The analyses of infrastructure and transit cargoes through Arctic region

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Motivation of study

- Constant growth of world flow (growing population, consumption, globalization, joint manufactories) -> increased load of the existing transport networks

- Constraints and risks of transits via the traditional international corridors such as Suez canal (strict regulation of ship journey, constraints for the size of vessels, pirates of Somalie, slow delivery) -> searching of new effective transport schemes

- Ice melting, new logistical infrastructure projects and growth of the resource development projects in the Arctic region -> non-analyzed new transport network
Case study

Logistics network between Asia and Europe

Analyzed types of cargo:
- General cargoes – groups of the spare parts, mechanisms and cars
- Offshore cargoes – drilling and exploration equipment
- Liquid cargoes – LNG from Yamal

Assumption: appx 20% of all transported cargo via Suez Canal could be transported via Arctic region

Source: made by authors

New planned infrastructure:
Arctic Corridor project (railroad from Helsinki via Rovaniemi till Kirkenes)
To develop decision support models to answer the following research questions of case study:

RQ1: How the flow will be distributed from the Asia cluster to West Europe and vice versa cluster, according to the transportation network?
RQ2: Where arcs should be expanded to satisfy the scenario demand?

- The first model solves **Linear multicommodity minimum cost flow problem** (finding the minimum cost of transportation the flow of several products from supplier with an existed network system and by all scenarios)

- The second model solves **Network design capacity expansion problem** (finding the minimum cost of transportation the flow of product from suppliers and the cost of expansion arcs with an existed network system by all scenarios)

Models are presented in Appendix 1
Linear multicommodity minimum cost flow problem mathematical formulation:

Sets:
- $P$ – set of ports (points)
- $B$ – set of commodities
- $L$ – set of links (arcs)

Variable:
- $X_{ijb}$ – the variable shows the flow of each commodity $b$ on link $(i,j)$, $(i,j) \in L$, $b \in B$.

Parameters:
- $a_{ib}$ – the supply of commodity $b$ of port $i$, $i \in P$, $b \in B$
- $d_{jb}$ – the demand of commodity $b$ of port $i$, $i \in P$, $b \in B$
- $u_{ijb}$ – the maximum flow of commodity $b$ on link $(i,j)$, $(i,j) \in L$, $b \in B$
- $c_{ijb}$ – the cost of transported flow of each commodity $b$ on each link $(i,j)$, $(i,j) \in L$, $b \in B$

The objective function:

$$\min \sum_{b \in B} \sum_{(i,j) \in L} c_{ijb} X_{ijb} \quad (1)$$

Subject to:

$$a_{ib} + \sum_{(i,s) \in L} X_{isb} = d_{sb} + \sum_{(s,j) \in L} X_{sjb} \quad s \in P, \ b \in B \quad (2)$$

Constraints for variables:

$$x_{ijb} \leq u_{ijb}, (i,j) \in L, b \in B \quad (3)$$

$$x_{ijb} \geq 0, (i,j) \in L, b \in B \quad (4)$$
Network design capacity expansion problem mathematical formulation:

Sets:
- \( I \) – set of suppliers
- \( K \) – set of routes
- \( J \) – set of arcs
- \( C \) – set of commodities

Parameters:
- \( f_i \) – the fix cost of using the supplier \( i, \ i \in I \)
- \( c_k \) – the cost of transportation per 1 km on route \( k, \ k \in K \)
- \( u_{ic} \) – the total capacity of commodity \( c \) from supplier \( i, \ i \in I, \ c \in C \)
- \( d_c \) – the total demand of each commodity \( c, \ c \in C \)
- \( r_j \) – capacity of each arc \( j, \ j \in J \)
- \( e \) – the amount of the road (arc) capacity expansion
- \( m \) – the cost of road expansion
- \( A_{tk} \) – which arc \( j \) belonged to the route \( k \) is used by supplier \( i, \ i \in I, \ k \in K, \ j \in J \)
- \( B_{tk} \) – which route \( k \) can be used by each supplier \( i, \ i \in I, \ k \in K \)
- \( g_k \) – the distance of route \( k, \ k \in K \)

Variables:
- \( Z_i \) – the binary variable, 1 if supplier \( i \) is contracted or 0 is otherwise, \( i \in I \)
- \( Y_j \) – the binary variable, where 1 if the capacity of the road \( j \) is increased, 0 is otherwise, \( j \in J \)
- \( X_{t_k} \) – Volume (amount) of the commodity \( c \), which is transported on the route \( k \) from supplier \( i, \ i \in I, \ k \in K, \ c \in C \)

The objective function

\[
\min \sum_{i \in I} f_i Z_i + m \sum_{j \in J} Y_j + \sum \sum_{i \in I, k \in K, c \in C} c_k g_k B_{tk} X_{t_k} \tag{1}
\]

Subject to:

\[
\sum_{k \in K} B_{tk} X_{t_k} \leq u_{ic} Z_i, \ \forall i \in I, \ \forall c \in C \tag{2}
\]

\[
\sum \sum_{i \in I, k \in K, c \in C} A_{tk} X_{t_k} \leq r_j + e Y_j, \ \forall j \in J \tag{3}
\]

\[
\sum \sum_{i \in I, k \in K} B_{tk} X_{t_k} \geq d_c, \ \forall c \in C \tag{4}
\]

