ENVIRONMENTAL CONSIDERATIONS
TO STRUCTURAL MATERIAL SELECTION FOR A BRIDGE

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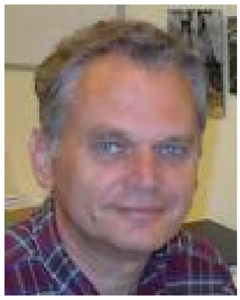

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About the author:

Ryszard A. Daniel (53) completed his study at the Silesian University of Technology in Gliwice, Poland, specialization: bridges. He has been active in various branches of industrial and civil engineering as a senior designer, project leader and in other functions. His recent activities cover steel hydraulic structures and bridges including innovative material applications. He is an author of numerous publications in this field. In the management of the project discussed in this paper, he was assisted by Gerland Nagtegaal (29).

Introduction:

Environmental consideration to the choice of construction materials is an issue of growing importance in engineering. In the Netherlands, as in some other countries, the government responds to this issue by promoting materials and technologies which reduce environmental impact of both, public and private projects. However, an assessment of this impact is quite complex, especially in regard to complex construction projects. The existing analytical methods like LCA (life-cycle analysis) require an extensive data input. These data are not known yet at the early stage of a project, when the materials are usually selected.

This paper presents a relatively simple ecological material analysis for a bridge. The method of this analysis was originally developed to evaluate a number of material options for a pedestrian bridge in the Noordland inner harbor, Province of Zeeland. In that particular project, the analysis resulted in an advice pointing to a bridge of pultruded FGRP sections as the environmentally best option. The customer, Regional Directorate for Public Works and Water Management (*Rijkswaterstaat*), followed this advice. The bridge is in service since November 2001. The environmental analysis performed for this project has already been presented on two EPTA conferences [1], [2]. It has also been published in the Netherlands [3] and in Germany [4]. For the purpose of the current presentation, however, some new aspects and an important new material option (concrete) have been investigated. The idea was to present an approach which can directly be applied in comparable environmental analyses for other construction projects.

Such analyses are rather new in engineering nowadays, but the call to perform them is growing. An example is the current discussion in Germany and some other countries about global climatic impacts of various technologies. There are strong indications and a growing public conviction that e.g. the recent floods in Central Europe are related to climatic changes caused by people. In the coming years the engineers will certainly have to face a demand to limit the environmental impact of their designs. This also applies to bridges.

1. Case study, data

In the autumn of 1998 the Regional Directorate for Public Works and Water Management in the province of Zeeland ordered an investigation on construction materials for a pedestrian bridge in the Noordland inner harbor. A year later an order for the entire project management followed. The new bridge was scheduled to replace an old structural steel bridge, which had been functioning for 35 years and was largely deteriorated by corrosion. This was not surprising considering the extreme conditions of that particular location. The Noordland inner harbor makes part of the Eastern Scheldt Storm Surge Barrier complex, which means severe weather conditions and high chloride exposure. The bridge had to provide a double span access to a mooring pontoon, Fig. 1. There is no navigation under the bridge. The span support on the pontoon has a variable level due to the tides. Other principal design data of the bridge were as follows:

- static system: 2 free beams, one in variable descent;
- bridge span length: 13.5 m each;
- deck width: 1.600 m;
- handrail height: 1.000 m above bridge deck;
- design service load: 4.0 kN/m² acc. to NEN 6788 [5];
- load factors: γ = 1.5 and an impact factor of 1.3;
- other loads: wind, snow acc. to NEN standards;
- acceptable deflection: 1/250 of beam span.

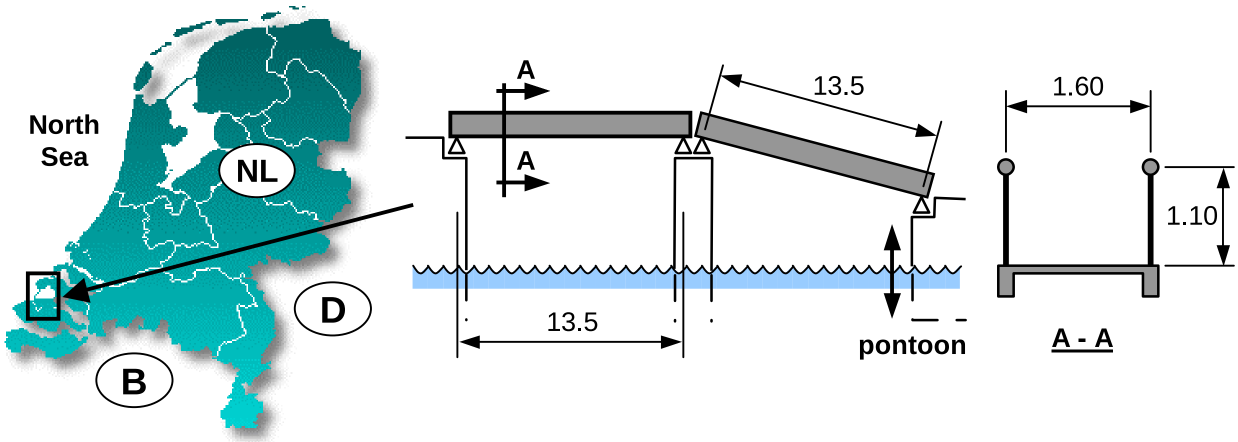


Fig. 1. Bridge scheme

The customer was interested in comparing the performances of the first four possible bridge materials from the list mentioned below. The fifth material in this list, concrete, was investigated later for the purpose of this presentation.

- structural steel (coated);
- stainless steel;
- synthetic material (composites);
- aluminum;
- concrete.

The main reason not to consider concrete was its high weight. It would jeopardize the stability of the existing bridge supports in this project. In a general case, however, concrete is often used in construction projects of this kind. Therefore it is should be considered in most other analyses. For this reason it was investigated separately; and the results are presented in this paper. Another material which has not been investigated, is timber. The reason was its combustibility and a short service life. Nevertheless, timber can certainly be advantageous – also in respect of environment – in other bridge projects. In this presentation timber is not included because the considerations, which determine its environmental performances are of a different nature. An important criterion is e.g. sustainable forest exploitation [6]. It is difficult to quantify such criteria in a manner which allows for a comparison with other materials.

2. Scope of investigation

Although the original investigation order did not mention that, it was clear that more bridges of the similar construction were to be replaced at that location in the nearest future. The customer wanted a thorough evaluation of the available material options. The performances of each option had to be quantified in the four following criteria:

- initial costs (construction);
- maintenance costs;
- service life;
- environmental impact.

Maintenance costs and service life appeared to show strong correlation between each other. It was, therefore, soon agreed to impose a uniform service life of 50 years on all material options. This service life reflects the current design views in the Netherlands. The number of the assessment criteria could in this way be reduced to three, without substantial objectivity loss.

The construction and maintenance costs are quite common criteria in engineering; therefore only the results will be presented. In order to quantify the environmental impact, however, an appropriate investigation method had to be set up. The existing methods, like life-cycle analysis LCA [7], [8] appeared not to be very helpful in this case. These methods had primarily been developed to investigate environmental impact of relatively simple products for which the technologies and service conditions were well determined (e.g. packing material, housing of household appliances, window- and door frames etc.). The pedestrian bridge was not only more complex but also very vague determined in this early stage. Making a detailed bridge design and a life cycle inventory for each material option was, obviously, not the intention. Therefore, a limited but workable two-way evaluation approach was chosen:

- in terms of energy consumption - taking account of the energy “stored” in materials and the products (so-called “exergy” method);
- in terms of water and air pollutions as result of the material winning, processing and the fabrication of the final product.

The first approach served as a measure not only to energy consumption as such (i.e. the decrease of global energy resources), but also to the processes resulting from fossil fuel combustion, like the "greenhouse effect", ocean level rising, global climatic changes etc. The results of the second approach (in fact 2 records for water and air apart) represented the global pollution impact of the bridge materials under consideration. Soil pollution was assumed to be insignificant, but it might have been analyzed in the same way, if relevant.

