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A DECISION SUPPORT SYSTEM FOR AN OPTIMAL TRANSPORTATION NETWORK PLANNING IN THE THIRD PARTY LOGISTICS

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ABSTRACT

In an effort to gain competitiveness, recently many companies are trying to outsource their logistics activities to the logistics specialists, while concentrating on their core and strategic business area. Because of this trend, the third party logistics comes to the fore, catching people's attention, and expanding its market rapidly. Under these circumstances, the third party logistics companies are making every effort to improve their logistics services and to develop an information system in order to enhance their competitiveness. In particular, among these efforts one of the critical parts is the decision support system for effective transportation network planning. To this end, this study has developed an efficient decision support system for an optimal transportation network planning by comprehensively considering the transportation mode, routing, assignment, and schedule. As a result of this study, the new system enables the expansion of the third party logistics companies' services including the multimodal transportation, not to mention one mode of transportation, and also gets them ready to plan an international transportation network.

Key words: Third-party logistics, Optimal transportation Network planning, Decision support system.

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INTRODUCTION

In an effort to gain competitiveness, recently many companies are making efforts to concentrate their limited management resources on the core businesses, while outsourcing non-core logistics activities to the logistics specialists. Here the outsourcing of logistics activity can be defined "third party logistics." The CLS (Council of Logistics Management) of the USA defines third party logistics (3PL) as a firm or an agent who provides outsourced logistics services to its client company in the logistics channel on a short term or long-term relationship basis, and so the owner of goods (the client company) makes an agreement with one or plural logistics specialists on a specified terms and conditions for a certain period time. Therefore, it is also called "contract logistics" (La Londe and Cooper, 1989). Meanwhile, a lot of researchers are emphasizing the importance of 3PL. Cantiz said that it is not easy for a company to gain a proper return of its investment in the logistics field, and that the best solution is to make use of the third party logistics company who can provide some or all of supply chain management function. Concerning the motive of many companies' logistics outsourcing, Baghi & Virum (1998) pointed out that it is because of the reduction of market size, increasing global competition, shortening product life cycle, excessive costs, the necessity of speedy and smooth customer service, and decreasing profitability (Baghi and Virum, 1998). Chan-Seok Park (2001) stressed in his research that the third party logistics, in addition to its main function of performing logistics activities, is conducting a very critical function of SLO (Strategic Logistics Outsourcing), which includes the client company's planning function (Park, 2003).

It is noteworthy that 3PL is rapidly growing because of the trend that the business activities between companies are moving from the existing transaction-oriented to the relationship-oriented. In particular, many US and European companies, the leaders in the logistics field, are widely taking advantage of 3PL in terms of a strategic viewpoint. In case of the USA, in 1995 the usage rate of 3PL is 60%, and in case of European countries, it amounts to 76%. From then on it has continued to grow. Western Europe reaches 72%, Asia 63%, Mexico 60%, and Canada 50%. Meanwhile, the market size of the logistics field also continues to grow. In the USA, the logistics market size in 1991 grew to be US$ 6 billion, US$ 16 billion in 1994, US$ 39.6 billion in 1998, and US$ 50 billion in 2000, thus showing a growth rate of 20% per year, and continually being expected to grow.

In case of Korea, third party logistics is still in the beginning stages, and its market size stands at 3 trillion won, quite small compared to the international logistics market (Kim et al., 2003). According to the survey of "Domestic Companies' Logistics Management Reality in 2001" (Dec. 2001) conducted by the Korea Chamber of Commerce and Industry (KCCI) with the survey objects of 603 manufacturers and distributors, and also the survey of "Reality Check on the Usage of 3PL of Domestic Traders," which was also conducted by the secretariat for shippers of KCCI (July,

2002) with the survey objects of 100 member traders, increasing companies are taking advantage of 3PL in order to obtain the specialist knowledge and to save costs (Lee and Kim, 2002). Also more companies, which have a relatively higher weight of logistics compared with that of foreign companies, are trying to transfer its logistics activities to the logistics specialist, while concentrating their resources on the key parts such as business, marketing, and production. As a result of this trend, the 3PL market is expected to be brighter.

However, along with the promising growth of 3PL market, its competition is also being intensified. Because of this, third party logistics companies have to take measures to strengthen their competition. As a way of offering specialized services, some researches are focusing on the introduction of a new information system. Londe & Maltz said that the purpose of outsourcing logistics was to obtain the differentiation of services rather than cost saving, while emphasizing the importance of a differentiated service. Young-Hyo Ahn explained in his study that many third party logistics companies are aggressively trying to invest in obtaining up-to-date information technology, and some of them are making a strategic alliance with an IT specialist in order to establish a new information system (Ahn, 1999). Bradley emphasized the importance of a unique information system to take the lead in providing 3PL services to the client companies. In an effort to activate domestic 3PL services, Chung-Kyu Lee et al. (2002) have stressed the importance of logistics information system, while pointing out the necessity of specialized service models and strategies (Lee and Kim, 2002).

For this purpose, this study has developed a new system, TNPS (Transportation Network Planning System), which can be of great help for 3PL's transportation network planning. Even now, most 3PL companies are depending upon the experiences and existing practices of the persons in charge in planning their transportation network, gathering information by means of a telephone and a facsimile, and consequently causing problems in terms of efficiency and cost. These problems include the following: First, the transportation network planning is manually made, based on the know-how of the persons in charge. Secondly, after completion of transportation network planning, it presents to the shipper only the results such as transportation costs and transportation period, not suggesting its generation process or alternatives, consequently giving the client company no opportunity to select a better alternative. Thirdly, it is impossible to systematically gather the know-how, data, and knowledge about transportation network planning. Even worse, the increasing number of client companies and rapid expanding cargo volume makes it almost impossible to manually perform its transportation network planning.

Therefore, in order to generate an optimal transportation network, the user's opinion should be successively reflected, so that the user can make a better decision. To this end, the decision support system is vitally necessary. In this respect, the TNPS developed by this study can be of great help for the solution of many problems inherent to the existing planning method. More importantly, the diverse transportation network and evaluation materials generated by this new system can build confidence in the client's mind, eventually improving relationships with the shippers. In particular, it is noteworthy that the business transaction in the 3PL is characterized by its relationship-oriented feature.

OPTIMAL TRANSPORTATION NETWORK PLANNING

In dealing with the problem of an optimal transportation network, this study has adopted the systematic approach instead of using an algorithm. Most researches using an algorithm approach are focusing on generating an optimal transportation network. However, this study judges that an optimal transportation network is selected not by a system, but by a user. So based on this judgment, this study has focused on providing diverse evaluation materials on transportation network, so that a user (a shipper) can easily select an optimal transportation network. That is to say, instead of approaching the problem of transportation network by way of optimization, this study has approached the problem by means of a decision support system. In general, when a system has suggested an optimal alternative to the user, the user has a tendency not to follow as suggested, and so it is very difficult to generate an optimal alternative fit to the user's requirements. In particular, in case of transportation network, various factors such as cost, time, and service should be considered simultaneously. Because of this, it is more difficult to generate an optimal alternative fit to all the users.

These characteristics are well revealed in the user's requirements survey. As the system in this study is a new system that has not yet developed and commercialized, we has made a thorough survey of user's requirements. The user's most common requirement is that instead of receiving a transportation network considered to be an optimal one, they want diverse alternatives as well as objective evaluation materials, so that they themselves can select the best alternative. Users judge that this method is not only useful to their business, but also makes a great contribution to the mutual relationship improvement. The objective evaluation materials for transportation network make it easy to gain access to the shippers for business, and also build confidence in the client's mind.

Meanwhile, in generating a transportation network, this study has considered a multimodal transportation network, not to mention the single transportation mode. Thanks to the appearance of containers, various kinds of transportation modes can be easily connected. In addition to this, automation in cargo handling has brought the rapid development of multimodal transportation network, which enables the linkage of diverse modes of transportation by land, sea, and air (Kim and Cheong, 2003). In particular, recently customers request a door-to-door delivery service. Therefore, to make a response to customer's demand, 3PL has to perform multi-

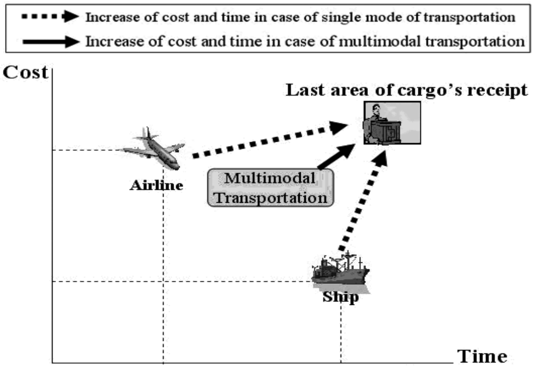

Figure 1: Necessity of multimodal transportation.

modal transportation services. Young-Tae Park (2001) said that the most important characteristics of leading 3PL companies in the USA and Europe are the diversification of their logistics services, and expansion of service areas in their efforts to take the lead in competing globally. This means the necessity of multimodal transportation. However, in reality, most domestic 3PL's are making their transportation network planning, depending upon "Shipping Gazette," "Schedule Bank," and other schedule materials provided by shipping companies or airlines. But those materials include the schedule for only single mode of transportation, not for multimodal transportation. Therefore, it is very difficult to prepare multimodal transportation network planning. For example, sea transportation costs less, but takes longer. Air transportation costs more, but takes shorter. If a customer requests a mid-level service of sea transport and air transport, the 3PL will have to provide a multimodal transportation service. As shown in the Figure 1, by using a multimodal transportation service, cargo delivery can be made faster than sea transportation, and cheaper than air transportation. In conclusion, in dealing with the problem of transportation network planning, this study is characterized by the adoption of a decision support system approach and transportation network planning based on multimodal transport.

DECISION SUPPORT SYSTEM FOR AN OPTIMAL TRANSPORTATION NETWORK PLANNING

System Structure

Our new system TNPS (Transportation Network Planning System) enables 3PL companies to consider transportation mode, routing, assignment, and scheduling comprehensively, so that its client can select an optimal transportation network by means of reciprocal action with the system. The system selects the proper transportation mode on the bases of the feature of customer's cargo, taking into consideration multimodal transportation in addition to single mode of transportation. When presenting to the customer all the possible transportation network, it suggests only available ones after considering all the schedules comprehensively. In addition, the time and cost of all the transportation networks are automatically calculated, thus making it possible to assign customer's cargo efficiently.

Figure 2 shows the structure of the whole system of TNPS. This system is composed of five modules: cargo information management, transportation network generation, transportation network management, transportation network evaluation, and statistical information generation. The cargo information management module is to receive and manage information, the transportation network generation module is to generate all available transportation networks, and the transportation network management module enables a customer to search, align, compare, and analyze all the available transportation networks generated. That is, based on the route, cost, time, and transportation mode that the customer wants, this module enables him to select an optimal network. The next step is to evaluate the transportation networks selected by the customer. In this stage, the customer can evaluate all the transportation networks generated or only the transportation network that he has selected. The transportation network evaluation module is to do the evaluation function. For evaluation, this study has used both the evaluation by mathematical model and evaluation by MADM (Multi Attribute Decision Making) methodology. Finally, the statistical information generation module is to use all the information accumulated from the usage of the system over a long period of time and to generate diverse statistical information.

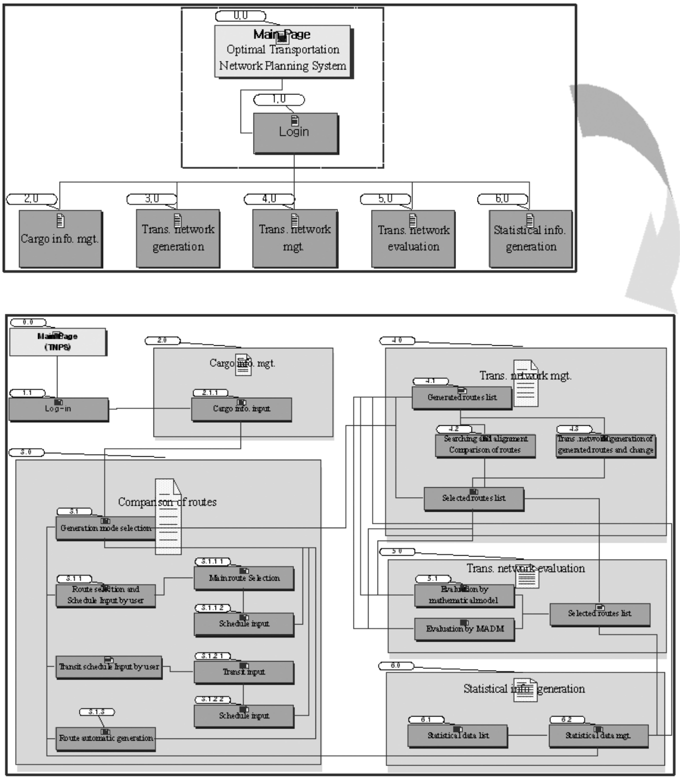

Figure 2:
Structure of
TNPS

If a lot of customers use this system over a long period of time, the statistical information such as the usage situation of many transportation networks and transportation network selection situation based on cargo type can be accumulated and generated. And these data can be useful information on international transportation market situation. Among these five modules of TNPS, the critical ones are the transportation network generation and the transportation network evaluation. It is because the key functions of TNPS are to generate the transportation network for customer's cargo delivery and to provide a customer with the evaluation information on the generated networks.

Transportation Network Generation

In generating the transportation network for customer's cargo, TNPS can provide a variety of methods according to the degree of expertise on transportation network planning. This idea has come from the user's survey. According to the survey, most users have wanted diverse functions suitable to the user's level instead of a one-sided function. Considering user's requirements, TNPS has adopted the following three methods to generate the transportation networks: transit place and schedule determination mode, schedule determination mode by route, and automatic generation mode.

If a user has much knowledge and experiences on transportation network planning, so that he knows about the transit places and routes of the cargo delivery, or if a customer requires a specified transit place, then the transit place and schedule determination mode are to be used. As illustrated in the Figure 3, the user can search and select the transit place he wants in the upper side of the screen, and then if he selects the schedule of the corresponding transit place, the transportation networks are to be generated as shown in the lower right side of the screen.

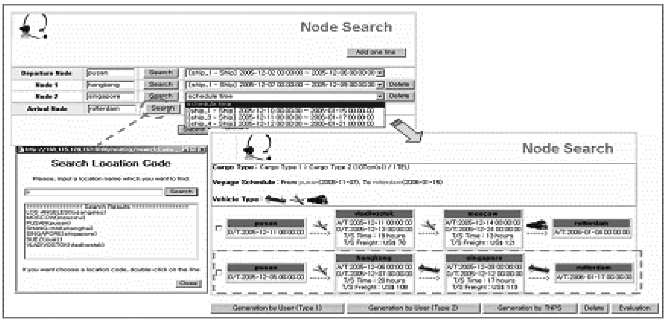

Figure 3: Transit place and schedule determination mode

The schedule determination mode by route can be used for the user who has not enough knowledge and experiences but has some knowledge of transportation routes. In this case, as illustrated in the upper left side of the screen of below Figure 4, the routes for cargo transportation are to be automatically generated, and the user can select one of them to find out available schedules. If he selects the schedule he wants, he can gain the transportation network as shown in the lower part of the screen. Of course, the user can select multiple routes and ensuing schedules.

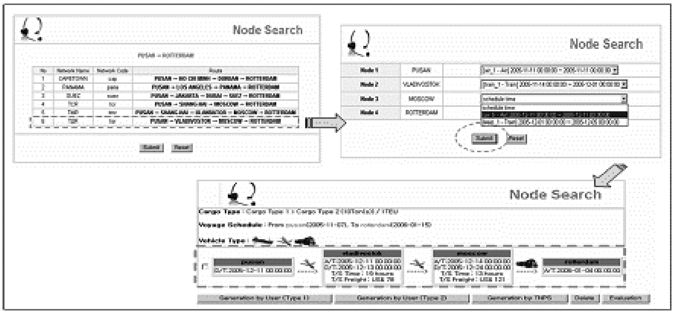

Figure 4: Schedule determination mode by route.

Finally, the automatic generation mode is to be used for a beginner who has little knowledge and experiences. Based on only cargo information, he can generate all possible transportation networks from the system. Figure 5 shows the process of automatic transportation network generation from the system. However, as this system is to consider multimodal transportation network, the user, first of all, has to judge which transportation mode is possible for the customer's cargo. By using "if-then" pattern knowledge, the user can select all possible transportation modes, and based on this, transportation networks are automatically generated. In case that the weight and size of cargo is too heavy and too big, it is not suitable to air transportation. Accordingly, air transportation is automatically dropped out from the available transportation network generation.

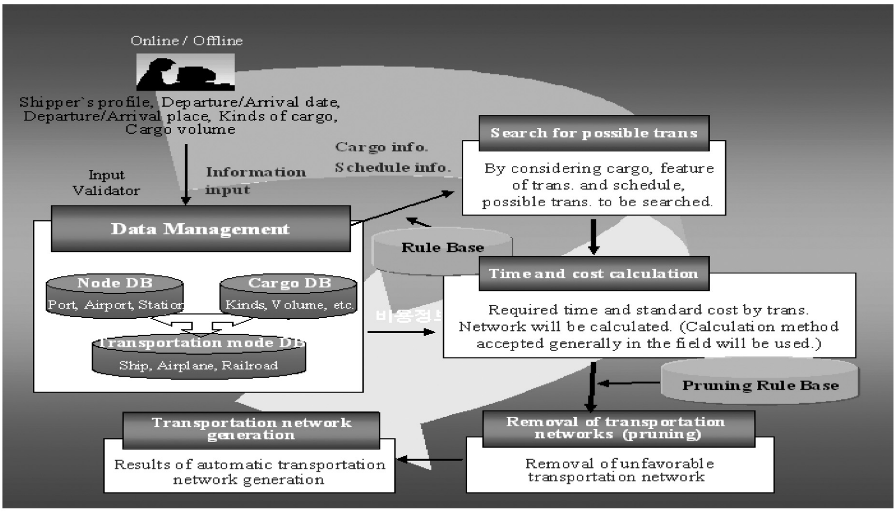

Figure 5: Process of automatic transportation network generation.

The time and cost for generated transportation networks is to be calculated automatically, and cost accounting has been based on the calculation method generally accepted in the field. For instance, in case of sea transportation, the following formula has been used:

(Number of containers x rates*) + surcharge (oil, currency, etc.) + incidental expenses
* Rates: freight by area (ex: North America – US$1,300 per 20ft.)

The transportation networks generated based on the cargo information alone can include some unreasonable transportation networks. Therefore, these kinds of networks are required to be removed. For this purpose, this study has introduced the pruning rule. That is, by using the pruning rule, the unfavorable transportation networks and schedules in terms of cost and time can be eliminated. The pruning rule adopted in this study is as follows:

If there are two arcs of "k" and "l" in one node (n), the transport cost (C) and transport time (T) comprise of one pair (C_n^k, T_n^k) and (C_n^l, T_n^l). Also, if one is in a dominant position, the other arc will be eliminated by the pruning rules. The pruning rules are as follows.

— *Rule 1.* The arc with a higher cost and time in one node will be eliminated.

If $C_n^l > C_n^k \;\; and \;\; T_n^l > T_n^k$, (C_n^l, T_n^l) is eliminated by (C_n^k, T_n^k)

— *Rule 2.* If the cost of both arcs is the same in one node, but the time taken is different, then, the arc with the longer time is eliminated. Also, if the time taken is the same, but their cost is different, the higher cost arc is to be eliminated.

If $(C_n^l = C_n^k \;\; and \;\; T_n^l > T_n^k) \;\; or \;\; (T_n^l = T_n^k \;\; and \;\; C_n^l > C_n^k)$,
(C_n^l, T_n^l) is eliminated by (C_n^k, T_n^k)

— *Rule 3.* If an arc in a node has an arrival date later than the latest departure date, it is to be eliminated.

$$\max(S_n^{\delta^+}) < (A_n^{\delta^-})$$

If there is a departure arc (δ^+) and arrival arc (δ^-) in a node, and the departure time of the departure arc is represented as $S_n^{\delta+}$, and the arrival time of the arrival arc is represented as $A_n^{\delta-}$, the arc $A_n^{\delta-}$ is larger than the maximum value of $S_n^{\delta+}$ so it is to be eliminated.

Transportation Network Evaluation

In order to evaluate the generated transportation networks, TNPS has introduced two kinds of evaluation methods – evaluation by mathematical model and evaluation by MADM methodology. Time and Cost is the two critical factors in evaluating the transportation networks. In this case, if the user selects the network that he wants based on a single factor, it is not difficult. What he has to do is put the networks in order. But if he has to integratively consider the two factors – time and cost, or if he has to consider additionally the service factors such as port service level and agent's capacity, he needs an additionally evaluation method. In this study, we haves adopted an algorithm for integrative consideration of time and cost, and an MADM for evaluating other factors including a service.

As illustrated in the below Figure 6, the effective area in the shade can be drawn as a way of considering time and cost integratively. The solutions in the effective area can be alternatives for an optimal transportation network. That is, the Pareto solution, an optimal transportation network, can be found in the effective area.

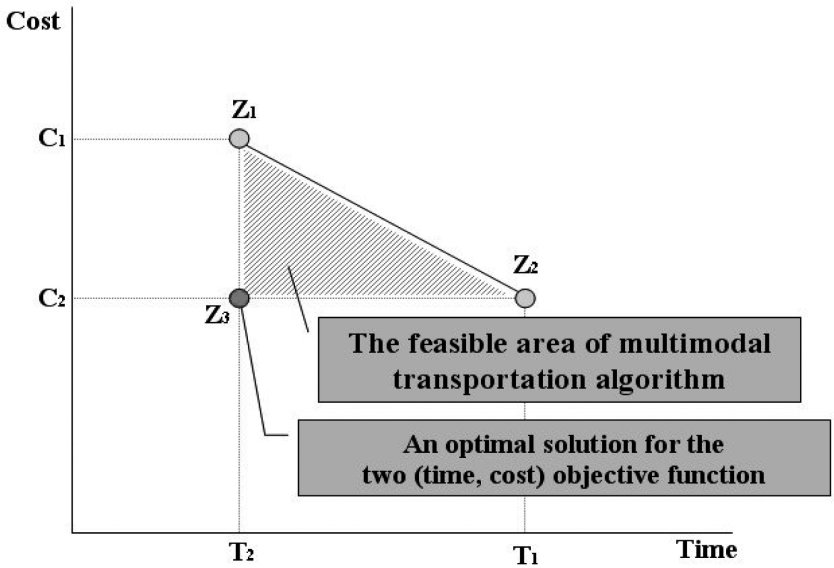

Figure 6: Effective area of mathematical model.

In order to determine the effective area, the function with the goals of least cost and shortest time can be used to discover the point Z1 and Z2, and the intersection of these two points becomes Z3. Accordingly, Z3 can be an optimal solution when considering the two goals of least cost and shortest time. But this value is an infeasible solution.

$$\min \sum_{a \in A} (c_a^m \cdot q_a \cdot x_a^m + q_a \cdot lc_n^a + q_a \cdot uc_n^a) \quad \ldots(1)$$

$$\text{such that} \sum_{a \in \delta^+(i)} x_a - \sum_{a \in \delta^-(i)} x_a = \begin{cases} 1, \text{if i} = \text{s} \\ -1, \text{if i} = \text{t} \\ 0, \text{if i} \in \text{V} \setminus \{\text{s,t}\} \end{cases} \quad \forall i \in V$$

$$\sum_{a \in A} w_a x_a \le W_t$$

$$x_a \in \{0,1\} \ \forall a \in A$$

$$\min \sum_{a \in A} (t_a^m \cdot x_a^m + lt_n^a + ut_n^a) \quad \ldots(2)$$

$$\text{such that} \sum_{a \in \delta^+(i)} x_a - \sum_{a \in \delta^-(i)} x_a = \begin{cases} 1, \text{if i} = \text{s} \\ -1, \text{if i} = \text{t} \\ 0, \text{if i} \in \text{V} \setminus \{\text{s,t}\} \end{cases} \quad \forall i \in V$$

$$\sum_{a \in A} w_a x_a \le W_c$$

$$x_a \in \{0,1\} \ \forall a \in A$$

c_a^m : Transport cost of transport mode m at the arc a
x_a^m : When transported from arc a by transport mode m, 1 or 0
q_a : Quantity of Cargo at the arc a
lc_n^a : Loading cost of arc a at node n
uc_n^a : Unloading cost of arc a at node n
lt_n^a : Loading time of arc a at node n
t_a^m : Transport time of transport mode m at the arc a
lt_n^a : Loading time of arc a at node n
ut_n^a : Unloading time of arc a at node n
w_a : Constraint at the arc a
W_c : Cost constraint
W_t : Time constraint

Formula (1) is the function to seek the shortest time. It includes not only the traveling time from one node to the next node, but also the shipment time at the departing place, unloading time in the arriving place, and all the transshipment time at the transit places. Formula (2) is the function to seek the least cost. It includes both the traveling cost and loading and unloading costs at the transit places. The constraining conditions of both formula (1) and formula (2) are identical, but in the Formula (1) seeking the least cost, the constraining condition "W" is time, and in the Formula (2) seeking the shortest time, the constraining condition is a cost.

