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E-Type self-propelled vessel: a novel concept for the Danube

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ABSTRACT

The goal of the present study is to encourage the discussion on the future of the Danube fleet by providing a novel approach to design of self-propelled dry bulk cargo vessels for the Danube. The main dimensions of a standard European CEMT Va class vessel are re-examined in the light of the Danube navigation conditions, characterized by the shallow-water sectors and thus, considerably affected by the low-water periods. As a result, a shallow-draught vessel of increased beam, the so called *E-Type*, is put forward. Given that the proposed design could be regarded as “unusual” by classification societies, the preliminary design study is followed by a thorough analysis of structural strength, with particular emphasis on the longitudinal strength issues. The study is complemented by an assessment of energy efficiency of the novel concept. It is believed that the proposed *E-Type* concept could represent a viable, cost-effective and environmentally-friendly solution for the present navigation conditions on the Danube.

Keywords: Innovative Danube vessel, Shallow-draught vessels, *E-Type* vessel, Unusual design, Energy efficiency in shallow water

1. INTRODUCTION

As a rule, a ship design study is based on the similar vessels of the existing fleet. Usually, a successful vessel is adopted as a prototype and modified so as to fulfil particular requirements. However, if the operational conditions and desired performance of the new design considerably deviate from those used in the development of the present vessels, the ship will most likely represent a “paradigm shift”. In such cases, as Lamb (2003) points out, the designer should rely on first principles rather than on the similar vessels. Several circumstances indicate that the Danube self-propelled vessel should represent such a shift from the standard European inland vessels.

The navigation conditions on individual inland waterways may significantly differ, as well as the hinterland development and the associated market that are equally important as the fairway itself. These differences affect the composition of the fleet, as it was elaborated by Radojčić (2005): the share of the self-propelled vessels is by far greater on the Rhine than on the Danube, where push boats and convoys proved to be more effective. Even so, the utilization of inland freight vessels on the Danube and the share of the inland waterway transport in most of the Danube countries are, for years, steadily low.

The present paper stems from the dilemma whether ineffectiveness of self-propelled vessels on the Danube should be, at least to a certain extent, attributed to inadequate design of the existing ships. Although Žigić (2006) demonstrated that there is more than one option for modernization and efficiency enhancement of the present vessels, up to 80% of the benefits and drawbacks of a particular design are in fact a consequence of “early design decisions”, as stated in the recent study by Germanischer Lloyd (2013). Therefore, the design of the standard European CEMT class Va (Large Rhine Vessel) is reconsidered taking into account navigation conditions on the Danube, primarily the waterway depth restrictions. Several concepts are introduced and compared based on

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the evaluation of transport costs and annual cargo carrying capacity. The most successful design is further elaborated so as to assess the technical feasibility (structural strength, powering) and environmental performance (energy-efficiency) of the concept.

So far, only a few studies dealt with the design of the self-propelled ships for the Danube. Hofman (2006) provided guidelines for the optimal design of the Danube container vessel, as the outcome of an analysis that included the hydrodynamic considerations and transport efficiency assessment of a series of containership arrangements. Radojčić (2009) proposed the design of a multi-purpose self-propelled dry cargo vessel that included a number of novel arrangement solutions and a state-of-the-art propulsion plant. Blaauw et al. (2006) sought the most feasible design of a Ro-Ro vessel for the Danube. Despite the different goals, all the aforementioned studies investigate the influence of a low design draught and the modification of principal dimensions of the standard European vessels and hence represent important references for the present work.

Finally, it should be noted that the authors were involved in the research project Innovative Danube Vessel, carried out within the framework of the EU Strategy for the Danube Region and that the present investigation was triggered, to an extent, by the discussions that took place during the project.

2. THE PRELIMINARY DESIGN, STAGE 1: DRAUGHT VARIATION

According to the Resolution 92/2 of the CEMT (1992), the design draught of the standard European self-propelled vessels of class Va, also known as the *Large Rhine vessels*, is 2.5m ÷ 4.5m. The relevant studies on the Danube navigation, however, point towards substantial draught limitations. Using several sources, Radojčić (2009) provided a comprehensive overview of navigation conditions on the Danube which indicated that water depth by LNRL[2] on a considerable number of sectors did not exceed 2.5m. The findings of Schweighofer et al. (2010) presented within the ECCONET project showed that between 1946 and 1995, the average number of days with water depth below 2.5m was 127 and 86 at two sectors on the Hungarian part of the Danube, whereas in 2005 the number of such days amounted to 137 and 133 at the same sectors. A recent study by ÖIR (2013) carried out within the Innovative Danube Vessel project concludes that unless extensive infrastructure upgrade projects take place, the vessel draught of 2.5m cannot be guaranteed in the low water periods even in those sectors where regular maintenance is sustained. However, permanent removal of bottlenecks is under scrutiny due to growing environmental concerns, see WWF (2005).

Therefore, in the first stage of the preliminary design, the effect of draught variation on transport capacity and costs is studied. In order to establish some design trends, four vessel series were initially modeled for relevant range of lengths, based on the following conditions:

- *A-Type* vessel series (Table A.1, Appendix) represents the shallow-draught vessels (design draught $d = 2$m) of standard breadth ($B = 11.4$m) and minimal freeboard for navigation zone 3, according to the Directive 2006/87/EC.
- *B-Type* vessel series (Table A.2, Appendix) represents the shallow-draught vessels (design draught $d = 2$m) of standard breadth ($B = 11.4$m) and freeboard derived from the provision of the Germanischer Lloyd rules for classification of inland vessels by which L/D ratio should be below 35 for "usual" designs. In case that $L/D > 35$, a

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[2] LNRL, Low Navigation and Regulation Level: water level that corresponds to the flow available for 94% of the navigable season.

number of additional conditions regarding structural strength are to be fulfilled. It should be highlighted that $L/D < 35$ condition also stems from the Rhine, where typical vessels have large d and consequently D, too.