3. Preliminary designs

The materials in question represent in fact five groups of different material grades. For practical reasons a distinct, well suitable grade had to be chosen in each group. In accordance with the existing practice, the following material grades were chosen:

- Structural steel: S235J0 or S355J0 according to EN 10025. As an option to conventional paint system, the aluminum arc-sprayed coating was considered.
- Stainless steel: X2CrNi18-11 or X2CrNiMo18-14-3 according to the Eurocode (AISI 304L or 316L).
- Composites: Fiberglass reinforced polyester resin (FGRP) in pultruded sections.
- Aluminum: AlMgSi1,0 F31 according to DIN 1748 (or 6061 and 6063 alloys according to ASTM B221).
- Concrete: B35 according to the Dutch standard NEN 6720, 150 kg reinforcement per 1 m^3, 100 kg other steel accessories (e.g. handrails) per 1 m^3.

The next step was to complete four rough preliminary designs of the bridge, one in each optional material. It soon became clear that each material required a quite different form, structural system, manufacturing approach etc. E.g. in structural steel and concrete, conventional beam girders with separate handrails were a self-evident choice, while in the other, more expensive materials an integration of handrails in truss (or truss alike) girders proved to be favorable. Major differences appeared also in section shapes, deck constructions etc. Figure 2 presents in outline one span of the bridge in each of the five material options discussed. The structural analysis was very brief in all cases; little effort has been put into optimizing cross sections, joints etc. It is, however, fair to say that the bridge spans shown in Figure 2 are representative for the five materials, and comparable with each other in the terms of strength and durability.

Remarkable is the difference in the total span masses in Figure 2. These masses were estimated using own rough calculations and the data from other similar projects. Examples of comparable pedestrian bridges in, respectively, stainless steel, composites (FGRP) and aluminum are shown in Figure 3. Structural steel and concrete are quite common options and do not require an illustration. This comparison demands a comment: The weight of the structural steel span would have been considerably lower (approximately 2200 ÷ 2500 kg) if a truss with integrated handrails was chosen instead of a conventional beam. Also then, however, the total weights of the composite and aluminum bridges appear to be much lower than of the steel bridges. On the contrary, the weight of the concrete bridge appears to be a magnitude (5 ÷ 10 times) higher than the weight of the other bridges. With the exception of concrete, the structure dead weight was of minor importance in this particular project. However, decreasing that weight can be very desirable in larger bridges. It leaves more material strength to variable loads and allows for lighter foundations, supports, transport and assembly equipment etc.

An important difference concerned also the maintenance requirements. While the structural steel bridge required two additional blast-cleaning and painting treatments during its service life, the maintenance of the other bridges could be limited to global inspections, bolt tightening and incidental small repairs. Except for the concrete bridge, one deck replacement per service life was scheduled in all the cases, although there was a reasonable chance that the plastic and the aluminum decks could serve the entire life. The reason to take their replacement into account was the unforeseeable mechanical damage rather than the normal use or suffering from the weather.