If the effective area is generated by mathematical model, then a lot of routes will be able to be generated by TNPS. Among these routes, the routes that enter the effective area belong to Pareto solution, but all the other routes out of effective area are to be eliminated. Meanwhile, as shown in the Figure 7, in order to evaluate each solution inside the effective area, the straight lines' distance from the point Z3 has been used. In evaluation, the weight of time and cost is not 1:1. It can be changed according to the user's requirements.

Figure 7 shows the results of our experiment, which takes the case of the routes between Busan port to Rotterdam port in Europe. Table 1, which is generated from the experiment, shows Pareto solutions for the evaluation of each transportation network. Among them, the shortest one is an optimal alternative. However, as time and cost have different criteria, they have to be normalized as illustrated in the Table 2.

Table 1: Results of Pareto solution

Frequency of transshipment	Pareto solution
Twice (	(18,167) (20,165) (23,152) (24,140) (27,130) (29,128) (30,120)
Three times	(21,160) (25,138)

Table 2: Normalized value of time and cost

Frequency of transshipment	Normalized Value
Twice	(0.080, 0.150), (0.090, 0.147), (0.105, 0.124), (0.110, 0.103), (0.125, 0.086), (0.135, 0.082), (0.140, 0.068)
Three times	(0.095, 0.138), (0.116, 0.100)
Z_3	(0.0, 0.0)

(x, y): x: time, y: cost

Table 2 shows the normalized value of each alternative and arbitrary optimal solution Z3. But as time and cost have different sizes, their relative distribution has been described as the values between "0" and "1". Table 3 illustrates the results of the evaluation on each Pareto alternative based on these values.

Table 3: Results of evaluation by mathematical model

Frequency of transshipment	Pareto solution	Distance to Z_3
2 times	(18,167)	0.0289
	(20,165)	0.0297
	(23,152)	0.0264
	(24,140)	**0.0227**
	(27,130)	0.0230
	(29,128)	0.0249
	(30,120)	0.0242
3 times	(21,160)	0.0280
	(25,138)	0.0255

Table 3 shows that the alternative with the value (24,140) is an optimal transportation network.

Secondly, the MADM has been introduced to evaluate the other factors such as port service and transporter's service except time factor and cost factor. MADM is usually used as a decision-making method in case that there are many factors to be considered. Because diverse factors with different criteria have to be evaluated, first of all, those factors have to be normalized for comparison on the basis of the same rule. Also, subjective weight among the evaluation items can be given to find out the opti-

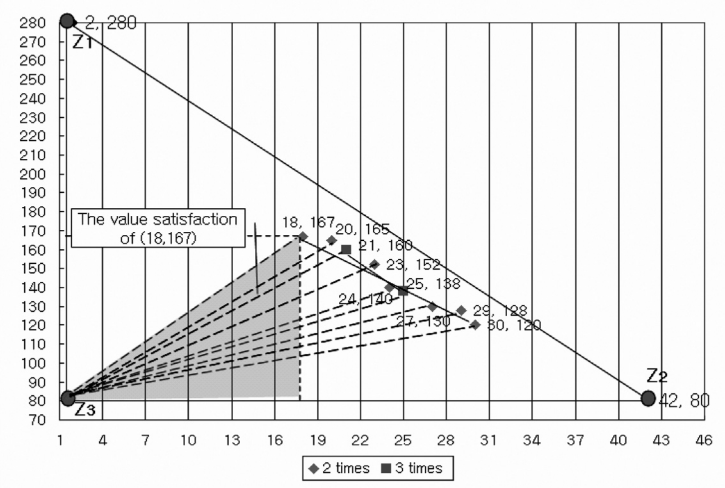

Figure 7: Generation of an optimal solution by mathematical model.

mal alternative that the user wants. In particular, in case of extraordinary cargo transportation, not a routine transportation, the service factors including transporter's capacity have to be considered comprehensively. The evaluation by MADM has been performed as shown in the Figure 8. First, the evaluation items such as cost, time, and service have been normalized. Then by using entropy method, the weight of each item has been given to each item, and also the user's subjective weight has to be given.

The evaluation of transportation networks may be able to be continued. If the user changes his conditions and weight to have another alternative, the evaluation for a new alternative can be made again. This means that the system doesn't deter-

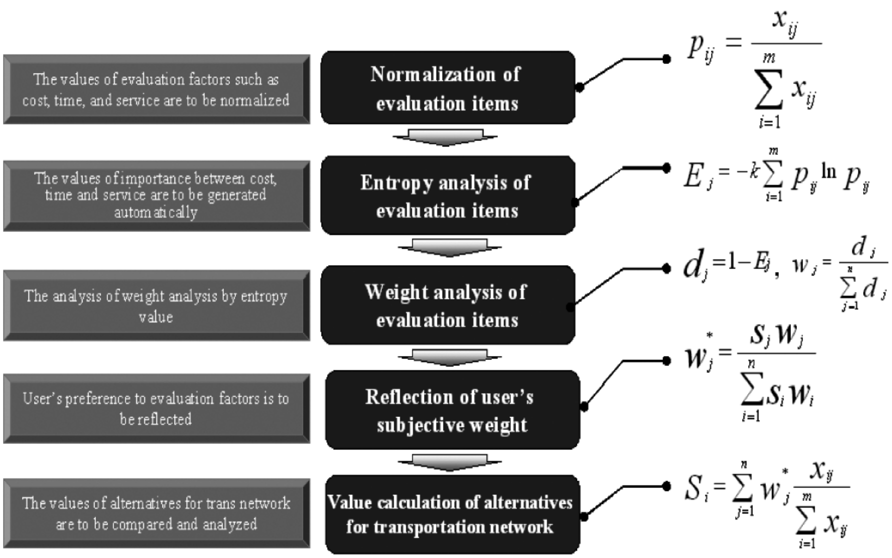

Figure 8: Process of MADM.

mine an optimal transportation network, but by means of mutual cooperation between a user and a system, an optimal network can be found.

Experiments on MADM-based evaluation have been made based on the same data used in the evaluation by mathematical model. Also the evaluation materials on the service level have been taken into consideration. Based on the service level-related data, which have been used by 3PL companies and forwarders over the years, along with the interviews with persons in charge in the field, virtual values have been calculated and applied to the evaluation by MADM. The results of evaluation by MADM are shown in the following Table 4.

Frequency of transshipment	Pareto solution	Results of evaluation by MADM
2	(18,167,5)	0.118
	(20,165,5)	0.109
	(23,152,4)	0.103
	(24,140,4)	0.121
	(27,130,5)	**0.135**
	(29,128,3)	0.100
	(30,120,3)	0.110
3	(21,160,5)	0.113
	(25,138,2)	0.090

Table 4: Results of evaluation by MADM

The evaluation by MADM has shown a different result compared with the evaluation by a mathematical model. In this evaluation by MADA, its value of 0.135 has generated the Pareto solution of (27,130.5), which is considered to be an optimal transportation network. Since a lot of factors such as cost, time, and service influence user's transportation networks, the optimal network can be changed according to the user's priority placed on those factors. In other words, an optimal transportation network cannot be presented by an algorithm, but it can be changed by user's priority. The TNPS developed in this study can effectively satisfy user's requirements.

CASE STUDY

In order to test the validity and practicality of the TNPS, this study has performed a case study in which we have suggested a virtual case of cargo transportation to the person in charge of transportation network planning in the frontline, asking him to make an actual transportation network planning based on the suggested case. For instance, suppose 3PL "A" is in charge of international cargo transportation of the shipper "B", and B's I TEU of container cargo is to be transported from Busan port to Rotterdam port of the Netherlands between November 7, 2005 and December 26, 2005. For this case, by using TNPS, the user has made transportation network planning as follows.

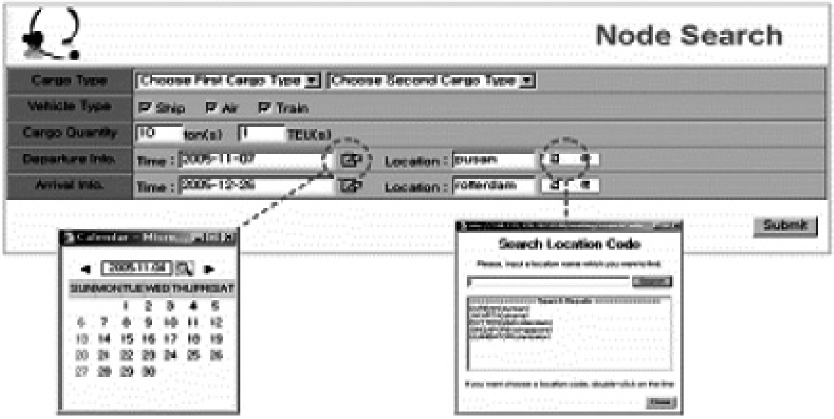

Figure 9: Cargo information input interface.

Step 2: Transportation Network Generation

The user generates some transportation networks by using the automatic generation mode. Instead of selecting by himself, the user has wanted TNPS to automatically generate diverse transportation networks.

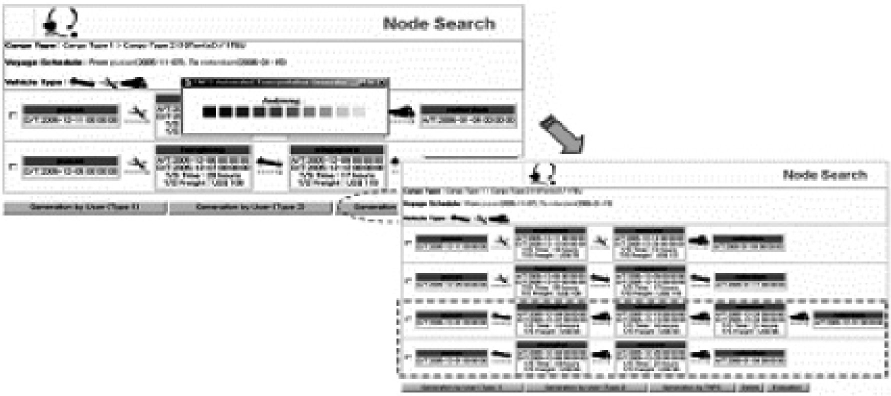

Figure 10: Automatic generation screen interface.

Step 3: Transportation Network Evaluation

The generated transportation networks have been evaluated by a mathematical model and by an MADM methodology. Both the evaluation in terms of time and cost and the evaluation including service have been performed for comparative analysis.

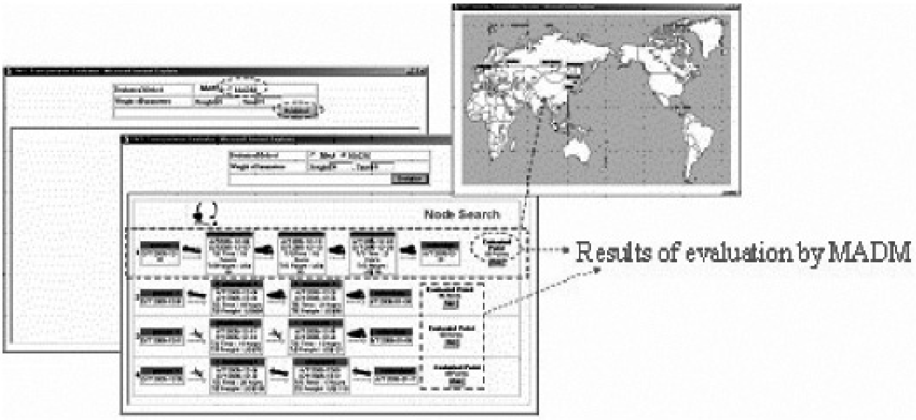

Figure 11: MADM-based evaluation process and its results.

Step 4: Transportation Network Selection

In case of considering time alone, in case of considering cost alone, and in case of using both evaluation methods: mathematical model and MADM, the three cases have been compared and analyzed, and as a result the following transportation network has been selected as shown in the Figure 12.

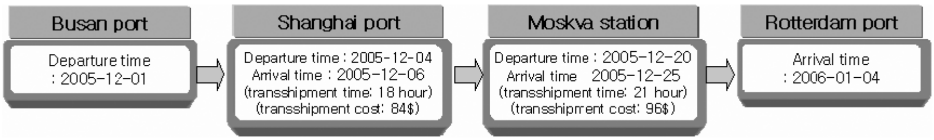

Figure 12: Selected schedule.77

The transportation network selected by the user is the best one when both cost and time have been considered integratively. The user, who works for a small freight forwarding company, has given more priority to time and cost rather than to service. Meanwhile, in order to raise the validity of our case study, and to find out common requirements of much more users, our case study has covered more persons and more companies. That is, 15 persons and 5 companies have been participated in the case study to upgrade the validity and practicality of TNPS. By using the five-point scale, a user satisfaction test has been conducted in terms of the following five aspects: performance results, decision-supporting function, database, handling speed, and practicality.

As illustrated in the Figure 13, the results of the user satisfaction tests is presented in percentage, indicating that most users are showing the satisfaction degree of

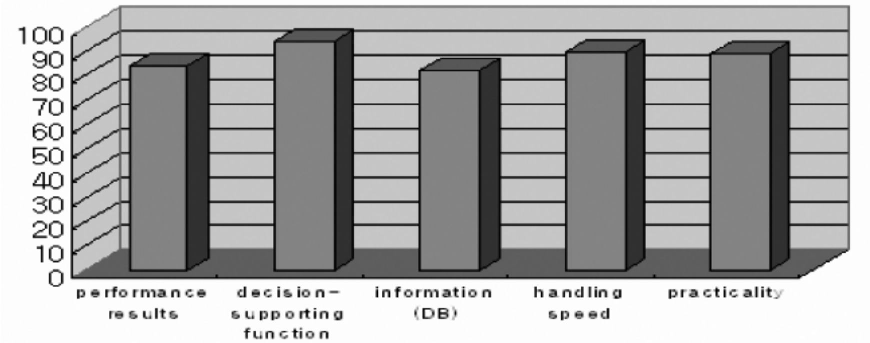

Figure 13: Results of user satisfaction tests.

more than 80% in all aspects of the test items. In particular, the decision-supporting function has shown the highest degree of satisfaction. Handling speed and practicality are showing relatively higher satisfaction, but performance results and database were relatively lower. The reason is that the developed prototype has some degree of limits, and so the results have not shown exceptional things. In fact, the prototype developed for a test has not yet contained enough exceptional information on individual routes, but has some information only on European routes. However, later on users have come to know that the main purpose of TNPS is to help efficiently transportation network planning, not to deal with exceptional things. Furthermore, users have expressed high expectations that TNPS is likely to quantitatively bring on not only profits and cost saving, but also the improvement of job process and job efficiency qualitatively.

CONCLUSION

Focusing on enhancing the competitiveness of third party logistics companies, this study has developed a TNPS. This new system is a decision supporting system that enables 3PL to deliver customer's cargo through an optimal transportation network planning.

Recently, in order to activate 3PL, a lot of efforts are being made emphasizing the importance of offering new logistics services and development of information system. TNPS is a completely new system. There is some decision supporting system for an optimal transportation network planning only within a restricted area. But there is no such system for multimodal transportation on a global basis. In particular, TNPS is not only providing new services but also presenting to the shippers objective evaluation materials on transportation networks, so that customers will be able to put trust in the 3PL. Also by using these materials, 3PS companies will be able to conduct more aggressive marketing activities, eventually bringing a symbiotic effect on both 3PL's and customers. Moreover, it is expected that TNPS will bring job efficiency and cost saving to the 3PL's.

More importantly, in dealing with the problem of an optimal transportation network planning, this study has focused on developing decision supporting system for users, rather than generating an optimal alternative proposal. That is to say, this study has suggested a new approach to find out an optimal alternative proposal. This study judges that what users want is not an optimal proposal suggested by a system, but the decision-supporting materials that enable them to select an optimal alternative.

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THE BALTIC SEA MOTORWAY - RECENT DEVELOPMENT AND OUTLOOK FOR THE FUTURE

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ABSTRACT

The Council of the European Union adopted a political agreement in the summer of 2004 on a common position concerning the new TEN Guidelines proposed by the Commission. These Guidelines introduced the concept of the Motorways of the Sea. Currently, there are four sea motorways in Europe, one of which is the Baltic Sea Motorway. The countries in the northern Baltic Sea area, such as Finland, are faced with long transport distance to Central Europe and seasonal ice coverage of the Baltic Sea. The concept of the Baltic Sea Motorway including land transport feeder connections provides an efficient maritime link and transport chain for the Baltic countries, promotes the internal cohesion of the Baltic Sea region to the core areas of the European Community and reduces high transport costs. The sea motorways have a priority project status just like the land transport connections of particular importance for the European Union. According to the TEN-Guidelines, there are two types of Sea Motorway projects. Horizontal projects, in which the benefits are not only allocated to particular ports (for example ice-breaking, the Baltic information systems etc.) and port-to-port -projects, which aim at providing opportunities for long multimodal transport chains between member countries.

Key words: Motorways of the Sea, Trans-European transport networks, Maritime link, Logistic chain.

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INTRODUCTION

The concept “Motorways of the Sea” was first introduced in the White Paper on European Transport Policy for 2010. According to the “White Paper”, sea transport is not just a means of carrying goods from one continent to another; but it is a real competitive alternative to land transport. For this reason, certain shipping links should be made part of the trans-European transport network, just like motorways or railways, in an effort to reduce road congestion and/or improve access to peripheral and island regions and countries (European Commission, 2001).

The Council of the European Union adopted a political agreement in the summer of 2004 on a common position concerning the new TEN-Guidelines proposed by the Commission in October 2003. According to the TEN-Guidelines, the Motorways of the Sea are one of the 30 priority projects in the development of the EU transport network. In addition to land transport connections, also sea connections, or “the Motorways of the Sea”, are now included in the TEN-network. This enables the logistic connection of land transport priority projects to each other which will contribute to the improvement of the overall efficiency of EU transport network operations. This is important especially to countries like Finland, as the previous TEN-system did not have tools to handle the accessibility problem or to improve connections from peripheral countries to the main market areas of the EU (European Commission, 2004).

The Motorways of the Sea are different than other transport priority projects. The “rules” of the Motorways of the Sea have been described in the Article 12a of the TEN-guidelines. Basically, the TEN-Guidelines give three main objectives for the sea motorways: (1) freight flow concentration on sea-based logistical routes, (2) increasing cohesion, (3) reducing road congestion through modal shift (Figure 1).

The sea motorways have a priority project status just like the land transport connections of particular importance for the European Union. According to the TEN-Guidelines, there are two types of Sea Motorway projects (European Commission, 2005):

- — Horizontal projects, in which the benefits are not only allocated to particular ports (for example icebreaking, information systems, development of rescue operations etc.)
- — Port-to-port -projects, which aim at providing opportunities for long multimodal transport chains between member countries.

Financial support can be applied from the Commission to the Motorways of the Sea projects. To be eligible for the higher funding rate of 20 %, the proposed project must be of common interest of the trans-European network of motorways of the sea (part of a Motorway of the Sea corridor). The network shall consist of facilities and infrastructure concerning at least two ports in two different member countries. Finally, the Motorways of the Sea should not exclude the combined transport of persons and goods, provided that freight transport is dominant (European Commission, 2005).

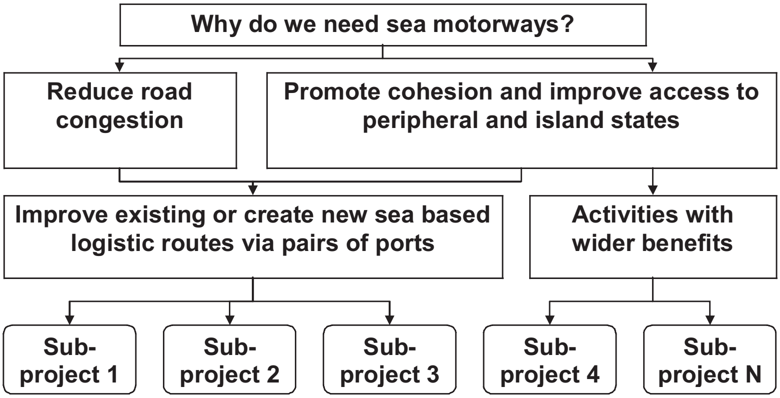


Figure 1. Basis for the development of concrete sea motorway projects.

The European Commission decided to establish a High Level Group in 2004 on the *"Extension of the major trans-European transport axes to the neighbouring countries and regions"*. This Group acknowledged that maritime transport plays a crucial role in freight traffic between the EU and the neighbouring countries. Therefore, the Group paid particular attention to actions related to the improvement of the organisation of intermodal freight transport, particularly in the context of the implementation of the Motorways of the Sea concept. Furthermore, the Group identified the extension of the Motorways of the Sea of the EU to all the sea regions (Atlantic, Baltic, Barents, Mediterranean, Black and Caspian Seas) as a priority for transport facilitation between the EU and the neighbouring regions (High Level Group of the European Commission, 2005).

SPECIAL FEATURES OF THE BALTIC SEA REGION

Since May 2004, eight out of the ten countries in the Baltic Sea Region are members of the European Union. The Baltic Sea has nearly become an inland sea of the EU and Russia is the only non-member of the EU which is located along the coastline of the Baltic Sea. Still, the Baltic Sea Region is fragmented with huge economic and social disparities, both in terms of growth and stability. The positive effect of the EU enlargement, which is reflected in increasing trade between the eastern Baltic Sea region and western (northern) Europe, does not automatically mean increasing freight volumes for all transport modes. Maritime transport capacities have been underutilised, even though the potential is huge and transport capacity is virtually unlimited. More competitive and integrated maritime transport is an important objective (Task Force of the Baltic Sea Motorway and European Commission, 2006).

The countries in the northern Baltic Sea area, such as Finland, are faced with long transport distance to Central Europe and seasonal ice coverage of the Baltic Sea which disturbs maritime operations and creates a barrier to Central European markets. Demand for punctuality in transport is growing, as there is no intermediate storing, and raw materials and products are transported directly to production. Ice conditions in the Baltic Sea cause seasonal delays to the transport chain from the northern Baltic Sea area to Central and Eastern Europe. Delays in transport chains will have a negative impact on the efficiency of transport operations and accessibility to markets.

Maritime transport plays an important role in the economic development of the Baltic Sea Region. The economy of especially new member countries grows rapidly, promotes trade and creates needs for the development of transport connections. A strong increase in the demand for transport is forecasted and a corresponding response from the shipping industry leading to more and bigger vessels calling in the ports of the Baltic Sea Region. In the transport sector, it must be taken care of that poor condition of transport connections is not a constraint to economic growth. It is obviously important in the Baltic countries to develop smooth multimodal transport chains between the member countries. The concept of the Motorways of the Sea provides good preconditions for the development of a logistics system connecting the Baltic Sea countries and their hinterland (Task Force of the Baltic Sea Motorway and European Commission, 2006).

The Baltic Sea area has many existing maritime links and the focus of the sea motorways is on the development of transport chains based on these links rather than on the creation of new links. In these circumstances, special attention must be paid to the question of distortion of competition (Task Force of the Baltic Sea Motorway and European Commission, 2006).

CONCEPT OF THE BALTIC SEA MOTORWAY

The Baltic Sea countries have been active in the concretisation of the sea motorway concept. The Baltic Sea Motorway Task Force was established in the year 2004 consisting of all the Baltic Sea countries and the European Commission. The Task Force coordinates the development of the Baltic Sea Motorway by, for example, declaring common statements, exchanging information and initiating various development actions. The Task Force has five informal sub-groups which concentrate their actions on infrastructure, icebreaking, financing, safety and security as well as information motorways. The Task Force has been chaired by Finland until the autumn of 2005. Hence, the chairmanship will be circulated every year and the Task Force is chaired by Sweden in the year 2006.

The assignment of the Task Force has been divided into two main sectors: promoting horizontal projects and developing of the concept of port-to-port projects. The infrastructure sub-group of the Task Force has e.g. prepared a list of infrastructure titles which could be part of a "physical" sea motorway project and for which TEN financial aid could be applied for.

