

Research Article

Towards Unbiased Environmental Material Selection for a Structure - Case Study of a Navigation Lock Gate

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Abstract

This paper presents a few relatively simple and transparent methods of material selection for a civil engineering structure in view of sustainability. It is addressed to practicing engineers, designers, production managers, other professionals and students intending to take account of sustainability when choosing the material for new structures or maintaining the existing structures. The presented methods are illustrated by a case study for a navigation lock gate. The materials that are currently applicable for this structure are: structural steel, stainless steel, aluminum, polymer composite, reinforced concrete and timber. Three most common sustainability criteria have been considered, which are: 1. Energy use, 2. Loads (pollutions) to the environment, 3. CO₂ emissions (called also “carbon footprint”). In the current engineering practice, sustainability criteria and the related material choices are often prone to emotional reactions and driven by politicized or biased arguments. This paper aims to help engineers deal with this issue by focusing on verifiable aspects of sustainable construction. An attempt has been made to encourage critical approach and corrections in available databases for a better match with the analyzed projects. The analysis covers the so-called “cradle to grave” life cycle, with some focus on manufacturing – the process that usually gives the highest environmental impact. The impact of less essential or less determined processes has been approximated, based on the authors’ experience in design and management of hydraulic structures. In order to quantify the required materials, conceptual designs of the lock gate have been developed in all materials. The structure type and sizes represent the medium-range of lock gate applications, which allows for general conclusions. Such conclusions must, however, take specific technological and other feasibility restraints into account.

Keywords

Sustainability, Environment, Material Choice, Energy, Pollution, CO₂, Structural Engineering, Waterways, Navigation Lock

1. Introduction

In the current engineering practice, material selection for a structure is determined by a number of aspects, the most essential of which are:

- 1) Mechanical, like strength, stiffness, ductility;
- 2) Economical, like availability, price, processability;
- 3) Functional, like life cycle, maintenance, local issues.

In the recent decades, ecological aspects become more and more significant. For the sake of simplicity, let us assume that this term is equivalent to “environmental aspects” and the aspects of so-called “sustainable development”, although some researchers may argue that it is not. There is still much arbitrariness in both the scope definitions and the ways of

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measuring ecological aspects.

The “environmental sustainability” will mean here “the ability to maintain rates of renewable resource harvest, pollution creation, and non-renewable resource depletion that can be continued indefinitely” [1]. This differs from the popular Brundtland Report definition that describes sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs [2]. There are several reasons why the latter definition will not be followed, including its vague and emotional character rather than the engineering precision. For similar reasons, all definitions that use terms like “requirement of our generation”, “quality of life” etc. are considered not to be helpful here.

Today, a comprehensive way to assess the sustainability of a structure is the Life Cycle Analysis (LCA), also called Life Cycle Assessment. The simplest and most direct task setting of LCA is to evaluate the environmental impacts of a structure “from cradle to grave”. This includes the extraction of resources, manufacturing, transport, distribution, utilization, and – finally – the end-of-life arrangements. However, also a route that ends at fabrication or delivery (“cradle to gate”, here factory gate) can be indicative; while at other occasions the entire cycle until reuse after recycling (“cradle to cradle”) should be analyzed. These cycles are schematically depicted in a Figure 1. This figure also indicates the idea of “circular economy” that begins to break through in technology.

