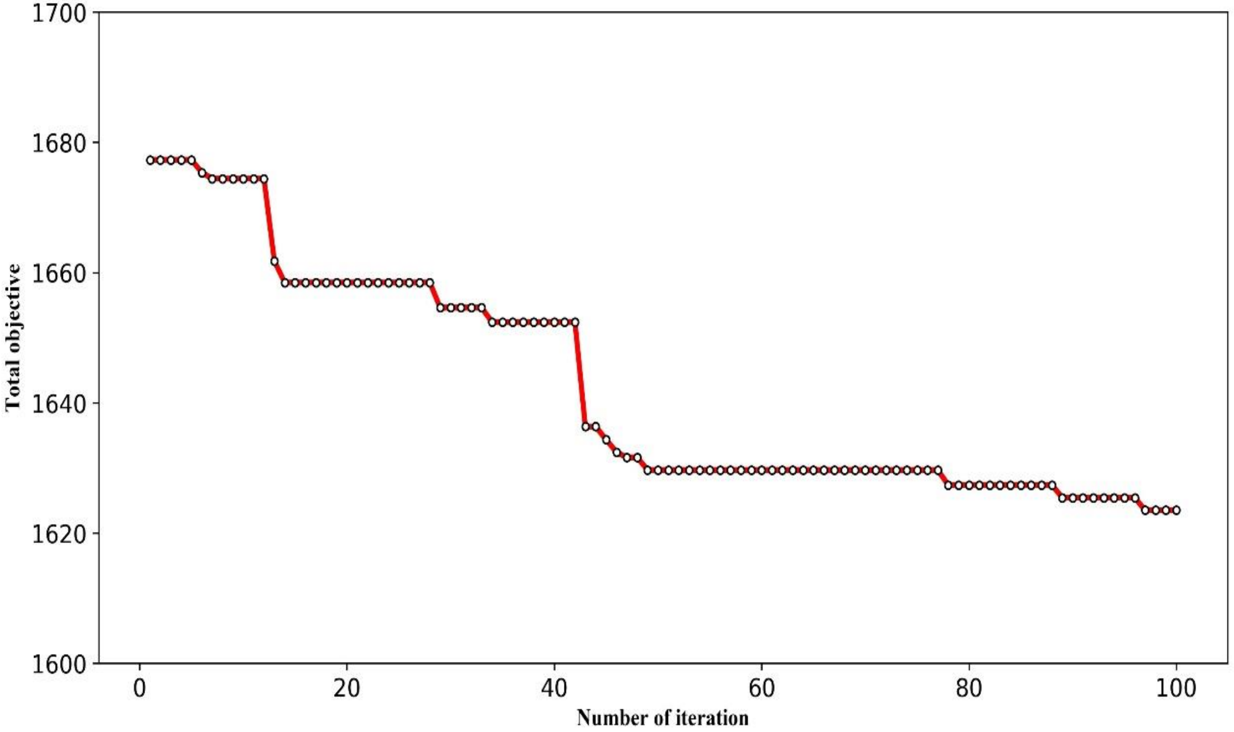
(4)

Case	Time window	Number of trains	Number of total passing stops
1	[0,240]	64	1442
2	[0,2520]	405	7658

