Optimum Design

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9.2 Determination of Optimal Ship Route
9.3 Determination of the Optimal Lifting Sequence of Erection Blocks by a Gantry Crane
9.4 Determination of the Optimal Transporting Sequence of Erection Blocks by Multiple Transporters

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

Minimize: TFOC(X)

Subject to:

- Requirement for the arrival time
- Acquisition of sea state
- Estimation of fuel consumption
- Estimation of arrival time

Optimization procedure

1. Module for acquiring real-time sea state information
2. Module for estimating fuel oil consumption
3. Module for determining optimal ship route

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

- DEPARTURE: Acapulco, Mexico
- ARRIVAL: Luanda, Angola
- Application to various routes

<table>
<thead>
<tr>
<th>Route/Fuel consumption</th>
<th>Manual route (A)</th>
<th>Optimal route (B)</th>
<th>Reduction (B-A)</th>
<th>Ratio (B/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston-Lagos</td>
<td>5765ton ($288K)</td>
<td>5727ton ($284K)</td>
<td>38ton ($19K)</td>
<td>99.6%</td>
</tr>
<tr>
<td>Tampico-Cape Town</td>
<td>6270ton ($314K)</td>
<td>6232ton ($310K)</td>
<td>38ton ($19K)</td>
<td>99.6%</td>
</tr>
<tr>
<td>Santos-Laua</td>
<td>6475ton ($323K)</td>
<td>6437ton ($319K)</td>
<td>38ton ($19K)</td>
<td>99.6%</td>
</tr>
<tr>
<td>Montevideo-Helsinki</td>
<td>7465ton ($373K)</td>
<td>7427ton ($369K)</td>
<td>38ton ($19K)</td>
<td>99.6%</td>
</tr>
</tbody>
</table>

- About 3.4% fuel reduction were made.
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”)
- Total number of blocks and transporters:
- Weight of each block and specifications of each transporter:
- Before and after positions of each block:
- Priority for transportation of blocks:

Output (“Find”)
- Optimal route and transportation sequence of blocks

Mathematical formulation

Find
- Lifting time for each block

Objective Functions
- Constraints

Mathematical formulation

Application to an actual problem of shipyard

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 transportation of blocks:

Output (“Find”)
- Optimal route and transportation sequence of blocks

Mathematical formulation

Application to an actual problem of shipyard
9.2 Determination of Optimal Ship Route

Concept of Optimal Ship Route

- Shortest route
- Route 1
- Route 2
- Shortest path
- Traffic free path
- Shortest route
- (Minimal fuel consumption)

* 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

\[
\text{Find } X \quad \text{Route} \\
\text{Minimize } TFOC(X) \quad \text{Total fuel consumption} \\
\text{Subject to } ETA_{\text{min}} - ETA(X) \leq 0 \\
\text{Requirement for the minimum arrival time} \\
ETA(X) - ETA_{\text{max}} \leq 0 \\
\text{Requirement for the maximum arrival time}
\]

- Optimization problem having 1 unknown and 2 inequality constraints
**Process for Determining Optimal Ship Route Using an Optimization Algorithm**

Given: Ports of departure and arrival, Required arrival time, Geographic information

Variation of principal dimensions $X$

Acquisition of sea state information
Estimated fuel consumption
Estimated arrival time

Criteria for determining optimum
Minimization of fuel consumption

Optimization algorithm
(Isochrone method, $A^*$ method, ...)

Optimum? No

Optimum? Yes

Finish

---

**Optimization Program for the Ship Route Design**

- **Configuration**

**Optimal ship routing program**

1. Module for acquiring real-time sea state information
2. Module for estimating fuel consumption
3. Module for determining optimal ship route
4. GUI
5. DB

- Sea state information
- Optimal ship route

- E-mail from satellite
- ISO 15016 method
Acquisition of Real-time Sea State Information

Various sea state information from ECMWF, AMI, etc. on land
e-mail
Satellite
INMARSAT

Visualization of sea state information

Process for automatic downloading of e-mail

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

Sea State Information from ECMWF*

* ECMWF: European Center for Medium range Weather Forecasting, AMI: Aerospace & Marine International
Scenario of the change in Ship Performance According to the 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**

ISO 15016 method

Sea state information

- **Increase of ship's resistance** according to sea state
  \[ \delta R = \delta R_{\text{wave}} + \delta R_{\text{wind}} + \delta R_{\text{steering}} + \delta R_{\text{drift}} + \delta R_{\text{wetting}} + \delta R_{\text{A}} + \delta R_{\text{D}} \]

- **Reduction of ship's speed** according to additional resistance
  \[ \delta V = \delta V_{\text{wave}} + \delta V_{\text{wind}} + \delta V_{\text{current}} + \delta V_{\text{depth}} \]

- **Increase of ship's horse power** to compensate for the ship's speed
  \[ \delta P = \frac{\delta V}{n} (n+1) \]

- **Increase of ship's fuel consumption** according to the increase in horse power
  \[ \Delta FOC = \Delta FOC + \frac{\delta P}{SFOC} \]

Note: \( \Delta \) denotes the change in the respective parameter.