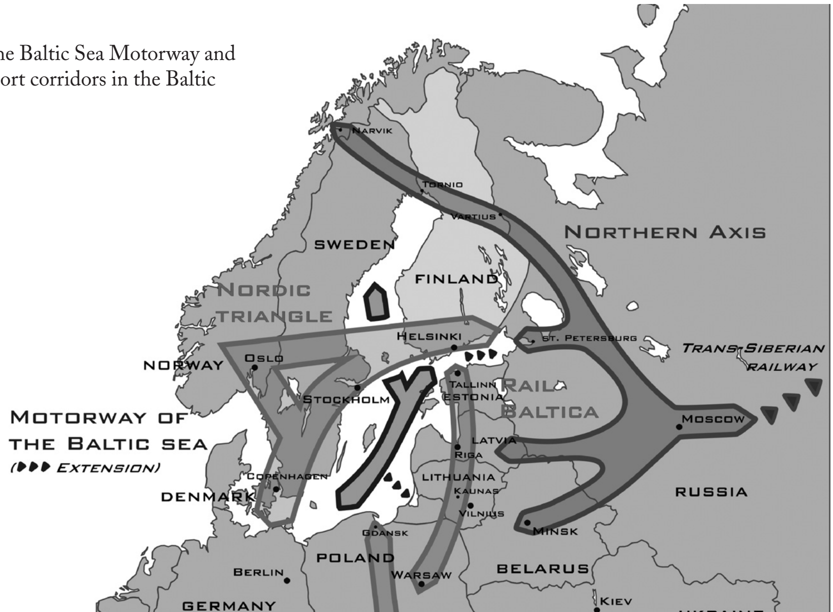
The impact area of every sea motorway project is, however, wider than the area in the immediate vicinity of ports. These projects should always be based on a "logistic idea" of developing a long transport chain between member countries. It is essential that the network of the trans-European transport corridors and the Baltic Sea Motorway will be connected to logistics systems which support each other (Figure 2).

HORIZONTAL PROJECTS

The horizontal projects of the Motorways of the Baltic Sea are mainly organized under the project "Master Plan Studies for the Development of the Motorways of the Baltic Sea" which is co-financed by the EU (Task Force of the Baltic Sea Motorway, 2005).

This package of studies is a result of the work of the Baltic Sea Motorway Task Force and its sub-groups and the study has been prepared in close cooperation with the Baltic Sea countries. The Master Plan study is managed by the Swedish Maritime Administration.

Figure 2. The Baltic Sea Motorway and main transport corridors in the Baltic Sea region.



The development of the Motorways of the Baltic Sea is a long-term joint task for the Baltic Sea countries. The main objective is to develop a framework which will provide a basis for further and more detailed planning of the Motorways of the Sea concept for the Baltic Sea region. The "Master Plan" project is currently divided into the following four sub-projects (Task Force of the Baltic Sea Motorway, 2005).

Study on goods flows and maritime infrastructure

The study aims at contributing to increased knowledge of the current situation of goods flows and maritime infrastructure as well as the likely future development and demand of maritime transport in the Baltic Sea region. The study will target both the intra-regional and extra-regional dimension of trade and transport. This is necessary for the further development of transport policies, infrastructure planning and other joint actions in the Baltic Sea region. This study has been completed in the spring of the year 2006.

Baltic Sea Winter Motorways

A well-functioning, all-year maritime traffic in the Baltic Sea is of high importance not only for the Baltic Sea countries, but for the transport system of the EU as a whole. A strategy to achieve this is by enhancing the strategic and operational cooperation between the Baltic Sea countries within the area of assistance to winter navigation. The icebreaking cooperation is one such area, in which a joint approach will give added value and improve winter navigation in the region. The long-term strategic vision is to develop a joint Baltic Icebreaking Service.

Safe major routes of the Motorways of the Baltic Sea

Existing hydrographic survey data in the Baltic Sea is not sufficient. Quality assurance by re-surveys of the main routes on the Motorway of the Baltic Sea has already been deemed necessary and a scheme is developed and approved by the IHO Baltic Sea Hydrographic Commission. Reliable surveyed routes and extended areas allow safe icebreaking operations also in heavy ice conditions.

North Sea Baltic Hub

There is a need to improve the supply of interregional and intermodal transport service within the North Sea and Baltic Sea regions, as interregional trade is expected to grow. The rapidly increasing containerised trade also requires improved supply of maritime services. The aim of this subproject is to create a basis for commercial as well as political decisions, fostering the development of a North Sea Baltic Hub.

New elements to be added to the package of Master Plan studies will be considered in the upcoming calls for proposals for TEN financial aid. For example, the so-called information motorways have been in discussion.

PORT-TO-PORT PROJECTS

The goal of port-to-port projects is to interconnect land transport connections of the TEN-network in order to develop multimodal transport chains between the member countries and neighbouring countries of the EU. Port-to-port projects are very challenging due to the participation of numerous stakeholders in the development of them (Figure 3). All participants should benefit from their participation.

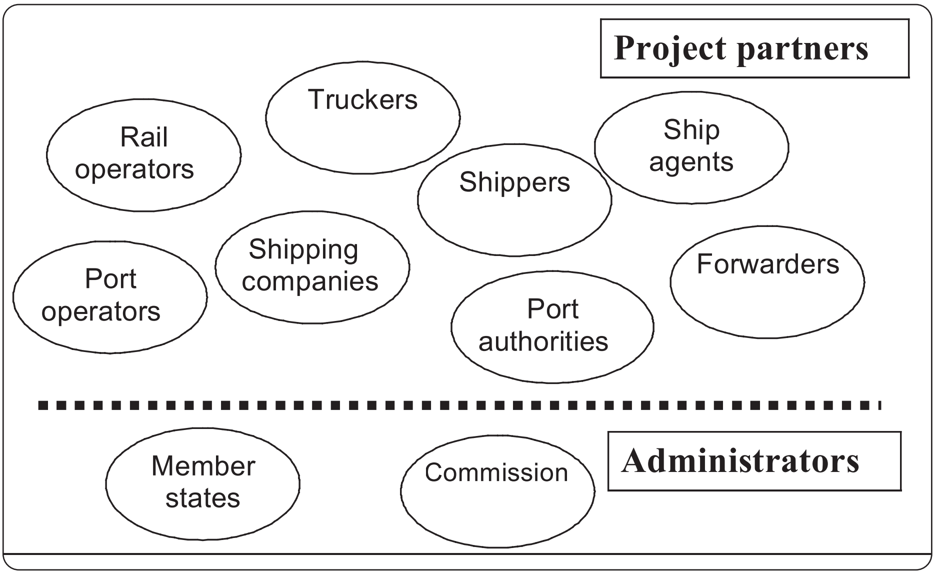


Figure 3.Different stakeholders in the development of port-to-port projects of the Motorways of the Sea.

The possible conflicts between stakeholders include, for example, different political cultures and priorities in infrastructure development, distortion of competition as well as balancing between the requirements of the EU Commission and project proposals of partners and competition between project partners.

A typical transport chain, for example from Finland to Central and Eastern Europe, involves feeder transport by rail or road to a port, sea transport over a long distance to a European port and a delivery transport from this port by rail or road to the destination possibly across national borders. Figure 4 illustrates costs in this transport chain.

The average logistics costs for example in Finland are 2-3 times higher than in Central European countries. Decreasing these costs improves the competitiveness of a transport chain including a maritime link. Identification of the “bottlenecks” of this transport chain especially with regard to hinterland connections, port infrastructure, information systems as well as customs and administrative procedures constitutes the basis for development projects and measures. On the other hand, the Baltic Sea is also an opportunity which must be utilized by Finland. Sea transport is economical and sustainable.

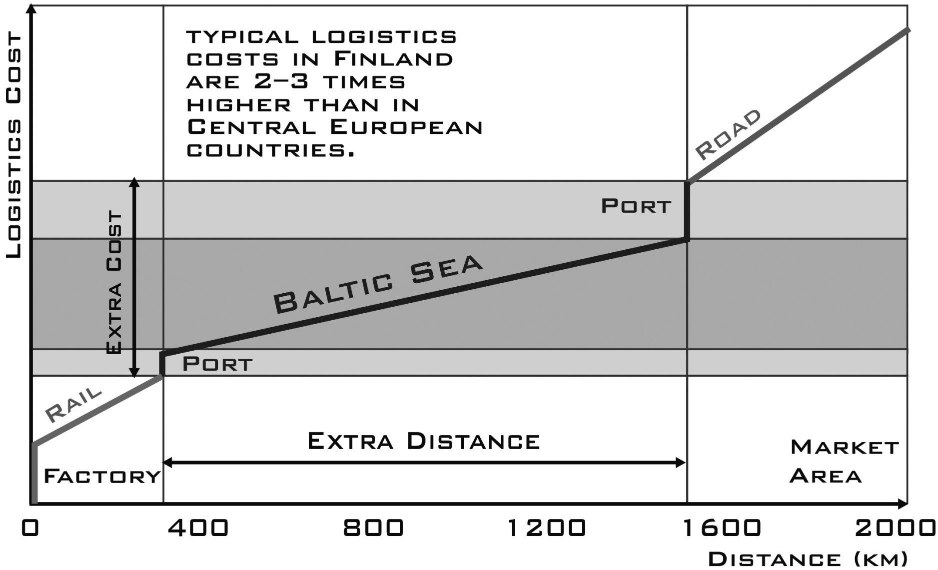


Figure 4. Typical transport chain and logistics costs in freight transport on the Baltic Sea Motorway between Finland and Central Europe.

Finland cannot change its geographical location, but given its peripheral location in the EU, it is better to be separated from the main market areas by sea than a mountainous region.

Finland and Germany have opened a call for proposals procedure in this spring to enable a structured way for development and evaluation of mature sea motorway projects. The goal set by the Ministries of Finland and Germany of preparing the project proposals is to implement land and sea transport chains through the ports of these two countries. Partners from other countries can also participate in these projects provided that the Ministries of these countries have publicly announced about this opportunity. There has been great interest for the call for proposals. Projects approved by the procedure are eligible for funding in the upcoming calls for proposals for TEN financial aid.

CONCLUSIONS

As the initiative of the Motorways of the Sea will be developed further, the following issues are essential in the success of the project:

It should be recognized that the four defined motorway corridors in the EU are quite different. Certain preset goals can be easily achieved in the Mediterranean Sea but not in the Baltic Sea, and vice versa. To give an example, the Baltic Sea has numerous sea connections, and thus the focus of development is in making the existing sea connections more efficient and connecting them as part of a multimodal logistics chain of land and sea transport.

The Motorways of the Sea are not a synonym for short sea shipping. Short sea shipping already exists, but the Motorways of the Sea should provide additional value in order to deserve their existence. This additional value is brought by the fact that the Motorways of the Sea are one of the 30 priority projects in the TEN-network of the EU and they interconnect the priority projects of land transport. This is especially important in peripheral countries, such as Finland, which have to overcome long-distance sea connections to reach the central market areas of the EU. Through the concept of the Motorways of the Sea, the system trans-European transport networks have a "tool" for solving this problem of market accessibility.

According to the TEN-guidelines, there are two types of projects of the Motorways of the Sea. The purpose of port-to-port projects is to develop multimodal transport chains between at least two member countries of the EU. Main attention has so far been paid to these port-to-port projects.

According to the TEN-guidelines, there can also be projects with wider benefits not linked to specific ports. For example, icebreaking is a good example of these *horizontal projects*. It can also be a question of alleviating the administrative burden of sea transport or developing an information system encompassing the entire sea region. These horizontal projects have great potential and they deserve more attention in further development of the concept of the Motorways of the Sea.

Port-to port projects are very challenging due to the large number of actors involved in them. It should be noted that all parties participating in these projects should benefit from their participation. Benefit for a certain party is often a disadvantage to another party. Especially in the circumstances of the Baltic Sea, which has numerous existing sea links, the question of distortion of competition requires a lot of attention. The role of Ministries and actors in the market should also be clarified. The Ministries can provide a general framework and set goals of development, but they should not get too much involved in single projects. A bottom-up -approach is the best way of developing concrete projects. Projects should be based on realistic estimates of transport volumes and create permanent and economically feasible transport chains.

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THE INLAND NAVIGATION IN EUROPE: BASIC FACTS, ADVANTAGES AND DISADVANTAGES

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Abstract

The inland waterway cargo transport in Europe is very competitive in relation to other, surface types of transport. Compositions of pushed barges can generate more ton-kilometers per distance unit then any other type of surface transport. Only pipeline transportation is more cost-effective than inland navigation, but it also has certain disadvantages like volume of investment, capability of only one type of liquid cargo (mostly crude oil), need for the flow to be always constant and to correspond to the full nominal capacity and travel conditions that reduce its flexibility. The development of this type of traffic in Europe was not satisfactory since its share according to traffic modal split was decreasing in the course of the last decades as a result of very rapid development of the road transportation. Circulation volume in tons on the inland waterways is significantly changing in very wide range from one European country to the other. It is, for example, very high in the Rhine region, while on the Danube it is app. 10 % of the possible throughput capacity of this navigable way.

This paper deals with advantages and disadvantages of the inland navigation, as well as, some specific characteristics of inland waterway cargo transport on main inland waterways in Europe.

Key Words: Inland navigation in Europe, Inland shipping, Specific characteristics of inland waterway cargo transport.

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GENERAL CONSIDERATION

Inland water transportation or inland navigation is very significant mode of cargo transportation, its role is locally significant for the passenger transportation in comparison to other inland modes. Major industries, business and service activities owe much of its survival and progress to low cost of raw materials, semi – finished products, energy, containers and other load units. Some industrial sectors may reach market only via inland waterway transport, since the other transport modes are unacceptable. For example, the construction industry, mining, forestry, metallurgy, chemical and oil industry, electrical power generation and agriculture are among those sectors that depend closely on the inland waterway transport. A large part of world industry and service rendering activities are developed on the water due to transportation and water supply at sites along navigable inland waterways. Industry was built logically where there are low transportation costs and low costs of trans-loading from self-propelled and non-self-propelled barges and vessels.

Inland waterway transportation includes the oldest and most progressive sector that has expanded from primitive vessels to highly automated pushers, which push compositions of barges loaded by tens of tones on the big rivers. Contemporary technology allows full integration of inland navigation with all inland transport modes and overseas navigation. For cargo to be transported and trans-loaded in large volumes does not require an extremely precise transportation schedule, the inland waterway transportation provides services at prices lower (by up to 30%) than the other modes of transportation. In inter-modal connection, highly cost-effective inland waterway transportation combined with faster railways and more elastic road transportation, seems to be the only solution in transport chains involving, for example, large number of containers.

The inland waterway transportation, oldest of all transport modes, depends considerably on environmental conditions like depth and width of the waterway, streams and their velocity, variation of water levels, radii of bends, maintenance and equipment of navigational aids; level of use of information and management systems; port equipment and capabilities, as well as from the market conditions. It requires relatively high investments in development of infrastructure on which quality mainly depends. By the condition of the infrastructure it is possible to observe the potential of this mode in a certain region (Radmilović, 2005).

The traffic load of the European navigable inland ways, total volume of the load divided with the total length of the navigable way in t/km shows that the highest rate of use of the navigable inland waterways is realized in Belgium, Holland and Germany. The traffic load of the Rhine is ten times higher than that of the Danube, which shows that the transportation capacities of the Danube are used extremely little (White paper, 1996; EUDET, 1999).

On the navigable inland waterways in Europe, which are open to the international traffic, the ships under foreign flags transport much larger volumes than ships with domestic flags.

BASIC FACTS INFLUENCING THE DEVELOPMENT OF THE INLAND WATERWAY TRANSPORT

Inland navigation is very competitive in relation to other inland transport modes. Pushed tow of barges can generate more ton – kilometers per distance unit than any other mode of the surface transport modes. Only pipeline transportation is more cost – effective than inland navigation, but it also has certain disadvantages like volume of investment, capability of only one type of liquid cargo (mostly crude oil and gas), need for the flow to be always constant and to correspond to the full nominal capacity and travel conditions that reduce its flexibility. All these results in transportation of the liquid cargo by inland waterways very often being more cost-effective that by the pipeline.

Advantages of the Inland Navigation

According to the data of the Economic Commission for Europe, Committee for Inland Transport of the United Nations operating from Geneva, Commission of the Transportation Ministries of the European Community Member Countries, various national associations and scientific organizations in the European countries, the advantages of the inland waterway transportation are the following ones:

1. Cost effectiveness.
2. Least consumption of the propulsion energy.
3. Least quantity of the material needed for the construction of the transportation means per ton of the transported cargo.
4. Navigational safety.
5. Environmentally most friendly type of cargo transportation.
6. Least land (soil) use.

It has to be noted that the specified advantages are interdependent and that between them multilayered relations and influences exist as well as that some advantages have to be proved when compared and quantified under real conditions in relation to other modes of the surface transport (Radmilović, 2005).

Overview of the cost effectiveness of the inland waterway transportation can be obtained through various indicators and relations. For example, group (tow) of two pushed barges of EUROPE II type with loading capacity 4400 tons is according to its transportation capacity equal to the load bearing capacity of 110 railway cars of individual capacity 40 t or 220 trucks of individual load bearing capacity of 20 t. The specific investment costs are least in inland waterway transportation, since the propulsion power of 1 kW transports on average 150 kg load by truck, 500 kg by railway and 4000 kg by the cargo ship or towboat and barge group (White paper, 1996).

The life period of the ship is 1.5 times longer than that of the railway car and over 5 times longer than that of the truck. According to German statistical data the transportation costs equivalent to 1 tkm in road transportation are € 12.15, in railway transportation are € 6.35 and in inland navigation € 1.95 (White paper, 1996).

Fifteen years experience in the operation of the navigable waterway Rhine-Main-Danube has confirmed the advantages of the inland navigation over the railway transportation. For example, the German Railways have reduced by 50 % tariffs for the transportation of grain on the Hamburg – Bamberg line as well as for the transportation of fodder on the line Hamburg – Nurnberg. The shipping company "Preumesser" charges for its services on the line Dunajvaros (Hungary) – Duisburg (Germany) on average 28.5 €/t while Austrian railway tariff the same services 71.5 €/t. Tariffs of the direct container line from the Danube ports in Austria to Hamburg and Rotterdam are 10-20 % lower than in case of railway transportation. On the Rhine the price for transportation of one TEU container on the line Strasbourg-Rotterdam/Antwerp is € 400 by inland waterways, € 917 by railway and € 800 by road (White paper, 1996).

Major economic advantage has the inland waterway transportation as compared to surface types in respect to costs of the part of infrastructure related to the use of the natural navigable waterways due to the fact that it does not burden the inland waterway traffic as in case of railway and road communications. However, on the artificial navigable waterways (channels) and channeled rivers with a large number of locks the competitiveness of the inland waterway traffic is diminished. It is anyway rarely the primary or the secondary main user in respect to intensity and significance of use of these waterways and waters those being rather the water economy, agriculture, electrical power generation etc.

The inland waterway transportation is the most economical type of traffic in respect to external and infrastructural costs. It has to be pointed out though that the evaluation of the transportation cost-effectiveness is highly dependent on the particular situation (Hilling, 1995; ECORYS Transport and METTLE, 2005; NAIADES, 2006).

The least consumption of the propulsion energy results from low needs of power in ships per unit of the transported cargo. According to the data of the USA Ministry of Transportation most economical propulsion units for the cargo transportation are large towed groups. The towed group with one liter of fuel effects on average 127.5 tkm, whereby with the same liter only 76 tkm are realized in case of railway traffic and only 23 tkm with average load by road (US Department of Transportation, 1994).

The comparison was made for the most represented, according to the load capacity, towed groups, railway compositions and road vehicles. For those transportation means the average power per cargo unit was within the following limits: 0.125 to 0.4 kW/t for inland ships, 0.588 to 1.91 for railway trains and 5.145 kW/t for road vehicles.

According to the data of the Royal Commission for Environmental Contamination Monitoring in Great Britain the use of energy per tkm according to the transport mode is as follows (Hilling, 1995):

	KJ/tkm
By air	15839
By road	2890
By rail	677
By river	423
By pipeline	168

According to the tkm made, the inland waterway transport is 1.6 times more efficient than the railway transportation and close to seven times than the road transport. Due to this the inland waterway transportation is emphasized and supported within the state energy conservation policy. The consumption of the propulsion energy in inland waterway transport depends to large extent on features and regulation of the navigable waterway because for higher velocities of the river flows larger power of the ship is needed, generally with limitation of its dimensions (draft, width and length). Similar situation is also with other transport modes where the road conditions are complex and severe.

In some cases the advantage of the railway transportation is emphasized over the inland waterway and road transport due to use of various or domestic energy sources (electrical power). However, in this case relatively high investment costs are needed for the necessary infrastructure in order that electric propulsion could be used as well as assessment of the external costs of contamination by power plants and electrical power supply implementation.

As an indicator of the competitiveness of the inland waterway transport in the intermodal transportation chains often is demonstrated the specific energy consumption per tkm, for example, for:

— Local transportation
  Truck 2.5 t (2210 Wh/tkm), truck 16 t (630 Wh/tkm);
— Long distance transportation
  Tractor with semi-trailer 38 t (300-325 Wh/tkm)
  Container river-road transportation: downstream/upstream (87-130/210-250 Wh/tkm)
  Hucke pack (240-280 Wh/tkm).

This means that in intermodal and multimodal transportation the reduction of the energy consumption on transportation chains is felt when inland navigation is included (White paper, 1996).

The least quantity of material for construction of the transportation means concerns the inland ships. They require less built-in steel per ton of the transported cargo than the railway cars, providing saving of the primary materials as well as energy and other production means. According to the USA Ministry of Transportation the barges require only 170 kg of ship construction steel per ton of the load capacity, while for the railway cars 250 kg per ton of the carrying load is needed. This is clearly reflected in the construction price of the barges and railway cars for bulk cargo, which according to USA prices have ratio of 1:3 to the advantage of the towboats (US Department of Transportation, 1994).

Navigation safety on the inland waterways is extremely high, which is partially result of relatively low traffic density as compared with other surface types. Accidents, causing major damages or injury of persons, are rare in the inland waterway traffic. This advantage is of particular significance for the transportation of hazardous cargo, when the transportation involves large annual quantities.

Environmentally friendliest type of cargo transportation is the inland waterway traffic as cleanest type of traffic which helps improve the quality of human life, flora and fauna.

The contamination of the water, air and noise generated by the ships used for inland waterway navigation are insignificant as compared to other modes of surface transportation. According to various analysis the inland waterway traffic has lower degree of contamination of air than railway, though it may use significant part of electric power from hydroelectric and nuclear power plants for which it is considered that they do not contaminate the environment like thermal power plants.

The traffic and transportation are the most significant sources of the air contamination and they are, according to the data of the Royal Commission for Environmental Contamination Monitoring in Great Britain, responsible for 90 % of carbon-monoxide, 57 % of nitrogen oxides, 48 % of particles, 38 % of volatile organic compounds and 4 % of sulfur dioxide in the total air contamination (Hilling, 1995).

According to data of USA Ministry of Transportation the annual emission in the Saint Louis region as reference area are shown in the Table 1 (US Department of Transportation, 1994).

Type (source) of Emission	Towed Groups (tons)	Other Types of Surface Traffic (tons)	Total Emission (tons)
Nitrogen Oxides	3297	105932	433637
Hydrocarbons	939	198603	295124
Carbon Monoxide	2101	980944	3852753
Sulfur-Dioxide	462	7887	1234395
Particles	198	8940	354672

Table 1. Air Quality Control in the Saint Louis region in 1992

The extent of role of the inland waterway traffic for the air cleanliness protection can be seen from this table. According to the calculations of the German Ministry of

Transportation, the construction of the Mittelland and Elba-Havel channel would reduce the carbon monoxide emission by 200 000 t/year. According to the Austrian estimates, increased rate of use if the inland waterway traffic on Danube could create savings of 150 Million Euros reducing by this sum the costs of the carbon monoxide emission within traffic and transportation system (White paper, 1996).

Since the traffic and transportation cause irreversible climatic changes, generate and encourage other forms of contamination and cause damage to the human health and quality of life, the criteria for so called outside or external costs for each type of traffic are becoming decisive for the selection of any type of the cargo transport. In this sense the advantages of the inland waterway traffic are obvious as well as its relatively positive impact on the environment. The external costs, which include mostly the costs of contamination and jamming, are lowest for the inland waterway transport (ECORYS Transport and METTLE, 2005).

Land use of soil is a real advantage of the inland waterway transport. The soil is final resource and its use for the communications is limited due to adverse impact on the natural, human and cultural environment. The inland navigation has the only need for soil when artificial navigable waterways are constructed – channels and ports and piers. According to German calculations, for the same quantity of cargo, for the inland navigation is needed 30000 ha as compared to 84000 ha for railway and 290000 ha for the road transport (Binnenschiffahrt und Umwelt, 2005).

Disadvantages of the inland waterway navigation

The main disadvantages of the inland waterway navigation are the following ones:

1. Limited geographic expansion
2. Pronounced influence of current hydro-meteorological conditions
3. Quality level of the traffic service.

It has to be noted that above mentioned disadvantages are, similar like the advantages, interrelated and that between them complex links and influence exist, which have always to be reviewed from one case to another, in dependence on the actual conditions.

Limited geographic expansion concerns the natural spatial distribution and directions of the inland waterways. The base of the inland waterways consists of navigable rivers, which are by nature alone not interconnected, save for the tributaries. Their transformation into a network requires construction of the artificial channels across the watersheds, which is very expensive. According to the German Ministry of Transportation, the construction of the channel costs approximately € 13.75 Millions per one kilometer, the construction of the motorway ⊠ 5-10 Millions per km and that of the high speed railways app. ⊠ 17.5 Million per km (White paper, 1996).