- *C-Type* vessel series (Table A.3, Appendix) represents the vessels of standard breadth (B = 11.4m), design draught d = 2.5m and freeboard derived from afore-mentioned provision of the Germanischer Lloyd ($L/D < 35$).
- *D-Type* vessel series (Table A.4, Appendix) represents the vessels of standard breadth (B = 11.4m), design draught d = 2.8m and freeboard derived from afore-mentioned provision of the Germanischer Lloyd ($L/D < 35$).

The displacement of all vessels is obtained assuming the block coefficient $C_B = 0.88$, a value typical for inland vessel hull forms. The lightship of the vessels represents the average of two values calculated using formulas (1) and (2) based on the cubic module *LBD*:

$$m_{LIG} = -6.6607 \cdot 10^{-6} \left(LBD \right)^2 + 0.21822 \cdot LBD - 4.1 \tag{1}$$

$$m_{LIG} = -4.44 \cdot 10^{-6} \left(LBD \right)^2 + 0.195 \cdot LBD \tag{2}$$

Formulas are based on Heuser (1986) and Hofman (2006). Once the deadweight and displacement are known, the deadweight coefficient may be calculated:

$$\eta_{DWT} = \frac{m_{DWT}}{\Delta} \tag{3}$$

The deadweight coefficient of the examined series is given in Fig. 1 as a function of vessel length. It may be noticed that for $L \approx 104$m, *D-Type* vessel attains an optimum. Furthermore, for this length, *D-Type* would have the highest deadweight / displacement ratio in comparison to other series. However, the deadweight coefficient of the shallow-draught *A-Type* vessel is insignificantly smaller. Low values of the *B-Type* vessel deadweight coefficient, which steadily decrease with the increase of length, indicate that vessels conforming the standard L/D ratios, cannot be feasible at low draughts.

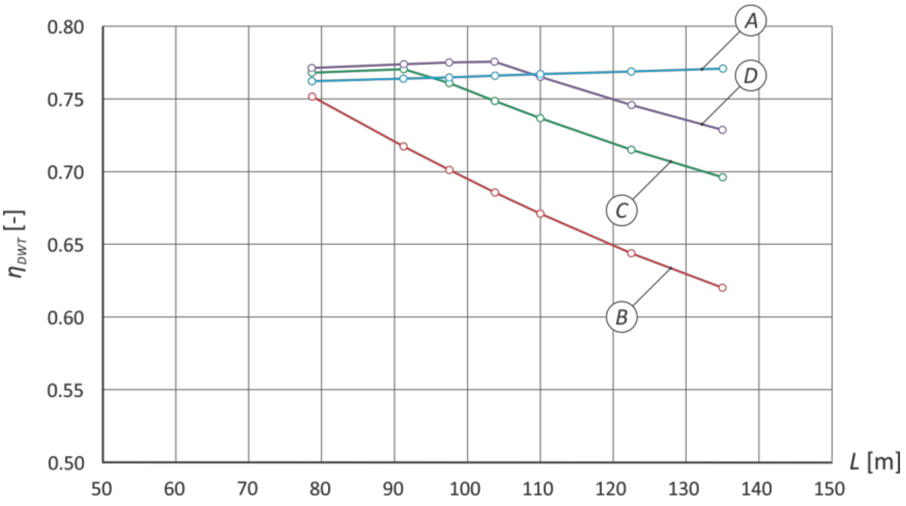


Figure 1. The deadweight coefficient of the examined vessel series

2.1. Reference cargo

In order to assess the transport capabilities of respective designs, the following parameter is introduced. Assuming that *A-Type* vessel operates fully laden 300 days a year, the “reference cargo” R_C is calculated as:

$$R_C = m_{DWT} \cdot 300 \tag{4}$$

Reference cargo may be described as maximal annual cargo carrying capacity of the vessel. R_C that corresponds to *A-Type* vessel series is given in Table 1. Furthermore, the minimal number of days required to transport the R_C (A) by *B*-, *C*- and *D-Type* series vessels when fully loaded, is calculated and presented in the same Table. The vessels with larger design draught would need less time to transport the same amount of cargo, provided, of course, that sufficient water depth on the fairway could be guaranteed. For instance, *B-Type* vessel of approximate length of 104m would have to sail fully laden some five weeks longer than the *A-Type* vessel of the same length. Contrary to that, *D-Type* vessel would transport the reference cargo in 212 days; the water depth, however, would have to be sufficient for safe navigation with draught of 2.8m throughout 30 weeks a year at least.

Table 1: Minimal number of days necessary to transport the reference cargo R_C (A)

	R_C (A)	A	B	C	D
L [m]	t/year	days	days	days	days
78.75	361199	300	304	238	212
91.25	419575	300	319	238	212
97.5	448881	300	327	241	211
103.75	478265	300	335	246	212
110	507726	300	343	250	215
122.5	566884	300	358	258	221
135	626355	300	373	266	227

It was previously demonstrated that depending on the year and the season, this could be a challenging demand for a number of the Danube sectors. However, regardless of the statistical data, the question remains what a sufficient water depth is and how does it relate to the costs of transport.

2.2. Transport costs

Out of four vessel series, only two sample vessels are selected for further analysis (Tables 2 and 3). The length of both of the vessels is limited to $L \approx 104$m, given that the highest deadweight coefficient in all the cases examined is attained (by *D-Type* vessel) for that length precisely. Besides, this length enables vessel to form a coupling train with a standard, 77m long Danube barge in total shorter than 185m, a restriction imposed by the size of locks on the Upper Danube. The vessels also have the same, standard breadth. Their design draughts are, however, considerably different: d = 2m and d = 2.8m, for *A-Type* and *D-Type* vessel, respectively. The displacement and deadweight of the *D-Type* sample vessel are also calculated for two additional operational draughts (d = 2m and d = 2.5m) whereby presuming that the block coefficient does not change considerably. It should be noted that two sample vessels have the same freeboard: $F_B \approx 0.15$m, as required by the Directive 2006/87/EC for navigation in zone 3.

