Lecture Note of Topics in Ship Design Automation

Optimum Design

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Ch. 9 Case Study of Optimal Route Design

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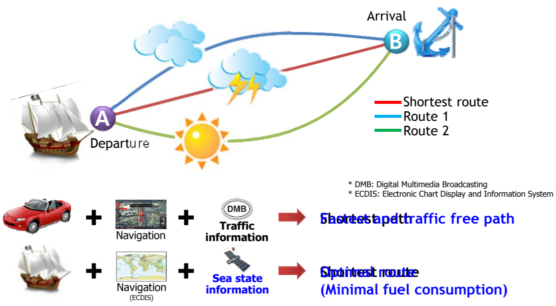
9.1 Overview

Optimal Route Design for Ship
- Determination of Optimal Ship Route (1/2)

Problem definition

- ❑ Objective
  - Minimization of the fuel consumption of ship
- ❑ Input("Given")
  - Positions of departure and arrival
  - Required arrival time
  - Information on ship and sea state
  - Geographic information
- ❑ Output("Find")
  - Optimal ship route



Mathematical formulation

Find **X** Route — Design Variables

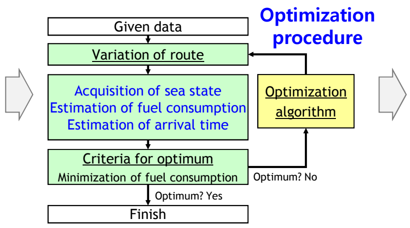
Minimize $TFOC(\mathbf{X})$ Total fuel consumption — Objective Function

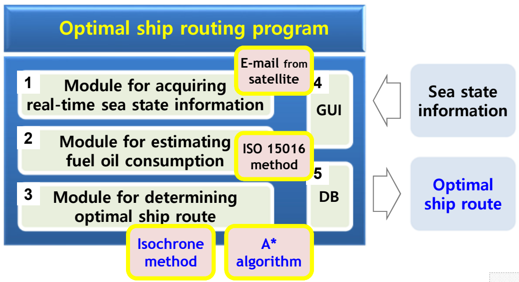
Subject to — Constraints

Requirement for the arrival time

$$ETA_{min} \le ETA(\mathbf{X}) \le ETA_{max}$$

Optimization procedure





* **M.I. Roh**, "Determination of an Economical Shipping Route Considering the Effects of Sea State for Lower Fuel Consumption", International Journal of Naval Architecture and Ocean Engineering(SCIE/IF:0.231), Vol. 5, No. 2, pp.246-262, 2013

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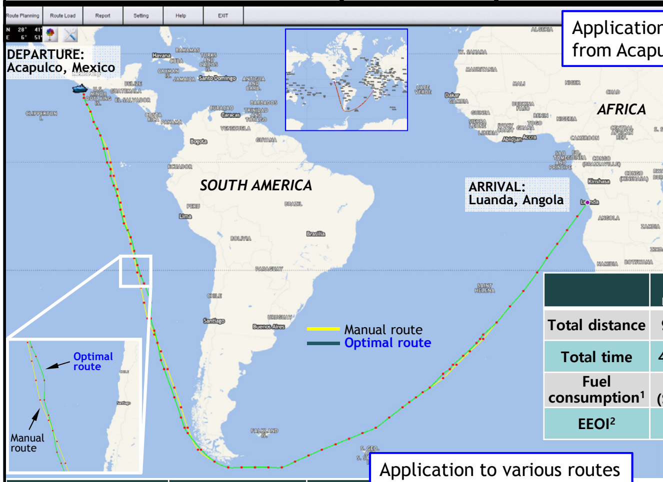
Optimal Route Design for Ship
- Determination of Optimal Ship Route (2/2)



Application to the route from Acapulco in Mexico to Luanda in Angola

- 4,600TEU container ship
- Lbp: 237.0m
- B: 37.5m
- D: 22.0m
- T_d/T_s: 12.4/13.4m
- C_B: 0.6600
- V: 22knots

3.0% fuel consumption were reduced for this route.

	Manual route [A]	Optimal route [B]	Reduction (B-A)	Ratio (B/A)
Total distance	9,381NM	9,395NM	-13NM	100.1%
Total time	447h 42m	437h 58m	9h 44m	97.8%
Fuel consumption[1]	1,720ton ($860,000)	1,669ton ($834,500)	51ton ($25,500)	97.0%
EEOI[2]	6.651	6.303	0.348	94.8%

Application to various routes

Route/Fuel consumption	Manual route [A]	Optimal route [B]	Reduction (B-A)	Ratio (B/A)
Venquber~Luanda	2,064ton ($1,032K)	1,968ton ($984K)	96ton ($48K)	95.3%
Boston~Lagos	872ton ($436K)	850ton ($425K)	23ton ($11.5K)	97.4%
Tampico~Cape Town	1,389ton ($694.5K)	1342ton ($671K)	47ton ($23.5K)	96.6%
Santos~Laum	1,057ton ($528.5K)	1,029ton ($514.5K)	28ton ($14K)	97.4%
Montevideo~Helsinki	1,179ton ($589.5K)	1,140ton ($570K)	39ton ($19.5K)	96.7%
...	...	...	...	...

➡ **About 3.4% fuel reduction were made.**

* 1: Fuel cost for HFO(Heavy Fuel Oil): $500/ton, 2: Energy Efficiency Operational Indicator
* **M.I. Roh**, "Determination of Economical Shipping Route Considering Effects of the Sea State for Lower Fuel Consumption", submitted to International Journal of Naval Architecture and Ocean Engineering, 2012

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Optimal Route Design for Ship
- Determination of Optimal Route and Sequence of Heavy Load (1/2)

Problem definition

- **Objective**
  - **Minimization of the travel distance without block of a goliath crane**
- **Input("Given")**
  - Before and after positions of each block
  - Priority for lifting of each block
  - Available earliest and latest time for lifting of each block
  - Required time for lifting of each block
  - Wires and shackles for lifting each block
- **Output("Find")**
  - **Optimal route and lifting sequence of blocks**

Design Variables

Find t_i — Lifting time for each block

Objective Functions

Minimize $F_1 = \sum_{i=0}^{N-1} \{(1-r_{i,i+1}) \cdot t_{i,i+1} + r_{i,i+1} \cdot (t_{i,W} + t_{W,i+1})\}$ *and* — Total travel time without block

Minimize $F_2 = \sum_{i=0}^{N-1} (r_{i,i+1} \cdot T_r)$ — Total time for wires and shackles replacement

Constraints

Subject to

Constraints about the start of the lifting time
$g_1 = l_i - s_i \le 0$

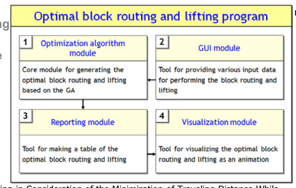
Constraints about the end of the lifting time
$g_2 = f_i - u_i \le 0$

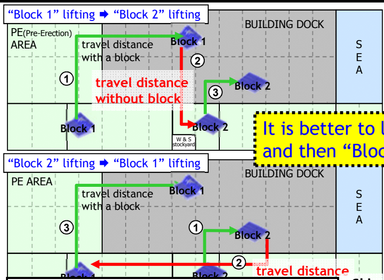
Constraints about the priority for lifting
$g_3 = p_j - p_k \le 0$

Constraints about the total lifting time
$g_4 = f_N - T_e \le 0$

$for\ i = 0, \cdots, N-1$ and
$j, k = 1, \cdots, N$

Mathematical formulation





It is better to lift "Block 1" and then "Block 2".

Applicable to transporter

Application to an actual problem of shipyard

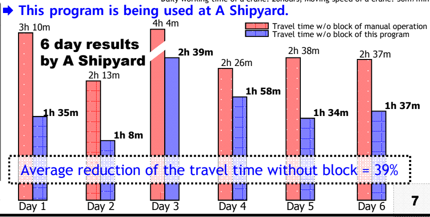
- Shipyard: A
- Number of blocks: 18

	Total travel time (distance) [A]	Travel time (distance) without block [B]	Ratio (B/A)
Manual operation	3h 20m (6.0km)	2h 6m (3.7km)	63.0%
Optimization	2h 38m (4.7km)	1h 24m (2.5km)	53.2%

33% reduction

* Daily working time of a crane: 20hours, Moving speed of a crane: 30m/min

➡ **This program is being used at A Shipyard.**



* **M.I. Roh**, K.Y. Lee, "Optimal Scheduling of Block Lifting in Consideration of the Minimization of Traveling Distance While Unloaded and Wire and Shackle Replacement of a Gantry Crane", Journal of Marine Science and Technology(SCIE/IF:0.830), Vol. 15, No. 2, pp.190-200, 2010

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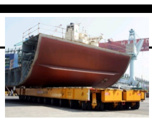
Optimal Route Design for Ship
- Determination of Optimal Route and Sequence of Heavy Load (2/2)

Problem definition



- **Objective**
  - **Minimization of the travel distance without block of transporters**
- **Input("Given")**
  - Total number of blocks and transporters
  - Weight of each block and specifications of each transporter
  - Before and after positions of each block
  - Priority for transporting of blocks
  - Available earliest and latest time for transporting of blocks
  - Roads in shipyard for the block transportation
- **Output("Find")**
  - **Optimal route and transporting sequence of blocks**

Design Variables

Find x_i — Transporting time for each block

Objective Function

Minimize $F_1 = \sum_{i=1}^{B} \sum_{k=1}^{T} x_i^k (e_i^k / V^k)$ *and* — Total transporting time

Minimize $F_2 = \sum_{i=2}^{B} \sum_{j=1}^{i-1} \sum_{k=2}^{T} \sum_{l=1}^{k-1} x_i^k x_j^l c_{kl}$ — Total number of interferences between transporters