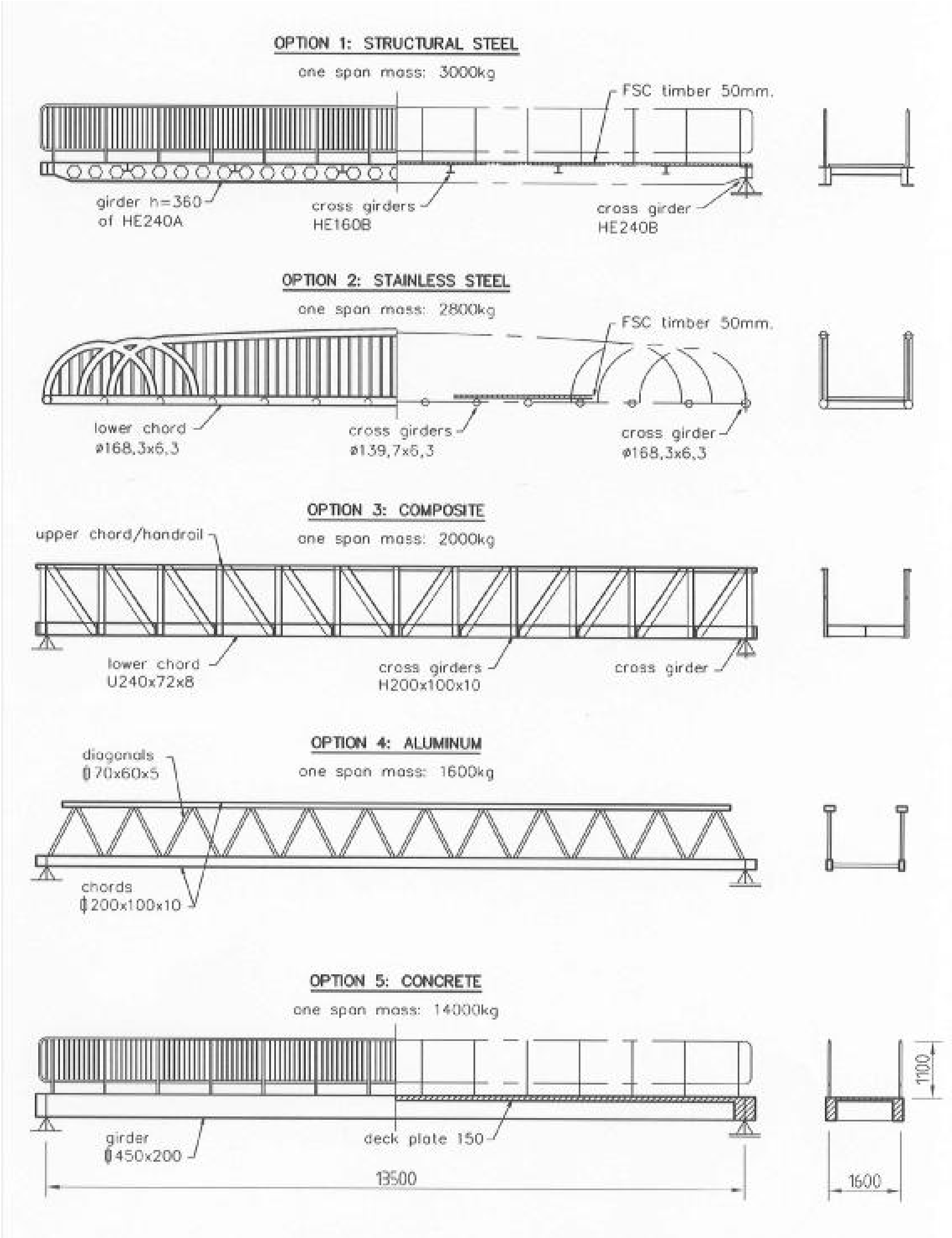


Fig. 2 One of the two bridge spans in five material options

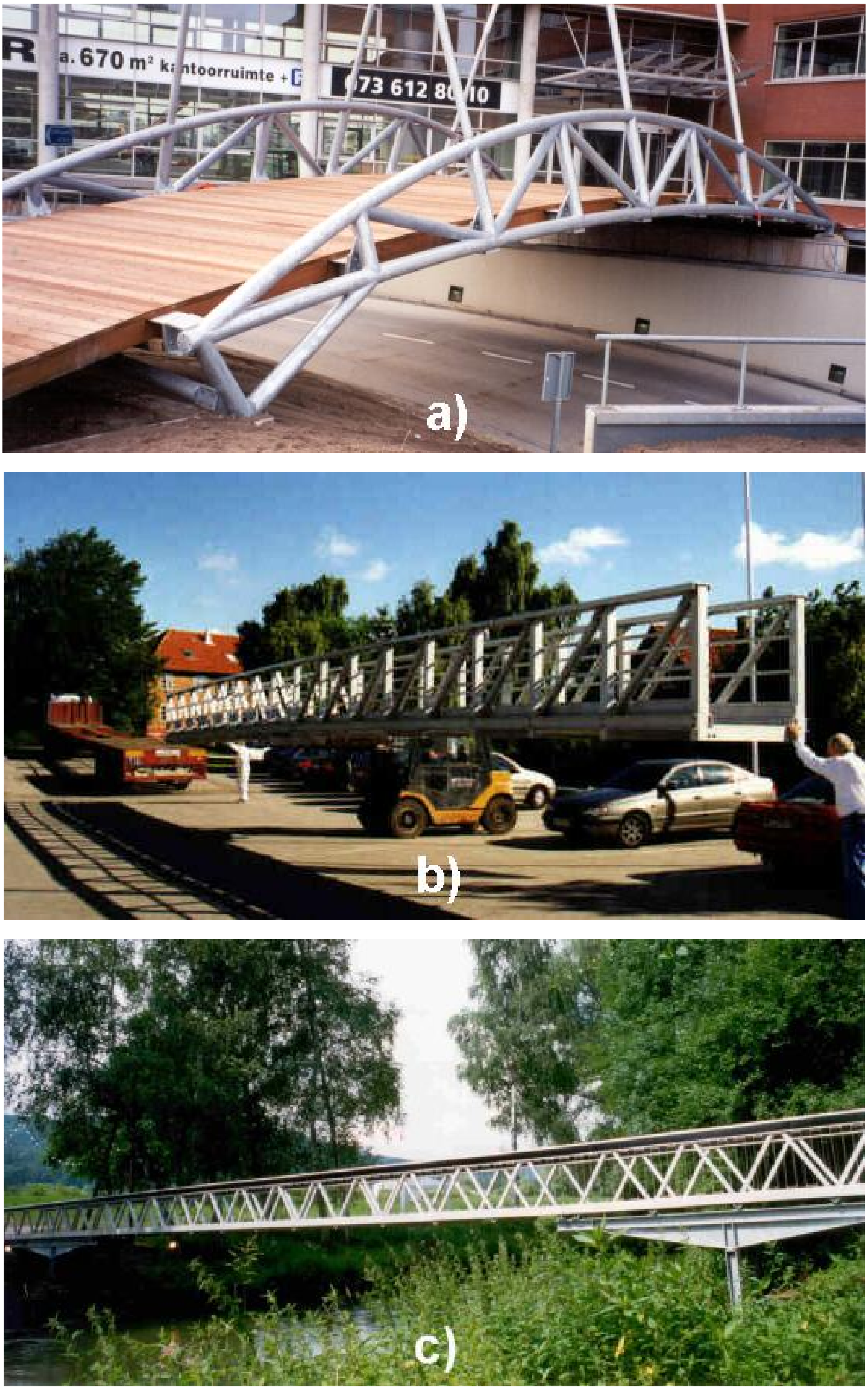


Fig. 3. a) Stainless steel bridge in Den Bosch, the Netherlands;
b) FGRP bridge near Łódź in Poland (courtesy Fiberline Composites A/S)**;**
c) Aluminum bridge near Böblingen, Germany (courtesy PML Logis-Systembrücke)**.**

4. Evaluation

The bridge primary designs were used to produce more data for the evaluation – not only the total material masses. The design drawings also helped to collect some data directly on the market, as they enabled asking better specified questions. In general, the desired data covered the following main subjects:

- Total quantities and unit prices of the materials involved;
- Manufacturing technologies to be employed, their costs, conditions, requirements, available quality assurances, environmental risks etc.;
- Transport and assembly conditions, required time, heavy equipment and other provisions;
- Inspection and maintenance requirements during the service life of the bridge;
- Environmental impact of all processes involved.

The accuracy of these data was often not high due to the concise character of the design in this early stage. In some cases, rough estimations had to be made in the absence of appropriate data. Nevertheless, all parties involved agreed at the end that a sufficient, well founded base had been provided to evaluate all material options. Brief results of this evaluation are shown in Table 1:

Material of the bridge	Criterion			
	Initial costs (euros)	**Maintenance costs (euros)**	Environment: **Energy consumption**	Environment: **Critical volume of polluted…**
Structural steel	painted: **€ 40.000,-** aluminum coated: **€ 50.000,-**	painted: **€ 30.000,-** aluminum coated: **€ 6.000,-**	"exergy" method: **294 000 MJ**	…water: **697.4 m³** ...air: **7.09 ·10⁶ m³**
Stainless steel	in steel AISI 316L: **€ 110.000,-** in steel AISI 304L: **€ 96.000,-**	in steel AISI 316L: **€ 6.000,-** in AISI 304L more, life cycle shorter	"exergy" method: **329 600 MJ**	Not investigated but certainly more water and air pollution than for structural steel.
Composites	pultruded sections of fiberglass reinforced polyester (FGRP): **€ 70.000,-**	rough estimation: **€ 17.000,-**	"exergy" method: **120 000 MJ**	…water: **85.8 m³** ...air: **7.92 ·10⁶ m³**
Aluminum	quality AlMgSi1 acc. to DIN 1748: **€ 77.000,-**	rough estimation: **€ 19.000,-**	"exergy" method: **268 700 MJ**	...water: **565.3 m³** ...air: **41.10 ·10⁶ m³**
Concrete	Concrete B35, reinforced, handrails etc. **€ 30.000,-**	rough estimation: **€ 10.000,-**	"exergy" method: **277 200 MJ**	...water: **341.9 m³** ...air: **31.04 ·10⁶ m³**

Table 1. Performances of the five material options for the bridge.

The general conclusions of this evaluation are as follows:

- In terms of initial costs, the structural steel and concrete bridges are favorable. The stainless steel bridge is the most expensive; the composite and aluminum bridges score in the middle.
- In terms of maintenance costs, the situation is quite different: The stainless steel bridge is the cheapest, followed by the concrete bridge. The structural steel bridge is the most expensive (if conventionally painted), in between lie the scores of the composite and aluminum bridges.
- Adding initial and maintenance costs (whether or not capitalized) puts the concrete bridge on the first and the structural steel bridge on the second place. Composite has a good third place, closely followed by aluminum. The stainless steel bridge is evidently the most expensive.
- Environmental analysis of the consumed energy makes the composite bridge a winner. Each other option results in a more then twice as high energy use. This is important, considering e.g. the growing awareness of the relation between energy consumption and climatic changes.
- The composite bridge came also as the best out of the comparison of water and air pollution involved. The structural steel bridge was the second, concrete the third, aluminum the fourth.

In the final report, the customer was advised to set the priorities. His situation was as follows: In case finances came first, the choice for a structural steel bridge was the best. In case he was willing to spend some more money in the interest of the environment, the composite bridge was his best choice. An additional argument in support of the composite bridge was the innovative character of that project. It was to be the first bridge of pultruded sections in the Netherlands. There was, however, enough confidence in this material. FGRP, though not pultruded, had already been applied e.g. in a pedestrian bridge in Harlingen and in a gate of the Spiering Lock in Werkendam [9]. The pultruded sections performed well in a number of walkways and banisters on hydraulic structures, e.g. the walkways of one of the new lock gates in the Wilhelmina Canal [6] in Tilburg. The Regional Directorate of *Rijkswaterstaat* in Zeeland became convinced by those arguments. The Directorate was in a position and willing to choose the second, pro-environmental option. This opened the way to invite tenders for the project.

5. Environmental analysis

5.1 Energy consumption

Energy consumption analysis does not say all about the environmental performances, but it is an important indicator in this field. The starting point is the data on energy use for the production and processing – from the winning of raw materials to the final product – of one mass unit of the materials in question (in MJ/kg). These data are not always the same because the same materials can be obtained using different technologies. As the environmental analyses are rather new, there is also much arbitrariness in defining these data. It is, therefore, advisable to check at first which processes are covered by the received data; and to use the data from one source throughout the entire analysis. For example, the following energy consumption rates for structural steel have been found during this project in various sources:

- NewProducts bv, Delft (NL), [10]: 46 MJ/kg;
- PRé Consultants, Amersfoort (NL), [11] : 31 MJ/kg;
- Intron Institute, Houten (NL), [12]: 18 MJ/kg;
- Carnegie-Mellon University, Pittsburgh (USA), [13]: 6 MJ/kg.