CASE STUDY

Optimized results and analysis

(1) Performance of the S-MOGA algorithm



Optimization result of the total objective of Case 1

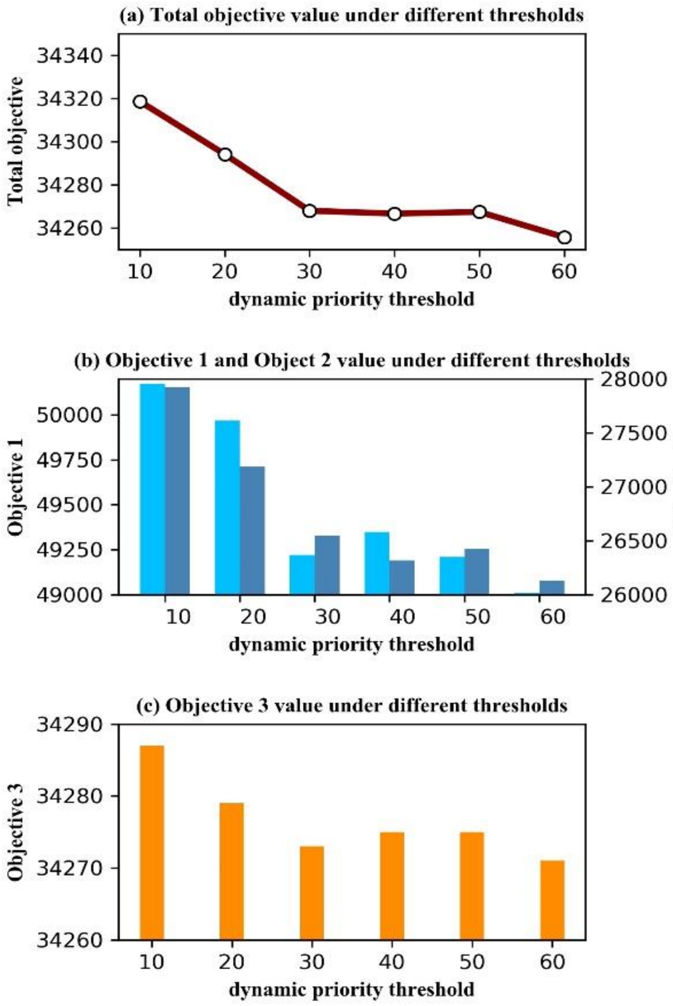
Case	Time window	Population scale/ Number of iterations	CPU time (h:m:s)
1	[0,240]	100 / 100	00:05:44
2	[0,2520]	20/100	01:44:02

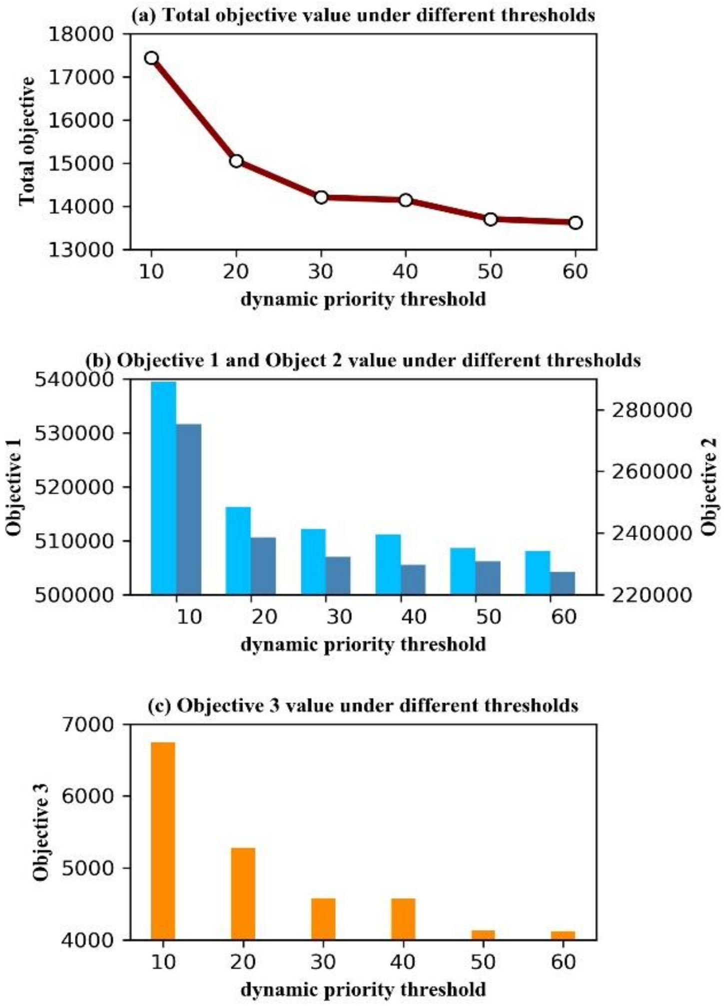
Test using an Intel Core I5 8400 hexa-core processor with 2.8 GHz and 8 GB RAM and python 3.7