Constraints

Subject to

Constraints about the maximum deadweight of transporter
$g_1 = w_i - t_k \le 0$

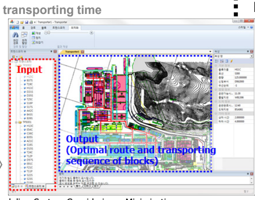
Constraints about the start of the transporting time
$g_2 = r_i - p_i^k \le 0$

Constraints about the end of the transporting time
$g_3 = d_i^k - s_i \le 0$

Constraints about the priority for transporting
$g_4 = p_i - p_j \le 0$

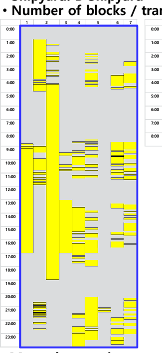
$for\ i, j = 1, \cdots, B$ and $k, l = 1, \cdots, T$

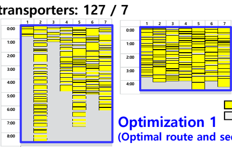
Mathematical formulation

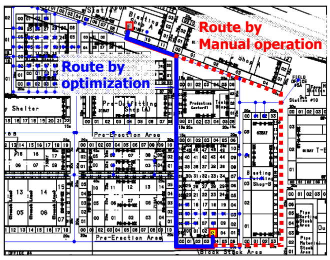


Application to an actual problem of shipyard

- Shipyard: B Shipyard
- Number of blocks / transporters: 127 / 7







	Total travel time (distance) [A]	Travel time (distance) without block [B]	Ratio (B/A)
Manual operation	122h 42m (N/A)	63h 20m (N/A)	52%
Optimization 1 (Optimal route+sequence)	34h 39m (184km)	9h 26m (121km)	27%
Optimization 2 (OPT 1+optimal block allocation)	29h 12m (115km)	4h 00m (52km)	14%

85% reduction; 94% reduction

* Moving speed of transporter: 5km/h (while loading), 12~14km/h (while unloading)

* **M.I. Roh**, J.H. Cha, "A Block Transportation Scheduling System Considering a Minimization of Travel Distance without Loading of and Interference between Multiple Transporters", International Journal of Production Research(SCI/IF:1.115), Vol. 49, No. 11, pp.3231-3250, 2011

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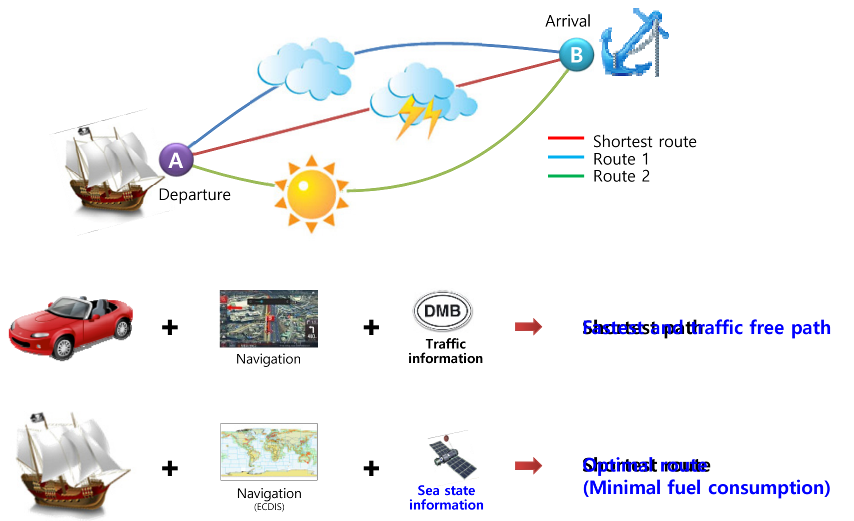
9.2 Determination of Optimal Ship Route

Concept of Optimal Ship Route



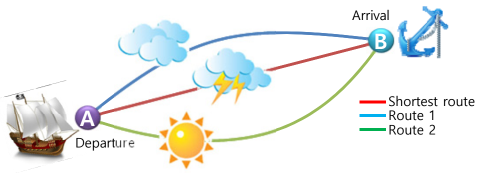
* DMB: Digital Multimedia Broadcasting
* ECDIS: Electronic Chart Display and Information System

Determination of Optimal Ship Route
- Problem Definition

☑ Criteria for determining optimal ship route (Objective function)
- Minimization of the fuel consumption of ship

☑ Given (Input)
- Positions of departure and arrival
- Required arrival time
- Information on ship and sea state
- Geographic information

☑ Find (Design variables)
- Optimal ship route

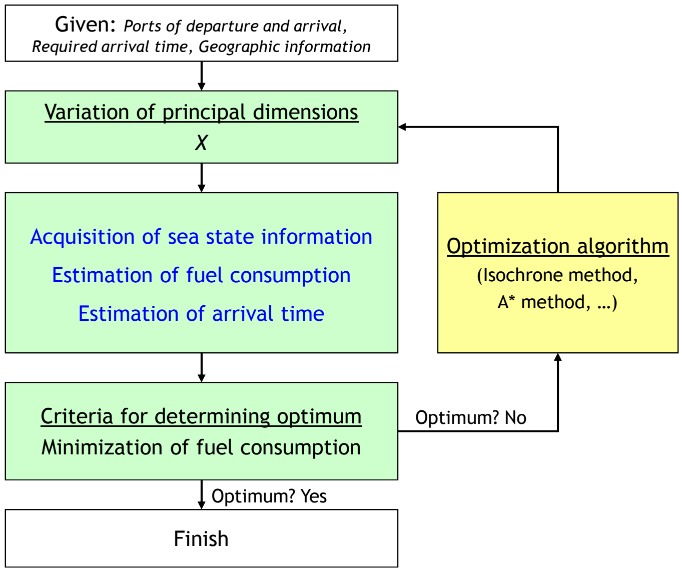


Determination of Optimal Ship Route
- Problem Formulation

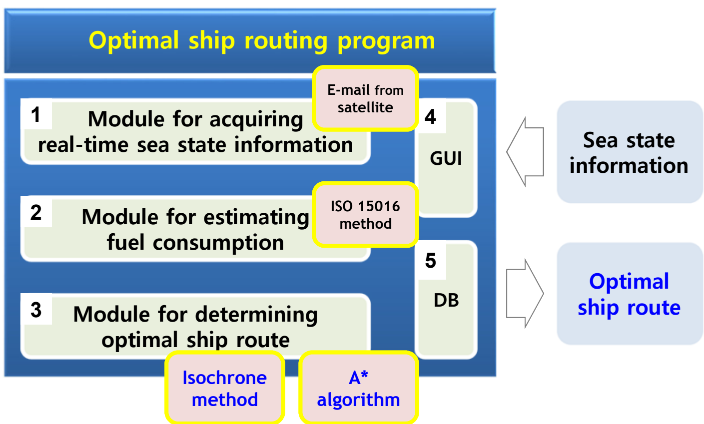
Find	$\mathbf{X}$	Route	Design Variables
Minimize	$TFOC(\mathbf{X})$	Total fuel consumption	Objective Function
Subject to	$ETA_{\min} - ETA(\mathbf{X}) \le 0$	Requirement for the minimum arrival time	Constraints
	$ETA(\mathbf{X}) - ETA_{\max} \le 0$	Requirement for the maximum arrival time	

➡ Optimization problem having 1 unknown and 2 inequality constraints

Process for Determining Optimal Ship Route Using an Optimization Algorithm

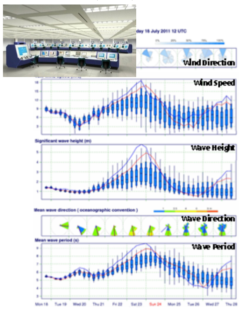


Optimization Program for the Ship Route Design - Configuration

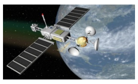


Acquisition of Real-time Sea State Information

Various sea state information from ECMWF, AMI, etc. on land



e-mail



Satellite

e-mail

INMARSAT

Optimal ship routing program

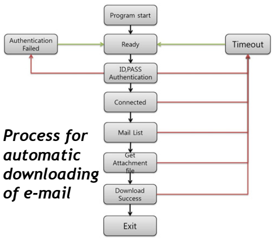
E-mail download
E-mail parsing

1 Module for acquiring real-time sea state information

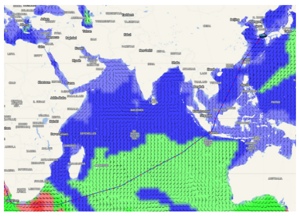
Sea state information
(wave direction, wave height, wave period, wind direction, wind speed)

2 Module for estimating fuel consumption

Process for automatic downloading of e-mail

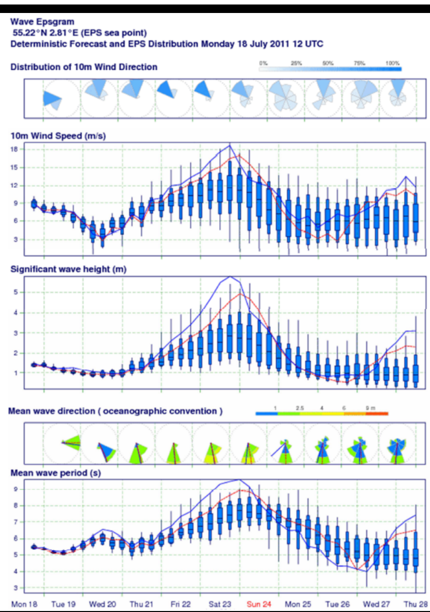


Visualization of sea state information



* ECMWF: European Center for Medium range Weather Forecasting, AMI: Aerospace & Marine International

Sea State Information from ECMWF*



Wind Direction

Wind Speed

Wave Height

Wave Direction

Wave Period

* ECMWF: European Center for Medium range Weather Forecasting, AMI: Aerospace & Marine International