This is something quite different than what we, engineers, are used to: approved specifications, standard codes, reliable, well tested data. It is, in fact, discouraging. On a second view, however, the data bases held by various institutes appear to be usable. When high figures e.g. for structural steel are quoted, they usually include the energy input for rolling, surface treatments, transport, welding, fabrication, delivery and assembly of the final structure. Low figures comprise a smaller number of these processes. Other materials are usually approached in a similar way, so that every data base as such is rather consequent. The absence of standard data should be accepted at this moment. For the sake of the environment, it is better to work with the data which there are, and complain about them, than to wait until they become better – in which case they will never do.

In this project the so-called "exergy" method was used to quantify the energy impact of the five material options. In this method, the total energy consumption is a sum of the energetic value decreases of the materials involved in the processes under consideration. These energetic values, called exergy, represent the potential of the energy "stored" in materials to deliver work [10]. The analysis was limited to the basic materials. Influence of wooden bridge decks in the two steel bridges, stainless steel or other metal bolts in the aluminum and plastic bridges etc., was ignored. The data on energy consumption per material unit were delivered by NewProducts BV; then reviewed and slightly modified for the purpose of this analysis. These data are shown in Table 2. Discussing the figures goes beyond the scope of this paper. Below are only two comments:

- For composites, no data for secondary condition are provided due to the difficult recycling. On the other hand, however, combustion and other utilization techniques are economically and energetically advantageous for these materials.
- The data for reinforced concrete have been computed from cement [13] and steel [10]. Sand, gravel, processing etc. have roughly been compensated by 75% increase of the cement rate. The assumed steel volume covers both, the reinforcement and handrails.

Material	Condition	Consumed energy and energetic material value (MJ/kg)	Energy "stored" in the product (MJ/kg)
Structural steel (e.g. S235J0)	primary	46	7
	secondary	36	7
Stainless steel (e.g. AISI 316L)	primary	69	11
	secondary	54	11
Composites (FGRP)	primary	33	9
	secondary	-	-
Aluminum (e.g. AlMgSi1)	primary	137	33
	secondary	45	33
Reinforced concrete (B35, steel handrails)	primary	11	2
	secondary	-	-

Table 2. Energy consumption data for the five material options for the bridge.

With these data, the energy consumption as result of the four bridge projects could be approximated as follows:

- **Structural steel bridge:**
  Total mass of 2 spans: 6000 kg. Assumed: 80% of primary and 20% of secondary material. Energy consumption on delivery:
  $Ex_0 = 6\,000 \cdot [0.8 \cdot (46-7) + 0.2 \cdot (36-7)] = \quad 222\,000\ MJ$.
  The energy use during maintenance (2 x blast cleaning and painting) is approximated by subtracting the figure for unpainted structure (31 MJ/kg) obtained from another data base [11]. To take the time delay into account (about 20 and 35 years), a factor of 0.75 is introduced:
  $Ex_1 = 6\,000 \cdot 2 \cdot 0.75 \cdot (46-7-31) = \ 72\,000\ MJ$. This gives the total energy consumption:
  $Ex \ = 222\,000 + 72\,000 = \quad 294\,000\ MJ$.

- **Stainless steel bridge:**
  Total mass of 2 spans: 5600 kg. Assumed: 80% of primary and 20% of secondary material. Energy consumption on delivery:
  $Ex_0 = Ex \ = 5\,600 \cdot [0.7 \cdot (69-11) + 0.3 \cdot (54-11)] = \quad 299\,600\ MJ$.
  The maintenance is limited to some cleaning and one deck replacement (10% of bridge costs):
  $Ex_1 = 0.10 \cdot 299\,600 = \quad 30\,000\ MJ$. This gives the total energy consumption:
  $Ex \ = 299\,600 + 30\,000 = \quad 329\,600\ MJ$.

- **Composite bridge:**
  Total mass of 2 spans: 4000 kg. No recycling assumed. Energy consumption on delivery:
  $Ex_0 = 4\,000 \cdot (33-9) = \quad 96\,000\ MJ$.
  The maintenance is marginal. Yet, in order to cover e.g. some uncertainties about ageing, one deck replacement (25% of the bridge) during the service life has been assumed:
  $Ex_1 = 0.25 \cdot 96\,000 = \quad 24\,000\ MJ$. This gives the total energy consumption:
  $Ex \ = 96\,000 + 24\,000 = \quad 120\,000\ MJ$.

- **Aluminum bridge:**
  Total mass of 2 spans: 3200 kg. Assumed: 60% of primary and 40% of secondary material. Energy consumption on delivery:
  $Ex_0 = 3\,200 \cdot [0.6 \cdot (137-33) + 0.4 \cdot (45-33)] = \quad 215\,000\ MJ$.
  Maintenance due to ageing is marginal. Yet, there is concern about mechanical damage during the service life. Therefore, one deck replacement (25% of the bridge) has been assumed:
  $Ex_1 = 0.25 \cdot 215\,000 = \quad 53\,700\ MJ$. This gives the total energy consumption:
  $Ex \ = 215\,000 + 53\,700 = \quad 268\,700\ MJ$.
  Note: The assumed 40% share of secondary aluminum is based on some individual signals from the European aluminum industry. This figure might be slightly colored. If possible, it should be verified because this analysis is very sensitive to it.

- **Concrete bridge:**
  Total mass of 2 spans: 28000 kg. No recycling assumed. Energy consumption on delivery:
  $Ex_0 = 28\,000 \cdot (11-2) = \quad 252\,000\ MJ$.
  The maintenance is limited to small repairs and 2 x handrail painting (or 1 x handrail replacement) during the service life, approximately 10% of the energy consumption on delivery:
  $Ex_1 = 0.10 \cdot 252\,000 = \quad 25\,200\ MJ$. This gives the total energy consumption:
  $Ex \ = 252\,000 + 25\,000 = \quad 277\,200\ MJ$.

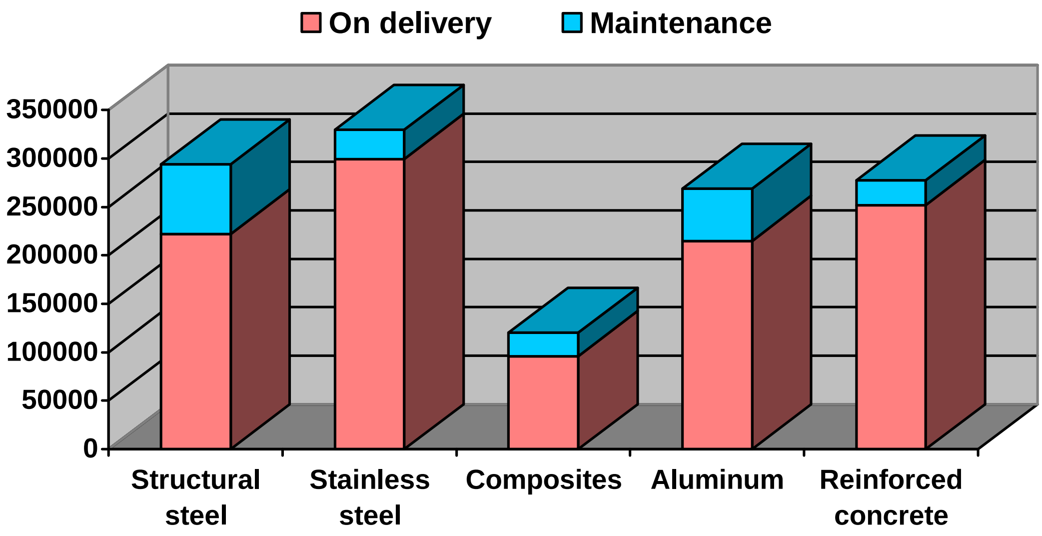


Fig. 4 Energy consumption as result of the five bridge projects

The computed energy consumptions have been put in a diagram in Figure 4. These results are not undisputable. It may e.g. be argued that the delay factor of 0.75 should not be used for the structural steel maintenance - and if so, than it should also be applied to the deck replacements in other bridge options. The assumption in this matter was that the spare decks of the composite and the aluminum bridges should somehow be secured, i.e. produced at the same time as the bridges. This assumption is, however, arbitrary. Another simplification is that no energy use for dismantling or demolition at the end of the service life has been added. Such an approach would probably point to the concrete bridge as the most energy consuming, i.e. more than the stainless steel bridge. The concrete demolition and utilization requires much energy. Despite some disputable assumptions, one low-energy option is a clear winner: the composite bridge.