---

*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**

\[
\delta R = \delta R_{\text{state}} + \delta R_{\text{wind}}
\]
- \(\delta R_{\text{state}}\): added resistance by sea state
- \(\delta R_{\text{wind}}\): added resistance by wind

\[
\delta V = R - R_0 + \delta R
\]
- \(R\): resistance in still water at \(\frac{1}{2} \delta V\)
- \(R_0\): resistance in still water at \(\frac{1}{2} \delta V\)

\[
\delta P = 2\pi / 75(N_0 - \delta N_p + \delta Q_p)
\]
- \(N_0\): propeller RPM at \(\frac{1}{2} \delta V\)
- \(\delta N_p\): increased propeller RPM (\%)
- \(\delta Q_p\): increased propeller torque (\%)

\[
\delta FOC = SFOC \cdot \delta P \cdot t
\]
- \(SFOC\): specific fuel oil consumption (\$/h)
- \(\delta P\): increased power by speed compensation (\%)
- \(t\): navigation time considering speed reduction (\%)

**Method 2**

\[
\delta R = \delta R_{\text{water}} + \delta R_{\text{wind}}
\]
- \(\delta R_{\text{water}}\): added resistance by sea state
- \(\delta R_{\text{wind}}\): added resistance by wind

\[
\delta V = \left(1 - t \right) \left(1 - \frac{1}{2} \right) \left(1 - \frac{1}{2} \right) \left(1 - \frac{1}{2} \right) \left(1 - \frac{1}{2} \right)
\]
- \(\delta V\): speed reduction

\[
\delta P = \delta V - (n + 1)
\]
- \(\delta P\): increased power by speed compensation (\%)
- \(n\): constant

\[
\delta FOC = SFOC \cdot \delta P \cdot t
\]
- \(SFOC\): specific fuel oil consumption (\$/h)
- \(\delta P\): increased power by speed compensation (\%)
- \(t\): navigation time considering speed reduction (\%)

---

**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.

**Improved isochrone method**

- Considering sea state
- Considering obstacles such as islands

Given: \(\Delta t\), Sea state
Find: Position, Fuel consumption

Fuel consumption considering sea state

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

Different speed due to sea state

Optimal ship route

---

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

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
  - Lpp: 237.0m
  - B: 37.7m
  - D: 22.0m
  - T/L: 12.4/13.4m
  - Cb: 0.6600
  - V: 22knots

3.0% fuel consumption were reduced for this route.

<table>
<thead>
<tr>
<th></th>
<th>Manual route</th>
<th>Optimal route</th>
<th>Reduction (Δ)</th>
<th>Saving (%/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total distance</td>
<td>9,381NM</td>
<td>9,395NM</td>
<td>-13NM</td>
<td>100.1%</td>
</tr>
<tr>
<td>Total time</td>
<td>447h 42m</td>
<td>437h 58m</td>
<td>9h 44m</td>
<td>97.8%</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>1,720ton</td>
<td>1,669ton</td>
<td>51ton</td>
<td>97.0%</td>
</tr>
<tr>
<td>EEOI</td>
<td>6.651</td>
<td>6.303</td>
<td>0.348</td>
<td>94.8%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Route/Fuel consumption</th>
<th>Manual route [A]</th>
<th>Optimal route [B]</th>
<th>Reduction (B-A)</th>
<th>Ratio (B/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venquber~Luanda</td>
<td>2,064ton ($1,032K)</td>
<td>1,968ton ($984K)</td>
<td>96ton ($48K)</td>
<td>95.3%</td>
</tr>
<tr>
<td>Boston~Lagos</td>
<td>872ton ($436K)</td>
<td>850ton ($425K)</td>
<td>23ton ($11.5K)</td>
<td>97.4%</td>
</tr>
<tr>
<td>Tampico~Cape Town</td>
<td>1,389ton ($694.5K)</td>
<td>1,342ton ($671K)</td>
<td>47ton ($23.5K)</td>
<td>96.6%</td>
</tr>
<tr>
<td>Santos~Laum</td>
<td>1,057ton ($528.5K)</td>
<td>1,029ton ($514.5K)</td>
<td>28ton ($14K)</td>
<td>97.4%</td>
</tr>
<tr>
<td>Montevideo~Helsinki</td>
<td>1,179ton ($589.5K)</td>
<td>1,140ton ($570K)</td>
<td>39ton ($19.5K)</td>
<td>96.7%</td>
</tr>
</tbody>
</table>