Scenario of the change in Ship Performance According to the Sea State

Sea state

↓

Increase of ship's resistance
according to sea state

→ *The increased amount of ship's resistance should be calculated.*

↓

Reduction of ship's speed
according to additional resistance

→ *The reduced amount of ship's speed should be calculated.*

↓

Increase of ship's horse power
to compensate for the ship's speed

→ *The increased amount of ship's horse power should be calculated.*

↓

Increase of ship's fuel consumption
according to the increase in horse power

→ *Additional fuel consumption according to the increase in horse power should be calculated.*

Estimation of Fuel Consumption by ISO 15016 Method

Sea state information

↓

Increase of ship's resistance
according to sea state

↓

Reduction of ship's speed
according to additional resistance

↓

Increase of ship's horse power
to compensate for the ship's speed

↓

Increase of ship's fuel consumption
according to the increase
in horse power

Scenario of the change in ship performance according to the sea state

ISO 15016 method

$$\delta R = \delta R_{wave} + \delta R_{wind} + \delta R_{\delta\delta} + \delta R_{\beta\beta} + \delta R_{AS} + \delta R_{ADIS}$$

δR: increased amount of ship's resistance
δR_{wave}: added resistance by wave
δR_{wind}: added resistance by wind
$\delta R_{\delta\delta}$: added resistance by steering
$\delta R_{\beta\beta}$: added resistance by drift
δR_{AS}: added resistance by seawater condition
δR_{ADIS}: added resistance by displacement

$$\delta V = \delta V_{wave} + \delta V_{wind} + \delta V_{AC} + \delta V_{AS}$$

δV: reduced amount of ship's speed
δV_{wave}: reduced amount of ship's speed by wave
δV_{wind}: reduced amount of ship's speed by wind
δV_{AC}: reduced amount of ship's speed by current
δV_{AS}: reduced amount of ship's speed by shallow water

$$\frac{\delta P_1}{P_0} = \frac{\delta V}{V_0} \cdot (n+1)$$

$$\delta P_2 = 2\pi / 75(N_{0p}\delta Q_p + Q_{0p}\delta N_p + \delta Q_p \delta N_p)$$

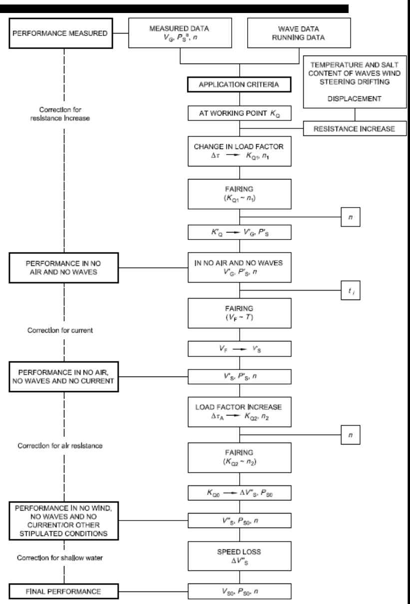
$$\delta P = (\delta P_1 + \delta P_2)/2$$

δP: increased amount of ship's horse power
P_0: ship's horse power at speed of V_0
δV: reduced amount of ship's speed
V_0: ship's speed in calm sea
n: coefficient according to ship's type
N_{0p}: propeller RPM at speed of V_0
δN_p: increase of propeller RPM
Q_{0p}: propeller torque at speed of V_0
δQ_p: increase of propeller torque

$$TFOC = FOC + \delta FOC$$

$$\delta FOC = SFOC \cdot \delta P \cdot ETA$$

TFOC: total fuel consumption
FOC: fuel consumption at speed of V_0
δFOC: additional fuel consumption according to δP
δP: increased amount of ship's horse power
SFOC: Specific Fuel Oil Consumption
ETA: Estimated Time of Arrival



Flowchart of speed trial analysis

* ISO, "Guidelines for the Assessment of Speed and Power Performance by Analysis of Speed Trial Data", ISO/DIS 15016, pp. 1-45, 2002

Estimation of Fuel Consumption by Other Methods

Method 1*

$$\delta R = \delta R_{wave} + \delta R_{wind}$$

δR : added resistance by sea state
δR_{wave} : added resistance by wave
δR_{wind} : added resistance by wind

$$\delta V = \frac{R - R_0 + \delta R}{(1-t)(1-w)(\tilde{P}_{TV} + \frac{\tilde{P}_{TN}\tilde{P}_{QV}}{r^2\tilde{E}_{QN} - \tilde{P}_{QN}})}$$

R_0 : resistance in still water at V_0 (KN)
R : resistance in still water at $(V_0 + \delta V)$ (KN)
δR : added resistance in wave at $(V_0 + \delta V)$ (KN)

$$\delta P = 2\pi / 75(N_{0p}\delta Q_p + Q_{0p}\delta N_p + \delta Q_p \delta N_p)$$

δP : increased power by speed compensation (KW)
N_{0p} : propeller RPM at V_0 $(1/s)$
δN_p : increase of propeller RPM $(1/s)$
Q_{0p} : propeller PRM at V_0 $(KN \cdot m)$
δQ_p : increase of propeller torque $(KN \cdot m)$

$$\delta FOC = SFOC \cdot \delta P \cdot t$$

δFOC : increased fuel consumption(g)
$SFOC$: specific fuel oil consumption $(g / KW \cdot s)$
δP : increased power by speed compensation (KW)
t : navigation time considering speed reduction (s)

Sea state

↓

(1) Increase of ship's resistance (δR)

↓

(2) Reduction of ship's speed (δV)

↓

(3) Increase of ship's horse power (δP)

↓

(4) Increase of ship's fuel consumption (δFOC)

Method 2**

$$\delta R = \delta R_{wave} + \delta R_{wind}$$

δR : added resistance by sea state
δR_{wave} : added resistance by wave
δR_{wind} : added resistance by wind

$$\frac{\delta V}{V_0} = (1 + \frac{\delta R}{R_0})^{\frac{1}{2}} - 1$$

V_0 : speed in still water
δV : speed reduction
R_0 : resistance in still water
δR : added resistance by sea state

$$\frac{\delta P}{P_0} = \frac{\delta V}{V_0} \cdot (n+1)$$

δP : increased power by speed compensation (KW)
P : delivered horse power in still water (KW)
n : constant

$$\delta FOC = SFOC \cdot \delta P \cdot t$$

δFOC : increased fuel consumption (g)
$SFOC$: specific fuel oil consumption $(g / KW \cdot s)$
δP : increased power by speed compensation (KW)
t : navigation time considering speed reduction (s)

* Nakamura, S., Naito, S., "Nominal Speed Loss and Propulsive Performance of a Ship in Waves", The Japan Society of Naval Architects and Ocean Engineers, Vol. 166, pp. 25-34, 1977.
** Townsin, R.L., Kwon, Y.J., "Estimating the Influence of Weather on Ship Performance", Trans. RINA, Vol. 135, pp. 191-209, 1993.

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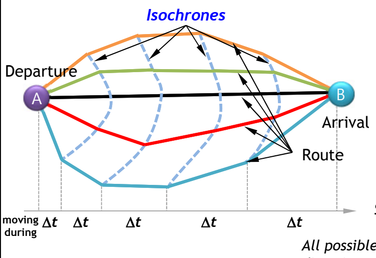
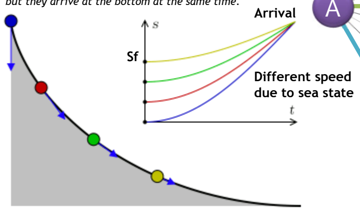
Determination of Optimal Ship Route by Isochrone Method

Isochrone method — Isochrone is a set of connected points that a ship can reach within the given time limit starting from one point and going in all possible directions.

Definition of an isochrone



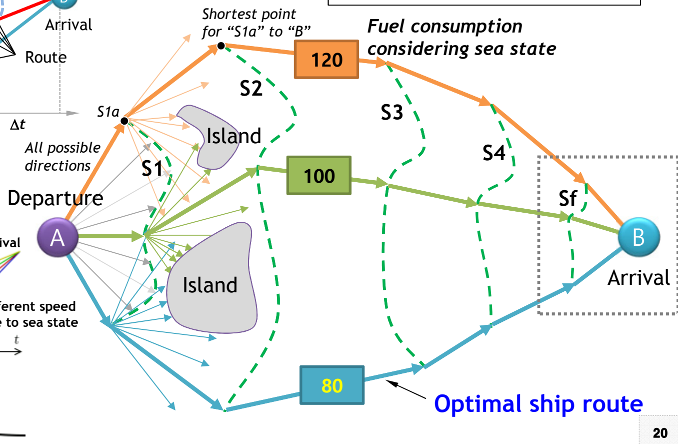
Four points run over a cycloid from different positions, but they arrive at the bottom at the same time.



Improved isochrone method

- Considering sea state
- Considering obstacles such as islands

Given: Time(Δt), Sea state
Find: Position, Fuel consumption



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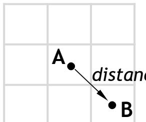
Determination of Optimal Ship Route by A* Algorithm

A* algorithm

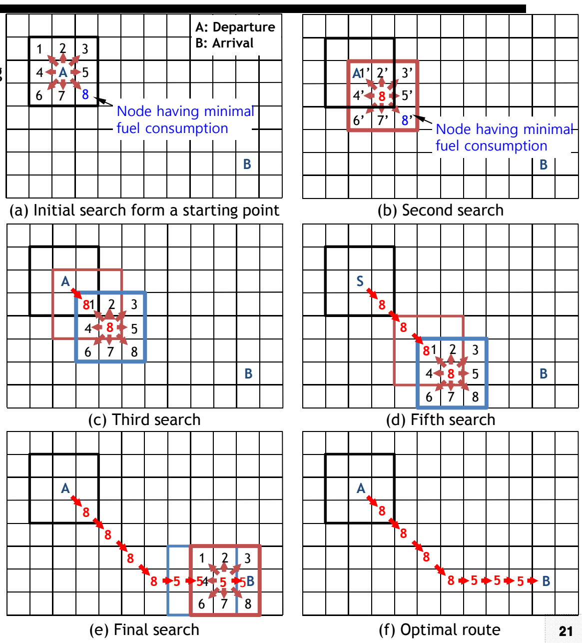
A* algorithm is widely used in path finding between nodes.