Table 2: *A-Type* sample vessel

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
103.75	11.4	2	2.15	2082	1594

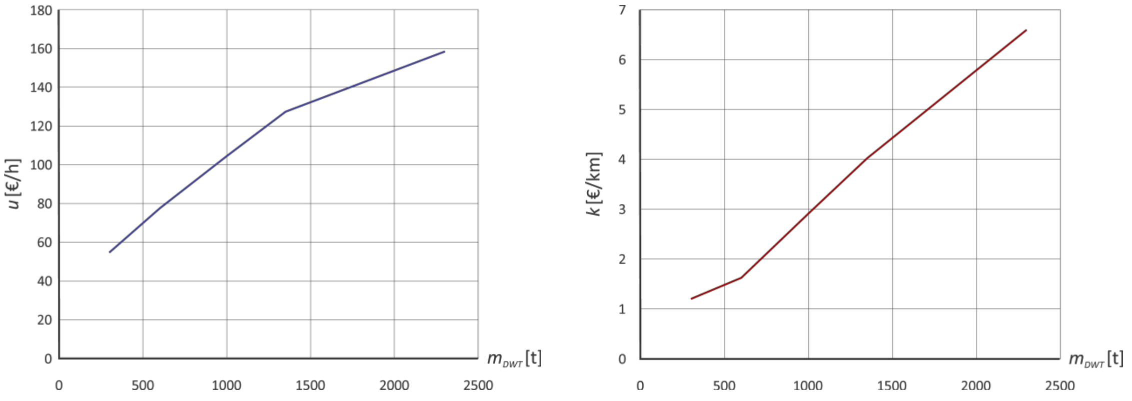
Table 3: *D-Type* sample vessel

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
103.75	11.4	2	2.96	2082	1428
103.75	11.4	2.5	2.96	2602	1948
103.75	11.4	2.8	2.96	2914	2260

The costs of transport are calculated using the model based on time and distance-related cost coefficients for inland waterway transport, as presented by Blauwens et al. (2008). The model is extrapolated so as to include m_{DWT} up to 2300t. Hour coefficient u and kilometre coefficient k estimated for year 2004 are given in Fig. 3, as a function of deadweight. In present analysis, for a known m_{DWT}, costs of transport T_C are calculated as:

$$T_C = \frac{l \cdot k + t \cdot u}{l \cdot m_{DWT}} \tag{5}$$

Here, l represents the length of the route in kilometres and t duration of the voyage in hours. The following should be noted. The cost coefficients refer to new vessels. The model includes a number of cost categories: crew wages, insurance, administrative costs (related to time), fuel consumption (related to distance), depreciation and maintenance costs (related to both time and distance travelled). Port dues, being neither time nor distance related, are excluded from the model. As port dues depend on the specific route, they are omitted from the present analysis.



(a) (b)

Figure 2. Cost coefficients for inland shipping: hour coefficient, u and kilometre coefficient, k

Duration of the voyage depends on the speed of the vessel. In limited water depth, the speed may be restrained by efficiency or safety requirements. Therefore, some “speed limits” are imposed on the examined vessels. For instance, the maximal service speed of the *A-Type* vessel may be limited by the shallow water condition $F_{nh} = 0.65$. Using the speeds derived from this condition, the costs of transport of 1594t by the *A-Type* sample vessel over *l* kilometres may be calculated for a range of water depths (Fig. 3).

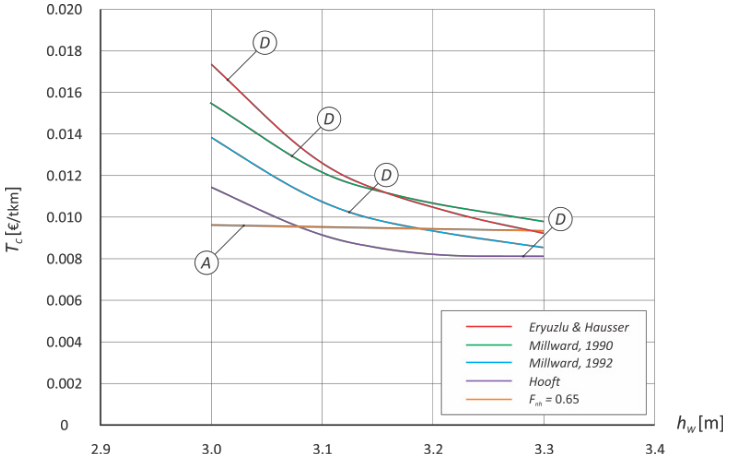


Figure 3. Costs of transport by *A-Type* and *D-Type* sample vessels

Hofman (2006), however, argues whether $F_{nh} = 0.65$ should be taken as an efficiency-related speed limit. Instead, the speed of the vessel could be optimized with the aim of attaining the highest profit possible ("economic speed"). In given conditions, this applies to the shallow-draught *A-Type* vessel only. Unlike that, the speed of the *D-Type* sample vessel has to be limited in order to avoid grounding and contact with the riverbed due to squat. Indeed, Schweighofer (2013) correctly points out that grounding is one of the major causes of accidents in inland navigation in low-water conditions. Therefore, in Fig. 3, the costs of transport of 2260t by vessel *D* over *l* km are given for a range of water depths, whereby T_C corresponds to speeds limited by squat estimated using several formulas, as given by Briggs (2006). Increase of transport costs for sample vessel *A* with the decrease of water depth is presented in the same figure. It may be noticed that the *A-Type* vessel remains practically unaffected by changes of water depth in the examined range. Contrary to that, T_C of *D-Type* vessel increases considerably as the water depth decreases, regardless of the squat estimation method used.