*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

- **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.**

- **VLCCs under construction in a dry dock**
- **During the block erection**
- **Before the block erection**
- **Before the block erection**

**Goliath crane**

**Dock**

**PE(Pre-Erection) area**
Example of a Gantry Crane for Lifting Ship Erection Blocks

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

* PE(Pre-Erection) area: Area for temporarily leaving erection blocks before erecting them on the dock
* Daily working time of a crane: 20 hours, Moving speed of a crane: 30m/min
Travel Distance of a Unloaded Crane According to the Lifting Sequence (2/2)

"Block 2" lifting ◀ "Block 1" lifting

Plan view

PE(Pre-Erection) Area → Dock

Block 1

Block 2

traveling distance at an idle state

It is advantageous to lift “Block 2” after “Block 1”.

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

**Find**
- \( t_i \) \quad Lifting time for each block

**Minimize**
- \( F_1 = \sum_{i=0}^{N-1} \left( (1-r_{i,1}) \cdot t_{i,1} + r_{i,1} \cdot (t_{i,0} + t_{i,2}) \right) \) \quad Total travel time without block
- \( F_2 = \sum_{i=0}^{N-1} (r_{i,3} \cdot T_i) \) \quad Total time for wires and shackles replacement

**Subject to**
- \( g_1 = l_i - s_i \leq 0 \) \quad Constraints about the start of the lifting time
- \( g_2 = f_i - u_i \leq 0 \) \quad Constraints about the end of the lifting time
- \( g_3 = p_j - p_k \leq 0 \) \quad Constraints about the priority for lifting
- \( g_4 = f_N - T_i \leq 0 \) \quad Constraints about the total lifting time

for \( i = 0, \cdots, N-1 \) and \( j, k = 1, \cdots, N \)
Proposed Algorithm for Scheduling of Block Lifting of a Gantry Crane

Evaluate Fitness
Perform Selection
Reproduction
Perform Modified Crossover
Until Temporary Population is full
Perform Mutation
Evaluate Fitness
Replace Population
Evaluate Fitness
Until Termination Criteria is met.
End

Scheduling of Block Lifting and the Corresponding Representation of the Chromosome

Block lifting scheduling of a gantry crane

Block 1 \rightarrow Block 3 \rightarrow Block 5 \rightarrow Block 8 \rightarrow Block 10

Block 2 \rightarrow Block 4 \rightarrow Block 6 \rightarrow Block 7 \rightarrow Block 9

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 ($D_1$) = $D_{1(0)} + D_{1(t)}$
Traveling time of the Block 1 ($T_1$) = $D_{1(0)} / V_{ll} + D_{1(t)} / V_{lt}$

Traveling distance at an idle state from the Blocks 1 to 2 ($d_{1,2}$) = $d_{1,2(0)} + d_{1,2(t)}$
Traveling time at an idle state from the Blocks 1 to 2 ($t_{1,2}$) = $d_{1,2(0)} / V_{ll} + d_{1,2(t)} / V_{lt}$
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 \(d_{1,w(0)}\):
\[d_{1,w(0)} = d_{l_{w(0)}} + d_{t_{w(0)}}\]

Travel time at an idle state from the Block 1 to WS \(t_{1,w} \): \[t_{1,w} = \frac{d_{l_{w(0)}}}{V_l} + \frac{d_{t_{w(0)}}}{V_t}\]

Travel distance at an idle state from WS to the Block 2 \(d_{w,2(0)}\):
\[d_{w,2(0)} = d_{l_{w(0)}}\]

Travel time at an idle state from WS to the Block 2 \(t_{w,2} \):
\[t_{w,2} = \frac{d_{l_{w(0)}}}{V_l}\]

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

- The modified crossover is simultaneously applied to each parent.
- A set \(s_1\) includes genes of the first parent to be replaced with those of the second parent, and initially is randomly selected.