Improved A algorithm*
- Considering sea state
- Considering obstacles such as islands

Given: Position, Sea state
Find: Time, Fuel consumption



- *Calculation of the required time from A to B considering sea state*
- *Calculation of fuel consumption from A to B considering sea state*



(a) Initial search form a starting point
(b) Second search
(c) Third search
(d) Fifth search
(e) Final search
(f) Optimal route

Example of Determination of Optimal Ship Route (1/2)

Application to the route from Acapulco in Mexico to Luanda in Angola

- 4,600TEU container ship
- Lbp: 237.0m
- B: 37.5m
- D: 22.0m
- T_d/T_s: 12.4/13.4m
- C_B: 0.6600
- V: 22knots

3.0% fuel consumption were reduced for this route.

	Manual route [A]	Optimal route [B]	Reduction (B-A)	Ratio (B/A)
Total distance	9,381NM	9,395NM	-13NM	100.1%
Total time	447h 42m	437h 58m	9h 44m	97.8%
Fuel consumption[1]	1,720ton ($860,000)	1,669ton ($834,500)	51ton ($25,500)	97.0%
EEOI[2]	6.651	6.303	0.348	94.8%

* 1: Fuel cost for HFO(Heavy Fuel Oil): $500/ton, 2: Energy Efficiency Operational Indicator

Example of Determination of Optimal Ship Route (2/2)

Application to various routes

Route/Fuel consumption	Manual route [A]	Optimal route [B]	Reduction (B-A)	Ratio (B/A)
Venquber~Luanda	2,064ton ($1,032K)	1,968ton ($984K)	96ton ($48K)	95.3%
Boston~Lagos	872ton ($436K)	850ton ($425K)	23ton ($11.5K)	97.4%
Tampico~Cape Town	1,389ton ($694.5K)	1342ton ($671K)	47ton ($23.5K)	96.6%
Santos~Laum	1,057ton ($528.5K)	1,029ton ($514.5K)	28ton ($14K)	97.4%
Montevideo~Helsinki	1,179ton ($589.5K)	1,140ton ($570K)	39ton ($19.5K)	96.7%
…	…	…	…	…

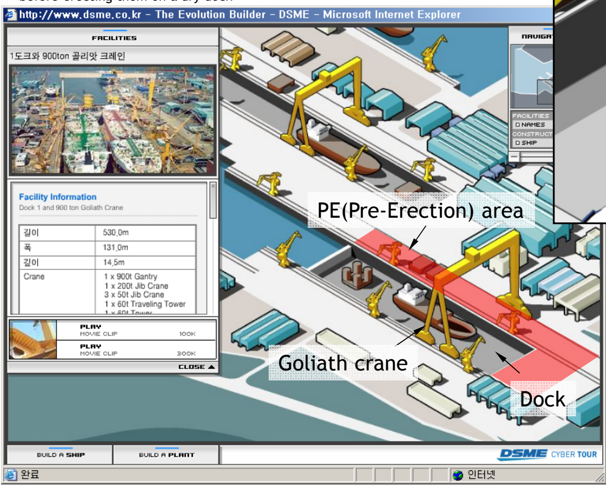
➡ **About 3.4% fuel reduction were made.**

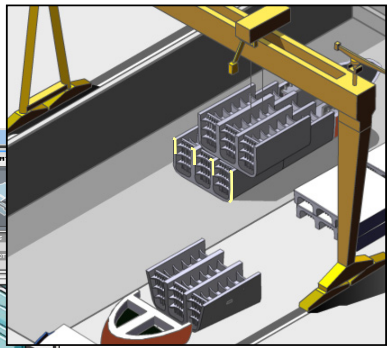
9.3 Determination of the Optimal Lifting Sequence of Erection Blocks by a Gantry Crane

Block Erection Using a Goliath Crane

* Reference: DSME Co., Ltd.

* PE(Pre-Erection) area: Area for temporarily placing erection blocks before erecting them on a dry dock





Erection process

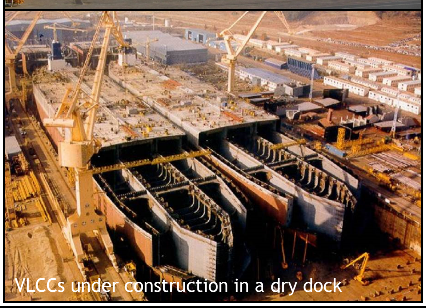
1. Start the erection of the block (or block lifting).
2. Start welding between adjacent erection blocks.
3. Repeat Steps 1 and 2 for each erection block.

Some Images of the Block Erection

* Reference: DSME Co., Ltd.

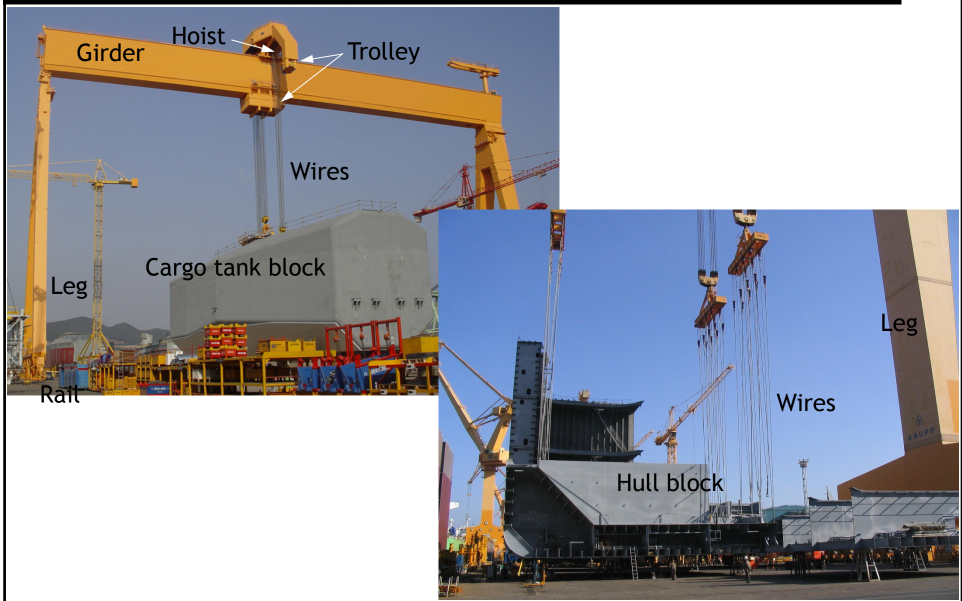
During the block erection

Before the block erection

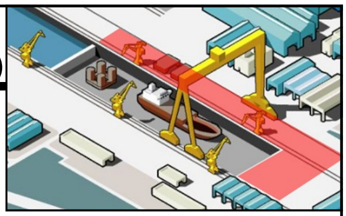


VLCCs under construction in a dry dock

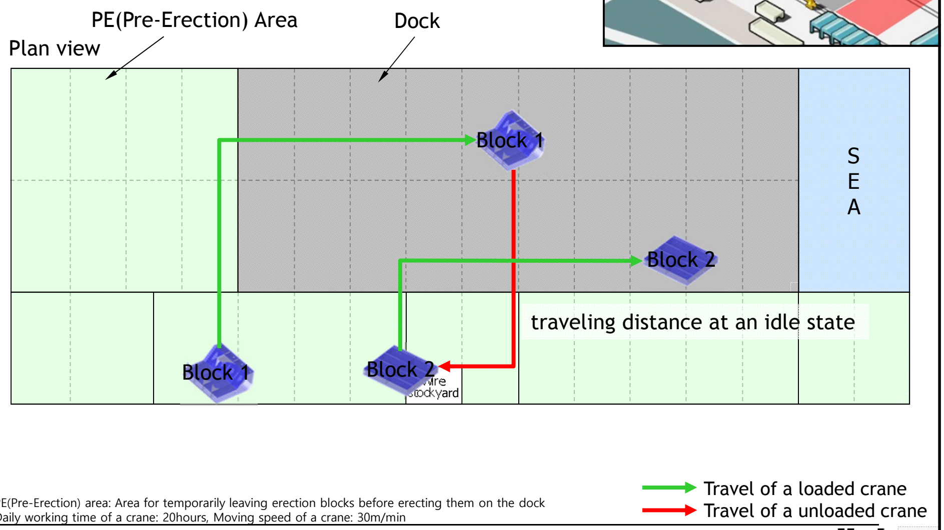
Example of a Gantry Crane for Lifting Ship Erection Blocks



Travel Distance of a Unloaded Crane According to the Lifting Sequence (1/2)