5.2 Pollution analysis, theory

The energy approach does not answer the question how "clean" or "dirty" the considered material options are, i.e. it provides no comparison in terms of environmental pollution. In order to make such a comparison possible, another approach has been chosen. The problem is that each material option results in a spectrum of qualitatively different pollutions which can not simply be added up. This has been solved by taking account of a so-called "legal threshold" of each single pollution. The applied method was, to the author's best knowledge, for the first time used in an eco-analysis of an infrastructural project. This method resembles the so-called critical load method [13], and is based on the two following data records:

- $\boldsymbol{B_{m,i}}$ (kg/m^3), emissions of the pollutants $\boldsymbol{i}$ in [kg] as a result of the production and processing of 1 m^3 of the considered material $\boldsymbol{m}$. Such emissions are usually recorded separately as loads to water, air and (exceptionally) soil.
- $\boldsymbol{B_{0,i}}$ [kg/m^3], legislated legal thresholds of the pollutants $\boldsymbol{i}$ in water, air and (exceptionally) soil.

When these two data records are known along with the total mass $\boldsymbol{G_m}$ and density g_m of the material $\boldsymbol{m}$, the total critical volume of polluted water $\boldsymbol{V^w_m}$ or air $\boldsymbol{V^a_m}$ [m^3] can be computed as follows:

$$V_m = \frac{G_m}{g_m} \cdot \sum_i \frac{B_{m,i}}{B_{0,i}}$$

In the Tables 3 and 4 the emissions $\boldsymbol{B_{m,i}}$ and the legal thresholds $\boldsymbol{B_{0,i}}$ are given for the four best materials of the bridge: structural steel, composites, aluminum and concrete. The stainless steel option was not considered any more at this stage. The data for structural steel and aluminum have been collected from [13] which, in turn, refers to [14] and [15]. The emission data for polyester have been collected through author's contacts by DSM Composite Resins, Zwolle, and combined with the data for glass to produce the aggregated emission data for composites (FGRP). In the same way the emissions for reinforced concrete were obtained, by combining the records for concrete (here only the cement part increased by 75%, see also 5.1) and steel.

Emissions to water					
Polluter	**Struct. steel** $\boldsymbol{B_{st,i}}$ (kg/m^3 of product)	**Composite** $\boldsymbol{B_{cp,i}}$ (kg/m^3 of product)	**Aluminum** $\boldsymbol{B_{al,i}}$ (kg/m^3 of product)	**Concrete*** $\boldsymbol{B_{cr,i}}$ (kg/m^3 of product)	**Threshold** $\boldsymbol{B_{0,i}}$ (kg/m^3 of water)
Aluminum	$3.33 \cdot 10^{-6}$	$2.00 \cdot 10^{-6}$	$3.09 \cdot 10^{-5}$	$1.65 \cdot 10^{-7}$	$5.0 \cdot 10^{-5}$
Ammonia	$4.58 \cdot 10^{-3}$	$1.10 \cdot 10^{-3}$	$4.23 \cdot 10^{-2}$	$2.38 \cdot 10^{-4}$	$2.2 \cdot 10^{-3}$
Cadmium	$4.57 \cdot 10^{-5}$	$2.10 \cdot 10^{-6}$	$4.28 \cdot 10^{-4}$	$2.18 \cdot 10^{-6}$	$3.5 \cdot 10^{-6}$
Copper	$1.96 \cdot 10^{-8}$	$7.90 \cdot 10^{-4}$	$1.82 \cdot 10^{-7}$	$0.99 \cdot 10^{-9}$	$2.0 \cdot 10^{-4}$
Cyanide	$3.08 \cdot 10^{-4}$	$7.40 \cdot 10^{-5}$	$2.85 \cdot 10^{-3}$	$1.60 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$
Fluoride	$1.03 \cdot 10^{-1}$	$2.00 \cdot 10^{-4}$	$6.49 \cdot 10^{-3}$	$3.51 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
Manganese	$6.07 \cdot 10^{-6}$	$3.60 \cdot 10^{-6}$	$5.64 \cdot 10^{-5}$	$3.03 \cdot 10^{-7}$	$5.0 \cdot 10^{-5}$
Mercury	$1.57 \cdot 10^{-4}$	$7.00 \cdot 10^{-7}$	$1.45 \cdot 10^{-3}$	$7.53 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$
Zinc	3.97	$1.40 \cdot 10^{-3}$	$5.44 \cdot 10^{-2}$	$1.35 \cdot 10^{-1}$	$5.0 \cdot 10^{-3}$
Cobalt	-	$3.00 \cdot 10^{-2}$	-	-	$1.0 \cdot 10^{-3}$

*/ reinforced and with steel accessories (handrails)

Table 3. Emissions to water for structural steel, composite, aluminum and concrete

Emissions to air					
Polluter	**Struct. steel** $\boldsymbol{B_{st,i}}$ (kg/m^3 of product)	**Composite** $\boldsymbol{B_{cp,i}}$ (kg/m^3 of product)	**Aluminum** $\boldsymbol{B_{al,i}}$ (kg/m^3 of product)	**Concrete*** $\boldsymbol{B_{cr,i}}$ (kg/m^3 of product)	**Threshold** $\boldsymbol{B_{0,i}}$ (kg/m^3 of air)
CO_2	$2.56 \cdot 10^{+3}$	$1.03 \cdot 10^{+3}$	$2.10 \cdot 10^{+4}$	$4.95 \cdot 10^{+2}$	$9.0 \cdot 10^{-3}$
CO	$9.58 \cdot 10^{+1}$	1.32	$5.15 \cdot 10^{+1}$	3.48	$4.0 \cdot 10^{-5}$
CH_4	5.95	1.21	$5.39 \cdot 10^{+1}$	$9.89 \cdot 10^{-1}$	$6.7 \cdot 10^{-3}$
N_2O	$3.70 \cdot 10^{-2}$	$4.80 \cdot 10^{-3}$	$2.94 \cdot 10^{-1}$	$1.51 \cdot 10^{-2}$	$1.0 \cdot 10^{-7}$
dust Fe/Al oxi	$2.20 \cdot 10^{-1}$	$1.05 \cdot 10^{-1}$	1.65	$6.00 \cdot 10^{-2}$	$1.0 \cdot 10^{-7}$
dust Si/Ca oxi	$4.20 \cdot 10^{-2}$	$5.05 \cdot 10^{-1}$	$2.70 \cdot 10^{-1}$	$4.70 \cdot 10^{-1}$	$3.0 \cdot 10^{-7}$
SO_2	3.28	$2.51 \cdot 10^{-3}$	$1.27 \cdot 10^{+1}$	$2.80 \cdot 10^{-1}$	$1.2 \cdot 10^{-6}$
NO_x	3.08	2.83	$2.45 \cdot 10^{+1}$	1.27	$1.0 \cdot 10^{-5}$
Styrene	-	$1.20 \cdot 10^{-1}$	-	-	$8.0 \cdot 10^{-7}$

*/ reinforced and with steel accessories (handrails)