\[s_1 = \left(\frac{Ft(p_l) + Ft(p_2) - Ft(p_l)}{Ft(p_l) + Ft(p_2)}\right) \times n \text{ (discard decimals)} \quad s_2 = n - s_1\]

where, \(s_1\): the number of genes of the first parent to be replaced with those of the second parent,
\(s_2\): 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 \(s_2\) positions of the first parent to be transmitted to the corresponding positions of the first child.
- Finally, the genes in the \(s_1\) 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)

<table>
<thead>
<tr>
<th>1 3 5 8 10 2 4 6 7 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st PARENT (fitness : 90) → s1 = (8, 10, 7, 9), s2 = (1, 3, 5, 2, 4, 6)</td>
</tr>
<tr>
<td>3 5 4 6 10 9 2 1 7 8</td>
</tr>
<tr>
<td>2nd PARENT (fitness : 60)</td>
</tr>
<tr>
<td>1 3 5 10 9 2 4 6 7 8</td>
</tr>
</tbody>
</table>

1st CHILD

(a) Modified crossover for the 1st CHILD

<table>
<thead>
<tr>
<th>1 3 5 8 10 2 4 6 7 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st PARENT (fitness : 90)</td>
</tr>
<tr>
<td>3 5 4 6 10 9 2 1 7 8</td>
</tr>
<tr>
<td>2nd PARENT (fitness : 60) → s1 = (5, 6, 10, 2, 7, 8), s2 = (3, 4, 9, 1)</td>
</tr>
<tr>
<td>3 5 4 8 10 9 2 1 6 7</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>1 3 5 10 9 2 4 6 7 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st CHILD – Before Mutation</td>
</tr>
<tr>
<td>1 10 5 3 9 8 4 6 7 2</td>
</tr>
<tr>
<td>1st CHILD – After Mutation</td>
</tr>
</tbody>
</table>
### Comparison of Computational Results of the Improved Genetic Operations and Conventional Genetic Operations for 100 Runs

<table>
<thead>
<tr>
<th></th>
<th>Result of the improved genetic operations</th>
<th>Result of the conventional genetic operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best objective function value</td>
<td>105.78</td>
<td>105.78</td>
</tr>
<tr>
<td>Mean objective function value</td>
<td>108.43</td>
<td>105.78</td>
</tr>
<tr>
<td>Mean time (sec)</td>
<td>4.71</td>
<td>3.38</td>
</tr>
</tbody>
</table>

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

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

![Diagram showing Pareto optimal set with different weighting factors](image)
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

![Screenshot of the Block Lifting Scheduling System](image)

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

<table>
<thead>
<tr>
<th></th>
<th>Result of manual scheduling</th>
<th>Result of the developed system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before optimization</td>
<td>After optimization</td>
</tr>
<tr>
<td>Total traveling time</td>
<td>3 hr 20 min</td>
<td>3 hr 41 min</td>
</tr>
<tr>
<td>Total traveling time at an idle state</td>
<td>2 hr 6 min</td>
<td>2 hr 26 min</td>
</tr>
<tr>
<td>No. of the wires &amp; shackles replacement</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>74+161+RUD+183+197</td>
<td>626+80A+182+192+152+171+161+RUD+183+193+625+626+636+635+635+635+636</td>
</tr>
</tbody>
</table>

*Topics in Ship Design Automation, Fall 2015, Myung Il Roh*
### Comparison of the Idleness Ratio of the Crane and the Number of the Wires & Shackles Replacement During Six Days (1/2)

<table>
<thead>
<tr>
<th></th>
<th>Result of manual scheduling</th>
<th>Result of the developed system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Idleness ratio</td>
<td>No. of the wires &amp; shackles replacement</td>
</tr>
<tr>
<td>Day #1 (19 blocks)</td>
<td>15.8%</td>
<td>9</td>
</tr>
<tr>
<td>Day #2 (18 blocks)</td>
<td>11.1%</td>
<td>7</td>
</tr>
<tr>
<td>Day #3 (22 blocks)</td>
<td>20.3%</td>
<td>14</td>
</tr>
<tr>
<td>Day #4 (18 blocks)</td>
<td>12.2%</td>
<td>9</td>
</tr>
<tr>
<td>Day #5 (20 blocks)</td>
<td>13.2%</td>
<td>10</td>
</tr>
<tr>
<td>Day #6 (17 blocks)</td>
<td>13.1%</td>
<td>8</td>
</tr>
<tr>
<td>Avg.</td>
<td>14.3%</td>
<td>10</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>23.3 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>6.6 m</td>
</tr>
<tr>
<td>Height</td>
<td>Avg. 2.2 m (1.55 - 2.2 m, adjustable)</td>
</tr>
<tr>
<td>Weight</td>
<td>126 ton</td>
</tr>
<tr>
<td>Speed</td>
<td>without loading 15 km/h, with loading 10 km/h</td>
</tr>
<tr>
<td>Number of wheels</td>
<td>88</td>
</tr>
</tbody>
</table>

| Purpose                 | Moving blocks, deck houses, main engines, large pipe equipments, etc. |
| Feature                 | 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