The available network of the inland waterways does not cover always the main flows of goods. Consequently, it results that a particular problem with inland navigation are the costs of trans-loading and transfer from one mode (inland waterway transport) to other modes of the surface transport. The participation of the inland waterway traffic requires relatively higher degree of organization of the production in transportation chains.

Pronounced influence of current weather conditions may include the seasonal conditions (occurrence of low and high water, unmovable and movable ice and strong winds). The navigation in some sectors of the inland waterways may be subject to current weather and hydrology conditions, which are very difficult to overcome even at relatively high costs. Since there is no alternative, serious traffic breaks may occur reducing the cost-effectiveness and reliability of the inland navigation.

Quality level of the traffic service depends on the transportation reliability, speed, capability of "door to door" cargo transportation, safety, security, flexibility, availability and energy efficiency. The traffic service quality of inland navigation is characterized by certain features when compared to road and railway traffic. The reliability of the transportation depends on technical and operational conditions on the navigable waterway, which may be variable and impose limitations in respect to ship loading and number of vessels in the group. "Door to door" cargo transportation capability is the least in the inland waterway transport and most frequently distribution transportation chains have to be organized to and from ports using road and/or railway transport. According to other elements of the traffic service quality the inland waterway traffic is or at advantage or at the service level provided by other surface traffic modes, since for this type there is practically no jamming (new shipping is possible at any time) and the transit time can be reliably planned.

Misconceptions about the inland waterway navigation

Inland waterway traffic is slow. Inland navigation ships have speed in the range between 10 and 20 km/h, which is much lower than the speed of trains or road vehicles. However, the speed element speaking against the inland waterway traffic is often exaggerated. If the comparison is made using so called "commercial speed" it may be seen that under present conditions all types of the surface traffic are relatively equal, in particular in case of the long-distance transportation. Inland navigation ships operate continually during 24 hours and they are entirely adapted to observing the navigation time table and cargo delivery deadlines. According to Austrian Ministry of Transportation, Innovation and Technology the commercial speed in the road transportation between Europe and Greece is small, 12 km/h, while between Antwerp and Rome it reaches 20 km/h. Each increase of demand for certain time related delivery of cargo obviously compensates for the disadvantages of the inland navigation related to cargo. It is a fact that in the contemporary traffic and transportation system the speed of the transportation means is not of great significance within good logistic chain but rather the regularity and reliability of the service. Contemporary inland water transportation is capable to fulfill those requirements though the reliability can be sometimes insufficient as compared to other surface transportation modes (White paper, 1996).

Type of cargo is of decisive influence for the choice of the inland water navigation as the main transportation carrier in the surface transportation chains. The inland water transportation is the primary transportation system for bulk and liquid freight in large quantities. However, the nature of the cargo is not essential for the inland waterway transport being the most suitable type of transport irrelevant of the fact that it is traditionally used for the transportation of cargo for the needs of civil engineering, metallurgy, agriculture, oil and chemical industry. The best example for that is rapid growth of container traffic on the Rhine, which has now reached 2 000 000 TEU/year and RO/RO traffic (Seitz, 2006).

The role of the inland waterway traffic as inexpensive and safe transportation shall be always significant for the transportation of all types of cargo in large quantities and shipments. The internal criteria which significantly influence the choice of the inland waterway transportation as the main mode are the following ones:

1. Ports and piers adequately enabled for the reception and dispatching of the cargo by inland navigation vessels
2. Flows of goods stable in time and regular supply with cargo
3. Navigable waterways which allow navigation of corresponding ships and groups
4. Level of use and development of the information and control systems.

Inland waterway transport is isolated and out-dated technology system. If observed isolated the inland waterway transport may seem inferior in relation to road or, up to a point, to railway transport. This is explained by the fact that the network of inland navigable waterways are geographically fixed mostly for plain regions, that it is extremely difficult and expensive to interconnect them, which results in them being of only regional and local significant. Great differences in navigation conditions on large navigable waterways (upper, middle and lower sectors) and on the network in general have adverse effect on the inland navigation and use of ships and ports and piers.

Today is the main goal of the transport policy, at continual and rapid growth of the cargo traffic, such type of traffic, which makes least environmental damage and uses the existing infrastructure as less as possible. In this sense, there is no doubt that the transportation by water in general is the least damaging mode and that its natural infrastructure can be most efficiently used.

SOME SPECIFIC CHARACTERISTICS OF INLAND WATERWAY CARGO TRANSPORTATION IN EUROPE

The European network of inland waterways can be divided on four separated and relatively connected navigable systems such as:

— Northwest navigable system (with main rivers: Rhine, Elba, Odra, Vistula (Wisla) and other rivers and canals)
— Southwest navigable system (with main rivers: Rhone, Seine, Saone, Marna and other small rivers and canals)
— Danubean navigable system (with tributaries and canals)
— East navigable system (Volga, Dnepr, Dniester, Don and other rivers, canals and lakes).

Also, the inland waterway cargo fleet can be divided depending on the transportation technology as follows (see Fig. 1):

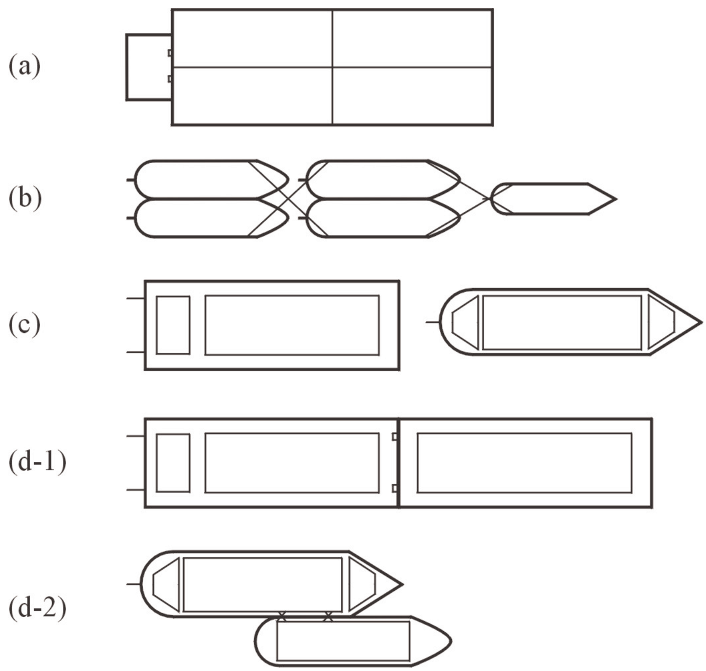

Fig. 1. Transport fleet and Types of Vessels in Inland Navigation in Europe, (a) Pushed barge tow with push-boat; (b) Pulled barge tow with pull tug; (c) Self-propelled barge or motor cargo ship; (d) 1 – Self-propelled pushed barge with pushed barge in tow; 2 – Self-propelled pulled barge with pulled barge in tow

All types of the above mentioned vessels in the inland waterway transport fleet exist on the European inland waterways. However, the pull-towing system is gradually being abandoned and only the existing fleet of pulltugs and pulled barges are in operation. These floating units are being replaced by pushboats and pushed barges, and, in smaller number of cases, by self-propelled barges (the Danube River is taken as example). These replacements depend on the class and hydro-meteorological conditions of the waterway, service quality in transport, cargo type, etc.

According to the presented researches and exploitation results, the push-towing system has no advantages in comparison with the self-propelled barge system in the European system of inland waterways. However, each system has its pros and cons, depending on numerous conditions (e.g. the minimum navigable depth and width of waterways, minimum width of turning areas, minimum equipment with navigational aids), (Radmilović et al., 1998; Radmilović et al., 2003).

On the basis of experiences gained at the European navigable network, there are a significant number of important advantages of push-towing system on all major waterways with the official waterway classification "IV" and above. Self-propelled barges have a great advantage, because of their high degree of flexibility. These vessels can reach almost any inland harbour on canal network.

As shown in Fig. 1, the power unit or motor ship and ship cargo space link in inland navigation can be divided into two groups: rigid and flexible. Rigid link, established between power unit and cargo space is dominant in maritime and road transport (sea ships and trucks), and occasionally in transport on inland waterways (self-propelled barges). Flexible link is used in railroad transport (between the locomotive and rail-road units), partially in road transport (systems with trailers and semi-trailers) and in inland waterway transport (push-towing, pulling systems and combinations of these systems).

Rigid link power unit has less exploitation time, since it has to wait along with ship cargo space at loading and unloading points (ports), depending on technology used, transportation process geography, and other operations (customs controls, change in transport conditions, etc.).

In the use of flexible link between power unit and cargo space, possibilities for higher exploitation time of power unit exist. This is true only for time periods during ship cargo space operations. For example, the motorboat and locomotive do not have to wait on tow or railcar units for cargo loading and unloading.

The self-propelled barge system is the simplest transport system, in an organizational sense, since the link that exists between the power unit and the cargo space is rigid. This system is the most frequent by used system in maritime transport, because these ships transport most of the total volume of cargo.

The pull-towing and push-towing systems are similar systems regarding transport operation, since they have non-rigid (flexible) connections between the power unit (pushboat or pull tug) and the cargo space (pushed and the pulled barge tows).

For example, in the inland waterway transport the pushboat-barge flexible link can operate as follows:

1. Continuous link between the pushboat and the barge tow;
2. Semi-continuous link between the pushboat and the barge tow;
3. Discontinuous link between the pushboat and the barge tow.

A continuous link (Fig. 2) is defined as an unruptured link between the pushboat and the barge tow during the traveling time and idle periods of the pushboat on the loading or unloading harbours or points, while the barges are served. The tow size or the number of barges in tow may be constant or variable values.

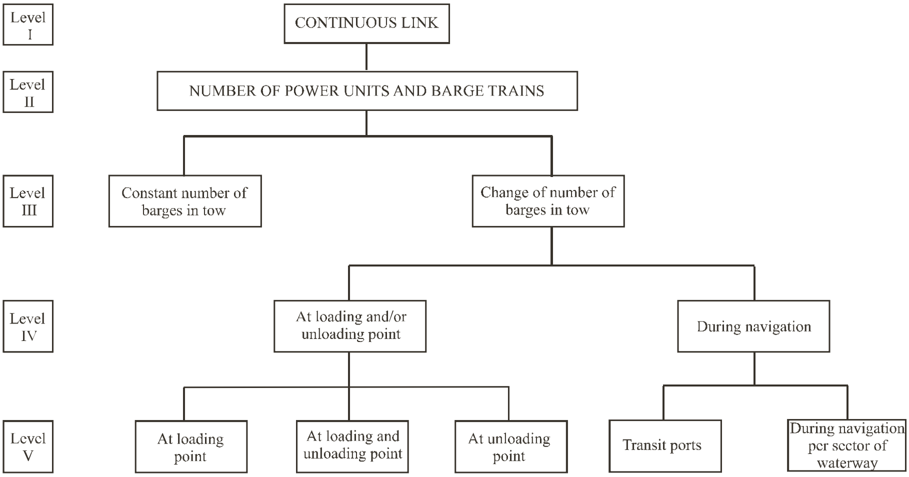

Fig. 2. Transportation's organization in continuous link between power unit (pushoboat) and cargo space (barge tow)

A semi-continuous link (Fig. 3) is defined as an unstable link between the pushboat and the barge tow. It means that the replacement of the pushboat can occur either during the traveling time, or at the loading or unloading points or harbours, and the pushing of barge tow by other pushboat. Like in the case one, the tow size or the number of barges in tow may be constant or variable values.

A discontinuous link (Fig. 3) represents the pushing of a barge tow with more than one pushboat. The replacement of the pushboat can occur during the traveling time and (or) at the loading/unloading points or harbours. Also, like as in the above mentioned cases, the tow size or number of barges in tow may be constant or variable values.

Two principles are obeyed in the definition of transportation organization. The first principle defines the number of ships or number of tows in operation. The second principle defines the number of barges in tow as a constant value or a variable.

Constant number of barges means the number of barges does not change at loading and unloading points and during the navigation (voyage).

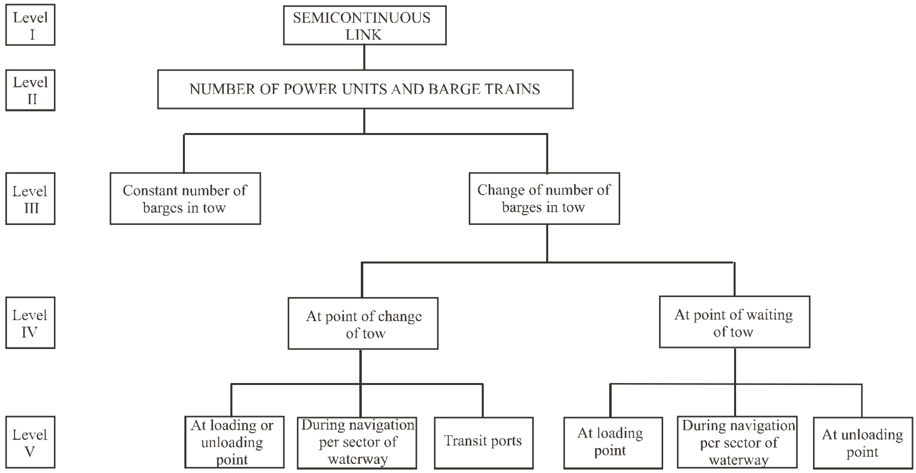

Fig. 3. Transportation's organization in semicontinuous link between power unit (pushoboat) and cargo space (barge tow)

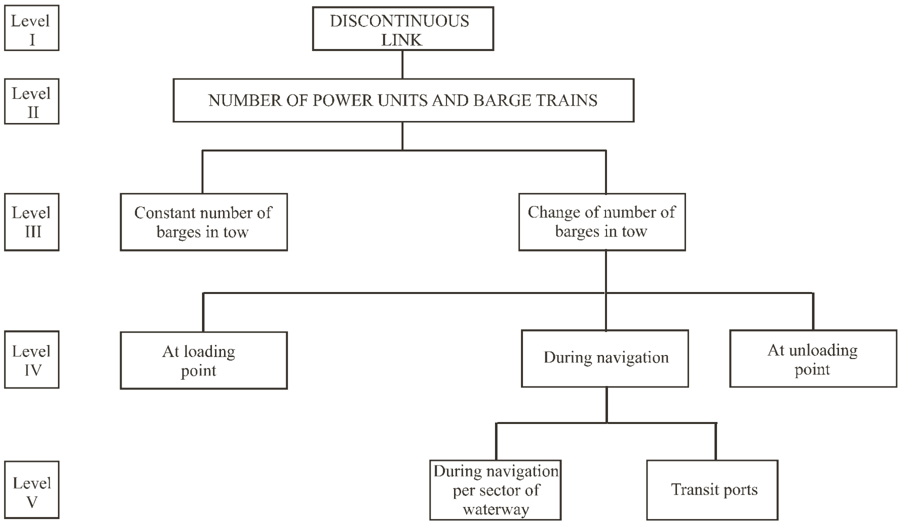

Fig. 3. Transportation's organization in discontinuous link between power unit (pushoboat) and cargo space (barge tow)

The variation in number of barges in tow means the tow size can change at loading/unloading points and during navigation.

Determination of the kind of link between the power unit and cargo space depends on the navigation conditions (change of classes of navigable waterways) and characteristics of cargo flows. For example, for longer waterway reaches in the case where navigation conditions can be rapidly changed, decision between non-disrupted or disrupted link should be made having in mind waiting costs of power unit or cargo space. In the case of favourable navigation conditions and when cargo flows are high-tonnage flows, it is necessary to make a decision on the type of link between power unit and cargo space. The type of link should depend on coordination between transport processes, cargo operation, port services, etc., or the ratio between travel time and standing time at the loading and unloading points or ports. The main objective is to ensure maximum exploitation of inland waterway ships per time, cargo capacity, power, and achievement of maximum transportation capacity.

CONCLUSION

For the European inland waterway transport, it is essential that a way be found to benefit from the strong advantages of this old transport system, i.e. transport of large volumes of cargo at low cost. This can be achieved mainly by organizational and technical adaptation in all basic parts: inland waterways, fleets and ports related to the intermodality and multimodality of inland waterway transport as a whole in Europe. Today, there are considerable differences between main rivers in Europe (in a view of methods of navigation, customs, degree of isolation and unequal share and distribution of cargo flows with the discrimination of inland waterway transport. Probably the inland waterway transport has big chance for its development in existing European transport network as trunk haul to the cargo transportation in many cases and countries with inland waterways, having in mind mentioned advantages, shortages and misconceptions.

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MODELING OF SHIP MOTION RESPONSES AND ITS APPLICATION TO RISK-BASED DESIGN AND OPERATION OF ENTRANCE CHANNELS

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Abstract

This paper presents the parametric modeling method of ship motion responses for risk-based optimization and operation of channel depths. The study focuses on computing response motion spectra as a function of the sea states (described by significant wave height *Hs* and wave period *Tz*) and transit conditions (ship speed *V* and loading *T*) using parametric modeling technique in combination with a numerical ship motion model; and then using these spectra applying a probabilistic model to determine the ship grounding risk. This makes it possible to establish the accessibility policy in which the guidance information for the safe transits will be provided. On the basis of the developed accessibility policy a long-term optimization of entrance channel depths can therefore be implemented. The aforementioned approach has been applied to Cam Pha Coal Port in Viet Nam as a case study.

Keywords: Parametric modeling; ship motion response; accessibility policy; long-term optimization; grounding risk

INTRODUCTION

The response spectrum of wave-induced ship motions, $S_r(\omega_e)$, can be achieved either from towing tank experiments or by numerical models based on the ordinary or

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the modified strip theory. The response spectrum is, however, only obtainable for a particular transit condition and a specified sea state. While for a long-term assessment of a ship response, much broader sea states and continuous variation of the parameters V and T are to be requested (Cramer and Hansen, 1994). Moreover, these two approaches cannot account for uncertainty present in these parameters in calculating the response spectrum, and later applying to performance of risk analysis. Hence, a demand is emerging for high quality and continuous description of the response spectrum for the problem at hand.

A sample linear regression model of the response spectrum related to the frequency wave spectrum was presented by Savenije (1995). The regression coefficients of the model depending on the transit conditions are defined by minimizing the mean squared error between the observed data and the predicted model values. This model is currently used in the computer program HARAP (HARbour APproach) for optimization of channel depths. A more advanced model was demonstrated by Cramer & Hansen (1994). The authors proposed a stochastic field model in the modulus squared of the frequency response function $H(\omega_e)$, which is defined as a ratio of ship motion to wave amplitude for a given wave encounter frequency, and then by use of the Kriging technique to better minimize the variance of the estimate error. However, as pointed out by the authors, there is a significant challenge to formulate a general model for the stochastic field governing the modulus squared of the frequency response function. Unfortunately, no numerically measured error for the qualification of these models has been found in the published papers.

Most recently, U.S. Army Engineer Research and Development Center has been developing a ship motion response model to use on the ship-handling simulator. However, according to U.S. Army Corps of Engineers (USACE, 2006), this model is still considered a research tool and needs further verification.

The present study is an ongoing effort that deals with the problem of modeling the ship motion responses applying parametric modeling method. The application of this model to navigation risk assessment and the model qualification has also been described in a case study.

PARAMETRIC MODELING OF SHIP MOTION RESPONSES

The wave-ship motion system

For restricted entrance channels and shallow waterways, the wave climate is generally not excessive; and since the ship dimensions are usually large relative to the wave length, ship response problems can be treated with linear models (all directly proportional to wave height) (Journee, 2002). The response spectrum of the ship motion based on the linear model is directly given by the wave spectrum as

$$S_r(\varpi_e) = |H(\varpi_e)|^2 S_\eta(\varpi_e) \tag{1}$$

where ω_e is the encounter frequency; $|H(\omega_e)|$ is the encounter frequency transfer, which depends on ship speed, sailing angle, loading condition and water depth (or underkeel clearance); $S_\eta(\omega_e)$ is the wave spectrum at the encounter frequency. For a given wave direction and a loading condition, Eq (1) can be rewritten as

$$S_r\left(\varpi_e | h_S, T_Z, V, kc\right) = \left|H\left(\varpi_e | V, kc\right)\right|^2 S_\eta\left(\varpi_e | H_S, T_Z\right) \tag{2}$$

The encounter frequency for shallow waters is determined as

$$\varpi_e = \varpi - kV\cos(\theta), \text{ here: } k = \frac{\varpi^2}{g\tanh(kd)} = \frac{\varpi^2}{g\tanh\left[k(kc+T)\right]} \tag{3}$$

where V (m/s) is the forward speed of ship; kc (m) is the average instantaneous underkeel clearance; d (m) is the water depth; θ (degree) is the angle between wave direction relative to the ship speed vector (θ =0 for waves from astern); T (m) is the ship draft depending on loading condition; ω (rad/s) is the wave frequency; k is the wave number.

It can be seen from Eq (2) that if the transfer function can be formulated as a function of the transit conditions (V and kc), the response spectrum of the motion, $S_r(\omega_e)$, can be determined for all possible transit conditions and sea states, described by wave spectrum $S_\eta(\omega_e)$.

With the assumption that the wave-ship motion is a linear input-output system, whose transfer function is faithfully modelled by an "all-pole" model:

$$H(z) = \frac{b(0)+b(1)z^{-1}+\ldots+b(n+1)z^{-n}}{1+a(1)z^{-1}+\ldots+a(m+1)z^{-m}} = \frac{\sum_{k=0}^{n} b(k)z^{-k}}{1+\sum_{k=1}^{m} a(k)z^{-k}} \tag{4}$$

Here, z is the angular frequency vector for which the transfer function $H(z)$ is determined by the (real or complex) numerator and denominator polynomials represented in the vectors b and a, respectively. For known $H(z)$ and z, nonlinear optimization to define $a(k)$ and $b(k)$ is generally realized in the iterative techniques proposed by Prony or Shank, both are available in the Matlab Signal Processing Toolbox. For the problem under discussion, Eq (4) can be rewritten as

$$H\left(\varpi_e | V, kc\right) = \frac{\sum_{k=0}^{n} b(k|V,kc)\varpi_e^{-k}}{1+\sum_{k=1}^{m} a(k|V,kc)\varpi_e^{-k}} \tag{5}$$

We assume the form of $a(k)$ and $b(k)$ as the polynomial functions of V and kc as

$$a(k \mid V, kc) = \sum_{j=1}^{p+1}\left[\sum_{i=1}^{q+1} \alpha_{i,j} V^{q+1-i}\right] kc^{p+1-j}, \quad k = 1 \div m \tag{6}$$

$$b(k \mid V, kc) = \sum_{j=1}^{p+1}\left[\sum_{i=1}^{q} \beta_{i,j} V^{q+1-i}\right] kc^{p+1-j}, \quad k = 0 \div n \tag{7}$$

The idea given to define the response function is that parametric modeling technique is applied to find the parameters $a(k)$ and $b(k)$ in the Eq (5), which corresponds to define the coefficients α and β in the proposed mathematical model given in Eqs (6) and (7). The estimation of the model parameters is achieved in two steps: the encounter frequencies and response functions considered as the data samples are obtained from either physical model tests or numerical ship motion model for various class values of V and kc, from which the corresponding parameters $ao(k)$ and $bo(k)$ can be estimated using Prony's algorithm (Jones, 2005). The estimated parameters are then used to define the coefficients α and β by doing a least square fit, which minimizes the sum of the squares of the deviations of the data from the model as

$$\varepsilon_{\alpha} = \min_{\alpha} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[a\left(\alpha | V_i, kc_j\right) - ao\left(V_i, kc_j\right)\right]^2 \tag{8}$$

$$\varepsilon_{\beta} = \min_{\beta} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[b\left(\beta | V_i, kc_j\right) - bo\left(V_i, kc_j\right)\right]^2 \tag{9}$$

Thus, the parametric modelling problem for the model given in Eq (5) is reduced to finding the minimum points of the function ε_α and ε_β in Eqs (8) and (9), which is called a prediction error method.