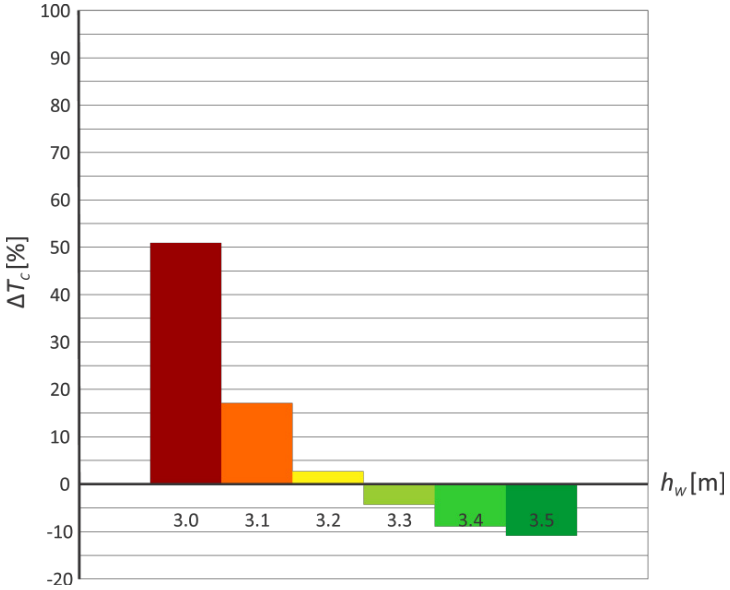


Figure 4. Average increase of transport costs of the *D-Type* vessel at 2.8m draught in comparison to the costs of the *A-Type* sample vessel

The average increase of T_C when utilizing the *D-Type* vessel at draught 2.8m instead of the shallow-draught *A-Type*, ΔT_C is given in Fig. 4 as a function of water depth. The cost-efficiency of the *D-Type* vessel would become tangible only in water depths greater than 3.3m.

3. THE PRELIMINARY DESIGN, STAGE 2: INCREASE OF BEAM

So far, it was demonstrated that shallow-draught vessels of standard breadth (*A-Type*) could be more cost-efficient in limited waterway depth conditions than the typical ones. In the next stage of preliminary design, the breadth of the *A-Type* vessel is increased to 15m so as to enlarge the cargo carrying capacity while preserving the low draught. As a result, the *E-Type* vessel series is generated (Table A.5, Appendix).

3.1 Reference cargo

Novel *E-Type* concept is analysed using the methodology laid out in the previous section. The reference cargo corresponding to the *E-Type* vessels is given in Table 4, as well as the minimum number of days required to transport the $R_C(E)$ using fully laden vessels of series B, C and D. The *D-Type* vessel would have to sail at full draught of 2.8m almost as long as the shallow-draught *E-Type* in order to transport the same amount of cargo on the annual basis. When only partially loaded, the *D-Type* vessels would have to sail much longer to attain the same R_C (for instance, at L = 103.75m and d = 2m, almost half a year longer).

Table 4: Minimal number of days necessary to transport the reference cargo R_C (E)

	R_C (E)	E	B	C	D
L [m]	t/year	days	days	days	days
78.75	477645	300	402	315	280
91.25	555340	300	423	315	280
97.5	594390	300	433	319	280
103.75	633575	300	444	325	280
110	672896	300	454	331	285
122.5	751943	300	475	342	293
135	831532	300	495	353	301

3.2 Transport costs

For the purpose of further analysis, a sample vessel of the length $L \approx$ 104m will be selected from the *E-Type* series (Table 5) and subsequently compared to the *D-Type* sample vessel.

Table 5: *E-Type* sample vessel

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
103.75	15	2	2.15	2739	2112

It was already demonstrated that water depth has a considerable effect on transport costs T_C. As a result, the *D-Type* sample vessel performed better than the *A-Type* shallow-draught ship only if the water depth was greater than 3.3m. In this section, the costs of transport by sample vessel D are weighed against the T_C of the *E-Type* sample vessel. The conclusions are principally the same as in the previous section, but the costeffectiveness of the shallow-draught vessel becomes even more evident. For all waterway depths up to $h_W = 3.5$m, the average costs of transport by the *D-Type* vessel exceed T_C of the *E-Type* (Fig. 5).

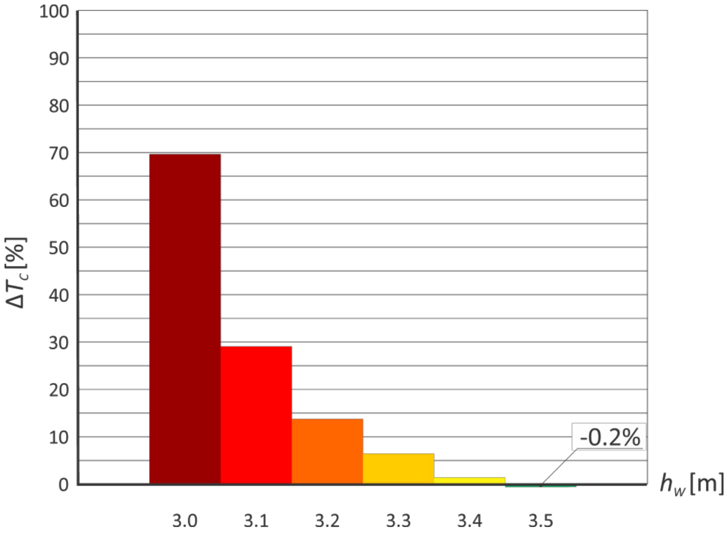


Figure 5. Average increase of transport costs of the *D-Type* vessel at 2.8m draught in comparison to the costs of the *E-Type* sample vessel