Find \( x_i \) 

Minimize \( F_1 = \sum_{i=1}^{B} \sum_{k=1}^{T} x_i^k (c_i^k / V_k) \) and \( \text{Transporting time for each block} \)

Minimize \( F_2 = \sum_{i=1}^{B} \sum_{j=1}^{T} \sum_{k=1}^{T} \sum_{l=1}^{T} x_i^k x_j^l c_{ij} \) 

\( \text{Total transporting time} \)

\( \text{Total number of interferences between transporters} \)

Subject to

\[ g_1 = w_i - t_i \leq 0 \] Constraints about the maximum deadweight of transporter

\[ g_2 = r_i - p_i \leq 0 \] Constraints about the start of the transporting time

\[ g_3 = d_i - s_i \leq 0 \] Constraints about the end of the transporting time

\[ g_4 = p_i - p_j \leq 0 \] Constraints about the priority for transporting

\( \text{for } i, j = 1, \ldots, B \text{ and } k, l = 1, \ldots, T \)
Proposed Algorithm for Scheduling of Block Transporting of Multiple Transporters

1. Generation of the information on the transporters, blocks, and paths in shipyard

2. Block allocation for each transporter using the ant algorithm
   - Satisfaction of constraints
   - Yes: Run of the ant algorithm
   - No: Determination of the block allocation for each transporter

3. Usage of the block allocation result as an initial population for the GA
   - Run of the GA
   - Satisfaction of constraints
   - Yes: Determination of the transportation sequence of the blocks using the GA
   - No: Usage of the block allocation result as an initial population for the GA

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

- Initialize Population → Evaluate Fitness
- Reproduction
- Perform Selection
- Perform Crossover
- Until Temporary Population is full, Perform Mutation
- Replace Population → Evaluate Fitness
- Until Termination Criteria is met → End

Example of the Graph Representation for All Available Transportation Paths
Block Allocation for Each Transporter Using the Ant Algorithm

Block allocation for $T_1$

$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E$

Block allocation for $T_2$

$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E$

$\Box$ : Amount of the pheromone

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

Block allocation obtained from the ant algorithm

<table>
<thead>
<tr>
<th>Transporter</th>
<th>Allocated blocks</th>
<th>No. of allocated blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>1, 3, 5, 8, 10</td>
<td>5</td>
</tr>
<tr>
<td>$T_2$</td>
<td>2, 4, 6, 7, 9</td>
<td>5</td>
</tr>
</tbody>
</table>

Chromosome representation of the block allocation

Allocated blocks for Transporter 1

$[1, 3, 5, 8, 10]$  

Allocated blocks for Transporter 2

$[2, 4, 6, 7, 9]$
Modified Crossover Operation for Generating the First and Second Children (1/2)

- The modified crossover is simultaneously applied to each parent.
- A set $s_1$ includes genes of the first parent to be replaced with those of the second parent, and initially is randomly selected.
  \[ s_1 = \left( \frac{F(p_1) + F(p_2)}{F(p_1) + F(p_2)} - F(p_1) \right) \times n \text{ (discard decimals)} \]
  \[ s_2 = n - s_1 \]
  where, $s_1$: the number of genes of the first parent to be replaced with those of the second parent,
  $s_2$: 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 $s_2$ positions of the first parent to be transmitted to the corresponding positions of the first child.
- Finally, the genes in the $s_1$ 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)

<table>
<thead>
<tr>
<th>Segment 1</th>
<th>Segment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 3, 5, 8, 10</td>
<td>2, 4, 6, 7, 9</td>
</tr>
</tbody>
</table>

1ST PARENT (fitness : 90) \( \triangleright \) $s_1 = (8, 10, 7, 9), s_2 = (1, 3, 5, 2, 4, 6)$

<table>
<thead>
<tr>
<th>Segment 1</th>
<th>Segment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, 5, 4, 6, 10</td>
<td>9, 2, 1, 7, 8</td>
</tr>
</tbody>
</table>