Estimating model parameters

Suppose we have sample data of $H(\omega_e)$ at various values V_i and kc_j (i=1÷M, j=1÷N). Using Prony's algorithm, we can find the (M×N) vectors bo each having n parameters $bo(k)_{ji}$, k=0÷n and the (M×N) vectors ao each having m parameters $ao(k)_{ji}$, k=1÷m. The parameter ao_{ji} (here we omitted "k" to simplify the notation) can be expressed as a nonlinear p-order polynomial model of kc_j for a given V_i as

$$r_{1,i}kc_j^{p} + r_{2,i}kc_j^{p-1} + \cdots r_{p,i}kc_j + r_{p+1,i} = ao_{ji} \tag{10}$$

In the matrix form

$$\begin{bmatrix} kc_1^{p} & kc_1^{p-1} & \cdots & kc_1 & 1 \\ kc_2^{p} & kc_2^{p-1} & \cdots & kc_2 & 1 \\ \cdots & \cdots & \ddots & \cdots & \cdots \\ kc_N^{p} & kc_N^{p-1} & \cdots & kc_N & 1 \end{bmatrix} \begin{bmatrix} r_{1,i} \\ r_{2,i} \\ \cdots \\ r_{p+1,i} \end{bmatrix} = \begin{bmatrix} ao_{1,i} \\ ao_{2,i} \\ \cdots \\ ao_{N,i} \end{bmatrix} \tag{11}$$

For all V_i, i=1÷M, Eq (11) in matrix form is

$$\left[kc_{N,p+1}\right]\left[r_{p+1,M}\right] = \left[ao_{N,M}\right] \tag{12}$$

here, $kc_{l,j} = kc_j^{p+1-l}, \quad l = 1 \div p+1,\ j = 1 \div N$

There are N equations and (p+1) unknowns. For regression solution N must therefore be larger than (p+1). We can easily define the coefficients r represented by the M-by-p+1 matrix using nonlinear regression technique. It is clear from Eq (10) that r_{ji} is as the coefficient in the (p+1-j) order polynomial model of kc_j for a given value of V_i. Thus, for instance, the equation of r at the p-order of kc is

$$\alpha_{1,1}V_i^{q} + \alpha_{2,1}V_i^{q-1} + \cdots \alpha_{q,1}V_i + \alpha_{q+1,1} = r_{1,i}, \qquad i = 1 \div M \tag{13}$$

For all V_i, i=1÷M at the p-order of kc in the matrix form

$$\begin{bmatrix} V_1^{q} & V_1^{q-1} & \cdots & V_1 & 1 \\ V_2^{q} & V_2^{q-1} & \cdots & V_2 & 1 \\ \cdots & \cdots & \ddots & \cdots & \cdots \\ V_M^{q} & V_M^{q-1} & \cdots & V_M & 1 \end{bmatrix} \begin{bmatrix} \alpha_{1,1} \\ \alpha_{2,1} \\ \cdots \\ \alpha_{q+1,1} \end{bmatrix} = \begin{bmatrix} r_{1,1} \\ r_{1,2} \\ \cdots \\ r_{1,M} \end{bmatrix} \tag{14}$$

For all orders of kc in the matrix form

$$\left[V_{M,q+1}\right]\left[\alpha_{q+1,p+1}\right] = \left[r_{p+1,M}\right]^{T} \tag{15}$$

here $V_{l,i} = V_i^{q+1-l}, \quad l = 1 \div q+1,\ i = 1 \div M$

We have M equations in the $(q+1)$ unknowns with the condition that $M>(q+1)$. Having determined the r from Eq (12) we can then use them to obtain α from Eq (15) with the prediction error given in the Eq (8). In the same way, we can also define β.

Minimizing ε_a and ε_b in Eqs (8) and (9) leads to the error of the response function over the $(N\times M)$ samples is minimized, which is given by

$$\varepsilon_H(\varpi_e)=\sum_{i=1}^{M}\sum_{j=1}^{N}\left[H\left(\varpi_e|V_i,kc_j\right)-H_0\left(\varpi_e|V_i,kc_j\right)\right]^2 \tag{16}$$

It is clear that the found curve fits in Eqs (10) and (13) in some cases may not perfectly approximate the data. To improve the approximation, the order (p and q) of the polynomial equations can be increased, which subsequently leads to increased sample data and therefore require a higher computational effort. This, however, does not amount to a problem with the mathematical model programmed in recent powerful computers.

One might prefer to use a regression coefficient R^2, as given in Eq (17), for assessment of the estimated response function, and thus we have to choose p and q that satisfy the condition $R>R_0$ (R_0 is an expected fitting coefficient). Hence, minimizing ε_H in Eq (16) is equivalent to maximizing R in the following

$$R^2=1-\frac{\Sigma\left(H_{oi}-H_i\right)^2}{\Sigma\left(H_{oi}-\overline{H_o}\right)^2} \tag{17}$$

where H_{oi} is the sample value of transfer function; and H_i is the regression prediction value; and $\overline{H_o}$ is the mean of the sample values.

The above procedure for defining the parametric model of the transfer function given in Eq (5) as well as for determining the response spectrum S_r in Eq (2) can be summarized as follows:

Use either numerical ship motion model or physical model to calculate the transfer functions for the concerned ranges of ship speeds and water depths. The numerically calculated transfer functions are considered as the sample functions, denoted here $H_0(\omega_e)$, for the parameter modeling progress. Note that the sample function values are calculated at the relatively discrete encounter frequencies, which are derived from Eq (3).

The estimated sample functions $H_0(\omega_e)$ and ω_e are then used to define the model parameters $ao(k)$ and $bo(k)$ by solving invert function of Eq (5) using Prony's algorithm. We calculate the parameters $bo(k)$ and $ao(k)$ by trying to find appropriate values of n and m.

Define $a(k)$ and $b(k)$ as the functions of V and kc as given in Eqs (6) and (7). This leads to a system of $M \times N$ equations in $(q+1)\times(p+1)$ unknowns which can be solved to find the best fitting coefficients (α and β) to fit the data, $a(k)$ to $ao(k)$ and $b(k)$ to $bo(k)$.

Finally, $H(\omega_e)$ will be found at the relatively discrete encounter frequencies using Eq (5), the corresponding ε and R^2 will also be estimated in Eqs (16) and (17). In practical, we usually consider choosing parameters $a(k)$ and $b(k)$ to maximize R^2.

SOME APPLICATIONS

There is a growing tendency in the application of probabilistic approach to risk-based optimization of entrance channel depths both in design (Briggs, 2003; Vantorre and Laforce, 2002) and navigational operation (Howell, 2002; Moes, 2002; O'brien, 2002). The optimization of channel depths is aimed at determining a depth to balance between the benefit of transport increment, downtime reduction and increase in costs of initial/maintenance dredging for a long-term channel project. It should be realized that the long-term optimization of channel depths requires guidance for minimum underkeel clearance allowances for the entrance accessibility to facilitate a required navigation safety. A level of the safety for the accessibility, in this context, can mainly be expressed in terms of probability of ship grounding risk.

However, the present design guidelines for underkeel clearance allowances for coastal entrance channels and shallow waterways are not comprehensive and practical (Zeki Demirbilek and Sargent, 1999). A simple general guideline for minimum depth clearance requirements in channels influenced by waves is given by PIANC (1997) . It is defined by ratios of water depth to ship draft, which should not be less than 1.3 when Hs is not higher than 1 m and at least 1.5 when Hs is higher than 1 m; and wave periods and directions are unfavourable. This guideline results in rather unrealistic depth under moderate wave actions. Whereas U.S. Army Corps of Engineers (USACE, 1998) states that "net depth allowance for waves is 1.2 Hs for deep-draft and 0.5 Hs for shallow-draft channels". It should be noted that the wave period contributes a significant effect on ship motion. Hence, an adequate guidance for ship accessibility, so called accessibility policy, should consider wave conditions (both Hs and wave period, Tz) in association with transit conditions (sailing speed and minimum underkeel clearance) for the navigation safety.

Recent efforts have focused on development of a system to predict ship dynamic underkeel clearance (DUKC) along ship passage. The predicted results are found by using a numerical ship motion model in combination with probabilistic computation (Briggs et al., 2003; Moes et al., 2002; Vantorre and Laforce, 2002). Based on these results, a minimum underkeel clearance allowance can be selected, which indicates a safety level of the particular channel transit. However, the cost of installation and operation of such systems is still prohibitive; Moreover, such system is not applicable during design stage.

The new parametric model developed in this study is useful for overcoming the above mentioned limitations, as presented in the following.

Development of a risk-based policy for ship entrance: first-passage failure model

The first-passage failure is an event that a random stationary process $X(t)$ cross a level $x=\beta$ (m) at once during a period T (s). It is frequently used for estimating the risk of a ship touching the bottom, which is assumed as a measure of the risk of ship grounding. This method is based on the assumption that successive up-crossings of a specified level are independent and constitute a Poisson process (Lin, 1967). Under this assumption probability of the first-passage failure, $P(\beta,T)$, of a response $X(t)$ can be estimated by

$$P(\beta,T) = 1 - \exp(-v_b T) \tag{18}$$

where v_b is the mean rate of crossing with a level β, if the response $X(t)$ has the Gaussian distribution and zero mean, v_b can then be expressed as

$$v_b = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_o}}\exp\left(-\frac{1}{2}\frac{\beta^2}{m_o}\right) \tag{19}$$

where m_o and m_2 represent zero and second moments of the response, respectively, which can be determined by the following equations

$$m_o = \int_0^\infty S_r(\varpi_e)d\varpi_e \tag{20}$$

$$m_2 = \int_0^\infty \varpi_e^2 S_r(\varpi_e)d\varpi_e \tag{21}$$

$S_r(\omega_e)$ is the response spectrum as defined in the previous section.

In the engineering design, it is highly desirable to know a certain level for which probability of first-passage failure is smaller than an acceptable value α. For example, before the ship enters we wish to know a specified level of the vertical motion corresponding to an acceptable probability of the ship grounding, α. So let , from Eqs (18) and (19), crossing level for probability of first-passage failure = α can be expressed by

$$\beta = \sqrt{m_0}\sqrt{-2\ln\left\{-\frac{\ln(1-\alpha)}{\frac{T^2}{2\pi}\sqrt{\frac{m_2}{m_0}}}\right\}} \tag{22}$$

Long-term simulation-based optimization of the channel depths

Having determined the model of ship motion responses, a simulation model can therefore be developed. It can be used as a decision support tool for channel performance evaluation and optimization. In general, the procedure of a long-term optimization of channel depths is presented in Figure 1.

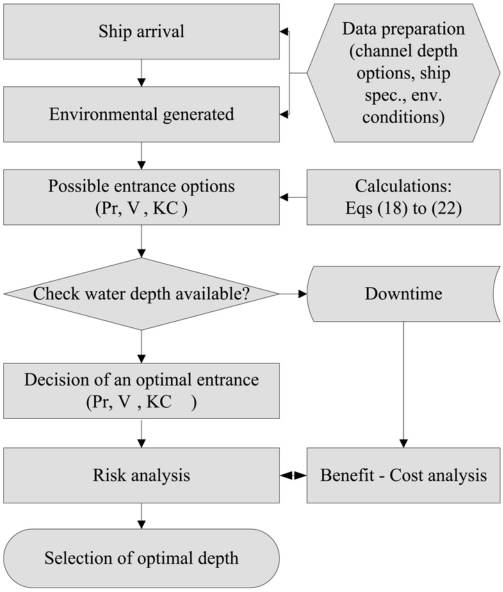

Figure 1: General procedure for the optimization of channel depths

As discussed earlier, a long-term optimization of channel depths should be considered a two-stage process, consisting of: (1) first, establishing a ship entrance guidance to facilitate a required navigation safety with respect to a possibility of touching the channel bed as discussed previously. This step is so-called the short term establishment of accessibility policy for safe navigation. (2) Secondly, using the Monte Carlo method and based on the established accessibility policy, a simulation model is developed to define a minimum underkeel clearance allowance and simultaneously determine downtimes that correspond to an acceptable grounding risk for a specified ship and a generated sea state. The process can be repeated over for a given time period and for all possible alternatives of the channel depths. To enable this, a stochastic model of the environmental conditions and ship arrivals on the basis of historical recorded or forecasted data have to be set up. Since the ship response spectrum has been defined as a function of the transit conditions and sea states, the model uncertainties can be assessed and included in the simulation. The final results derived from the simulation model can be considered as the key parameters in analysis and selection of an optimal depth.

THE CASE STUDY

Project description

The entrance channel at Cam Pha Coal Port in the North Sea of Viet Nam is the largest specialized port in Viet Nam serving export of coal to Europe, Japan and

China. In recent years, the demand on exporting coal to Europe and Japan has increased rapidly and ships entering the port are becoming larger which are beyond the present capacity of the entrance channel. Therefore, in 2001, Viet Nam Coal Incorporation initiated an expansion project of the Port (Quy, 2001) in which the entrance channel will be enlarged to allow the ships of up to 65,000DWT (full loaded) using a high tide for leaving the port. But till now, the rehabilitation of the channel has not been commenced yet. The main reason of this delay is that a part the channel with the length of 7.5 km is very shallow (only -7.4 m from the sea datum) and the seabed is rocky, this results in very high costs in dredging work. Hence, economic and environmental pressures have revealed the need to minimize the dredging when determining the depth of the entrance channel. Establishment of an appropriate and reliable policy for the ship entry also gives an opportunity to reduce the dredging depth requirement. This study, as a part of the mentioned project, deals with the rehabilitation of the entrance channel with the following objectives:

Establishing an accessibility policy by which pilots can use it with a sufficient confident to decide the transit conditions before leaving the port.

Optimizing the channel depths in the long-term with regarding to an acceptable probability of the ship grounding on the basis of the established accessibility policy.

However, only the results of the first objective have been presented in the following. The calculation procedure of the optimization has been developed, as will be reported in future publication.

Input data

The design ship is a bulk carrier 65.000 DWT with the main representative dimensions as:

overall length (loa):	274.000 m
beam (b):	32.000 m
full loaded draft (T):	13.000 m
block coefficient (C_B):	0.8142
wetted hull surface:	3.487 m^2

To obtain sample data for parametric modeling of the frequency transfer function, a numerical ship motion model, called SEAWAY (Journee, 2001), has been used. The program is a frequency-domain ship motion model, which - based on the modified strip theory - calculates the wave-induced loads and motions with six degrees of freedom of ship hull. The program has been validated for the motion calculation in a very shallow water area (Marc Vantorre and Journee, 2003).

Five values of ship speed ranged from 5 knots to 15 knots and seven values of water depth, *d*, with ratio of *d/T* varied from 1.25 to 1.55 were used in the calculation, amounting in total to thirty five transit conditions. In the absence of study on the shape of wave spectrum in this area for the time being, two parameters, *Hs* and

Tz, of Pierson-Moskowitz spectrum has been proposed to calculate the ship motions. The calculation focused on the hull motion at stern, because the risk of bottom touch is most critical for this part of the ship. The reason for this is the export function of the port where the outbound ships - loaded to full draft - faces incoming waves (Quy, 2006).

The ship squat has also been taken into account to reduce the underkeel clearance. The empirical expression, proposed by Barrass II (PIANC, 1997), has been used as follows:

$$S_{\max} = \frac{C_B S_2^{2/3} V^{2.08}}{30} \tag{23}$$

where C_B is the block coefficient; V is the ship speed (knots); S_2 is the blockage factor defined as a ratio of midship section area to the wetted cross section area of the waterway.

Modeling results and comparisons

The parameters in vectors *ao*(*k*) and *bo*(*k*) were found with the average regression coefficient over all the sample data was 0.994 for the orders *n* and *m* in the numerator and denominator polynomials of 25 and 16 respectively, where the fit presented in Figure 2 with *V*=10 knots and *kc*=3.25 m represents the case having the smallest value of all fits performed. These results confirmed that the "all-pole" model represents well the behavior of the ship response in the linear wave-motion system.

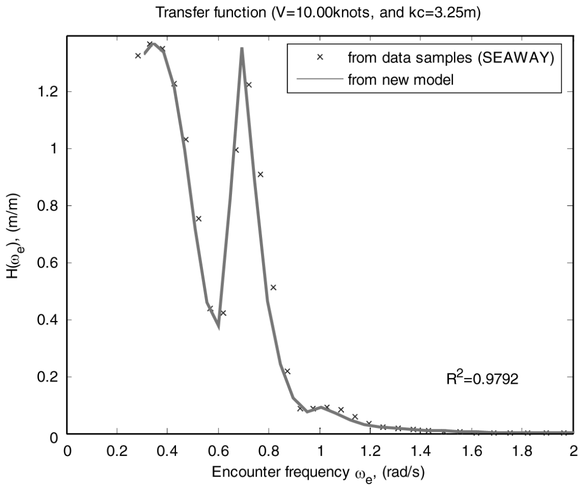

Figure 2: Comparison between the theoretical transfer function calculations (SEAWAY) and the results from the parametric model.

Figure 3 presents the results of the model parameters in Eqs (6) and (7) as function of *kc* and *V*=10 knots with the index *k*=3 based on the estimated values of *ao*(*k*) and *bo*(*k*). The *q*- and *p*-orders of the polynomials were 3 and 2, respectively. It can be primarily concluded that the polynomial model can fit well the data with only low orders. It is more interesting to find out that the error in the estimated response spectrum is very insensitive with the errors in the model parameters $a(k)$ and $b(k)$ because the "all-pole" model is usually computed with the high n- and m-orders.

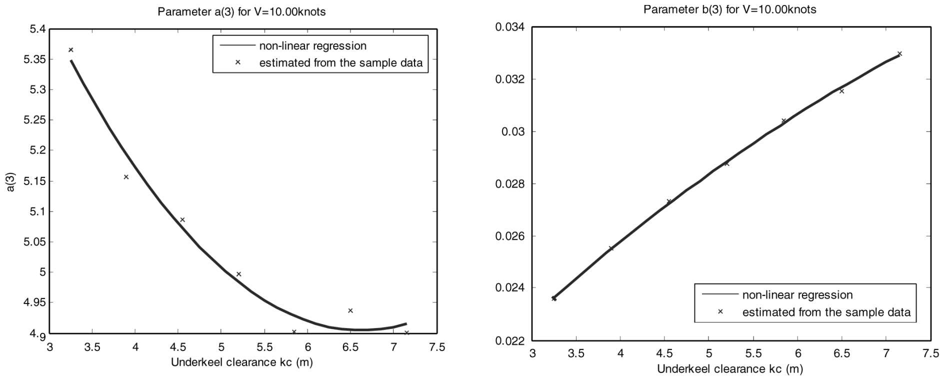

Figure 3: Examples of non-linear regression of parameters *a* and *b*

The response spectral estimations based on the parametric model were also compared well to those obtained from the numerical ship motion model, as presented in Figure 4. Many sea states were randomly generated from which five hundred of response spectra with thirty five transit conditions (five speed classes and seven values of *kc*) were estimated to test the model fit. The average fit coefficient was 0.991 and the smallest fit was 0.9716 as shown in Figure 4. Finally, the probability of ship grounding for a certain transit condition and a minimum allowable underkeel clearance with a predefined acceptable grounding risk can be estimated using the first-passage failure model given in Eqs (18) and (22) respectively.

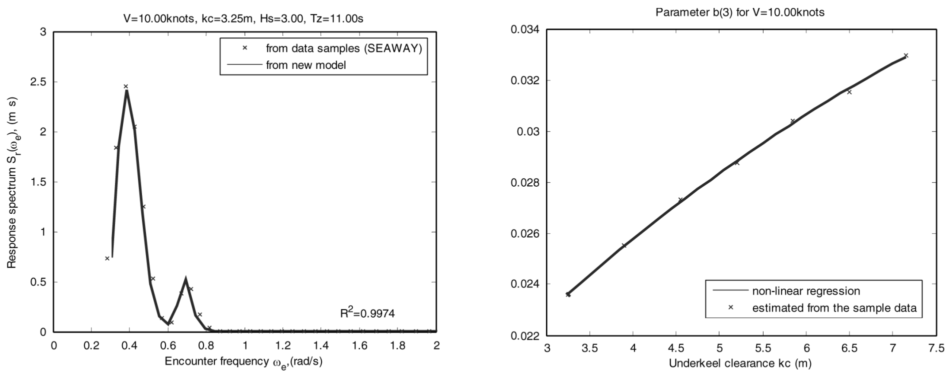

Figure 4: Comparison between the theoretical ship response calculations (SEAWAY) and the results from the parametric model.

Discussions

Concerning the PIANC guideline, the ratio of water depth to ship draft (*d/T*) has been investigated for various sea states and transit conditions, as shown in Figure 5 and Figure 6. It can be seen from Figure 5 that the risk levels indicated by the probabilities of ship grounding are strongly dependent on the wave period. The probability increases quickly with slowly decreasing ratios of *d/T* or with increasing wave period. However, for small value of the acceptable probability of grounding, let say $\alpha=3\times10^{-5}$ (3 per 100,000 ship movements) as an observed value for Northern European Ports (Vrijling, 1995), the results are less sensitive to the wave period. But with the ratio *d/T* =1.5 for the *Hs* is higher 1 m as suggested in PIANC seems very high and unrealistic, which is equivalent to the *Hs*=6 m for $\alpha=3\times10^{-5}$. From an operational point of view, it is almost impossible for a ship to navigate in restricted channels with such a wave height.

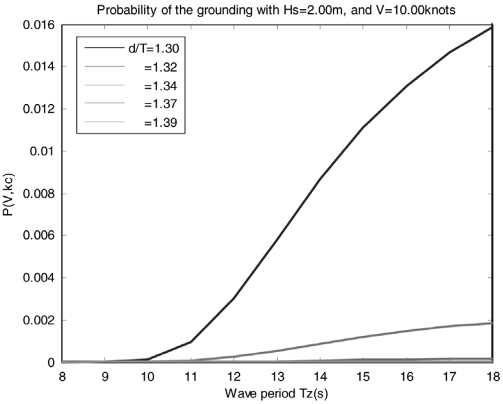

Figure 5: Relationship between probabilities of the grounding and wave periods for different values of *d/T* (relates to the PIANC).

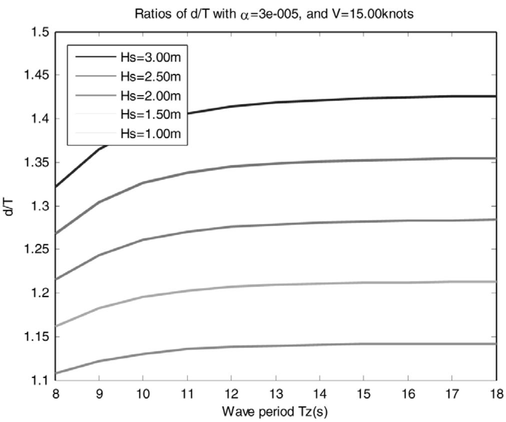

Figure 6: Relationship between ratio of d/T and wave periods for different values of Hs with an acceptable grounding value $\alpha=3\times10^{-5}$.

Regarding the USACE guideline, considering the ratio of net depth allowance to wave height *β/Hs*, the wave period has considerably effective to the results of the grounding risk, as shown in Figure 7. For $\alpha=3\times10^{-5}$ and *V*=5 knots, the required net depth allowance varies from 0.90*Hs* for the wave period of 8 second to 1.8*Hs* for wave period of 18 second. This requirement is higher for faster ship speeds and larger wave periods. With the value of 1.2*Hs* as recommended by USACE for deep-draft channel, the ship speed should be less than 10 knots for wave periods less than 10 seconds. For the higher sea states, the depth requirement is almost impossible to fulfill.

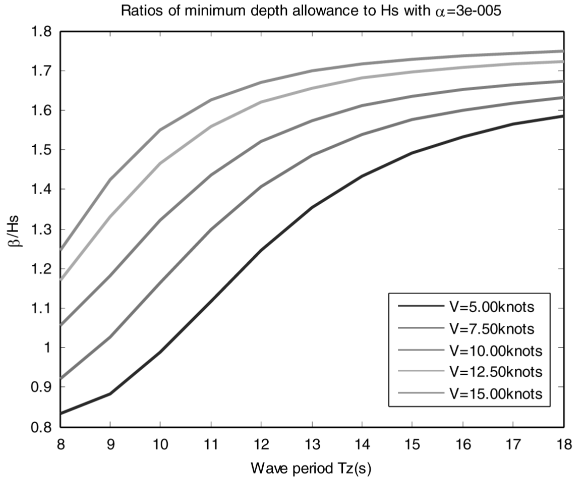

Figure 7: Relationship between ratio of *β/Hs* and wave periods for different ship speeds with an acceptable grounding value $\alpha=3\times10^{-5}$ (relates to the USACE).

CONCLUSIONS

Parametric modeling of ship motion responses, of how transit conditions and waves affect the ship motion and grounding risk, has been presented. The model is useful for many purposes: risk management of ship operation in harbor and waterways; simulation-based optimization of channel depths in which all uncertainties involved can be introduced into the simulation; for use on ship handling simulator; and study behavior of ship structure itself. The model could be applicable for "closer analysis" in near real time to predict ship dynamic underkeel clearance along ship passage (Howell, 2002) for maximizing allowable ship draft. An actual bulk export terminal in Viet Nam was used to demonstrate the applicability of this model for decision making relating to improving the channel operation and capacity expansion.

The results of the regression confirmed that the new model with its parameters expressed by polynomial functions represents well the behavior of the ship motion response in the linear wave-motion system.

The limitations of the PIANC and USACE guidelines for the underkeel clearance allowances have been investigated by taking wave parameters and transit conditions into consideration. It should be concluded that the wave periods have great effect on the ship grounding risk with very different degrees depending on the transit conditions. These results could be useful for improvement of the existing guidelines with a condition that an acceptable probability of ship grounding should be allowed; the accessibility policy for the ship entrance as well as for approach channel design will therefore be more accurately and practically established.