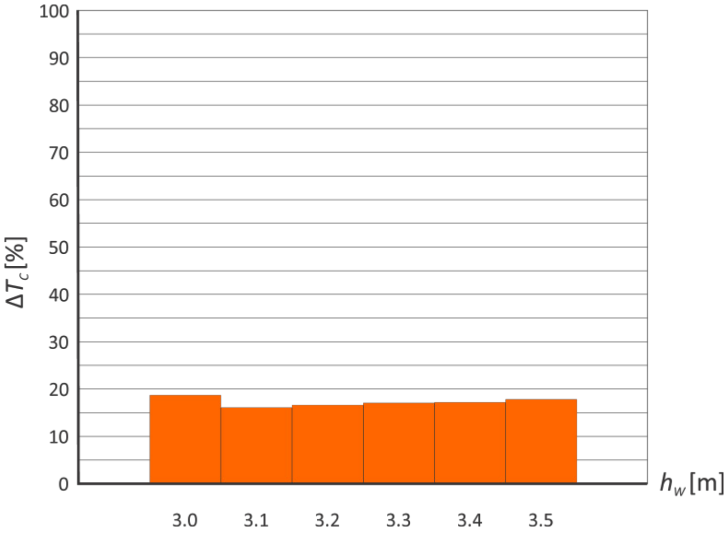


Figure 6. Average increase of transport costs of the *D-Type* vessel at 2m draught in comparison to the costs of the *E-Type* sample vessel

In case that the *D-Type* vessel sails only partially loaded, at 2m draught, the same speed restrictions would apply to both of the vessels in the examined range of water depths, but the capacity of the *D-Type* would be only just above 1400t (Table 2). In that case, the transport costs of *D-Type* vessel would rise up to about 20% in comparison with the novel *E-Type* (Fig. 6). Furthermore, the annual cargo carrying capacity of the *D-Type* would be less than 70% of $R_C(E)$.

So far, it may be concluded that the wide, shallow-draught vessel is competitive in terms of cargo carrying capacity and more cost-efficient than the standard self-propelled inland ships in water depth up to 3.5m. However, due to atypical main particulars and, consequently, exceptionally high length to depth ratio, the vessel could be regarded as an "unusual" design by the classification societies. Such designs should be additionally verified with respect to structural strength issues: buckling, longitudinal strength, torsion. It may be expected that some structural elements need to be reinforced thus making the hull structure heavier and deadweight smaller than predicted by the formulas (1) and (2) that were developed based on the typical vessels of the Rhine fleet. Therefore, in order to assess the technical feasibility of the *E-Type* vessel on one hand, and to check the evaluated deadweight (as given in Table 3), on the other, a detailed calculation of her structure is carried out.

4. STRUCTURAL STRENGTH OF THE *E-Type* VESSEL

Scantling determination of the novel vessel concept is performed according to the Rules of Germanischer Lloyd (2011) and with respect to the principles and criteria provided by the Rules. The Rules state that the vessels with $L/D > 35$ are to be considered on a case by case basis. Consequently, it was assumed that the vessel would be regarded as an "unusual design", whereby a direct calculation of the still water bending moment is to be carried out along with structural checks which include proof of buckling strength and verification of strength in testing conditions.

The Rules provide equations for determination of net thickness and net cross section modulus of platings and structural members. Net scantlings do not include margin for corrosion. All structural checks and direct calculations are performed based on calculated net scantlings. In order to obtain gross (adopted) values, corrosion additions were taken into account according to the member position, tank type etc.

The vessel is assumed to be longitudinally stiffened. Scantling calculation is performed for two cases of floors and web frames spacing: $S_1 = 2$m and $S_2 = 3$m.

Proof of buckling strength is assessed for single plate fields and lateral and torsion buckling of stiffeners. Compressive stresses for each structural member are calculated with respect to the rule bending moment (hogging and/or sagging) and cross section properties of the vessel. Single plate field buckling check includes unstiffened part of the plates between stiffeners and girders. Lateral buckling check takes into account bending and compressive stresses acting on stiffener while torsional buckling check considers torsional cross section properties of stiffener. Cross section properties are also checked for minimal scantling requirements of platings and structural members of compartments subjected to testing conditions.

Due to extraordinary low depth of the vessel, high normal stresses occur in the elements furthermost positioned from the neutral axis (deck, hatch coaming, bottom plating). High compressive stresses made some structural members prone to buckling issues. Consequently, hull girder modulus had to be enlarged by reinforcing net scantlings of the hatch coaming and deck structure. Hatch coaming net thickness was increased from 16.5mm up to 30mm and strengthened with three stiffeners instead of two. The deck net thickness was increased from 12mm to 16.5mm.

Adopted gross scantlings for $S_2 = 3$m that fulfilled the described requirements, are given in Fig. 9. Gross floor and web frame thicknesses are 9mm and 11mm respectively. For the $S_1 = 2$m case all plating thicknesses remain almost the same (except for the hatch coaming, reduced by 2mm and the bottom girders, reduced by 4mm in comparison to the $S_2 = 3$m arrangement). Moreover, stiffeners have lower hull section modulus due to decreased span, so their dimensions have also been slightly reduced.