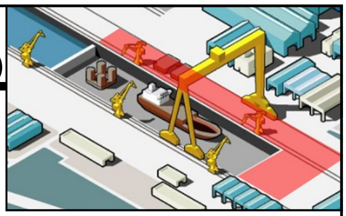


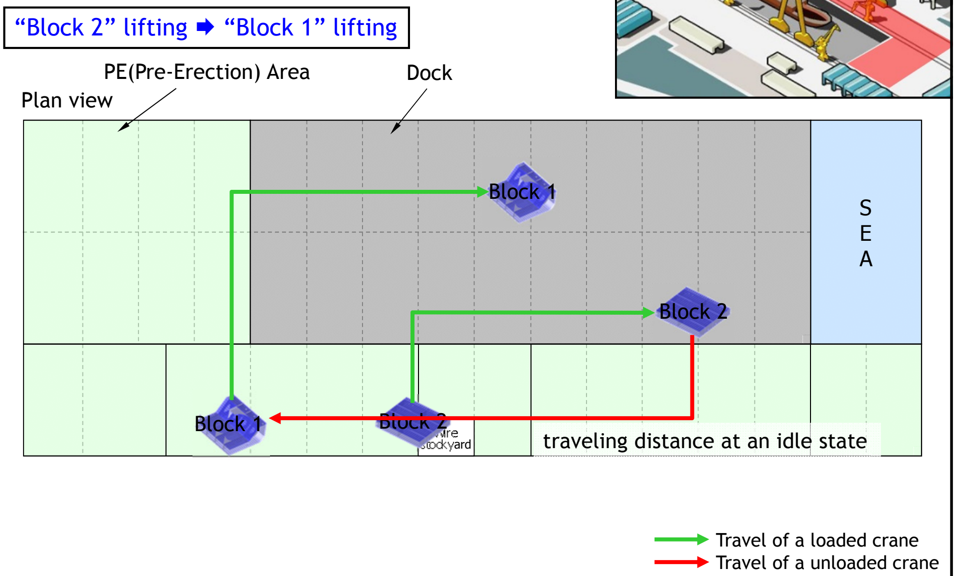
"Block 1" lifting ➡ "Block 2" lifting

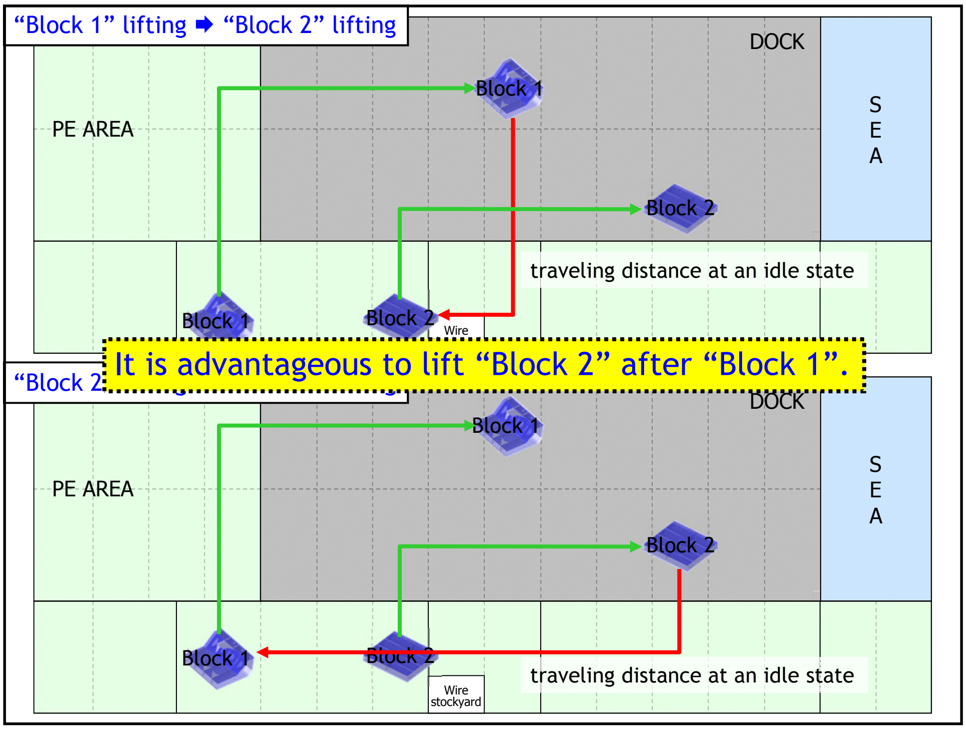


* PE(Pre-Erection) area: Area for temporarily leaving erection blocks before erecting them on the dock
* Daily working time of a crane: 20hours, Moving speed of a crane: 30m/min

Travel Distance of a Unloaded Crane According to the Lifting Sequence (2/2)





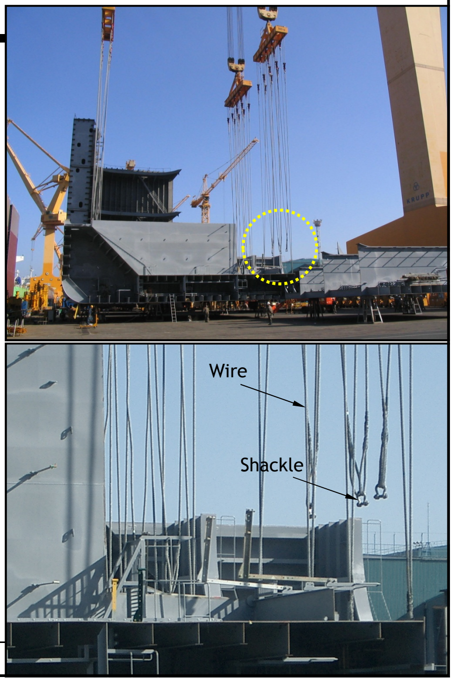


Problem for the Determination of the Optimal Lifting Sequence of Erection Blocks

☑ **Objective**
- Minimization of the travel distance without load of a crane

☑ **Input ("Given")**
- Before and after positions of each erection block
- Priority for lifting of each erection block per ship number
- Available earliest and latest time for lifting of each erection block
- Required time for lifting of each erection block
- Specification and number of wires and shackles for lifting each erection block

☑ **Output ("Find")**
- Optimal lifting sequence of erection blocks



Formulation of a Problem for the Determination of the Optimal Lifting Sequence of Erection Blocks

Design Variables

Find t_i — Lifting time for each block

Objective Function

Minimize $F_1 = \sum_{i=0}^{N-1} \{(1 - r_{i,i+1}) \cdot t_{i,i+1} + r_{i,i+1} \cdot (t_{i,W} + t_{W,i+1})\}$ — Total travel time without block

Minimize $F_2 = \sum_{i=0}^{N-1} (r_{i,i+1} \cdot T_r)$ — Total time for wires and shackles replacement

Constraints

Subject to

$g_1 = l_i - s_i \le 0$ — Constraints about the start of the lifting time

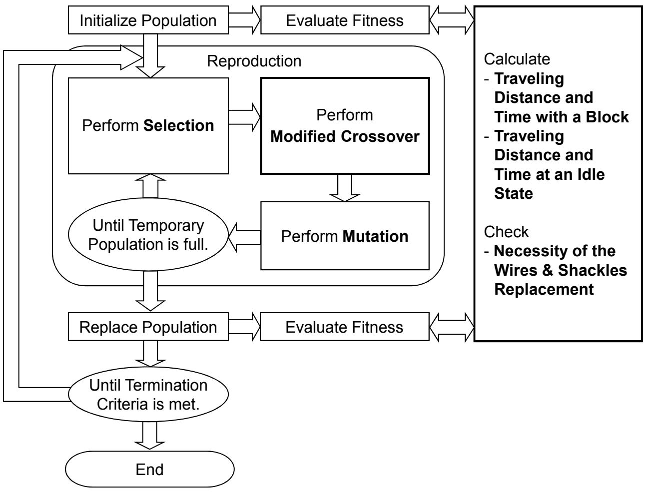
$g_2 = f_i - u_i \le 0$ — Constraints about the end of the lifting time

$g_3 = p_j - p_k \le 0$ — Constraints about the priority for lifting

$g_4 = f_N - T_e \le 0$ — Constraints about the total lifting time

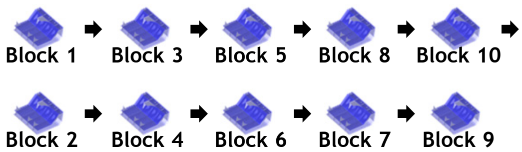
$for\ i = 0, \cdots, N-1 \text{ and } j, k = 1, \cdots, N$

Proposed Algorithm for Scheduling of Block Lifting of a Gantry Crane



Scheduling of Block Lifting and the Corresponding Representation of the Chromosome

Block lifting scheduling of a gantry crane



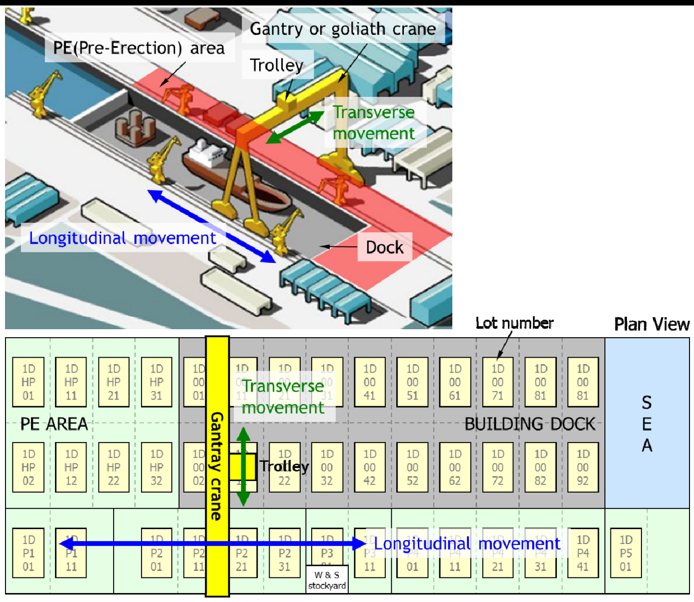
Encoding

Chromosome representation of the block lifting scheduling

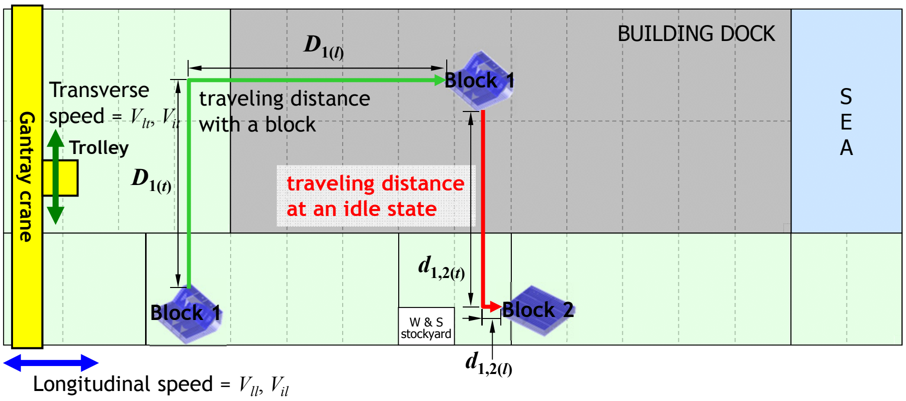
1	3	5	8	10	2	4	6	7	9

Chromosome of a 1-dimensional array type

Movement of a Gantry Crane Alongside the Building Dock of a Shipyard



Example of Calculating the Traveling Distance and Time of a Gantry Crane Using the Rectilinear Distance Method