Table 4. Emissions to air for structural steel, composite, aluminum and concrete

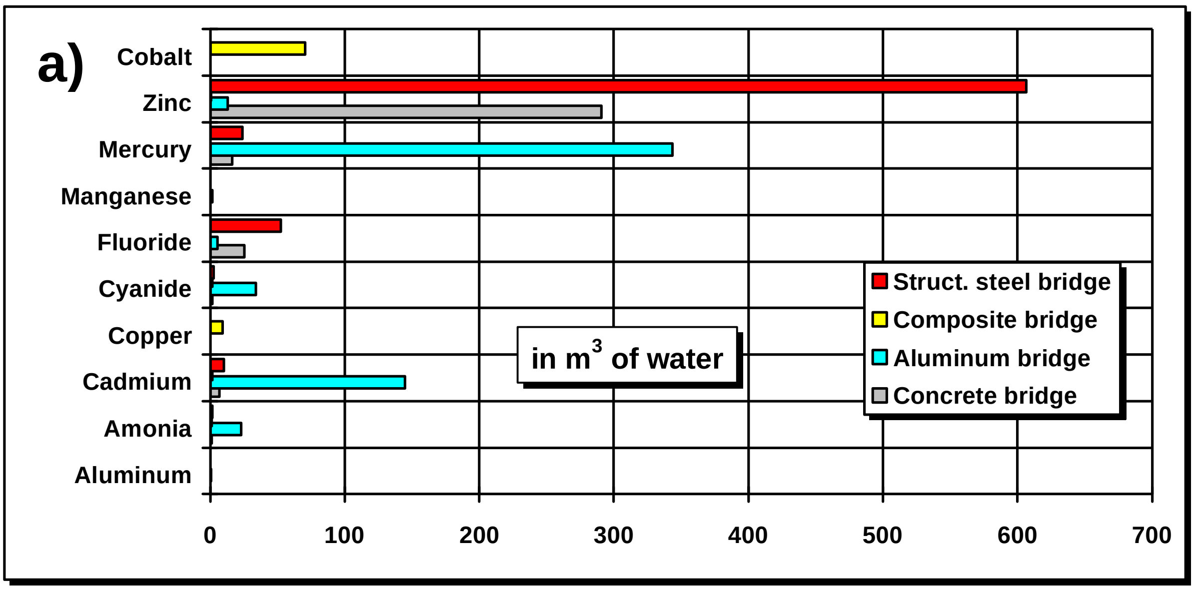
5.3 Pollution analysis, results

Global results of the environmental analysis have already been presented in Table 1. However, it is interesting to compare the pollutions to water and air in a qualitative sense. The method presented in 5.2 generates all necessary data for such a comparison. Using the formula for $\boldsymbol{V_m}$ and, e.g., the records for composites (FGRP) from Table 3 the following critical volumes of polluted water $\boldsymbol{V^w_{cp}}$ will be obtained:

$$V^w_{cp} = \frac{G_{cp}}{g_{cp}} \cdot \sum_i \frac{B_{cp,i}}{B_{0,i}} =$$

$$\frac{4000}{1700} \cdot \left(\frac{2.00 \cdot 10^{-6}}{5.0 \cdot 10^{-5}} + \cdots + \frac{3.00 \cdot 10^{-2}}{1.0 \cdot 10^{-3}} \right) = 2.350 \cdot 36.50 = 85.8 \quad \text{m}^3.$$

The components of this summation, multiplied by the ratio $\boldsymbol{G_{cp}/g_{cp}}$, can be put in a diagram along with the similar figures for structural steel, aluminum and concrete. This has been done in Figure 5a. In Figure 5b the total critical volumes of polluted water are compared:



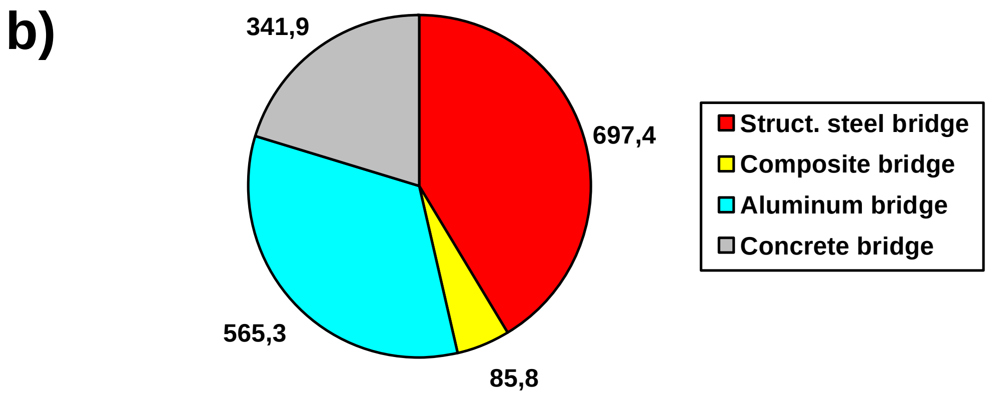


Figure 5. Critical polluted water volumes in qualitative comparison (a) and totally (b)

In the same way a diagram for the emissions to air can be generated. Using the formula for $\boldsymbol{V_m}$ and e.g. the records for composites (FGRP) from Table 4 the following critical volumes of polluted air $\boldsymbol{V^a_{cp}}$ will be obtained:

$$\boldsymbol{V^a_{cp}} = \frac{G_{cp}}{g_{cp}} \cdot \sum_i \frac{B_{cp,i}}{B_{0,i}} =$$

$$\frac{4000}{1700} \cdot \left(\frac{1.03 \cdot 10^{+3}}{9.0 \cdot 10^{-3}} + \cdots + \frac{1.20 \cdot 10^{-1}}{8.0 \cdot 10^{-7}} \right) = 2.350 \cdot 3.37 \cdot 10^6 = 7.92 \cdot 10^6 \quad m^3.$$

The components of this summation, multiplied by the ratio $\boldsymbol{G_{cp}}/g_{cp}$, have been put in a diagram along with the similar figures for structural steel, aluminum and concrete, see Figure 6a. In Figure 6b the total critical volumes of polluted air are compared:

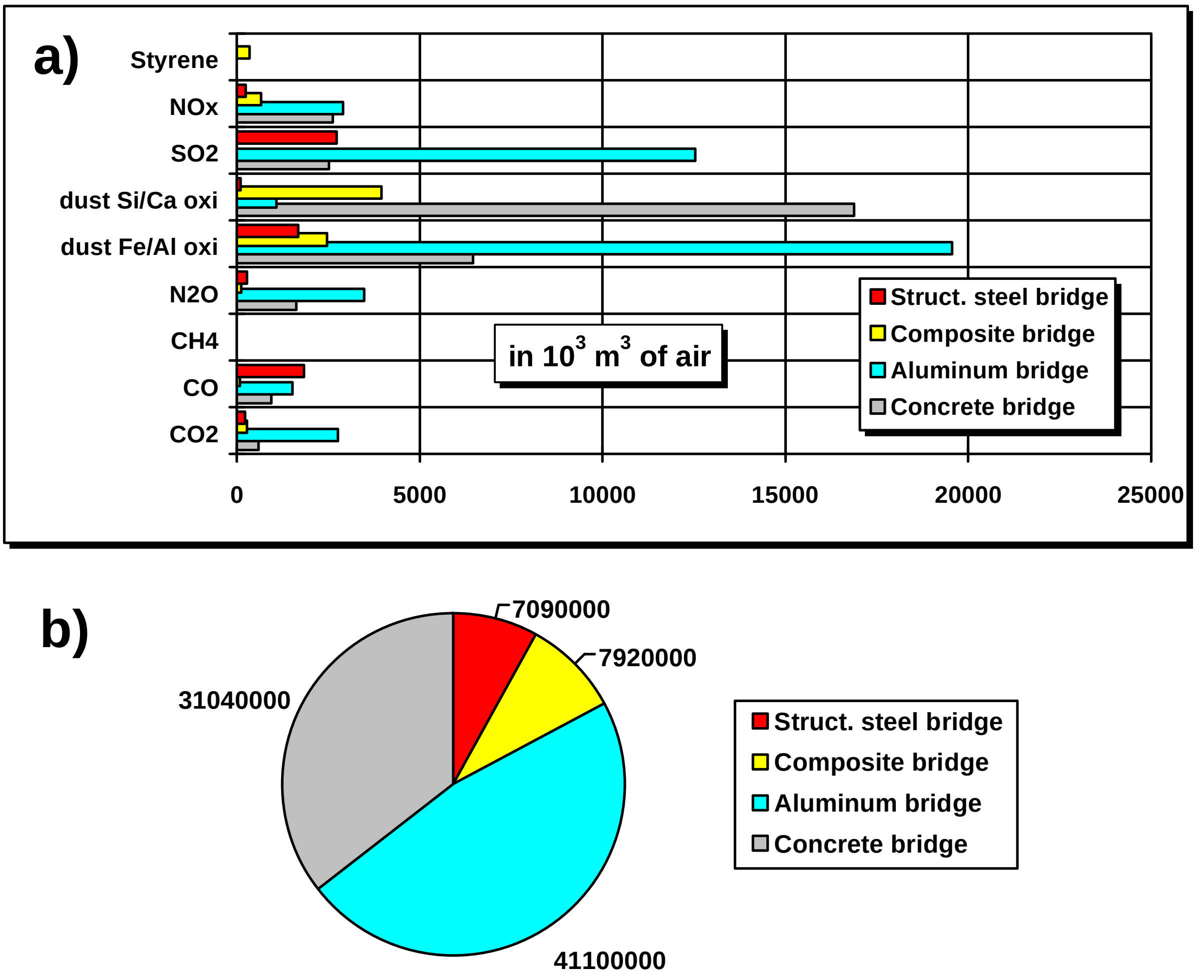


Figure 6. Critical polluted air volumes in qualitative comparison (a) and totally (b)

It might be argued that these results bear an inaccuracy at the expense of the steel option. As mentioned, the weight of the structural steel bridge would have been lower if a truss system was used instead of a beam - the same as for composites or aluminum. However, one of the reasons of this difference was to allow the environmental impact of paint coatings be ignored. The error of this approximation is small and does not effect the conclusions. These conclusions are as follows:

- When water pollution is concerned, the composite (FGRP) bridge proves to be a magnitude "cleaner" than both, the steel and the aluminum bridge. The emission of cobalt which is often used in polyester resin processing, does not mean much when compared to the zinc emission in structural steel processing, or the mercury and cadmium emission in aluminum processing. The concrete bridge takes a middle position, with the large part of its zinc emission coming in fact from the steel reinforcement and handrails.
- The above shows also that any reduction of the zinc emission by steel processing can significantly improve the scores of structural steel and concrete bridges. The aluminum bridge is a less hopeful case; its spectrum of emissions is more complex.
- In terms of air pollution, the structural steel and composite bridges are a few times "cleaner" than the concrete and aluminum bridges. The slide lead of structural steel over composites is almost entirely caused by the fiberglass reinforcement in the latter. Glass processing is rather dusty [13]. An improvement in this field would put the composite bridge on the first place.
- From the two "losers", the aluminum and concrete bridges, there seems to be a better prospect of improvement for the concrete bridge. The emissions to air consist in this case mainly of dust and are probably easier to reduce than the complex emission spectrum of aluminum.
- The above shows that the presented method generates more than the scores of the considered options. It can as well be used to evaluate environmental effects of technological or other improvements. This is an important property because it shows the industry where to direct the improvement efforts.
- The presented method can also be used to investigate structures comprising more materials. In such cases, the critical volumes V_m can be computed for each single material apart, and added to each other. E.g. for the composite bridge, the V_m's for polyester resin (60% of volume) and fiberglass (40% of volume) could have been computed first instead of combining the pollution records for these materials into one. The same applies to reinforced concrete.

6. Project contracting and execution

The selected composite bridge was brought on the market in a so-called Design & Construct contract. One of the reasons was that the pultrusion technology appeared to be neither widely known, nor standardized enough to order the engineering by a third party. The pultrusion company could in this way root the bridge design in its own manufacturing program, using the own know-how, section shapes, sizes etc. After some market research the following three tenders were invited:

- Fiberline Composites A/S, Kolding, Denmark;
- Fibergate B.V., Terneuzen, the Netherlands;
- Vink N.V., Heist op den Berg, Belgium.

The specifications comprised the delivery and installation of the two operational bridge spans and one middle pillar, including a maintenance contract for 10 years. The intention was to minimize the maintenance requirements from the very first moment of the design. After all, the low maintenance costs were one of the main reasons to choose a composite bridge. The order was placed by the lowest bidder, in this case Fiberline Composites A/S. That company, in turn, hired a Dutch subcontractor, Van Hattum & Blankevoort, to complete works in situ including the construction of the middle pillar. The entire project was executed under the quality assurance system of Fiberline Composites A/S, within the contractual quality requirements. The *Rijkswaterstaat* engineers supervised it from a distance, ensuring the compliance with the contract specifications.

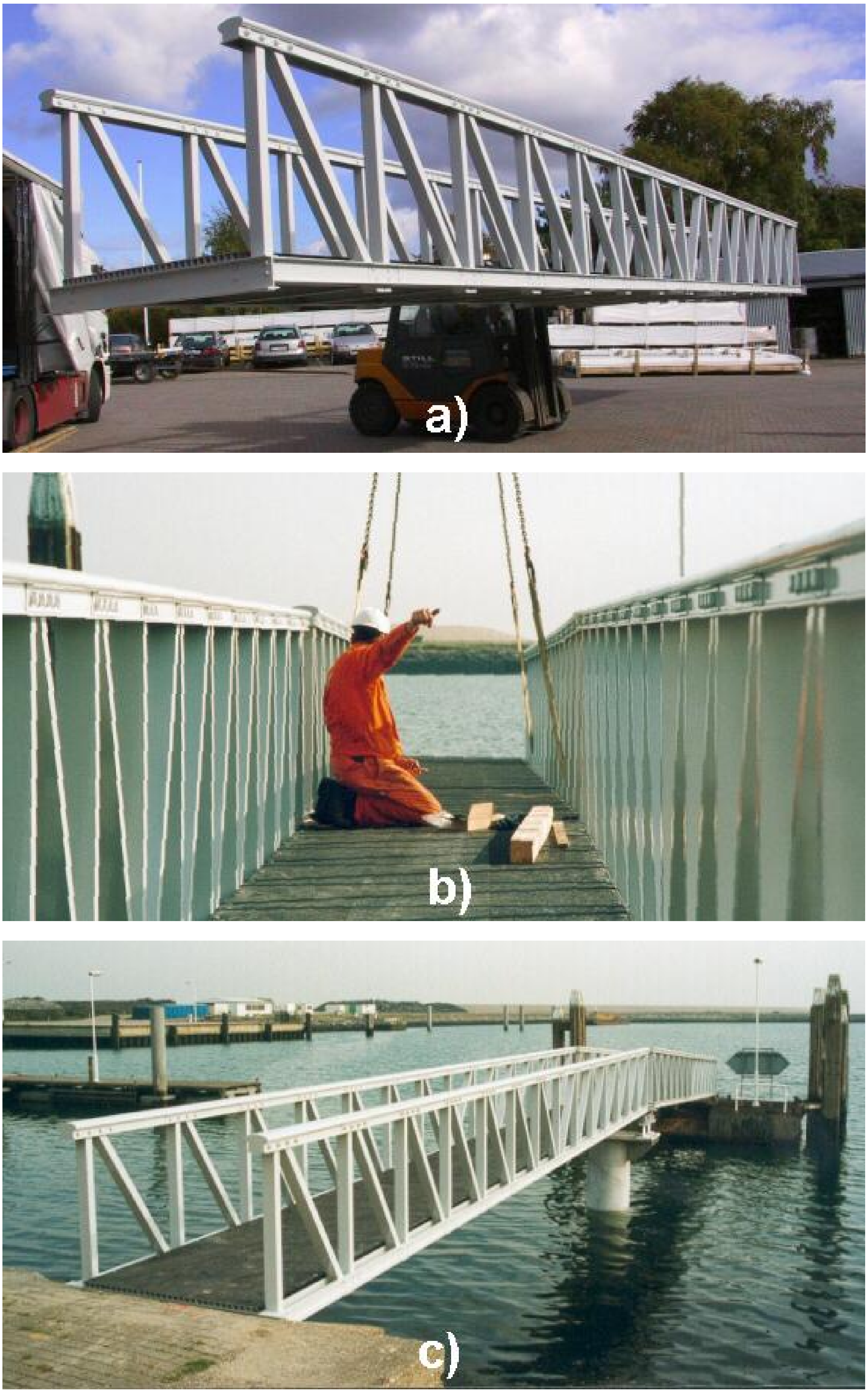


Fig. 7. Noordland pedestrian bridge: a) ready for shipment;
b) installation;
c) in service.