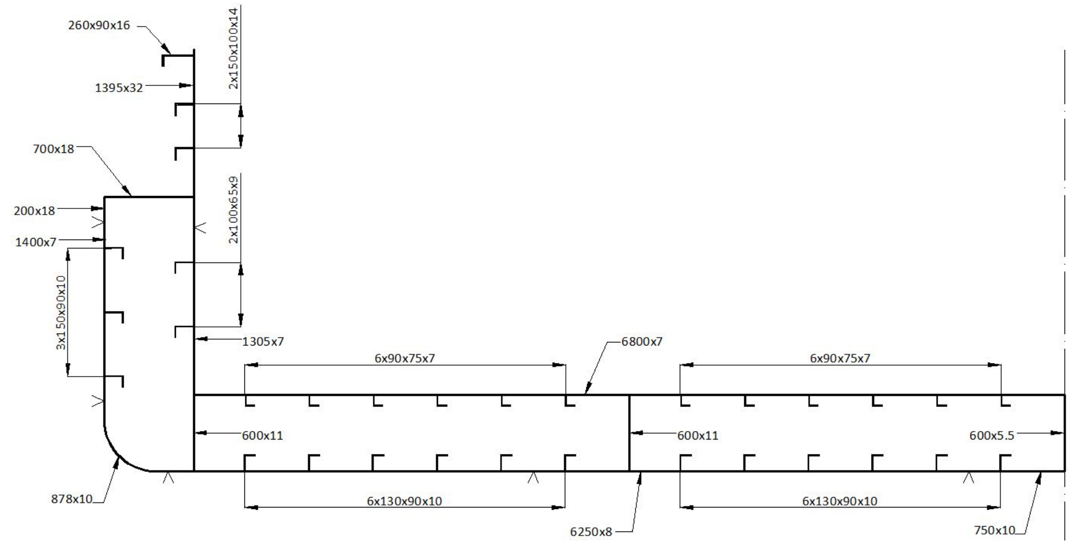
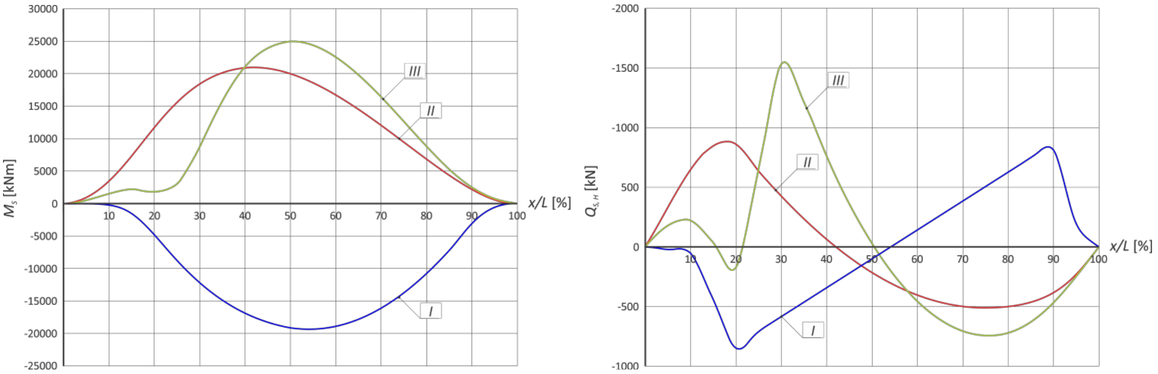


Figure 7: Gross scantlings of the web frame corresponding to S_2 = 3m structural arrangement (all dimensions are given in mm)



(a) (b)

Figure 8: Bending moments (a) and shear forces (b) in examined loading cases, corresponding to S_2 = 3m structural arrangement

Although the rule bending moment was calculated (M_H = 53459kNm for hogging and M_S = 45371kNm for sagging condition) and used for cross section properties evaluation, unusual design of the vessel required further analysis including direct longitudinal strength calculation. Longitudinal bending moments and shear forces are calculated for: fully loaded vessel (I), lightship condition (II) and loading in one run starting from the aft end of the cargo hold (III), and given in Fig. 8.

The calculations have shown that the maximal bending moment, 25000kNm, occurred in case III (loading in one run). This value is twice as low as the rule bending moment used for scantling determination of cross section properties of the vessel. Thus, the adopted gross scantlings given in Fig. 7 are also the final ones.

It should be emphasized that, following the shipbuilding practice, the inner bottom thickness t_{IB} is increased to 10mm even though 7mm would be sufficient according to the Rules requirements and all strength checks. Such reinforcement of the structural part subjected to frequent wear and tear is a typical choice of ship-owners who strive to extend the life of the vessel.

Mass of deadweight corresponding to the examined structural arrangements is given in Table 6. Hull weight is calculated based on structure weight per length distribution, whereas total mass of lightship can be estimated using standard weights of the engine, equipment, welding, paint, hatches, superstructure etc. Interestingly, it turned out that formulas (1) by Heuser (1986) and (2) by Hofman (2006) predicted the mass of lightship of the *E-Type* considerably accurate (thus confirming the results of the preliminary design stage) even though they were based on the properties of the typical Rhine vessels. This is in particular valid for the formula of Hofman (2006) giving $m_{LIG} \approx 603$t.

Table 6. Mass of deadweight corresponding to examined structural arrangements

$S_1 = 2$m	m_{HULL} [t]	m_{LIG} [t]	m_{DWT} [t]
t_{IB} = 7mm	408.9	573.5	2136.5
t_{IB} = 9mm	430.6	595.2	2114.8
t_{IB} = 10mm	442.2	606.8	2103.2
$S_2 = 3$m	m_{HULL} [t]	m_{LIG} [t]	m_{DWT} [t]
t_{IB} = 7mm	397.3	561.9	2148.1
t_{IB} = 9mm	420.2	584.8	2125.2
t_{IB} = 10mm	431.4	596.0	2114.0

5. ENERGY-EFFICIENCY IN LIMITED WATER DEPTH

Energy-efficiency (related to the amount of CO_2 emitted while transporting given mass of deadweight by certain speed) is being put forward by International Maritime Organisation (IMO) as one of the key indicators of environmental performance of sea-going ships. For inland fleet, however, a similar legal framework presently does not exist. There are, nevertheless, research attempts to establish a proper approach to assessment of the energy-efficiency of inland vessels as well. In present paper, the method proposed by Simić (2012) was employed. The so called “modified energy-efficiency design index”, $EEDI^*$ is calculated as:

$$EEDI^* = \frac{P_{Bref} \cdot SFC \cdot CF}{m_{DWT} \cdot v_s} \tag{6}$$

Formula (6) is shaped following the general idea put forward by IMO, see IMO (2011) and IMO (2012). There are, however, some important differences. P_{Bref} represents brake power required for attaining certain service speed v_s, instead of 75% of installed power, as envisaged for the seagoing ships. For each ship, $EEDI^*$ is calculated for a range of service speeds, instead for one, reference or design speed. Although the reasons for such deviation from the approach implemented by IMO are beyond the scope of this paper, it should be noted that they are inherent to the exploitation of inland vessels, as outlined in Simić & Radojčić (2013).