Traveling distance of the Block 1(D_1) = $D_{1(l)} + D_{1(t)}$

Traveling time of the Block 1(T_1) = $D_{1(l)} / V_{ll} + D_{1(t)} / V_{lt}$

Traveling distance at an idle state from the Blocks 1 to 2($d_{1,2}$) = $d_{1,2(l)} + d_{1,2(t)}$

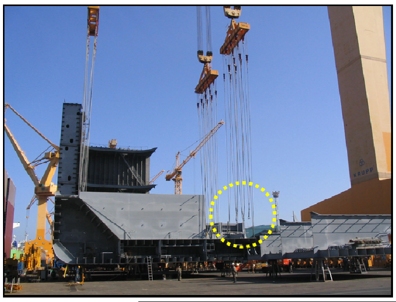
Traveling time at an idle state from the Blocks 1 to 2($t_{1,2}$) = $d_{1,2(l)} / V_{il} + d_{1,2(t)} / V_{it}$

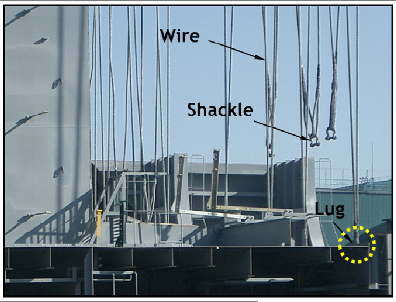
Necessity of Replacement of Wires and Shackles

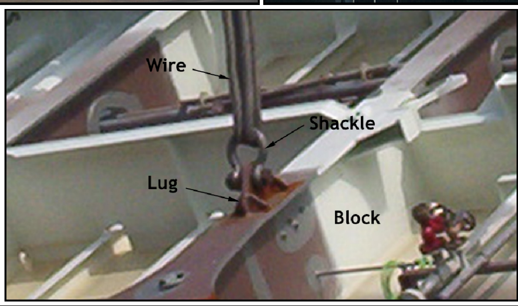
- ☑ Shackle: a kind of fittings to connect a wire rope with a lug of the block.
- ☑ Lug: structural part which has already been welded to the block before lifting

- ☑ Erection blocks vary in size and weight, and thus the replacement of wires and shackles is often needed.
- ☑ The replacement is made at stockyard of wire and shackle in PE area.
- ☑ Consequently, this fact must be considered in the scheduling of block lifting.

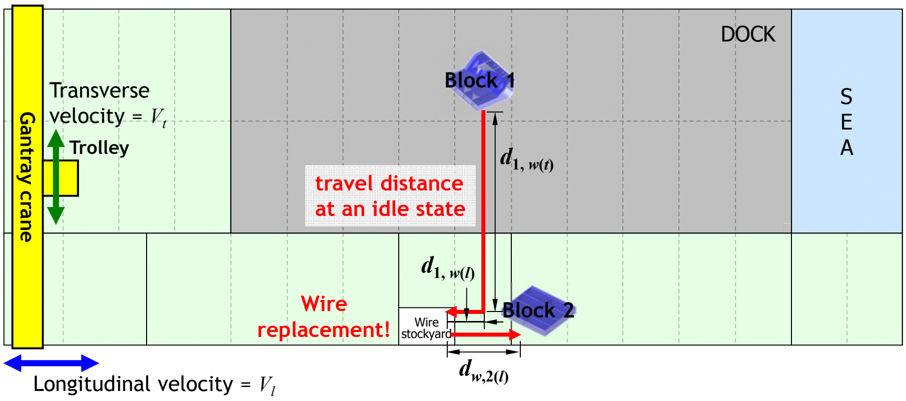
Connection between a Gantry Crane and a Block by Means of Wires, Shackles, and Lugs







Example of Calculating the Traveling Distance of a Gantry Crane Requiring Wire and Shackle Replacement



Travel distance at an idle state from the Block 1 to WS($d_{1,w}$) = $d_{1,\,w(l)} + d_{1,w(t)}$
Travel time at an idle state from the Block 1 to WS($t_{1,w}$) = $d_{1,w(l)} / V_l + d_{1,w(t)} / V_t$
Travel distance at an idle state from WS to the Block 2($d_{w,2}$) = $d_{w,2(l)}$
Travel time at an idle state from WS to the Block 2($t_{w,2}$) = $d_{w,2(l)} / V_l$

Modified Crossover Operation for Generating the First and Second Children (1/2)

- ☑ The modified crossover is simultaneously applied to each parent.
- ☑ A set s1 includes genes of the first parent to be replaced with those of the second parent, and initially is randomly selected.

$$s1 = \frac{\{Ft(p1) + Ft(p2)\} - Ft(p1)}{Ft(p1) + Ft(p2)} \times n \ \ \text{(discard decimals)} \qquad s2 = n - s1$$

where, s1: the number of genes of the first parent to be replaced with those of the second parent,
s2: the number of genes of the first parent to be transmitted to the first child,
n: the number of the genes in the first or second parent

- ☑ Next step is for the genes in the s2 positions of the first parent to be transmitted to the corresponding positions of the first child.
- ☑ Finally, the genes in the s1 positions are reordered according to the order of the corresponding genes in the second parent and then they are transmitted to the corresponding positions of the first child.
- ☑ These similar steps are applied to the second parent to also generate the second child.

Modified Crossover Operation for Generating the First and Second Children (2/2)

1	3	5	**8**	**10**	2	4	6	**7**	**9**

1st PARENT(fitness : 90) ➨ s1 = {8, 10, 7, 9}, s2 = {1, 3, 5, 2, 4, 6}

3	5	4	6	**10**	**9**	2	1	**7**	**8**

2nd PARENT(fitness : 60)

⇩

1	3	5	**10**	**9**	2	4	6	**7**	**8**

1st CHILD

(a) Modified crossover for the 1st CHILD

1	3	**5**	**8**	**10**	**2**	4	**6**	**7**	9

1st PARENT(fitness : 90)

3	**5**	4	**6**	**10**	9	**2**	1	**7**	**8**

2nd PARENT(fitness : 60) ➨ s1 = {5, 6, 10, 2, 7, 8}, s2 = {3, 4, 9, 1}

⇩

3	**5**	4	**8**	**10**	9	**2**	1	**6**	**7**

2nd CHILD

(b) Modified crossover for the 2nd CHILD

Mutation Operation Applied to the First Child

- ☑ The mutation operation is simultaneously applied to each child generated from the crossover operation.
- ☑ The mutation operation occurs with a very low probability (typically $p_{mutation}$ = 0.01 from Grefenstette's study).
- ☑ Two genes in each child are randomly selected and are exchanged with each other.

1	**3**	5	**10**	9	**2**	4	6	7	**8**

1st CHILD – Before Mutation

⇩

1	**10**	5	**3**	9	**8**	4	6	7	**2**

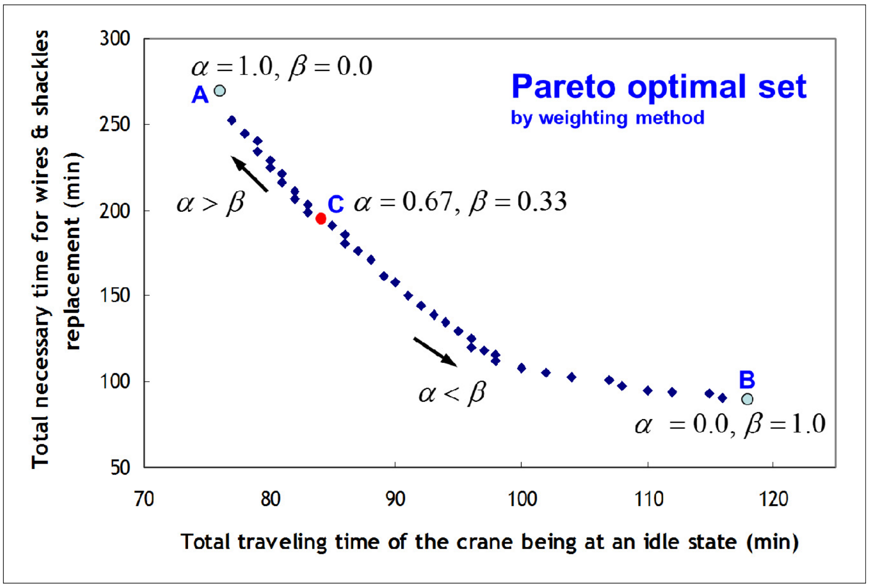
1st CHILD – After Mutation

Comparison of Computational Results of the Improved Genetic Operations and Conventional Genetic Operations for 100 Runs

	Result of the improved genetic operations	Result of the conventional genetic operations
Best objective function value	**105.78**	105.78
Mean objective function value	**108.43**	105.78
Mean time (sec)	**4.71**	3.38

* Test System: Pentium IV system (2.0GHz, 1GB RAM)

Influence of Weighting Factors in the Objective Function of the Block Transportation Scheduling Problem