CASE STUDY

Optimized results and analysis

(2) Sensitivity analysis on dynamic priority adjustment threshold





dynamic level {
1 If dwell time>threshold
0 Otherwise

CASE STUDY

Optimized results and analysis

(2) Statistics of the **delay at the destination**

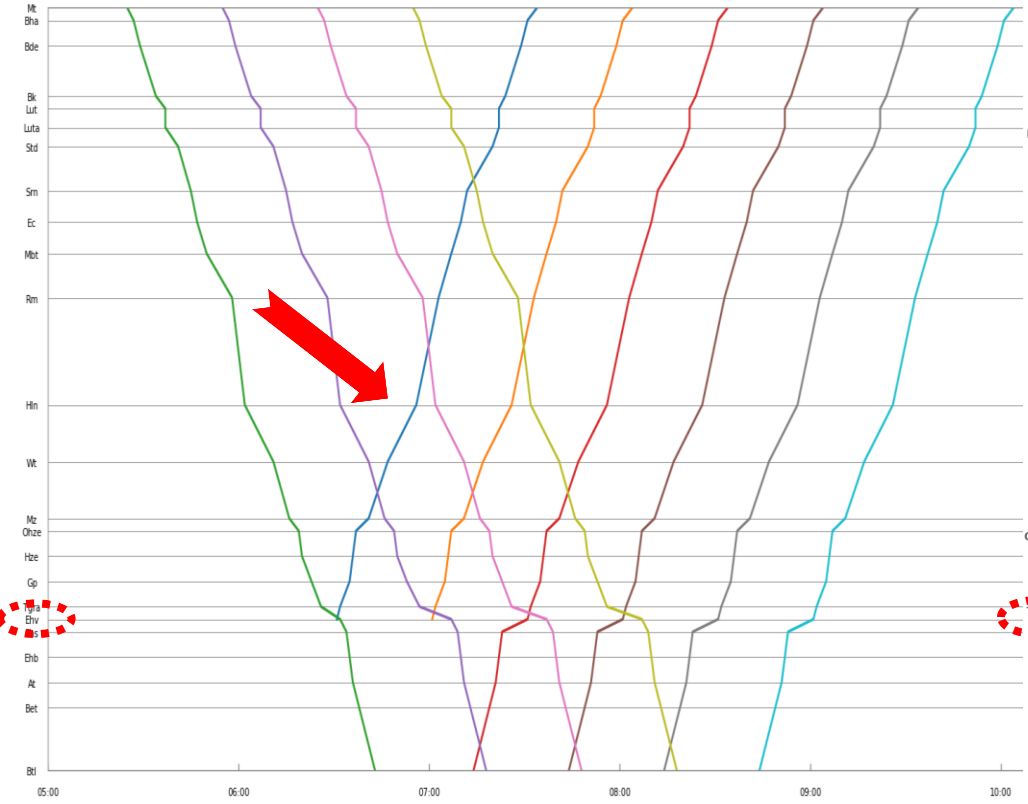
units: minutes

Statistics \ Threshold		10	20	30	40	50	60
Case 1	Summary	15205	14053	13933	14919	13711	14575
	Average	233.9	216.2	214.4	229.5	210.9	224.2
	Max	379	350	380	384	336	378
	Min	121	90	90	90	90	90
	Standard deviation	47.9	51.9	56.5	58.5	57.6	56.9
Case 2	Summary	135358	116557	113387	111755	111095	110702
	Average	335.0	288.5	280.7	276.6	275.0	274.0
	Max	800	813	633	682	590	540
	Min	42	42	52	42	42	42
	Standard deviation	97.7	75.5	72.0	72.1	72.5	70.1