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INLAND WATERWAY TRANSPORT OF CONTAINERISED CARGO: FROM INFANCY TO A FULLY-FLEDGED TRANSPORT MODE

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ABSTRACT

In a time span of twenty five years, container transport by barge has acquired a significant share in the hinterland modal split for containers of the seaports of Rotterdam and Antwerp. In other European load centres, barge container transport as yet plays a modest role, but the interest in the barge option is growing. This paper addresses the dynamics in the European barging industry that have taken place in the last twenty five years. The paper analyses structural changes in liner service schedules by barge, the changing functional interdependencies between inland terminals in the network and the organizational changes in the industry. The paper will conclude by discussing some current issues related to the barging network in the Rhine basin, but also outside this main waterway artery.

THE DEVELOPMENT OF THE EUROPEAN CONTAINER BARGE NETWORK

The European container barge network up to now has always been primarily focused on maritime container flows. As such, the development pattern of the barging network is strongly entwined with the development of the associated seaport system. The container barge network in Europe has its origins in transport between Antwerp, Rotterdam and the Rhine basin, and in the last decade it has also developed greatly along the north-south axis between the Benelux countries and northern France. Figure 1 provides an overview of the core of the European inland waterway network.

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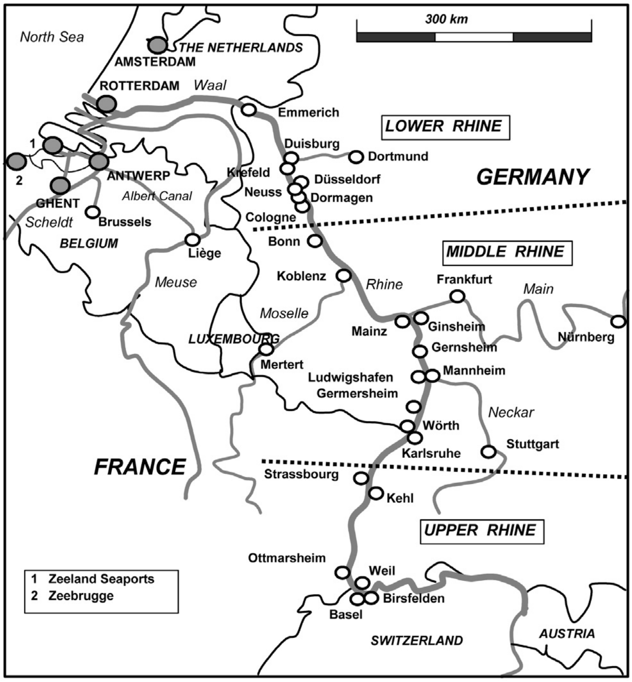


Figure 1: The Rhine axes: core of the European inland waterway network.

It is possible to distinguish four phases in the historical growth pattern of the European container barge network, each with distinctive characteristics related to terminal development, barge service design, container volumes and market organisation. These four elements are strongly entwined and together explain the dynamics in the European container barge industry.

FIRST PHASE (MID-1968 TILL EARLY 1970s)

The first phase is the pioneering stage of container transport by barge. Small containerised volumes were carried at irregular intervals by conventional barges from Rotterdam to conventional transhipment points on the upper Rhine (Basel and Strasbourg) and middle Rhine (Mannheim and Karlsruhe) (Van Driel, 1993). These services primarily grouped empty containers in the immediate vicinity of the users. The first container terminal was set up in Mannheim (lower Rhine) in 1968. This was followed shortly afterwards by specialised terminals in Strasbourg and Basel (upper Rhine). The first phase featured only few pioneering barge operators in the market such as NRM. Cargo volumes remained low. Total annual transport volume on the Rhine did not exceed 10.000 TEU until 1975. Since the service offered by barge operators did not include transhipment and pre- and endhauls by truck, barge transport long remained unattractive to deepsea carriers and shippers, despite the price advantage per TEU.

SECOND PHASE (MID 1970S TILL MID 1980S)

By the mid 1970s, the growth in maritime container transport and the limitation in the number of ports of call led to a high concentration of container volumes in just a few seaports. This port concentration resulted in a gradual build-up of the necessary critical mass for the more volume-oriented barge container transport. Hence, scheduled liner container services by barge developed gradually. For this purpose, operators divided the Rhine into three navigation stretches, namely the Lower Rhine (as far as Cologne/Bonn – only limited number of services at that time), the Middle Rhine (from Bonn up to Karlsruhe) and the Upper Rhine (from Karlsruhe up to Basel in Switzerland) – see also figure 1. Barge transport quickly gained in competitiveness once punctuality could be guaranteed by fixed departure schedules for each navigation area, with exceptions only occurring in case of problems with water levels. Annual transport volumes on the Rhine grew from 20.000 TEU in 1976 to 210.000 TEU in 1985. The market was dominated by carriers such as CCS (48% of the barge container market in 1985), Rhinecontainer (31%) and Frankenbach (12%). Each carrier operated own liner services.

Terminal development kept pace with the rising volumes. A number of established inland ports along the Rhine set aside part of the existing multifunctional terminals for container transhipment. New terminals were also set up within the perimeter of existing ports, or at new locations along the main navigation route. No less than twenty new Rhine terminals were opened in the period 1980-1987. The initiative for setting up inland waterway terminals now also came from the Rhine carriers, who saw the operation of their own single-user terminals as a way to guarantee success of their liner services. Independent terminal operators tried to get around the system of single-user terminals by setting up common-user terminals. A good example is the opening of ICG (Inland Container terminal Germersheim) in 1984.

THIRD PHASE (MID 1980s TILL MID 1990s)

In phases 1 and 2, the terminal initiatives mainly developed along the upper and middle Rhine. The Rhine carriers and other terminal operators took the view that barge container transport could only be competitive with road transport over distances of at least 500 km, given the comparatively high fixed costs and low variable costs. The development of the basic volume for barge transport only started to bring large-scale initiatives on the lower Rhine from 1985 onwards. The volumes carried on the Rhine increased from about 200,000 TEU in 1985 to 800,000 TEU in 1995. In Antwerp containerised barge traffic evolved from 128,700 TEU in 1985 to 675,000 TEU in 1995, in Rotterdam from 225,000 TEU to 1,15 million TEU.

In order to raise the level of service and prevent destructive competition, the existing barge carriers started to operate joint liner services on the different navigation areas of the Rhine, backed by operational collaboration agreements. These are characterised by a limited degree of central planning and commitment of barge units, with each of the participating parties maintaining its own commercial identity and freedom. Examples are the Fahrgemeinschaft Oberrhein (Upper Rhine transport collective founded by Haniel Container Line, Interfeeder Ducotra, Haeger & Schmidt and Rhinecontainer) and the Fahrgemeinschaft Niederrhein (Lower Rhine transport collective). CCS, Rhinecontainer, Haniel and Haeger & Schmidt set up Fahrgemeinschaft Niederrhein at the beginning of 1992 to tackle the problem of low load factors and heavy losses in the industry. By setting up collaboration in capacity the load factor was soon above 60% and the carriers were put back into the black (Van Driel, 1993, Konings, 1999 and Boer, 1999). The partners streamlined their sailing schedules so as to offer a high frequency of departures from the seaports to the lower Rhine. Other co-operation agreements involved the Danube (e.g. Penta Container Line with initial partners Danser Container Line, Rhenus Alpina, CCS, CNFR, Conteba and Natural Van Dam) and the link Antwerp-Rotterdam (e.g. Barge Planning Center with partners CEM, Eurobarge, WCT-MTA and Interfeeder). Jointly operated and frequent liner services to each of the three navigation areas on the Rhine (i.e. line-bundling services with typically five inland ports of call per loop) were complemented by a limited number of direct point-to-point shuttles.

FOURTH PHASE (SINCE MID 1990s)

Terminal developments

Since the mid 1990s, container transport by barge started to outgrow the Rhine basin. The growing realisation of the potential offered by barge container shipping led to a wave of investment in new terminals in northern France, the Netherlands and Belgium (table 1). The Benelux and northern France now have over 40 container barge terminals (excluding barge terminals in seaport areas). In 1991 there was still no terminal network on the north-south axis (only two terminals), while the Rhine basin already had 25 container terminals. This coincided with the emergence of a new set of terminal operators offering their own shuttle services to and from the main ports Antwerp and or Rotterdam. A noteworthy feature of this development is that some of the new terminals are located at a short distance from the seaports (even less than 50 km). The growth of the terminal network has been partly initiated by financial incentives given by local, regional or national authorities, with government subsidies in some cases encouraging the emergence of less viable terminal initiatives. As governments are now curbing direct subsidies to the barging industry, a rationalisation in the Benelux terminal network is to be expected. Clear signs of this rationalisation process can already be observed in the eastern part of the Netherlands and along the Sea Canal Brussels-Rupel in Belgium (from four terminals in 2002 to only two successful ones today, i.e. TCT Belgium operated by Rotterdam-based ECT and Cargovil Container Terminal). In other parts of the Benelux, the number of terminals is still increasing.

The fourth phase also meant the introduction of barge services and inland terminals outside the Rhine-Scheldt-Meuse basins. Noteworthy examples are the terminal of Gennevilliers near Paris along the Seine, terminals along the Rhône Saône Basin (Lyon, Mâcon and Chalon) and new container handling facilities along the Elbe river.

Table 1. The start of operations at new terminals (number of terminals per navigation area).

	Start of terminal activities (number of terminals per navigation area)					
	Before 1985	1985-1990	1991-1997	1998-2002	N.A.	TOTAL
Upper Rhine	4	2	0	1	1	8
Middle Rhine	7	5	2	2	0	16
Lower Rhine	3	4	0	3	1	11
Northern France & Luxembourg	0	0	4	1	0	5
Belgium	0	1	2	9	0	12
the Netherlands	0	1	6	19	0	26
Total number of terminals	**14**	**13**	**14**	**35**	**2**	**78**

	Start of terminal activities (number of terminals per navigation area)			
	Before 1985	Before 1991	Before 1998	Before 2002
Rhine Basin (D, F and CH)	100%	93%	66%	43%
Other navigation areas	0%	7%	34%	57%
Total number of terminals	**14**	**27**	**41**	**76**

Remark: barge terminals in seaports and along the Danube river are not included
Source: author based on individual terminal data

Despite the spatial concentration of freight in terms of carriers, the number of terminals in the Rhine basin is still increasing. This is partly the result of new terminal operators arriving on the market (e.g. ECT in Duisburg since 1999 and the P&O Ports/Logport combination also in Duisburg in 2002). However, it is also due to new terminals appearing along the Rhine and its tributaries, e.g. Aschaffenburg, Hoechst terminal, Krefeld and Mannheim Container Terminal.

A number of inland terminals are increasingly concentrating on complementarity between rail and barge transport. The German inland terminals are seeking to emphasise the trimodal character of the facilities offered, seeking connections to the KLV (Kombinierten Ladungsverkehr) network operated by Deutsche Bahn. Emmerich, Neuss, Mainz, Mannheim, Cologne, Duisburg and Dortmund are some of the inland ports trying to combine their leading role in barge transport with a hub function in international intermodal rail networks. However, in most of them there is still no combined barge/rail transport to speak of: the transit volumes between barge and rail on most of the Rhine terminals are still very low.

Barge service schedules

After a period of decentralisation in the Rhine basin, the large container carriers are following a strategy aimed at concentrating river freight volumes in just a few freight terminals. This rationalisation in the number of Rhine terminals served (in particular on the lower and middle Rhine) opened up the possibility of larger barges being introduced. Exceptional examples are the sister ships Jowi and Amistade, motorised barges with a slot capacity of 398 TEU used on the CCS services between Antwerp/Rotterdam and the Rhine. Outside the Rhine basin and the Antwerp-Rotterdam link, smaller barges are used in a direct shuttle configuration. The next step is to arrive at a network of liner services connecting several terminals outside the Rhine basin. For instance, some container barge services from the Lille-Kortrijk border region (France-Belgium) to the ports of Antwerp and Rotterdam are now organised on a line-bundling principle, which means they load/discharge at another inland terminal along the route before proceeding to the seaport of destination.

Barge container volumes

The Rhine remains by far the most important corridor, notwithstanding rising volumes in the other navigation areas and on the link Antwerp-Rotterdam (figure 2). The middle Rhine still accounts for nearly half of the total container volumes on the Rhine (table 2).

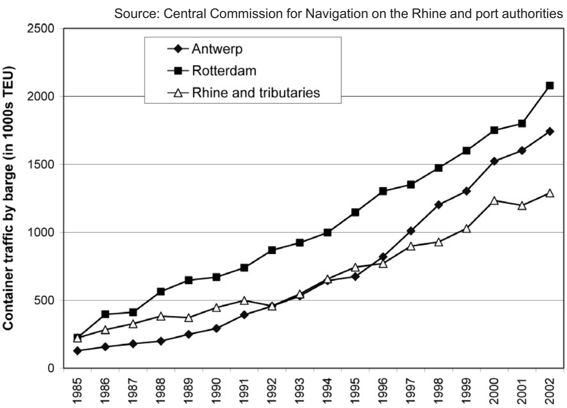


Figure 2. Growth of container traffic by barge in Antwerp, Rotterdam and on the Rhine (in TEU)

Rotterdam and Antwerp account for around 95% of barge container transport to and from the European seaport system. Table 3 summarises the modal split in a number of European load centres. The German ports have developed a strong orientation on rail shuttles, whereas Antwerp and Rotterdam heavily rely on barges to reach water-linked hinterland regions. Most ports have

Source: Central Commission for Navigation on the Rhine.

	Lower Rhine	Middle Rhine	Upper Rhine	Total Rhine (in TEU)
1994	28.9%	56.3%	14.8%	657000
1995	29.6%	54.5%	16.0%	743492
1996	26.6%	57.3%	16.1%	771000
1997	28.4%	56.0%	15.7%	898983
1998	31.2%	52.2%	16.6%	929398
1999	32.2%	51.2%	16.6%	1028681
2000	32.0%	49.8%	18.2%	1233670
2001	32.9%	49.5%	17.6%	1196866
2002	31.9%	50.4%	17.7%	1289424

Table 2. Relative importance of the navigation areas on the Rhine (based on volumes in TEU).

achieved a considerable modal shift in hinterland container transport, but rail and inland navigation still have not reached their maximum potential. Trucking remains the most important transport mode in all ports, especially in traffic relations to France and to inland destinations outside the large economic centres.

Source: based on data respective port authorities.

	Rail			Road			Barge		
	1998	2001	2003	1998	2001	2003	1998	2001	2003
Rotterdam	14,5%	13,0%	10,0%	51,3%	48,7%	50,0%	34,2%	39,0%	40,0%
Antwerp	7,8%	8,8%	9,5%	64,5%	61,3%	59,5%	27,7%	29,9%	31,0%
Le Havre	14,3%	11,4%	12,4%	84,6%	85,3%	82,8%	1,3%	3,1%	4,8%
Zeebrugge	34,4%	41,9%	40,2%	50,6%	48,8%	55,1%	15,1%	9,2%	4,7%
Dunkirk	9,0%	13,5%	20,5%	90,0%	82,5%	76,7%	1,0%	4,0%	2,7%
Hamburg	29,7%	28,7%	28,7%	70,1%	69,9%	69,8%	0,2%	1,4%	1,7%
Bremerhaven	33,1%	36,0%	30,6%	65,0%	62,0%	67,3%	1,9%	2,0%	2,0%

Table 3. Container modal split for load centres in the Le Havre – Hamburg range (in %, excluding sea-sea transhipment).

In the other container ports of the Hamburg-Le Havre range, barge container transport as yet plays a modest but increasing role. Inland navigation had a market share of some 4.8% in the modal split of Le Havre in 2003 (based on TEU-figures), compared to only 1.3% in 1998. The barge services of GIE Logiseine (a company founded in 1994 by barge operator Compagnie Fluviale de Transport, terminal operator Terminaux de Normandie of Le Havre and Paris Terminal SA) carried 37,500 TEU between Le Havre, Rouen, Gennevilliers (Paris) in 2002, compared to 19,500 TEU in 1999 and 6,000 TEU in 1995. Logiseine has developed relationships with around 15 trucking companies for the delivery of containers in a radius of up to 120 km around Gennevilliers. Since 2003, Bonneuil sur Marne (east of Paris) has been added as inland port of call in the Logiseine line-bundling network along the Seine, bringing total volumes to 151,900 TEU in 2003. Barge units of up to 176 TEU unit capacity are used. In December 2004, Mediterranean Shipping Company started two barge services between Le Havre (Terminal TN/MSC) and Gennevilliers. In 2005 traffic volumes reached about 20,000 TEU.

Hamburg is slowly developing barge services on the Elbe, with annual volumes in 2003 exceeding 60,000 TEU compared to only 30,000 TEU in 2000 and 1,755 TEU in 1997. Barge transportation is being used more and more on the Elbe from Hamburg in the direction of Magdeburg, Aken, Torgau, Riesa, Dresden even as far as the Czech Republic to places such as Decin, Usti, Melnik, Prague, Kolin and Pardubice. Also the Elbe side canals to Berlin, Hanover and Lübeck are regaining significance for the inland waterway traffic.

The port of Marseilles is supporting the development of barge services in the Rhône Saône basin. Two operators are active on the link: (a) Rhône Saône Conteneur, a subsidiary of CMA-CGM with services between Marseilles-Fos to Lyon, Mâcon and Chalon, and (b) Alcotrans with services from Fos to Lyon and Valence.

Rhône Saône Conteneur transported 33,000 TEU in 2003 for different clients, including Ikea, Danone, DHL, Géodis, Michelin and Volvic. The unit capacity of the barges of Rhône Saône Conteneur amounts to 132 TEU. The transit time Fos-Lyon is around 38 hours upstream and 24 hours downstream.

Market organisation

The new millennium brought rising pressure on the existing co-operation agreements on the Rhine as more and more operators are eager to start services independently from their partners. For instance, CCS withdrew from the Fahrgemeinschaft Niederrhein collective on 1 January 2000, but the collaboration agreement continued with the three remaining partners, under the name of NFG 2000. The departure of CCS from Fahrgemeinschaft Niederrhein occurred against the background of a strongly expanding market. In 2006, the Fahrgemeinschaft Oberrhein (OFG) nearly ceased to exist when Rhinecontainer and Haeger&Schmidt decided to step out of the OFG partnership and to start up the Upper Rhine Container Alliance (URCA). The two remaining operators, Interfeeder and Alcotrans, kept operations of OFG up and running. A major restructuring of the barge services within OFG took place once Interfeeder was taken over by Contargo in October 2006. The new OFG with partners Contargo and Alcotrans introduced reconfigured service schedules in early 2007. The above examples demonstrate a clear shift from partnerships with a large number of barge operators towards independent operators or partnerships with only few partners. The only large partnership still operational is the Penta Consortium on the Upper Rhine with partners DCL, SRN/Natural (Danser), Conteba/Swiss Terminals, CFNR and Contargo subsidiary Basler Marine Terminals (BMT).

Collaborative agreements are making their appearance in other navigation areas such as shuttle services between the two leading seaports in the Benelux, namely Antwerp and Rotterdam. Joint ventures, mergers and takeovers form a relatively new aspect, aimed at increasing the geographical scope of the services offered, and at developing the operators' own barge transport networks. The initiatives being developed in this connection are aimed at increasing the geographical scope of the services offered, and at developing the operators' own barge transport networks. Danser Container Line, for instance, which offers services on the Rhine and Neckar and between Rotterdam and Oss, acquired Eurobarge from Nedlloyd Rijn & Binnenvaart in 1999. Eurobarge mainly operates barges on the Antwerp-Rotterdam route. Since January 2006, Danser Container Line controls the barge services of Natural Van Dam AG, an operator formerly owned by the logistics group Cronat from Basel. Both companies already worked together before the takeover, i.e. in the framework of Penta Container Line. In 2000, Rhinecontainer acquired Container Exploitatiemaatschappij (CEM), a main player on the Antwerp-Rotterdam axis with 160,000 TEU in 2000. In the same year, CCS and SRN Alpina came under the same ownership, as a result of Rhenus (the parent company of CCS - SRN Alpina) acquiring the Swiss holding company Migros. Since 2004, Rhenus Logistics integrated Combined Container Service (CCS) in its container transport division Contargo.

A number of operators are now focusing on expanding their service packages outside the Rhine basin. For instance, Alcotrans is active on the Rhône river and Danser Container Line offers container services to Brussels.

In addition, the leading barge container carriers are increasingly trying to achieve a functional vertical integration of the container transport chain by extending the logistical services package to include complete door-to-door logistical solutions. Combined Container Service (CCS) was the first Rhine carrier to begin operating on this principle, as early as in 1976 (Denis, 1999). Rhinecontainer too was able to offer a wider logistical service to customers soon after been set up in 1978, thanks to the logistics know-how of its co-founder Kühne & Nagel. In practical terms, the barge operators will if required take care of the entire continental route from the seaport to the consignee's door. For the actual transport operation on the continental route, the leading barge carriers call on independent bargees, who frequently own just one or at most a few units, together with road hauliers for the feeder services. The desire for direct access to the shippers has led the barge operators to enlarge their role as transport organisers, by setting up joint ventures with forwarders and other logistics operators.

In the 1990s, three logistics holdings got a strong grip on the barging market. Wincanton controlled 33% of containers moved by barge in the Rhine basin in 2004. Wincanton is the mother company of Rhenania with subsidiary Rhinecontainer (375,000 TEU in 2004). Rhenus Logistics, mother company of Contargo (including SRN Alpina and CCS), reached a market share of 22% and Imperial Logistics Group, mother company of Alcotrans, 15% (Zurbach, 2005). Alcotrans transported around 220,000 TEU on the Rhine in 2006. The Contargo network, comprising of 19 inland container terminals in Germany, the Netherlands, France and Switzerland, handled some 840,000 TEU in 2006. The integration of leading barge operating companies in the structures of highly-diversified logistics groups further strengthens the functional integration in the logistics chain.

Inland terminals often play a key role within the logistics strategy followed. Some two thirds of the barge carriers on the Rhine operate one or more Rhine terminals and/or participate as a shareholder in a terminal. Barge container carriers in fact control about half of the Rhine terminals. A large number of the remaining inland barge terminals are operated by subsidiaries, parent companies or allied companies of container terminal operators based in seaports. The remaining inland terminals are operated by rail operators (who wish to exploit the complementarities of rail and barge transport by setting up trimodal hubs), independent logistics service providers (who set up terminal activities to assure their own supply of freight), inland port authorities (such as the Port Autonome de Strasbourg, who sees a barge terminal and the associated logistics activities as a means of regional development and as a way of increasing regional competitiveness) and holding companies (they acquire stakes in inland terminals in order to diversify their portfolio or package of activities).

A last and fairly new aspect of the vertical integration strategy followed by barge operators is the desire to fully exploit the complementarity with rail transport, by forging closer links with existing rail companies, or if required even acting as rail operator themselves. The present market consolidation in European rail transport leaves a certain limited scope for barge operators to position themselves as rail shuttle operators, allowing them to overcome the restricted geographical coverage of the European inland waterway network. Rhenania Intermodal, one of the market leaders in container hinterland traffics of the European sea ports, launched a number of river-rail services in 2005 in association with German rail operator Conliner. In 2006 the Conliner services were taken over and restructured by the Stinnes Group. Rhenus Logistics offers a similar service through the RheinRail Service of CCS. In both cases, the ports of Antwerp and Rotterdam are linked by barge to an inland port from where onward rail connections bring the goods to the final destinations. Rhenania uses Mannheim as rail-river facility for all-rail destinations such as Stuttgart and Nürnberg. CCS uses its terminal network on the Rhine to offer river–rail services to Dresden, Leipzig and Munich.

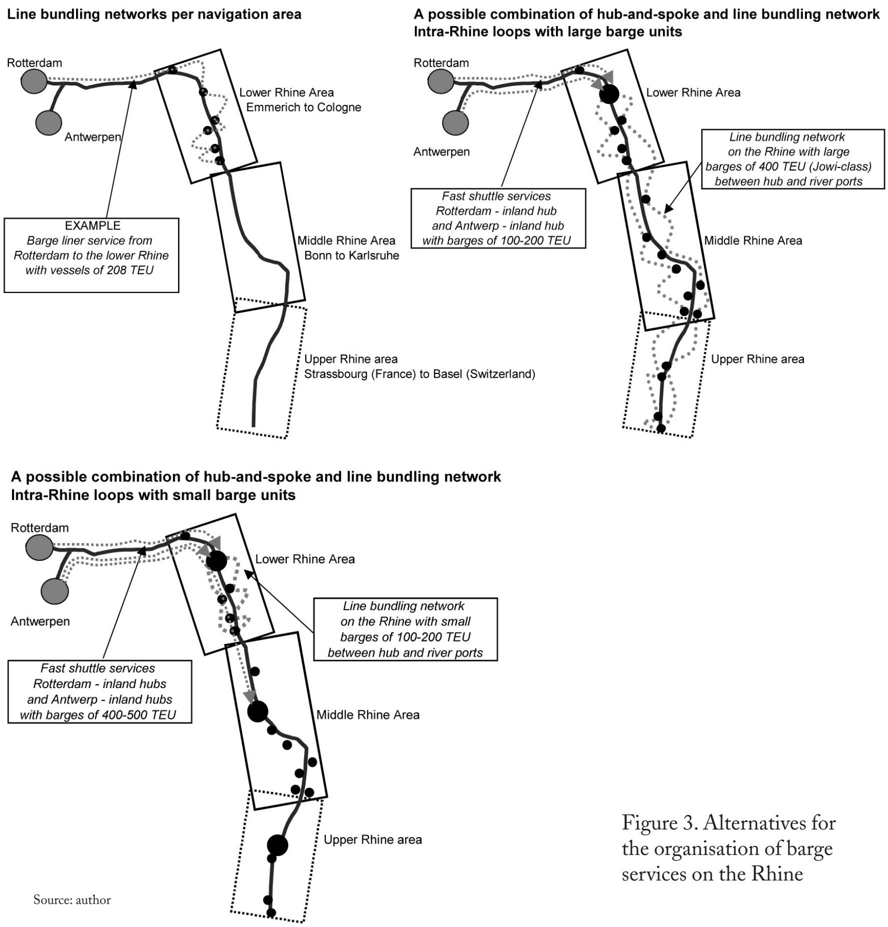
CURRENT ISSUES IN THE EUROPEAN CONTAINER BARGE NETWORK

Towards a reconfiguration of service networks ?