In the present study, $EEDI^*$ of *D-Type* and *E-Type* sample vessels attained in $h_W = 3.5$m was calculated for a range of service speeds (Fig. 9). At this water depth, fully laden *D-Type* vessel becomes as cost-efficient as the proposed *E-Type* (see Fig. 5). Nevertheless, from the environmental protection point of view, the novel concept remains considerably advantageous. Namely, $EEDI^*$ attained by the *D-Type* at design draught is higher than the value corresponding to the *E-Type* at the same service speed, even at moderate speeds. For instance, at 13km/h, the overall costs for society (environmental costs vs. benefits for society) double when sailing with the standard vessel at large draught, in comparison to the exploitation of the shallow-draught *E-Type*. On the other hand, the novel concept may attain the same level of energy-efficiency at higher speeds, thus enabling shorter transportation times.

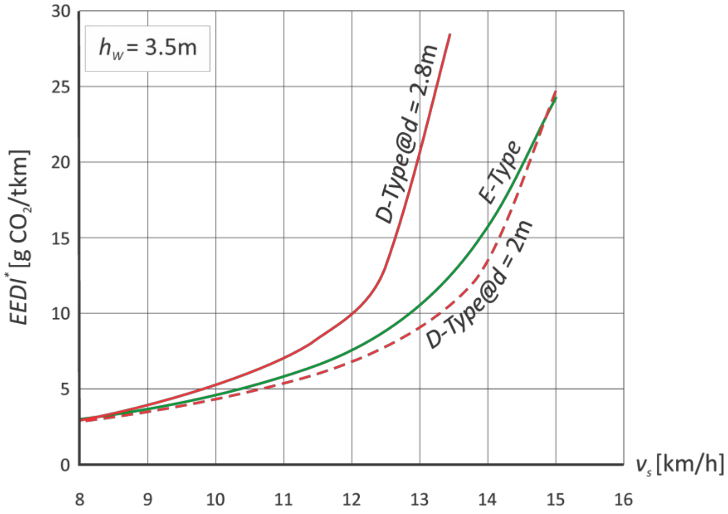


Figure 9. Modified energy-efficiency design index of examined vessels

In order to attain the energy-efficiency level of the *E-Type* sample vessel, the *D-Type* ship would have to sail partially loaded, at d = 2m. In that case, however, due to a considerably smaller deadweight (see Table 2), the transport costs would be up to 20% higher in comparison to the fully laden shallow-draught *E-Type* (Fig. 6).

6. CONCLUDING REMARKS

The starting point of the study was a dilemma whether a shift in the design of the standard European inland ships could improve the performance of self-propelled vessels on the Danube. The analysis of influence of main particulars on transport costs led to conclusion that improvements are possible. The novel *E-Type* concept, presented in Fig. 10, was proposed, featuring shallow-draught that would enable a regular service throughout the most of the year, and increased beam so as to regain the cargo capacity of a standard vessel.

It is well known that ship design is a trade-off between opposing demands. Accordingly, the proposed *E-Type* concept has certain drawbacks as well. Possibly the most significant one comes as a consequence of increased beam; the upstream navigation range of the vessel would be limited to Regensburg, due to the 12m width of the local lock. Another operational issue could represent the radius / the reaching point of existing port cranes corresponding to breadth of the standard vessels (up to 11.4m).

E-Type has not been optimized for transport of containers. Hofman (2006), however, indicated that a container vessel for the Danube should be “beamy” (rather than long and narrow), with the length to beam ratio 7 ÷ 9. Being on the lower boundary of the suggested *L/B* range, the proposed concept could be, perhaps, suitable for efficient transport of containers. Still, a number of aspects would have to be reconsidered. Among other issues, vulnerability to wind gusts and related intact stability failures in realistic weather conditions would have to be investigated. Having in mind that the novel designs may not be properly taken into account by the existing stability criteria, as it was noted by Belenky et al. (2008), it would be advisable to use a risk-based approach to stability of inland vessels, proposed by Hofman & Bačkalov (2010).