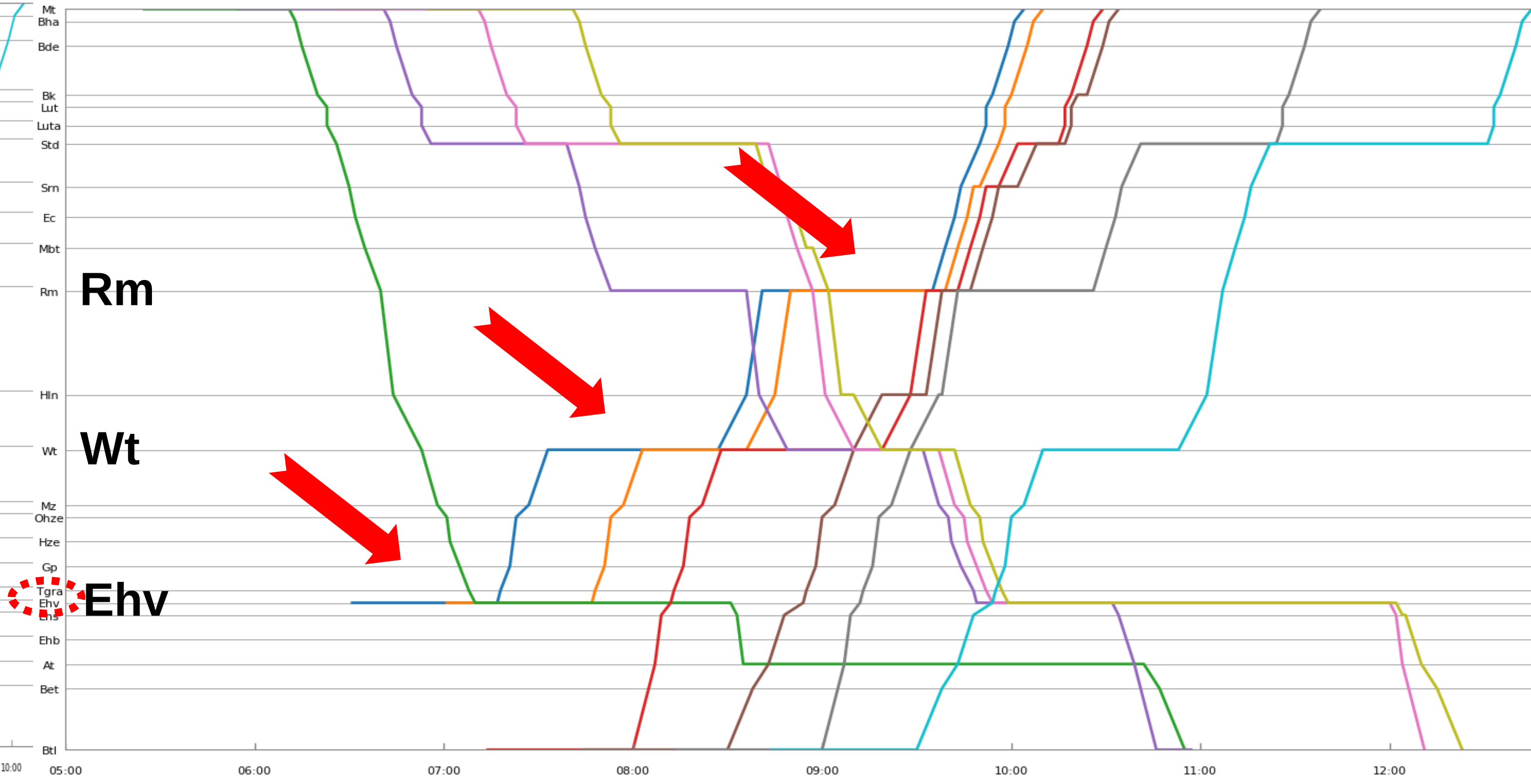
CASE STUDY

Optimized results and analysis

(3) Comparison between timetables



Scheduled timetable



Rescheduled timetable

CONCLUSION AND FUTURE WORK

Conclusion

- (1) A **multi-objective** railway freight timetable rescheduling optimization model with extensive and stochastic delays was proposed.
- (2) **Re-time, Re-order and Re-track**.
- (3) **The comprehensive level：** static level + dynamic level.
- (4) The solution (**S-MOGA**) was designed.
- (5) The **threshold of 50(60)** is suggested for timetable rescheduling in our case 1(2).

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Thank you for your attention