2ND PARENT (fitness : 60)

\[ \text{(a) Modified crossover for the 1ST CHILD} \]

<table>
<thead>
<tr>
<th>Segment 1</th>
<th>Segment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 3, 5, 10, 9</td>
<td>2, 4, 6, 7, 8</td>
</tr>
</tbody>
</table>

1ST CHILD

<table>
<thead>
<tr>
<th>Segment 1</th>
<th>Segment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 3, 5, 8, 10</td>
<td>2, 4, 6, 7, 9</td>
</tr>
</tbody>
</table>

1ST PARENT (fitness : 90)

<table>
<thead>
<tr>
<th>Segment 1</th>
<th>Segment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, 5, 4, 6, 19</td>
<td>9, 2, 1, 7, 8</td>
</tr>
</tbody>
</table>

2ND PARENT (fitness : 60) \( \triangleright \) $s_1 = (5, 6, 10, 2, 7, 8), s_2 = (3, 4, 9, 1)$

<table>
<thead>
<tr>
<th>Segment 1</th>
<th>Segment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, 5, 4, 8, 19</td>
<td>9, 2, 1, 6, 7</td>
</tr>
</tbody>
</table>

2ND CHILD

\[ \text{(b) Modified crossover for the 2ND CHILD} \]
**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 $p_{\text{mutation}} = 0.01$ from Grefenstette's study).
- Two genes in each segment of each child are randomly selected and are exchanged with each other.

<table>
<thead>
<tr>
<th>Segment 1</th>
<th>Segment 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 3, 5, 10, 9</td>
<td>2, 4, 6, 7, 8</td>
</tr>
<tr>
<td><strong>1st CHILD – Before Mutation</strong></td>
<td></td>
</tr>
<tr>
<td>1, 10, 5, 3, 9</td>
<td>8, 4, 6, 7, 2</td>
</tr>
<tr>
<td><strong>1st CHILD – After Mutation</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Configuration of the Block Transportation Scheduling System**

<table>
<thead>
<tr>
<th>Block transportation scheduling system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> Optimization algorithm module</td>
</tr>
<tr>
<td>Core module for generating the optimal block transportation scheduling result based on the ant algorithm and the GA</td>
</tr>
<tr>
<td><strong>2</strong> GUI module</td>
</tr>
<tr>
<td>Tool for providing various input data for performing the block transportation scheduling</td>
</tr>
<tr>
<td><strong>3</strong> Reporting module</td>
</tr>
<tr>
<td>Tool for visualizing the optimal block transportation scheduling result as a table</td>
</tr>
<tr>
<td><strong>4</strong> Visualization module</td>
</tr>
<tr>
<td>Tool for visualizing the optimal block transportation scheduling result as an animation</td>
</tr>
</tbody>
</table>
### Comparison of the Performance Resulting from Manual Scheduling and Automatic Scheduling by the Developed System

<table>
<thead>
<tr>
<th></th>
<th>Manual scheduling</th>
<th>Genetic algorithm</th>
<th>Proposed algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total transportation time</strong></td>
<td>14 hr 16 min</td>
<td>12 hr 24 min</td>
<td>12 hr 13 min</td>
</tr>
<tr>
<td><strong>Total transportation time without loading</strong></td>
<td>6 hr 10 min</td>
<td>4 hr 18 min</td>
<td>4 hr 7 min</td>
</tr>
<tr>
<td><strong>No. of interferences between the transporters during the transportation</strong></td>
<td>7</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$T_1$</td>
<td>11 blocks</td>
<td>12 blocks</td>
<td>13 blocks</td>
</tr>
<tr>
<td>$T_2$</td>
<td>34 blocks</td>
<td>34 blocks</td>
<td>32 blocks</td>
</tr>
<tr>
<td>$T_3$</td>
<td>24 blocks</td>
<td>25 blocks</td>
<td>27 blocks</td>
</tr>
<tr>
<td>$T_4$</td>
<td>28 blocks</td>
<td>26 blocks</td>
<td>25 blocks</td>
</tr>
</tbody>
</table>

### Convergence History of the Objective Function Value During Iteration

![Convergence History Graph]

- **Manual scheduling**
- **Genetic algorithm**
- **Proposed algorithm**

The graph shows the convergence history of the objective function value during iteration, with the total transportation time on the y-axis and the number of generations on the x-axis. The graph demonstrates the improvement in performance as the number of generations increases, with distinct lines for each scheduling method.