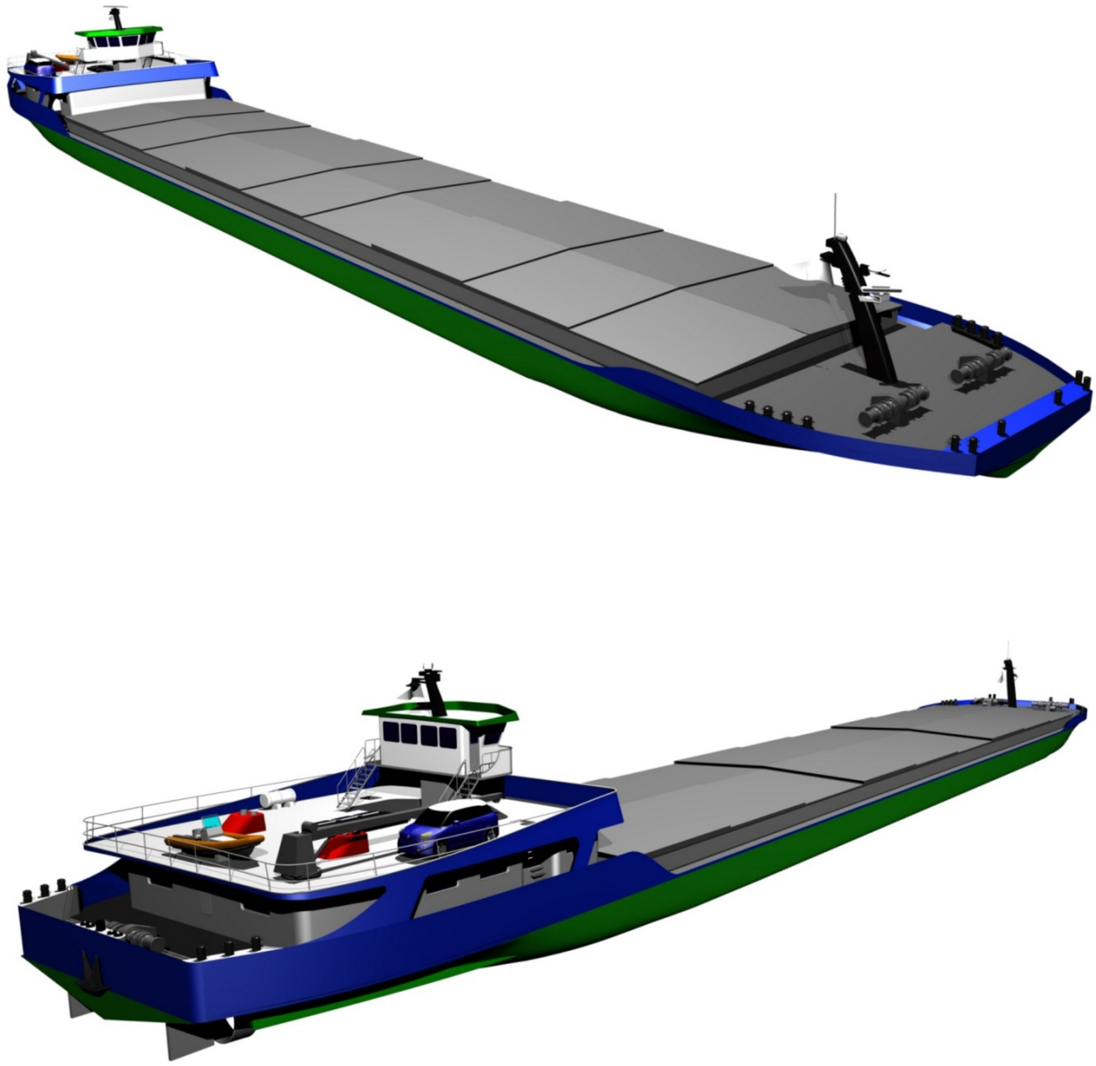


Figure 12. *E-Type* self-propelled vessel for the Danube

Finally, the proposed breadth B = 15m and draught d = 2m should not be considered as ultimate. The main dimensions could be further optimized and fine-tuned to attain better economic performance. Moreover, the study demonstrated the importance of the vessel speed. Given that the low draught allows for larger grounding-related safety margin in the restricted water depths, the speed of the *E-Type* concept could be adjusted to the economic speed related to the highest profit possible, as defined by Hofman (2006). On the other hand, it was also shown that *E-Type* could sail at a higher speed at the same energy efficienc level (same $EEDI^*$) when compared to the standard vessel of a deeper draught. It is, therefore, considered that proposed *E-Type* concept represents a sound basis for development of an innovative, environmentally-friendly and economically viable self-propelled vessel for the Danube.

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NOMENCLATURE

B	vessel breadth (m)
C_B	block coefficient (-)
CF	carbon emission factor (g CO_2/t fuel)
D	vessel depth (m)
d	vessel draught (m)
$EEDI^*$	modified energy-efficiency design index (g CO_2/tkm)
F_B	vessel freeboard (m)
F_{nh}	depth-based Froude number (-)
h_W	water depth (m)
k	kilometre cost coefficient (€/km)
l	length of the route (km)
L	vessel length (m)
m_{DWT}	mass of deadweight (t)
M_H	bending moment for hogging (kNm)
m_{HULL}	hull weight (t)
m_{LIG}	mass of lightship (t)
M_S	bending moment for sagging (kNm)
R_C	reference cargo (t/year)
$S_{1,2}$	floors and web frames spacing (m)
SFC	specific fuel consumption (g/kWh)
t	voyage duration (h)
T_C	transport costs (€/tkm)
t_{IB}	thickness of inner bottom (mm)
u	hour cost coefficient (€/h)
v_s	service speed (km/h)
Δ	vessel displacement (t)
η_{DWT}	deadweight coefficient (-)

Appendix: Examined vessel series

Table A.1: *A-Type* series of vessels

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
78.75	11.4	2	2.15	1580	1204
91.25	11.4	2	2.15	1831	1399
97.5	11.4	2	2.15	1956	1496
103.75	11.4	2	2.15	2082	1594
110	11.4	2	2.15	2207	1692
122.5	11.4	2	2.15	2458	1890
135	11.4	2	2.15	2709	2088

Table A.2: *B-Type* series of vessels

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
78.75	11.4	2	2.25	1580	1187
91.25	11.4	2	2.61	1831	1313
97.5	11.4	2	2.79	1956	1372
103.75	11.4	2	2.96	2082	1428
110	11.4	2	3.14	2207	1481
122.5	11.4	2	3.50	2458	1583
135	11.4	2	3.86	2709	1680

Table A.3: *C-Type* series of vessels

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
78.75	11.4	2.5	2.65	1975	1517
91.25	11.4	2.5	2.65	2289	1763
97.5	11.4	2.5	2.79	2445	1861
103.75	11.4	2.5	2.96	2602	1948
110	11.4	2.5	3.14	2759	2033
122.5	11.4	2.5	3.50	3072	2197
135	11.4	2.5	3.86	3386	2357

Table A.4: *D-Type* series of vessels

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
78.75	11.4	2.8	2.95	2212	1706
91.25	11.4	2.8	2.95	2563	1983
97.5	11.4	2.8	2.95	2739	2123
103.75	11.4	2.8	2.96	2914	2260
110	11.4	2.8	3.14	3090	2364
122.5	11.4	2.8	3.50	3441	2566
135	11.4	2.8	3.86	3792	2763

Table A.5: *E-Type* series of vessels

L [m]	B [m]	d [m]	D [m]	Δ [t]	m_{DWT} [t]
78.75	15	2	2.15	2079	1592
91.25	15	2	2.15	2409	1851
97.5	15	2	2.15	2574	1981
103.75	15	2	2.15	2739	2112
110	15	2	2.15	2904	2243
122.5	15	2	2.15	3234	2506
135	15	2	2.15	3564	2772