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Analysed scenarios

Basic model 1 (including Arctic Corridor project)
S1.1 Increasing demand of main goods from both clusters by China and Europe
S1.2 Including the port of Narvik in the network (as one more new alternative):

Basic model 2 (including Arctic Corridor project)
S2.1 Increasing capacity of Arctic corridor and the port of Kirkenes
S2.2 Increasing capacity Murmansk port and railroad from Murmansk to East Europe cluster railroad
S2.3 Unlimited capacity of NSR
Results of basic scenario of model 1

From Asia cluster to West Europe cluster

From West Europe cluster to Asia cluster

Analysed arcs:
- Asia - West EU
- Asia-Kirkenes - West EU
- Asia-Kirkenes-Helsinki - West EU
- Asia - Murmansk – West EU
- Asia - Murmansk - East EU -West EU
- Yamal -West EU
- Yamal - Murmansk - East EU - West EU
- Yamal - Murmansk - West

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S1.1 Increasing demand of main goods from both clusters by China and Europe in 30%

From Asia cluster to West Europe cluster

From West Europe cluster to Asia cluster

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S1.2 Including the port of Narvik in the network

From Asia cluster to West Europe cluster

From West Europe cluster to Asia cluster

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Results of basic scenario of the second model
(only mechanical appliances and LNG flows are considered in the tests)

From Asia cluster to West Europe cluster

From West Europe cluster to Asia cluster
S2.1 Increasing capacity of Arctic corridor and the port of Kirkenes in 40%

From Asia cluster to West Europe cluster

From West Europe cluster to Asia cluster

FLOW of mechanical appliances and electrical equipment in tones:
- Asia cluster – West Europe cluster (A) 1 800 470 t
- Asia cluster – Kirkenes – West Europe cluster (KB) 2 800 000 t
- Asia cluster – Murmansk – West Europe cluster (ME) 200 000 t
- Asia cluster – Murmansk – West Europe cluster (MG) 2 860 000 t
- Asia cluster – Kirkenes – Helsinki – West Europe cluster (BCF) 4 200 000 t

FLOW of LNG in tones:
- Yamal – Murmansk – West Europe cluster (S) 1 140 000 t
- Yamal – West Europe cluster (XG) 6 000 000 t

FLOW of mechanical appliances and electrical equipment in tones:
- West Europe cluster – Murmansk – Asia cluster (GM) 1 470 910 t
- West Europe cluster – Helsinki – Kirkenes – Asia cluster (FKK) 4 200 000 t

FLOW of LNG in tones:
- Yamal – Asia cluster (X) 1 500 000 t
S2.2 Increasing capacity Murmansk port and railroad from Murmansk to East Europe cluster railroad in 30% (without including railroad Helsinki-Kirkenes)

From Asia cluster to West Europe cluster

From West Europe cluster to Asia cluster
S 2.3 Unlimited capacity of NSR

From Asia cluster to West Europe cluster

FLOW of mechanical appliances and electrical equipment in tones:
- Asia cluster – West Europe cluster (A) 6,003,470 t
- Asia cluster – Murmansk – West Europe cluster (MG) 2,860,000 t
- Asia cluster – Kirkenes – Helsinki – West Europe cluster (KCI) 3,000,000 t

FLOW of LNG in tones:
- Yamal – Murmansk – West Europe cluster (S) 1,140,000 t
- Yamal – West Europe cluster (XG) 6,000,000 t

From West Europe cluster to Asia cluster

FLOW of mechanical appliances and electrical equipment in tones:
- West Europe cluster – Asia cluster (A) 6,003,470 t
- Yamal – Asia cluster (X) 1,500,000 t

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Total transportation costs of each scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>From Asia cluster to West Europe cluster ($)</th>
<th>From West Europe cluster to Asia cluster ($)</th>
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<tr>
<td>Model 1</td>
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<tr>
<td>Basic scenario</td>
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<td>S2.3</td>
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</tr>
</tbody>
</table>
• The costs influence on the flow mostly than another parameters at each model. The first model showed, that diversification of the commodity can vary, depending on the quantity of the flow.

• The flow is also sensitive to the amount of transported goods.

• New projects are able to be effective, if their price will be attractive for the transporting company in future, comparing with the NSR.

• The experiments of the second model helped us to understand, that climate changes would influence to the future flow of the NSR.

• Developed models can be useful for stakeholders for planning new logistical infrastructure and choosing new effective logistical scheme for the transported cargo.
Limitations and further research

- More assumptions with the volumes of cargo flows, port capacities and costs than real data were used for the study.
- More realistic data could provide more insight in the studied context.

Further actions:
- Adding new types of cargoes for transit (fluids, load in bulk, bulk-loaded, perishables);
- Developing the using network (include more railways, accounting air transport and roads);
- Adding new links (Underwater tunnel from Helsinki to Tallinn);
- Analyzing more parameters, for instance, capacities of port in details (including the weather condition);
- Identification separately each hubs and ports, using their own rates;
- Creating new scenarios of future network system;
- Including risks during the transportation on each link (weather, heavy condition of roads, force majeure events).