At present, the liner service networks offered on the Rhine are mainly of the line bundling type with each rotation calling at 3 to 6 terminals per navigation area (Lower Rhine, Middle Rhine, Upper Rhine), while in the seaports the average number of terminal calls can be as high as ten. The inland vessels used on the Rhine have capacities ranging from 90 to 208 TEU, although some bigger units and push convoys of up to 500 TEU can be spotted occasionally. The average frequencies of barge services out of Rotterdam and Antwerp to the Rhine now amount to at least a daily service. Rotterdam has a strong position on barge traffic from/to the lower Rhine and middle Rhine, whereas Antwerp and Rotterdam are equally strong on the upper Rhine.

Dependent on transport volumes and the usability of different vessel sizes, a reorganisation of barge services on the Rhine is not unthinkable. The hub-and-spoke model built around an inland hub could form an alternative to the existing line-bundling services on the Rhine (figure 3). The cost savings on the trunk route will to some extent be absorbed by the transhipment from the trunk to feeder route, but the net benefit might be an improvement of the cost performance of barge services to these regional terminals. An example is the Rhein-Waal Shuttle between Rotterdam/Antwerp – Duisburg DeCeTe (trunk route) and Duisburg - Dortmund (feeder route). Key elements in setting up hub-and-spoke networks in the barging industry relate to the location of hub and feeder terminals and the matching of arrival and departure times of trunk and feeder lines.

In navigation areas outside the Rhine basin, vessels typically call at only one end terminal in the hinterland, thereby reducing turnaround time and increasing reliability. The basic conditions for developing line bundling networks and hub-and-spokes networks outside the Rhine basin seem not favourable because of the high number of new terminal initiatives and the limited scale of many of these facilities (i.e. annual terminal capacities lower than 10,000 TEU are quite common). A network based on many small terminals leads to fragmentation of cargo volumes, which can partly or even completely obviate the scale advantages. As mentioned earlier in this paper,



Source: author

Figure 3. Alternatives for the organisation of barge services on the Rhine

it is therefore expected that in the years to come a partial rationalisation (as a result of mergers/acquisitions and terminal close downs) and specialisation (e.g. terminals focused solely on the transport of containerised waste) will take place within the terminal networks outside the Rhine basin. This would pave the way for major revisions of sailing schedules and network architecture.

The role of deepsea shipping lines in shaping the container barge industry

The organisational control over hinterland transport via carrier haulage is an important strategy for shipping lines to control the logistic chain and to generate additional revenues (Notteboom, 2004). Some shipping lines, such as CMA-CGM, have already entered the barging industry. Carriers will have great interest to concentrate transport volumes to a very limited number of inland terminals to take full advantage of economies of scale in sailing (large vessels) and terminal operations (including block stowage and scale benefits in repositioning and depot activities). These conditions will encourage the development of some local hubs (large inland terminals) that will be directly served from the seaport (one-stop services). If transport volumes are large enough and carrier haulage is dominant ultimately direct point-to-point services might emerge. It is most likely that the port and inland terminals strategically located near the major load bases and to on-going rail and barge connections will be most eligible for this hub status (e.g. Duisburg, Ludwigshaven, Mannheim and Basel).

The functions of inland terminals

In the last fifteen years, the dynamics in logistics networks have created the right conditions for a large-scale development of inland ports throughout Europe. The range of functions of inland logistics centres is wide ranging from simple cargo consolidation to advanced logistics services. Many inland locations with multimodal access have become broader logistics zones. They not only have assumed a significant number of traditional cargo handling functions and services, but also have attracted many related services, a.o. distribution centres, shipping agents, trucking companies, forwarders, container repair facilities and packing firms. The concept of logistics zones in the hinterland is now well-advanced in Europe: e.g. 'platformes logistiques' in France, the Güterverkehrszentren (GVZ) in Germany, Interporti in Italy, Freight Villages in the UK and the Zonas de Actividades Logisticas (ZAL) in Spain. Logistics zones are usually created within the framework of regional development policies as joint initiatives by firms, intermodal operators, regional and local authorities, the central government and or the Chambers of Commerce and Industry.

Quite a few of these logistics zones are competing with seaports for what the location of European distribution facilities are concerned. Shortage of industrial premises, the high land prices, congestion problems, the inland location of the European markets and severe environmental restrictions are some of the well-known arguments for companies not to locate in a seaport. The availability of fast, efficient and reliable intermodal connections is one of the most important prerequisites for the further development of inland terminals. The interaction between seaports and inland locations leads to the development of a large logistics pole consisting of several logistics zones. Seaports are the central nodes driving the dynamics in such a large logistics pole. But at the same time seaports rely heavily on inland ports to preserve their attractiveness. For example, the ports of Antwerp and Rotterdam have become the main drivers of a large logistics pole covering the Benelux, northern France and western Germany (figure 4). The existing geographical concentration of logistics sites has stimulated the development of inland terminals in these areas.

Source: author

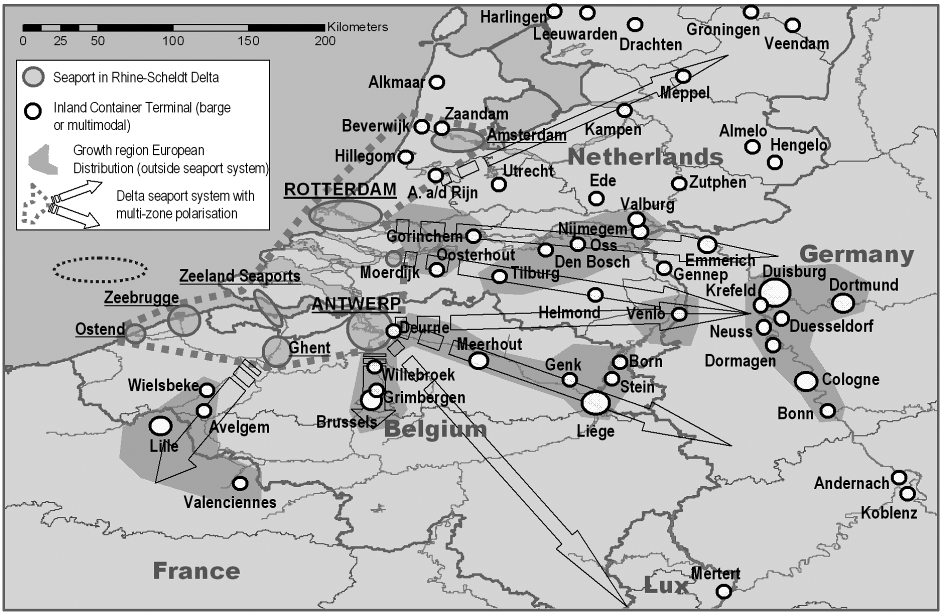


Figure 4. Logistics polarisation in the Benelux

Traditionally, container transhipment centres for barge transport play a regional function for distribution and collection of maritime containers and consolidation of containerised freight. The area served by the average container terminal covers a radius of between 25 and 60 km. As the distance between the inland terminal and the maritime loading centre becomes larger, the relative proportion of pre- and end-haul by truck in the total door-to-door cost structure becomes lower, while the potential area served by the terminal becomes greater.

A number of terminals are still trying to manifest themselves more in intra-European haulage of continental containers to terminals located farther upstream. But so far, continental transport of containers has not met with success. When it comes to maritime containers, the inland terminals are generally not located in the centre of the area served, but instead tend to be closer to the maritime loading centres.

Frequently, the necessary basic volume is supplied by just a few large shippers, who form a solid basis for the market and participate in new terminal initiatives. For example, Nike is by far the largest customer of WCT in Meerhout, while Barge Terminal Born mainly deals with DSM. The large shippers ensure that the basic volume of the container terminal is very homogenous and repetitive in nature. A terminal in the immediate vicinity of a large shipper often plays an important role as a depot, for the purpose of JIT deliveries. Manufacturers can call up the full import containers whenever the container load is needed in the production process, and by the same token they can call up empty containers in order to fill them with export loads.

Barge container transport has an influence on competitive relationships within the European container port system. It enables the Benelux ports in particular to create a patchwork of overlapping areas served by individual inland terminals, within which it is possible to achieve a cost advantage over other European container ports. The huge scale of barge operations in Rotterdam and Antwerp generates advantages not found in smaller container ports. The advantages are apparent in the clustering of barge operators and related companies (e.g. ship repairs and ship chandlers). However, the development of barge container transport is sometimes handicapped by large time losses in those seaports, due to the deepsea container terminals being too widely spread out in the port area, and due also to the non-priority character of barges in comparison with seagoing vessels. Both Antwerp and Rotterdam have taken initiatives in the past few years to reduce this by making use of IT for quay planning and electronic document processing, and by building specialised barge terminals within the port area.

The supremacy of Rotterdam and Antwerp does not mean that other European ports cannot also profit from the upward growth spiral in the inland barging industry. Le Havre, Marseilles, Hamburg and Zeebrugge are some of the load centres seeking to give inland barging a more prominent place in their inland distribution patterns of maritime containers.

Barge networks versus rail networks: competition and cooperation

The development of barge networks is different from rail networks, given specific geographical and operating conditions. First of all, there is the geographical component. River systems typically have a treelike structure with limited or no lateral connections between the different branches. Under these conditions, a network design based on the hub-and-spoke concept is less obvious compared to rail systems consisting of many lateral connections. Secondly, the deployable vessel capacity is restricted and not homogeneous due to variations in draft limitations and other physical conditions in segments of the river system. Thirdly, wagons of shuttle and block trains can be regrouped quite easily through shunting. As such, the handling of containers in rail networks can be based either on horizontal operations (i.e. shunting of wagons) or on vertical operations (i.e. the loading/unloading of containers). In inland barge networks the regrouping of containers requires vertical container handling operations by crane. Horizontal operations might only occur when an operator uses push barges in view of regrouping large container batches. But even in that case the flexibility of push convoys is rather limited compared to trains.

Fourthly, there is the organisational component. The railway industry historically was dominated by national railway companies. They acted as monopolists on each of the national railway networks they managed and owned (captive infrastructure). Government intervention was high and customer focus rather poor. Due to European liberalisation (see e.g. Directive 91/440 of the European Commission and subsequent directives in 1995, 2001 and 2003), the railway industry is opening up and new licensed players are entering the market. Moreover, infrastructure management is being decoupled from the actual rail services as to allow licensed railway undertakings to operate services on the formerly national railway networks. In contrast, the barge industry historically is a family-driven industry with independent skippers offering services to barge operators. Even today, 90% of all barge owners possess no more than one vessel (figures for Belgium provided by National Institute for Statistics). There has always been a strict division between inland barge operations and the provision and maintenance of the inland waterway infrastructure (canals, locks and natural waterways). All barge operators in principle can get access to the same inland waterway network (shared infrastructure), which gives impetus to strong competition in the industry and an elevated customer focus.

Barges are competing with rail services on quite a number of major transport corridors (Rhine basin, corridors in Benelux, Seine axis, Rhône axis). But at the same time, attempts are being made to develop the rail-river business. Given certain convergence in the organizational aspects of the barging and rail markets, it can be expected that the feasibility of such rail-river initiatives will increase in the future. A growing number of terminals could develop into real rail-river transit ports.

CONCLUSIONS

Barge container transport has won a significant share of the market in a number of transport corridors between the Rhine-Scheldt-Meuse delta and the European hinterland. The improvement in the position of barge container transport has gone hand in hand with radical organizational changes in the barging industry, together with the explosive growth of the European inland terminal network. The development of inland terminals has contributed to a modal shift, with part of the collection and distribution function of the port areas being transferred to the hinterland. In this way, the container sorting function is to a certain extent being displaced from the maritime terminals to the inland terminals. This enables seaports to take full advantage of the comparative advantages, while limiting the possible disadvantages of scale arising from the growing volume of maritime throughput.

The rise of inland terminals is also being driven by new players such as large logistics groups, shipping lines and container terminal companies based in seaports, prompted partly by the realization that efficient hinterland transport has become a very important element in the competitive battle for control over logistics chains. Barge transport and inland terminals have won their place in the supply and collection systems for manufacturers, and as such play an undeniably important role in the further logistical development of major economic centres in the West-European hinterland.

Barge container transport is still closely associated with point-to-point service and line bundling services to and from the large loading centres of Antwerp and Rotterdam. Important challenges for the future are for barge container transport to be opened up further to other seaports, and for this mode to fit in better with rail-river activities. It is possible for barge container transport to overcome the limitations of the inland waterway network by linking up with rail transport. There are also opportunities for forming better networks among inland terminals, many of which are very recent. A sustainable network of inland terminals is not necessarily the same as having many terminals, but it does mean a network that makes maximum use of the functional interdependencies with seaports and other transport modes, offering added value in logistics activities.

It is very likely that barge transport operations will continue to change in the near future. The terminal hierarchy is under scrutiny by shipping lines, barge operators and other market players. It is expected that some selected strategically located terminals will obtain a hub status with important exchange functions (between barges and barges and rail) and serving very large and on long distance located markets, while other terminals become subordinated to these hub terminals concentrating on serving local and regional markets. This configuration will meet the demand for large transport volumes to a selected number of terminals which will be served directly and possibly by very large vessels even with high frequencies, and demand for fine-meshed transport to small terminals with fast small to medium-sized vessels.

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FUTURE TRENDS IN ELECTRIC PROPULSION SYSTEMS FOR COMMERCIAL VESSELS

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Abstract

Since the application of the thyristor to power control in the 1970's, the advances in power electronic devices, converter topologies and digital technologies have allowed the development of electric propulsion systems, which reduce fuel consumption and environmental emissions and increase safety levels. Considering the increasing costs of fossil fuels and the strict regulations concerning environmental and safety issues, commercial vessels in the near future will include this propulsion system and the associated technologies.

New trends in power generation, emerging technologies and system integration can be applied to electric propulsion systems making them more reliable, efficient and clean. Renewable energies, such as fuel-cells based on hydrogen, can be considered as energy sources of future vessels. Moreover, new technologies based on high temperature superconductors (HTS) and innovative power converter topologies, i.e. multilevel converters, will increase the system's efficiency.

This paper reviews new power sources and emerging technologies in electronic and electrical engineering which can be applied to future electrically propelled commercial ships.

Keywords: Electric ship propulsion, power electronic devices, converter topologies, power sources.

INTRODUCTION

The analysis of future trends in ship propulsion systems must consider diverse factors such as the expected rising price of fossil fuels and more strict regulation,

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both in safety and environmental issues (Lin, 2006). The forecast of crude oil production in a near future for different authors is represented in figure 1 (The Oil Drum, 2007). Under these conditions, electric propulsion can be considered as an alternative to conventional systems due to lower pollution levels and higher efficiency. Moreover, the introduction of alterative energy sources and their associated technologies will allow a new scenario to improve the performance of electric propulsion systems (EPS).

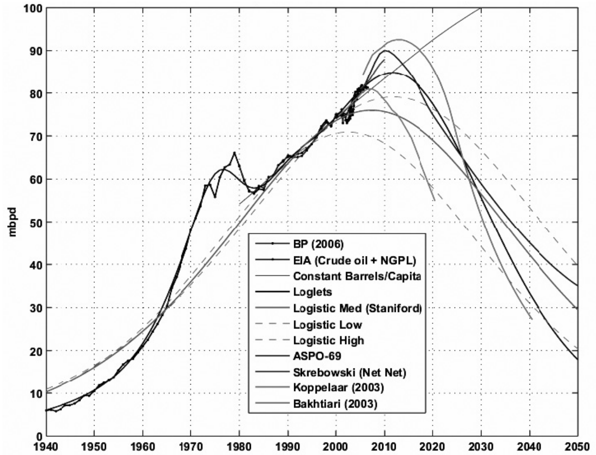

Figure 1. World oil production and various forecasts (1940-2050).

The general structure of current EPS consists of a set of prime movers (diesel engines or gas turbines) mechanically coupled to electrical power generators which feed the propeller motors through electronic converters. At present, EPS are mainly applied to cruise vessels, ferries, DP drilling vessels, shuttle tankers, cable layers and icebreakers.

EPS have been developed in parallel with power electronic device technology. In this sense, the appearance of the thyristor in the 1970's allowed the design of variable speed drives based on ac/dc rectifiers and ac/ac converters in the early 1980's. Podded propulsion, where the electric motor is installed directly on the fixed pitch propeller shaft in a submerged rotateable pod, was introduced in the 1990's. This propulsion system introduced additional benefits in hydrodynamic efficiency and maneuverability. During the last decade, isolated gate bipolar transistors (IGBTs) have allowed the development of more efficient power converters controlled by means of pulse width modulation (PWM) techniques. Advances in power electronic device technologies, e.g. isolated gate controlled thyristor (IGCT), make possible the development of more efficient converter topologies and controllers for EPS, such as multilevel rectifiers and inverters. Moreover, advances in material science and technology, such as high-temperature superconductors (HTS), applied to the design of electric motors allow the power density to be increased.

The introduction of new power sources, such as hydrogen, biofuels, photovoltaics and other renewable energies, can substitute conventional energy sources for prime movers, reducing emission levels. An example of a zero emission ship model for the future is the *E/S Orcelle* project (figure 2). This ship design was developed in

2005 by the Scandinavian shipping company *Wallenius Wilhelmsen* for an almost zero-emission car carrier capable of transporting 10,000 cars (about 50% more than today's car carriers) that uses renewable energy to meet all propulsion and onboard power requirements. The pentamaran-hulled design employs fuel cells to generate about one-half of the ship's energy, as well as wind power, solar power, and wave power. This latter is captured through 12 horizontal fins that would transform wave energy into hydrogen (for the fuel cells), electricity, or mechanical power. The fins would also act as propulsion units in combination with two podded propulsors. The developers believe a ship containing some of the *Orcelle*'s features might be possible by 2010, and that a ship with all of its features could conceivably be built by 2025.

Figure 2. E/S Orcelle.

This paper reviews new power sources and emerging technologies in electronic and electric engineering which can be applied to future ships with EPS. After a brief history of electrically propelled vessels and a revision of the state of the art at the present, new trends in power generation, motors, propellers and power electronic converters applied to EPS are analyzed.

EPS HISTORY

Due to the lack of turn reversibility associated to marine diesel engines in the early 1900's, other kind of propulsion systems appeared. In this sense, a low power electric motor based system was proposed to simplify port maneuvers in 1903. This patent was known as Patent of *Cesidio of the Proposto* (Koehler, 1998). The first merchant vessel with diesel-electric propulsion was the *Vandal*, a ship river tanker with base in San Petersburg delivered in the autumn of 1902 (figure 3). The ship had three diesel engines with three cylinders. The engines were mechanically coupled to 87kW 500V dc generators feeding 75kW electric motors, which were applied to the propellers. In 1905, the first diesel engine directly reversible, including two and four pistons, appeared and the researching efforts on electric propulsion systems decayed. However, the US Navy continued the researching on this topic and ordered a number of electrically propelled battleships: the *Jupiter* in 1912, one *New Mexico* class battleship in 1914, five *Tennessee* and *Colorado* class battleships in 1915 and two battle cruisers, *Lexington* and *Saratoga*, over 1916-1919.

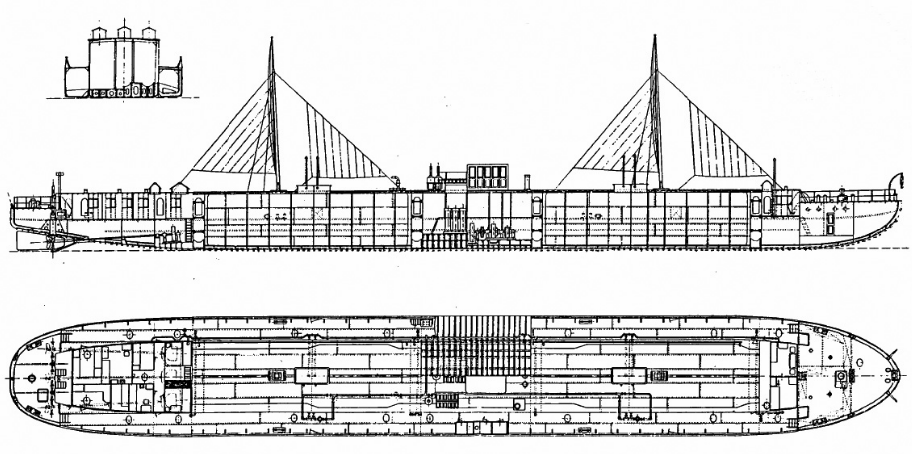

Figure 3. Vandal (San Petersburg)

In the early 1920's, due to a strong competence of transatlantic passenger liners, turbo-electric machinery was employed to increase the available propulsion power, which allowed travel times to be reduced. A French line cruiser including this propulsion system was the *S/S Normandie* (figure 4). It was launched in 1932, being the largest and fastest ship in the world, and employed electric generators coupled to steam turbines to feed four 29MW synchronous motors on each screw shaft. The propellers' speed could be changed by adjusting the electrical generator frequencies. At the rated speed, each generator fed one synchronous motor but, at lower speeds, the configuration could be changed feeding two motors per generator. However, in general, electric propulsion systems were no viable technically neither economically.

In certain cases, such as icebreakers and scientific ships, the electric propulsion presents more flexibility and maneuverability than conventional systems. The first diesel-electric propelled icebreaker was the *Ymer*, a Swedish flag ship with 9000HP and 4330 displacement tons, which was operated from 1933 until 1970 (Koehler, 1998).

The electrical propulsion systems were widely applied in US Navy ships during World War II. More than 300 vessels were built including this propulsion system. Most of these warships included 6000HP diesel-electric groups although in certain

Figure 4. Normandie (Compagnie Générale Transatlantique).

cases, such as T-2 tankers, turbo-electric systems were also applied. After World War II, the mechanical-drive technology was improved due to high efficiency diesel engines and the electric propulsion systems almost disappeared in merchant vessels until the 1980's. The *SS Canberra* line cruiser, launched in 1960, can be considered as an example of such electrically propelled vessels. Two synchronous three-phase 6000V electrical motors were applied to twin screws and fed by means of two 32.2MW steam turbine driven alternators. With 42500HP, the *SS Canberra* becomes the most powerful steam turbo-electric propelled passenger ship ever built. In the 1980's, the introduction of new power semiconductor devices allowed the development of modern electric propulsion systems.

FROM THE THYRISTOR UNTIL THE IGBT

The thyristor is the first controlled solid-state electronic device that manages high electrical powers and was employed for industrial variable speed drives in the 1970's (ABB AS Marine, 2003). The cruiser *Queen Elizabeth II*, restructured including electrical propulsion (95.5 MW) in the mid 1980's, was a pioneer using thyristor-based power converters. Other line cruisers, such as the *Fantasy* (USA) and the *Crystal Harmony* (Japan), were modified including thyristor-based electrical propulsion systems. In the 1990's, the Finnish shipyards and ABB developed the Azipod system, an innovative design for electrically propelled vessels, which improved their performance and maneuverability. The *Seili*, a service vessel modified in 1990, was the first ship including a 1.5MW Azipod system.

The basic components of an EPS are the electric power generation subsystem, the power conversion stage and the electric motors applied to propellers. Recent and current developments of these electric propulsion components are discussed inside this section.

Electric Power Generation

The power source of EPS is a set of electrical generators mechanically coupled to combustion engines which are fueled with diesel or heavy fuel oil. Alternative power sources, especially at high power levels, are gas engines, gas turbines, steam turbines or combined cycle turbines (Mowill, 1998). Moreover, in certain cases such as LNG carriers, gas is a low-cost option (U.S. Congress, 2006).

In comparison to mechanical propulsion systems, a conventional EPS consists of a number of diesel engines operating at medium or high speeds, with lower weight and cost. This prime movers redundancy allows the system reliability and the design flexibility to be increased reducing the repairing times. Moreover, new developments on combustion engines increase their efficiency and reduce the NOx and SOx emissions at their rated speed. In case of an EPS consisting of several diesel engines, the optimum operational point can be maintained by starting and stopping the generator sets depending on the connected electrical loads and trying to maintain the optimum load point of the diesel engine (Mahon, 1992).