The engineering and the manufacturing of the bridge required about 10 months and was carried out as scheduled. Both spans were entirely assembled on the contractor's location in Denmark (Fig. 7a) and shipped to the Netherlands. The installation in situ (Fig. 7b, 7c) took place in the last week of October 2001. Thanks to the moderate span weight (about 20 kN each), no heavy transport and hoisting equipment was required. It can also be observed that the main girders are more open than e.g. the girders in Fig. 3b. This has been done to minimize the wind load which is rather high at that location. Another modification was a specially developed, Ω-shaped upper chord section (Fig. 8a). It gives a better hand support and it provides a sufficient buckling stability, which is a critical issue in a structure where the upper chord serves also as a handrail.

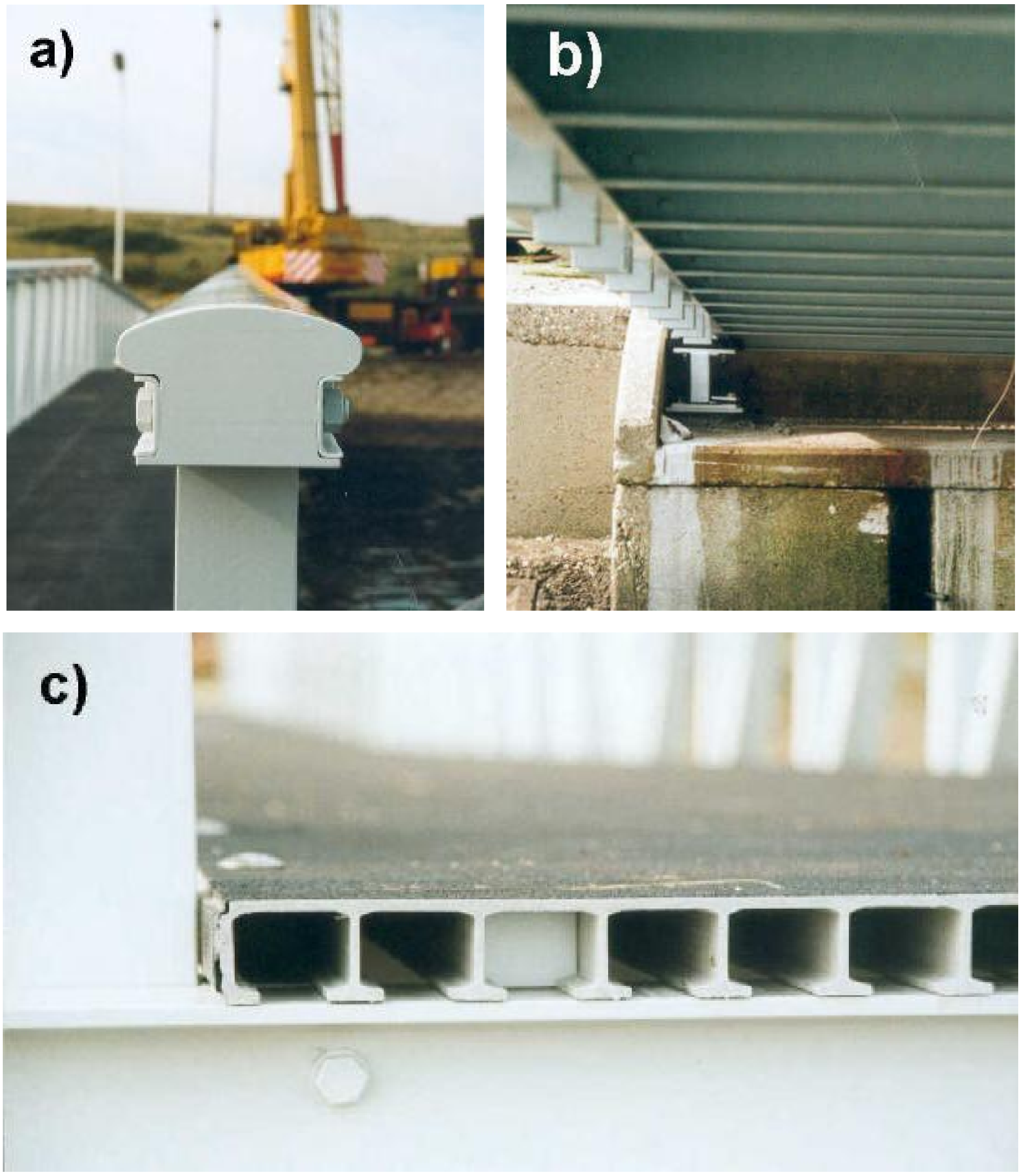


Fig. 8. Noordland pedestrian bridge, details: a) upper chord / handrail;
b) deck cross girders;
c) deck plank.

The bridge deck is supported on a number of cross girders (Fig. 8b). The deck has been built of the ribbed FGRP planks, 40 mm thick, with an anti-slip top layer (Fig. 8c). The planks are a Fiberline A/S standard product. They are pultruded in the width of 500 mm; and can be adjusted to any length and width required by the customer. The connections to the cross girders and between the planks are bolted, using special stainless steel clips. The deck can easily be assembled on the contractor's location as well as in situ. This is an advantage because it allows for a quick replacement of a deck section in case of a mechanical damage.

The bridge is in service (Fig. 7c) and it performs well. So far, it has not required any maintenance or other intervention. The behavior of the bridge will closely be followed by ***Rijkswaterstaat***. If the satisfactory service continues, there is a fair chance that more pedestrian bridges of this type will be ordered in the nearest future.

7. Concluding remarks

The project presented here is the first bridge of pultruded FGRP sections in the Netherlands. Its successful realization proves that there are no major problems in applying this new material within a variety of infrastructural projects. The environmental advantages of this material are clear; and the importance of this criterion grows steadily. As such, the construction of the Noordland bridge has a pilot function for other prospective projects of this kind.

The environmental analysis applied in this project met the interest of many professionals already. It caused diverse discussions, which proves that the idea of pro-ecological, so-called "sustainable" construction projects has a broad support of the customers and of the market. Continuing these discussions is perhaps more important than the results of the study presented in this paper. Every construction project is peculiar. Material which offers the best environmental solution in one project, does not necessarily do it in the other. The intention of this presentation was to prove that it is possible to evaluate the environmental performances of these projects in a reliable, systematic way, taking account of all the peculiarities. The presented evaluation method shows a way to do it. As the method is based on the existing legislation in this field (see "legal thresholds" for the involved pollutants), its great advantage is the objectivity. Any attempt to influence the results, industrial as well as ecologist, is - in theory at least - doomed to fail.

A serious problem in the environmental analyses of this kind is the quality of the available data records. There is still much arbitrariness in this field. A critical approach and good, professional estimations are usually more important than the computing precision. This should not refrain the engineers from investigating the environmental impacts of their projects. As already mentioned, it is better to work with the data which there are and complain about their quality, than to wait until they become better – in which case they will never do. Being an engineer, the author is also convinced that it is better to investigate this matter as part of the engineering, than to leave it to the politicians, environmentalists and layers.

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