Configuration of the Block Lifting Scheduling System

Block lifting scheduling system

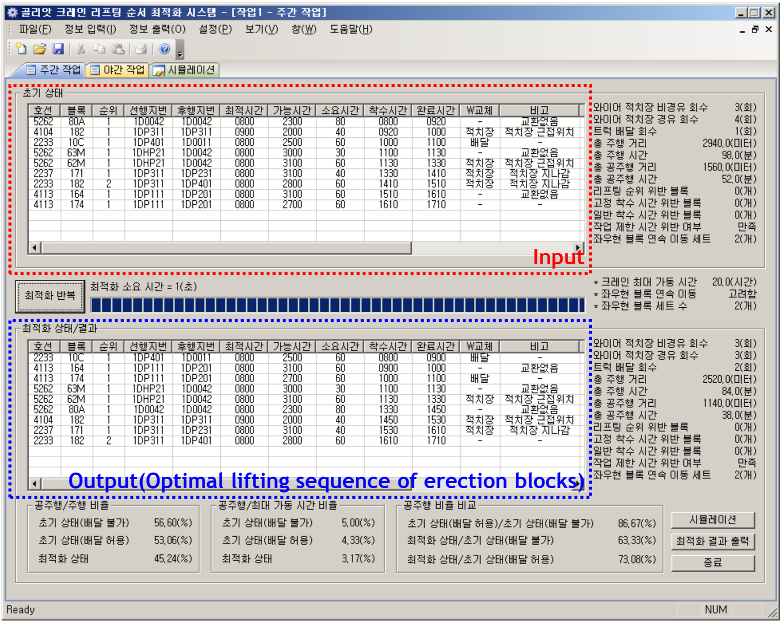
1 Optimization algorithm module
Core module for generating the optimal block lifting scheduling based on the GA

2 GUI module
Tool for providing various input data for performing the block lifting scheduling

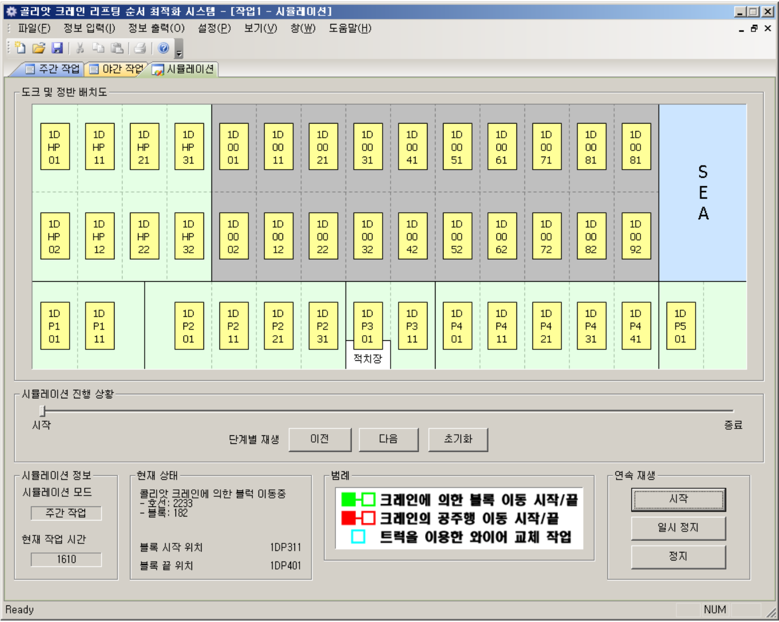
3 Reporting module
Tool for making a table of the optimal block lifting scheduling

4 Visualization module
Tool for visualizing the optimal block lifting scheduling as an animation

Screenshot of the Block Lifting Scheduling System - Optimization View



Screenshot of the Block Lifting Scheduling System - Visualization View



Comparison of the Performance on a Specific Day Resulting from Manual Scheduling and Automatic Scheduling by the Developed System

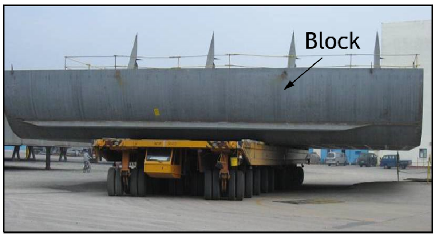
	Result of manual scheduling	Result of the developed system	
		Before optimization	**After optimization**
Total traveling time	3 hr 20 min	3 hr 41 min	**2 hr 38 min**
Total traveling time at an idle state	2 hr 6 min	2 hr 26 min	**1 hr 24 min**
No. of the wires & shackles replacement	9	11	**5**
Block lifting scheduling (ID of the blocks)	**80A⬩182⬩10C⬩63M⬩62M⬩171⬩152⬩164⬩174⬩161⬩RUD⬩183⬩192⬩193⬩625⬩626⬩635⬩636**	**174⬩164⬩63M⬩62M⬩10C⬩193⬩183⬩625⬩626⬩80A⬩182⬩192⬩152⬩171⬩161⬩RUD⬩636⬩635**	**10C⬩174⬩164⬩62M⬩63M⬩80A⬩182⬩192⬩152⬩161⬩171⬩RUD⬩183⬩193⬩625⬩626⬩635⬩636**

Comparison of the Idleness Ratio of the Crane and the Number of the Wires & Shackles Replacement During Six Days (1/2)

	Result of manual scheduling		Result of the developed system	
	Idleness ratio	No. of the wires & shackles replacement	Idleness ratio	No. of the wires & shackles replacement
Day #1 (19 blocks)	15.8%	9	**7.9%**	**5**
Day #2 (18 blocks)	11.1%	7	**5.7%**	**4**
Day #3 (22 blocks)	20.3%	14	**13.2%**	**9**
Day #4 (18 blocks)	12.2%	9	**9.8%**	**6**
Day #5 (20 blocks)	13.2%	10	**7.8%**	**6**
Day #6 (17 blocks)	13.1%	8	**8.1%**	**5**
Avg.	14.3%	10	**8.8%**	**6**

9.4 Determination of the Optimal Transporting Sequence of Erection Blocks by Multiple Transporters

Example of a Deadweight 600 ton Transporter for Moving Blocks in Shipyards



(a) Transporter with loading

(b) Transporter without loading

Specifications	• Length : 23.3 m • Breadth : 6.6 m • Height : Avg. 2.2 m (1.55 ~ 2.2 m, adjustable) • Lightweight : 126 ton • Speed : without loading 15 km/h, with loading 10 km/h • Number of wheels : 88
Purpose	Moving blocks, deck houses, main engines, large pipe equipments, etc.
Features	• Moving forward and backward, 360° at the current position • Two control rooms at the front and back • Two signalmen are required for ensuring against risks

Problem for the Determination of the Optimal Transporting Sequence of Erection Blocks

☑ **Objective**
- **Minimization of the travel distance without block of transporters**

☑ **Input (“Given”)**
- **Total number of blocks and transporters**
- **Weight of each block and specifications of each transporter**
- **Before and after positions of each block**
- **Priority for transporting of blocks**
- **Available earliest and latest time for transporting of blocks**
- **Roads in shipyard for the block transportation**

☑ **Output (“Find”)**
- **Optimal route and transporting sequence of blocks**

Detailed Input Data for the Determination of the Optimal Transporting Sequence of Erection Blocks

☑ Data on the transporters
- Total number and ID of the transporters
- Specifications (e.g., the speed, maximum deadweight, service time, etc.) of each transporter
- Initial position of each transporter

☑ Data on the blocks
- Total number and ID of the blocks to be moved by the transporters
- Weight of each block
- Initial position and target position after moving each block
- Transportation time limit (lower and upper bounds) of each block
- Priority for the transportation among the blocks

☑ Miscellaneous data
- Information on the shipyard roads for the block transportation

Formulation of a Problem for the Determination of the Optimal Transporting Sequence of Erection Blocks

Design Variables

Find x_i — Transporting time for each block

Objective Function

Minimize $F_1 = \sum_{i=1}^{B}\sum_{k=1}^{T} x_i^k (e_i^k / V^k)$ *and* — Total transporting time

Minimize $F_2 = \sum_{i=2}^{B}\sum_{j=1}^{i-1}\sum_{k=2}^{T}\sum_{l=1}^{k-1} x_i^k x_j^l c_{kl}$ — Total number of interferences between transporters

Constraints

Subject to

$g_1 = w_i - t_k \le 0$ — Constraints about the maximum deadweight of transporter

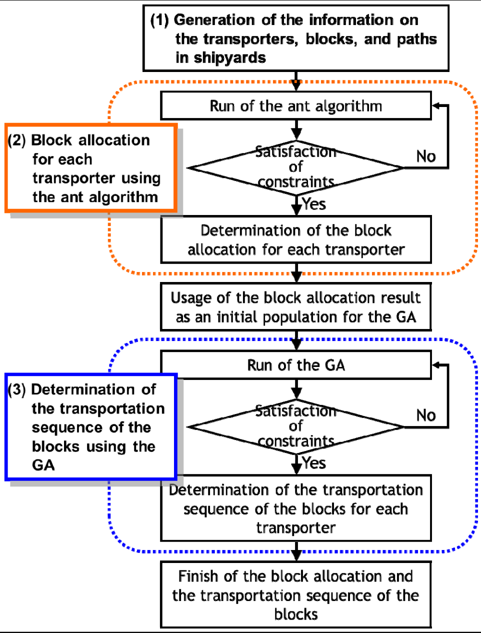
$g_2 = r_i - p_i^k \le 0$ — Constraints about the start of the transporting time