Power electronic devices

Since the appearance of the first semiconductor power electronic device, the thyristor in late 1950's, a number of new devices, whose technology is now mature, were introduced e.g. the TRIAC, gate turn-off thyristor (GTO), bipolar power transistor (BJT) or power metal-oxide-semiconductor field-effect-transistor (MOSFET) (Bose, 1992).

Controlled devices, such as thyristors, TRIACs and GTOs switch at low frequency and their activation can be controlled by means of a current pulse. Moreover, in case of GTOs, if the gate circuit is properly designed, the device can be switched off. Switching at higher frequencies, the power levels which can be managed by BJTs and MOSFETs are lower but the obtained voltage and current signal waveforms are improved.

Power converters based on thyristors and GTOs have been successfully developed and applied to drive electric motors. Due to the low efficiency of these converters, new devices were introduced, e.g. insulated gate bipolar transistors (IGBTs) in 1983, static induction transistors (SITs) in 1987, static induction thyristors (SITHs) and MOS-controlled thyristors (MCTs) in 1988. Power converters based on these semiconductors are commercially available but new advances of design techniques and electronic technology allow these devices to evolve continuously, i.e. reverse-blocking IGBTs (Klumpner, 2006).

Power Converters

Power converters have evolved trying to reduce size, weight, losses and cost while increasing efficiency, reliability and safety. The most employed converter topologies in EPS are rectifiers, cycloconverters, synchroconverters and PWM voltage source inverters (VSI) (see figure 5).

Controlled rectifiers are employed as low-power dc-motor drives (up to 5MW) and, as a consequence, they are not applied to EPS in vessels. Cyclo- and synchro-converters are employed as synchronous motor drives. Cycloconverters are commonly applied to EPS in icebreakers due to their high torque at low speed. Other vessels, propelled by means of synchronous motors and without the previous requirement, can take advantage of size reduction, controller simplicity and fixed harmonic spectrum associated to synchroconverters. Being the low frequency converter topologies commonly based on thyristors, whose efficiency is low in comparison to high frequency converters, PWM VSIs have been proposed to drive synchronous, asynchronous, permanent magnet and induction motors.

Cycloconverters allow fixed amplitude and frequency input signals to be converted to variable amplitude and frequency output signals at low switching frequency and without an inner dc bus. It must be considered that the output frequency must be lower than the input frequency. Due to the variable frequency and amplitude of the output signal, they are especially appropriate in vessels which require high torque at low speed, i.e. icebreakers or dynamic positioning (DP) vessels. Typical loads of these converters are 30MW, 500 rpm ac motors.

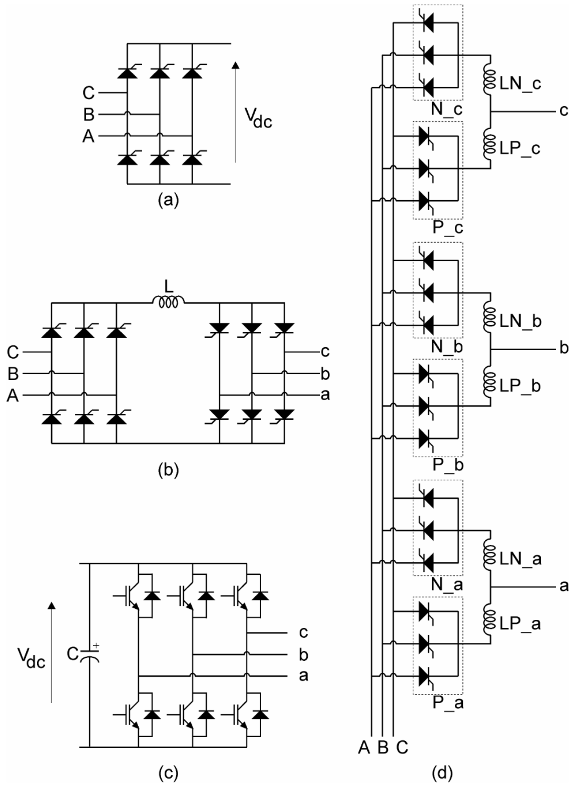

Figure 5. a) Controlled rectifier, b) Synchroconverter c) PWM VSI and d) Cycloconverter.

Synchroconverters contain a controlled thyristor rectifier, an inductive dc-link and a thyristor inverter which is operated as a current source inverter. The motor speed can be controlled by adjusting the frequency of the output current while torque and power are managed by regulation of the dc bus voltage. Due to the fact that the operation of rectification and inverting stages can be changed dynamically, the propellers can be stopped or changed their rotation sense very fast. As a consequence of the available dc bus, input and output converters can be independently controlled, which improves the quality of the input current waveform (Clegg 1999). Moreover, this topology can manage higher powers than cycloconverters (around 100MW). However, due to low frequency switching, the motor torque can beat at low speeds. At rated speed, this topology generates less noise and vibrations than cycloconverters, which makes it interesting in passenger vessels.

PWM VSIs are based on power devices with controlled turn-off, such as IGBTs and GTOs, and operate at higher frequencies than thyristor-based converters. In order to generate the gate patterns which control the converter devices, pulse width modulation (PWM) is employed (Holmes 2003). A typical PWM VSI drive is composed of a full bridge diode rectifier as input stage, a capacitive dc-link and an output inverter. The diode rectifier can be substituted by a PWM controller rectifier in order to improve the electrical characteristics of the drive front-end stage (Kazmierkowski 2002), which avoids large passive harmonic filters. The amplitude and frequency of the output voltage waveform can be controlled and, due to high frequency switching, the motor torque can be controlled accurately and smoothly. The drive performance is maintained in the whole range of available voltage amplitudes and frequencies. Typical rated values of motors connected to these drives are 20MW, 2000rpm and 6.6kVac. Gear boxes, with high efficiency, small size and low weight, can be applied between the motor and the propeller if required.

Electrical Motors in Propulsion

The electrical motors are applied in EPS, including thrusters, and other on-board loads such as winches, pumps or fans. Typically, 80-90% of the ship electrical loads are electrical motors such as dc, asynchronous (induction), synchronous and permanent magnet synchronous motors (Mitcham, 1995).

The dc motor must be fed from a dc supply, and since the power generation and distribution system use to be a three-phase system, the dc motor must be fed from a thyristor controlled rectifier which also gives speed control. Maintenance costs and power limitations associated to these motors (up to 5MW) reduce their applicability in naval designs (Sponer, 1995).

The asynchronous or induction motor can be directly connected to the electrical network and, hence, being operated at constant speed, or can be fed from a cycloconverter or a PWM VSI in order to obtain a variable speed control. In despite of a low power range (up to 5-10MW), it can be useful due to their low maintenance costs in comparison to dc motors.

The synchronous machine is employed in large propulsion drives, typically >5MW in configurations with direct connection to the propeller shaft and >8-10MW in case of a connection through a gear box. In smaller power ranges, the asynchronous motor is a cost-competitive solution. Diverse synchronous motors are commercially available due to their design similarities to synchronous generators. The synchronous motor is controlled by means of a synchroconverter. Figure 6 shows an example of synchroconverter-based EPS.

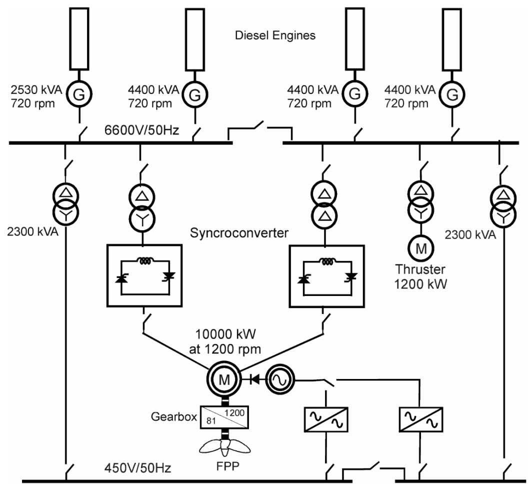

Figure 6. EPS with synchroconverter and synchronous machine.

Permanent magnet synchronous motors have been included for large power applications, such as navy vessels. The benefits associated to these machines are their high efficiency and compact design. This makes them appropriate in podded propulsion systems where the dimensions must be minimized to improve the hydrodynamic characteristics and direct water cooling can be applied. A frequency converter is applied to control the motor speed and torque. Moreover, the design and installation of podded propellers are simplified by means of these electrical motors. There are three basic approaches in podded propulsion (figure 7): fixed pod, azimuth pod (Nicod, 1998) and *Contra Rotating Propellers* (CRP) (Pakaste, 1998).

TRENDS IN EPS

Electric Power Generation

Considering decreasing fossil fuel reserves (Van Geuns, 2005), alternative energy sources, such as hydrogen, photovoltaic, wind, wave, biomass or methane hydrate, will become necessary in a near future. This section describes the application of these energy sources in future EPS (U.S. Congress, 2000).

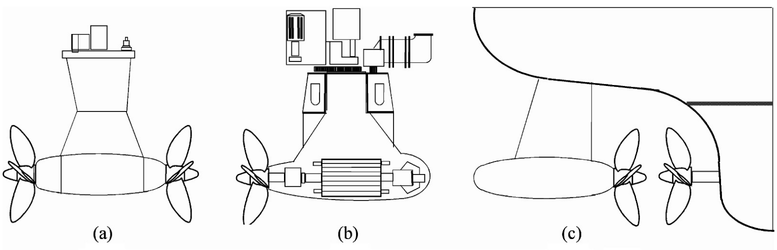

Figure 7. a) Pod, b) Azimuth pod and c) CRP.

Fuel cells are based on an electrochemical reaction which allows the hydrogen to be converted into electricity directly, continuously and efficiently. The reaction continues if hydrogen and oxygen are available and only water and heat are generated as residues. The efficiency of this technology is a 15% greater than conventional-combustion based generation plants, which reduces the required fuel consumption. As a consequence, the interest on this technology applied to powering shipboard equipment and EPS is rising in Europe, Japan and the United States (Lever, 1998, The Society of Naval Architects and Marine Engineers, 2001). In this sense, and due to the international environmental regulations, the appearance of a fuel cell based commercial ship is expected in some years. Moreover, the absence of noise and vibrations make this technology appropriate to be applied to future passenger vessels. The life cycle of fuel cells, which is highly dependent of the temperature, must be considered as a drawback.

A fuel cell-powered passenger ship is being currently designed by *Proton Power Systems* and will be operative during the summer of 2008 (Proton Power Systems, 2007). The ship, is being developed as a part of a *Zero Emission Ship* project which is funded by the European Commission. The vessel will carry up to 100 passengers through the Alster river in Hamburg, Germany.

Renewable hydrocarbon fuels, such as biodiesel and methane hydrate, allow the structure of diesel-electric propulsion systems to be maintained and, hence, can be considered as alternative energy sources to fossil fuels. The biodiesel is produced from vegetable oils or animal grease and, being employed in terrestrial vehicles, it is expected to have a great impact in marine power systems. The methane is produced by the microbiological decay of organic compounds and, being encapsulated inside a water ice-like cage, it is named methane hydrate. These fuels, in comparison to fossil fuels, reduce particle, carbon monoxide and nitrate and sulfate oxides emissions (National Biodiesel Board, 2007).

Photovoltaic (PV) panels allow the solar radiation to be transformed to electric energy. Main technologies commercially available are monocrystalline silicon cells (12-15% efficiency), polycrystalline silicon cells (10-12% efficiency), amorphous silicon cells (4-9 % efficiency) and thin film PV modules (11% efficiency). New technologies are being developed in order to increase the transformation efficiency, i.e. multijunction concentration technologies reaches up to 36% efficiency (National Renewable Energy Laboratory, 2007). Due to the fact that a number of solar cells are required to build a solar panel, control algorithms and electronic power converters are needed in order to ensure the maximum power transfer under all possible radiation conditions. As drawbacks of this technology applied to EPS it must be considered that the solar panels must be directly faced to the sun in order to extract the maximum available power, the maintenance due to marine environment and the required ship surface to attach the panels.

Nowadays there are available different ships with photovoltaic based EPS. The *Solar Sailor Ferry Boat* (figure 8) is a small hybrid diesel-solar-electric ship (69-foot 100-person) with eight maneuverable "solar wing sails" which can be used for both sail-assist propulsion and electricity generation. The ferry was built in 1999-2000 as a demonstration project and can operate on wind power, solar power, stored battery power, diesel power, or any combination. The ship was developed and built by Solar Sailor Holdings Ltd. with assistance from the Australian government, and operates in Sydney harbor.

As in the case of PV systems, wave and wind based energy sources can not be directly applied to EPS and must be combined with other generation systems due to their low efficiency and power level. The *Andromeda Leader* is a car carrier ship which includes a 4-meters-diameter and 4.5-meters-high vertical-axes wind turbine which allows 30kW to be extracted from a 25m/s wind for auxiliary machinery (Nippon Yusen Kaisha, 2004)

Power electronic devices

Three main areas focus new developments in power electronic devices: new manufacturing technologies, the improvement of already known devices and integration issues. Silicon carbide power (SiC) device technology is growing quickly (Elasser, 2003) and different research works show first results applying it to power devices. Switching frequencies of SiC devices can be 100 higher than conventional Si, with conduction resistances 100 times lower (Hefner, 2001) and higher voltage capability, and, as consequence, faster and more efficient power devices can be commercially available in a near future (Zhang, 2006, McNutt, 2007). Advances on present day power devices allow converter topologies to be re-designed improving their performance. In this sense, reverse blocking insulated gate bipolar transistors (IGBTs) have been proposed in order to obtain bidirectional switches, as required by matrix converters (Takei, 2004). Bidirectional switches based on conventional IGBTs require additional series connected diodes in order to obtain reverse blocking capability but these diodes introduce extra power losses which reduce the matrix converter efficiency (Itoh, 2005). New MOS-controlled thyristors (MCT) architectures have also been proposed in (Spullber, 2000) to decrease

Figure 8. Solar Sailor Ferry Boat.

the forward voltage drop of IGBTs in high-voltage applications. Great efforts have also been carried out on integration issues in power electronic devices. Mass-produced power electronics building blocks (PEBBs) will be available in near future and will include the electronic power converter, input and output passive filters, current and voltage sensors and the programmable controller (Ericsen, 2006) with communications interface, which will simplify the design of new EPS (Logan, 2007) and allow the management of electric loads in order to reduce the vessel operational costs (Domaschk, 2007). Other issues under researching are the minimization of thermal losses and the improvement of passive elements, i.e. inductors and capacitors.

Power converters

A number of new power converter topologies have been proposed in diverse researching papers but, probably, the most interesting ones considering future EPS are multilevel, matrix and multiphase converters (figure 9).

Multilevel converters were proposed in the early 1980's (Nabae, 1981, Bhagwat, 1983) and their importance has been growing up to date due to the continuous technology developments and new modulation techniques (Holmes, 2003). The operation principle of these converters is the generation of different dc-bus voltages in order to improve the quality of the ac voltage waveform. Three main classes have been proposed in literature: diode-clamped, flying-capacitor and cascaded series converters. In case of n-level diode-clamped and flying-capacitor multilevel converters the dc bus is unique and consists of n-1 capacitors which are connected to 2(n-1) switches composed of IGBT with FWD diode. As a consequence, the ac voltage waveform can be synthesized from n available dc voltages, including zero voltage level, which reduces the harmonic distortion of the ac output signal (Pan, 2005). Cascaded series converter topologies consist of single-phase H-bridges with separated dc buses which, depending of

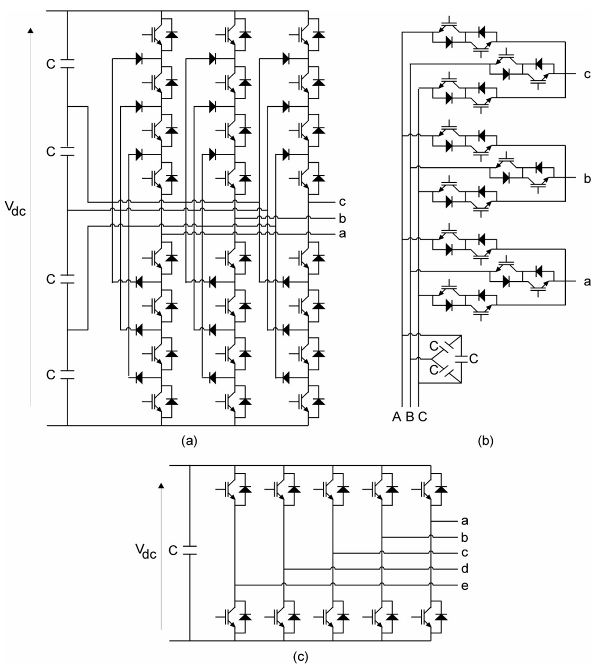

Figure 9. a) Multilevel , b) Matrix and c) Multiphase converters.

their switching status, change the overall ac voltage at each time instant (Loh, 2005). Three main control techniques are applied to generate the gate patterns controlling these topologies: low frequency PWM (Du, 2006), high frequency PWM (Holmes 2003) and hybrid (Manjrekar, 2000). In first case, each switch composed of IGBT and FWD diode switches one time at the fundamental ac frequency. As a consequence, a higher number of levels is required to minimize the output harmonic distortion. In case of high frequency PWM operation, different techniques are available but probably, if cascaded PWM converters are considering, the most interesting approach is the carrier shifting technique, which minimizes the output harmonic distortion in case of equal dc voltages. A hybrid multilevel converter considers that one converter, composed of IGCTs, switches at low frequency and a second high frequency PWM converter cleans the harmonic spectrum of the first one. Commercial multilevel converters based on IGCTs are already available for EPS, such as ACS series from *ABB*, reaching 25MW. Being a recent technology, a fast evolution of commercially available drives can be expected during the next decade.

Matrix converters were proposed in the early 1990's as an alternative to buck-to-buck high frequency PWM topologies without dc-link, which reduces drive maintenance costs and increases reliability. Matrix converters consist of an array of m×n bidirectional switches, where m and n are the number of input and output phases respectively, which allows the interconnection status of input and output phases to be changed (Kazmierkowski, 2002). It must be considered that two input lines can not be connected to the same output phase and the output line circuits can not be disconnected. Under these assumptions 27 different switching states can be applied to a 3×3 matrix converter, which increases the complexity of pulse width modulators (in case of a 3-phase 3-wires inverter, only 8 switching states are available). Moreover, different practical issues, such as the passive input filter for compensation of reactive power or a clamp circuit to avoid over-voltages during the converter operation, must be considered during the converter design (Wheeler, 2002). The amplitude and frequency, for low frequency components, of matrix converter output voltages can be changed by applying properly a modulation technique. The first modulation technique was attributed to Venturini in the early 1980's but the maximum output voltage was limited to 50% of the input voltage and the displacement factor must be equal to 1. Being impractical, it was modified to reach 87% and variable displacement factors in (Alesina, 1989). Due to its complex implementation in real-time, scalar modulation methods were proposed obtaining equivalent results at high switching frequencies. SVPM methods, as in case of PWM inverters, were proposed in order to simplify the modulation technique conceptually. Moreover, these methods can result into a better performance in case of unbalanced input voltages, as it is shown in (Jussila, 2007). Commercially 75kW motor drives based on matrix converters are available nowadays (Yaskawa, 2007) but it can be expected a fast growth of this technology due to developments in power modules, i.e. a new 360kVA module from *SEMELAB* is available, and new reduced size input filters.

Multiphase converters have been proposed, firstly in 1969 (Ward, 1969), to drive multiphase induction motors. As will be shown in the following section, these motors have greater reliability than conventional 3-phase motors (Singh, 2002) and, as a consequence, can be successfully applied to EPS. Multilevel converters share a common dc-bus and include so many legs, composed of two or more (multilevel) switches, as phases of the controlled motor. It must be considered that 3-phase inverters can be treated as a particular case of multiphase topologies and the modulation techniques applied to 3-phase inverters, such as sinusoidal or space-vector PWM, have been extended to multiphase converters (Iqbal, Ojo, 2005).

Electrical Motors in Propulsion

Conventional electrical motor technologies have reached their maturity and only permanent magnet motors could be improved in a near future. The expected advances in electrical motors are related to the introduction of superconductors and multiphase technologies.

Researching advances on electrically loss-less materials, known as superconducting wires (Gubser, 2003), has improved the efficiencies and power densities of rotating machines while reducing their sizes and weights. There are two basic superconductor types: Low temperature superconductor (LTS), around 10K, and high temperature superconductor (HTS), above 100K. Due to the operation temperature both technologies require a refrigeration system, being smaller and simpler in case of HTS wires. It must be considered that the power consumption of these refrigerators is negligible related to the generator or motor power (Bretz, 2004).

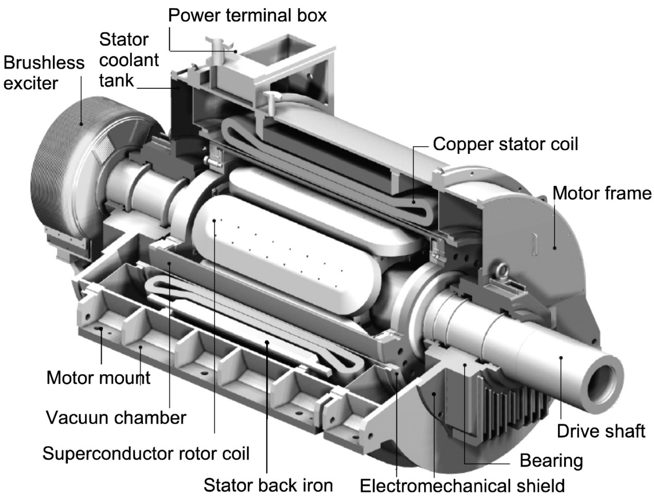

Figure 10. 5MW HTS motor prototype (source: American Superconductor)

Depending on the selected superconductor material and the motor configuration, different researching prototypes of these electrical machines have been proposed (Pallarès, 2002) but first commercially available approaches are based on HTS synchronous motors (American Superconductor, 2007). These motors are more power-dense, quieter, lighter and smaller than the equivalent conventionally designed machine. American Superconductors, Inc. has developed two HTS synchronous motors at 5MW (figure 10) and 36.5MW for the US Navy (Snitchler, 2005). Siemens have also developed electrical machine prototypes based on HTS for ship propulsion systems (Siemens, 2005).

Multiphase induction motors are known since 1969 (Ward 1969) and, due to their characteristics, during the last years, the researching efforts on this topic have been increased (Levi 2006). In comparison to ac three-phase induction motors, multiphase machines decrease the per-phase required power, reduce the torque ripple and noise, have a higher reliability and reduce the rotor harmonic currents (Terrier 2004). These characteristics make these multiphase machines appropriate in high-power and high-current applications, such as EPS.

The general structure of a possible future EPS is shown in figure 11. The electrical power is generated by means of conventional and renewable energy sources such as diesel, fuel cells or PV. HTS motors and generators can be included during the design stage in order to improve the electrical power consumption efficiency and power density. Moreover, the overall efficiency and reliability is ensured by applying power electronic converters which allows a global electrical power flux management. In this sense, a flywheel-based active compensator can be considered to mitigate the dc-bus power disturbances.

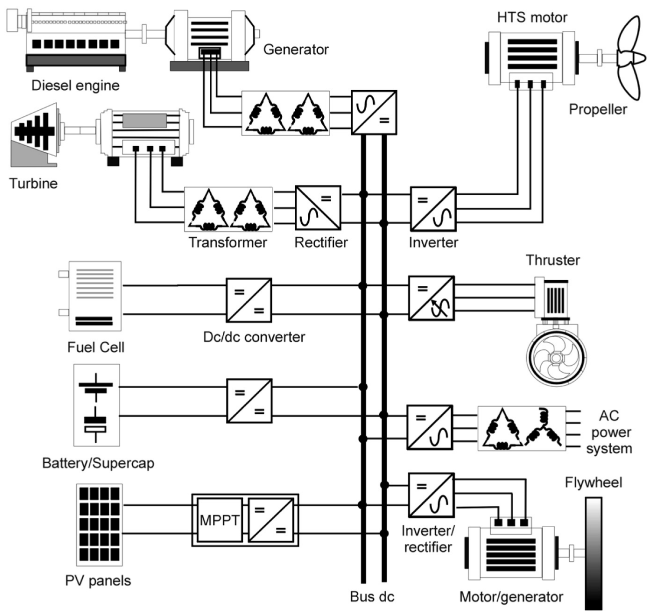

Figure 11. EPS including new trends

CONCLUSIONS

This paper shows the historical evolution, the state of art and analyzes future trends in electric propulsion systems in commercial vessels. Diverse issues related to EPS, such as electric power generation, electronic devices, power converters and electrical motors, have been discussed considering the present day available technology and their future developments.

Advances in power electronic devices and converters, new renewable energy sources and applications of material science to the design of electrical motors will allow conventional EPS to be improved: higher efficiency, reliability and security, easier EPS design and automation process, lower emission levels and better power management.

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