$g_3 = d_i^k - s_i \le 0$ — Constraints about the end of the transporting time

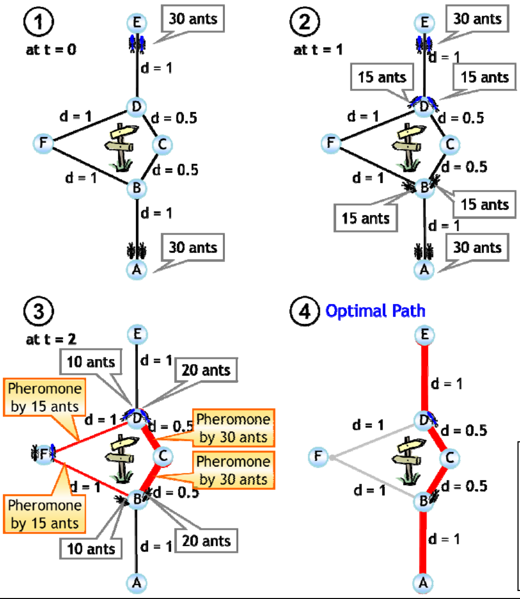
$g_4 = p_i - p_j \le 0$ — Constraints about the priority for transporting

for $i, j = 1, \cdots, B$ and $k, l = 1, \cdots, T$

Proposed Algorithm for Scheduling of Block Transporting of Multiple Transporters

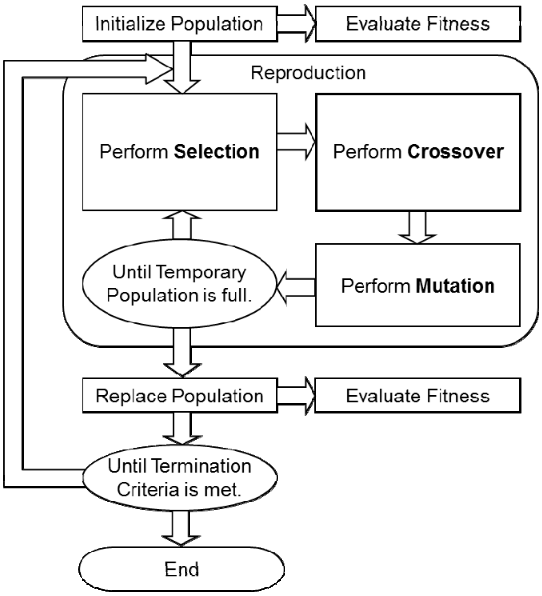


Example of Ants Finding an Optimal Path

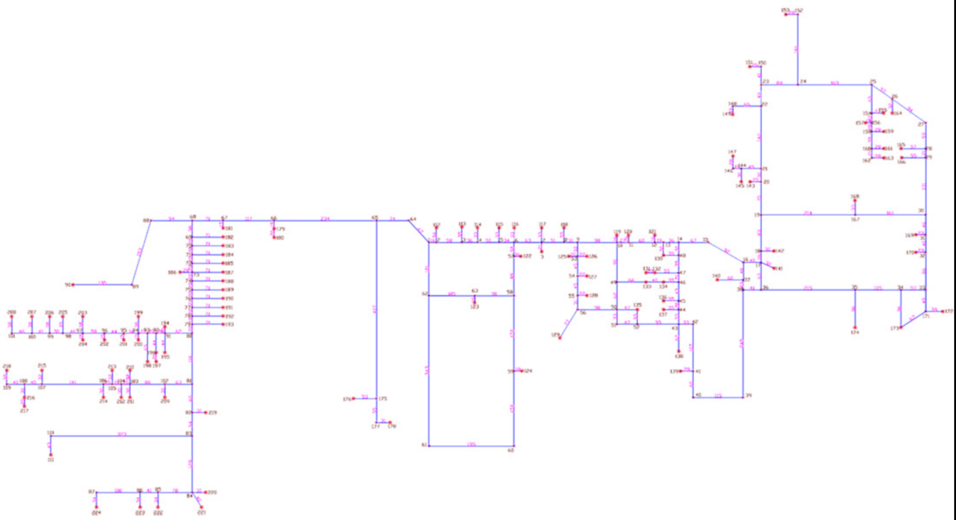


Assumptions
- 30 ants start from A and E every unit time ('t') 1, respectively.
- The ants move by the distance ('d') 1 during the time 1 with a constant speed.

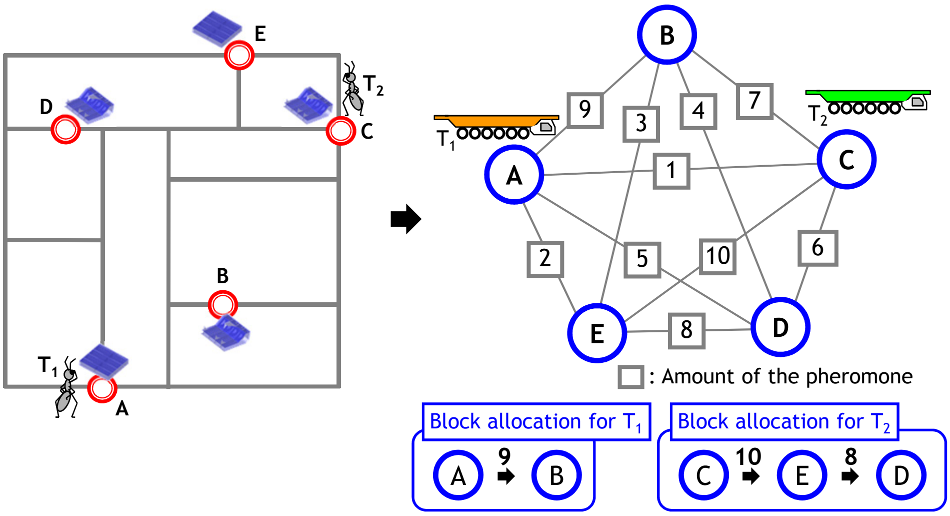
Schematic Diagram of the Genetic Algorithms



Example of the Graph Representation for All Available Transportation Paths



Block Allocation for Each Transporter Using the Ant Algorithm

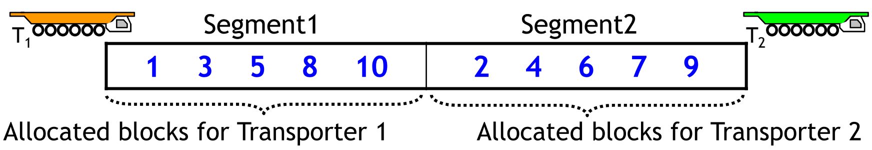


Block Transportation Scheduling and the Corresponding Representation of the Two-Segmented Chromosome

Block allocation obtained from the ant algorithm

Transporter	Allocated blocks	No. of allocated blocks
T_1	1, 3, 5, 8, 10	5
T_2	2, 4, 6, 7, 9	5

Chromosome representation of the block allocation



Modified Crossover Operation for Generating the First and Second Children (1/2)

- ☑ **The modified crossover is simultaneously applied to each parent.**
- ☑ **A set s1 includes genes of the first parent to be replaced with those of the second parent, and initially is randomly selected.**

$$s1 = \frac{\{Ft(p1) + Ft(p2)\} - Ft(p1)}{Ft(p1) + Ft(p2)} \times n \quad \text{(discard decimals)} \qquad s2 = n - s1$$

where, s1: the number of genes of the first parent to be replaced with those of the second parent,
s2: the number of genes of the first parent to be transmitted to the first child,
n: the number of the genes in the first or second parent

- ☑ **Next step is for the genes in the s2 positions of the first parent to be transmitted to the corresponding positions of the first child.**
- ☑ **Finally, the genes in the s1 positions are reordered according to the order of the corresponding genes in the second parent and then they are transmitted to the corresponding positions of the first child.**
- ☑ **These similar steps are applied to the second parent to also generate the second child.**

Modified Crossover Operation for Generating the First and Second Children (2/2)

Segment 1	Segment 2
1, 3, 5, **8**, **10**	2, 4, 6, **7**, **9**

1st PARENT(fitness : 90) ➡ s1 = {8, 10, 7, 9}, s2 = {1, 3, 5, 2, 4, 6}

3, 5, 4, 6, **10**	**9**, 2, 1, **7**, **8**

2nd PARENT(fitness : 60)

⇩

1, 3, 5, **10**, **9**	2, 4, 6, **7**, **8**

1st CHILD

(a) Modified crossover for the 1st CHILD

Segment 1	Segment 2
1, 3, **5**, **8**, **10**	**2**, 4, **6**, **7**, 9

1st PARENT(fitness : 90)

3, **5**, 4, **6**, **10**	9, **2**, 1, **7**, **8**

2nd PARENT(fitness : 60) ➡ s1 = {5, 6, 10, 2, 7, 8}, s2 = {3, 4, 9, 1}

⇩

3, **5**, 4, **8**, **10**	9, **2**, 1, **6**, **7**

2nd CHILD

(b) Modified crossover for the 2nd CHILD

Mutation Operation Applied to Each Segment of the First Child

- ☑ The mutation operation is simultaneously applied to each segment of each child generated from the crossover operation.
- ☑ The mutation operation occurs with a very low probability (typically $p_{mutation}$ = 0.01 from Grefenstette's study).
- ☑ Two genes in each segment of each child are randomly selected and are exchanged with each other.

Segment 1	Segment 2
1, **3**, 5, **10**, 9	**2**, 4, 6, 7, **8**

1st CHILD – Before Mutation

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Segment 1	Segment 2
1, **10**, 5, **3**, 9	**8**, 4, 6, 7, **2**

1st CHILD – After Mutation

Configuration of the Block Transportation Scheduling System

Block transportation scheduling system

1 Optimization algorithm module
Core module for generating the optimal block transportation scheduling result based on the ant algorithm and the GA

2 GUI module
Tool for providing various input data for performing the block transportation scheduling

3 Reporting module
Tool for visualizing the optimal block transportation scheduling result as a table

4 Visualization module
Tool for visualizing the optimal block transportation scheduling result as an animation

Comparison of the Performance Resulting from Manual Scheduling and Automatic Scheduling by the Developed System

		Manual scheduling	Genetic algorithm	Proposed algorithm
Total transportation time		14 hr 16 min	12 hr 24 min	**12 hr 13 min**
Total transportation time without loading		6 hr 10 min	4 hr 18 min	**4 hr 7 min**
No. of interferences between the transporters during the transportation		7	2	**1**
No. of allocated blocks for each transporter	T_1	11 blocks	12 blocks	**13 blocks**
	T_2	34 blocks	34 blocks	**32 blocks**
	T_3	24 blocks	25 blocks	**27 blocks**
	T_4	28 blocks	26 blocks	**25 blocks**

Convergence History of the Objective Function Value During Iteration