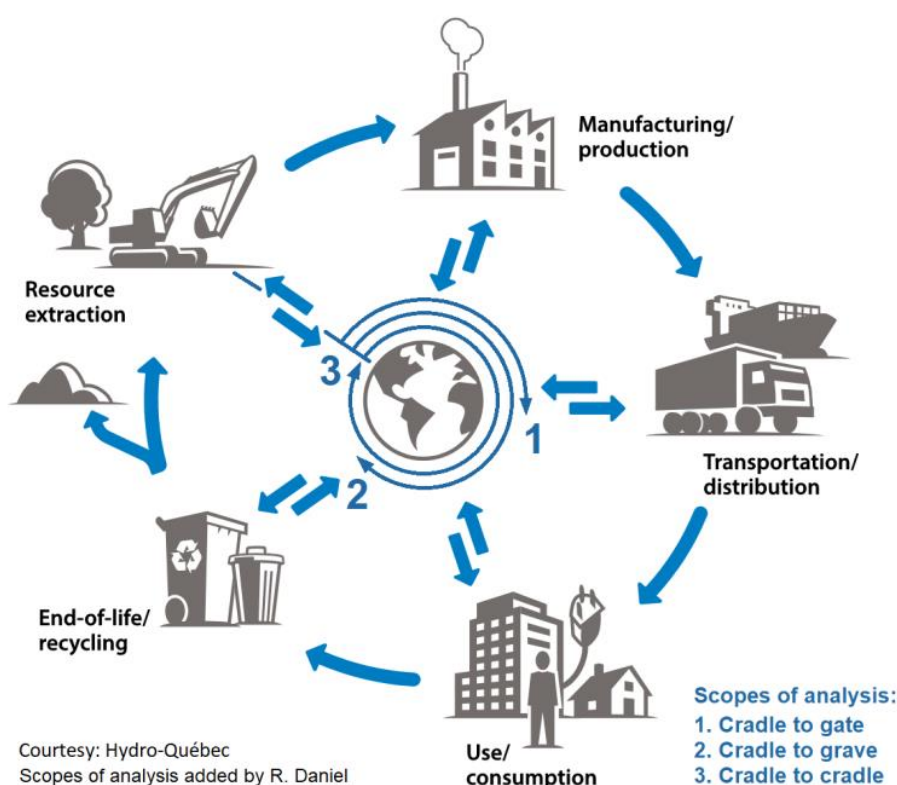


Figure 1. Main phases of Life Cycle Analysis (LCA), based on image by Hydro-Québec.

The product considered in this paper is a navigation lock gate – a structure that requires high quality materials but of relatively low variety. Large parts of this analysis were also discussed in the book on hydraulic structures [3], to which both authors have contributed. This paper is an updated and condensed version of that discussion and of a subsequent article [4] in the Polish language.

- 1) In case of a navigation lock gate, the following specific properties should be noted as regards the Life Cycle pictured in Figure 1:
- 2) Normally, there are still intermediate steps between resource extraction and actual manufacturing. The life

cycle of, e.g., a steel gate accounts for the extraction of iron ore, ores of other alloy metals, scrap collection – followed by the processing that leads to products steel like plate, rolled sections and castings. This may include heavy transportations over large distances.

- 3) Transportation may also require shutting off the navigation, temporary adjustment of water levels; and will be followed by the gate installation on site. This does not last long but it often utilizes heavy equipment like tugs and cranes. It may also require actions like dewatering of a lock chamber or a temporary flow diversion.

- 4) The phase “Use/consumption” in Figure 1 covers operation and maintenance. These processes usually comprise numerous handlings, consume energy, and cause other impacts to the environment. For example, gate maintenance may require its disassembly, use of emergency closures, shipment to construction yard and back, renewal of paint layers and reinstallation on the site.
- 5) Also the end of gate service life is not necessarily as definitive as on the chart in Figure 1. Some used gates can be removed from one to another location that imposes lower loads or lower requirements in other terms. Other gates can be reconstructed, strengthened and made fit for a prolonged service. If such refurbishments are likely, they can be included in the LCA.

These properties also explain why a comprehensive LCA, desirable as it is, can easier be performed for simple products (like staircases or handrails) than for more complex, large structures like hydraulic gates. The number of particular products should also be taken into account. While simple products are often standardized and fabricated in large quantities, most hydraulic gates are individually designed for a desired location. Therefore, a comprehensive LCA provides lower return for structures like navigation lock gates.

Nonetheless, environmental studies will likely cover more and more products and structures in future. As the urgency of such analyses grows, so will the scope of considered aspects, the clarity of assessment criteria and the objectivity of input data. Also relatively complex structures like hydraulic gates will more and more often be subjected to such analyses.

Currently, there is not an all-inclusive, unequivocal criterion or method to assess the sustainability of material choice in construction projects. This is the case with regard to all phases of the life cycle shown in Figure 1. Depending on individual preferences, sometimes subject to lobbying by diverse interest groups, various criteria and assessment methods are used. The reasons of this are complex and can roughly be split into the following two groups:

Objective reasons:

- 1) Environmental analysis is a new discipline with few rules and practices;
- 2) There are many factors that co-define the sustainability of materials;
- 3) There are no uniform units to measure and compare all these factors;
- 4) Sustainability has a global and local sense that may conflict each other.

Subjective reasons:

- 1) Sustainability effects are not as direct as, e.g., strength effects;
- 2) There are barely standards for sustainability, like those for strength;
- 3) Sustainability assessments may conflict the interests of material suppliers;

- 4) Sustainability is largely subject to varying emotions and pressures;
- 5) Assessing institutions can hardly remain unbiased under these conditions.

This does not mean that all assessments practiced nowadays are equally relative, biased or lobbied. There are better and worse practices. Therefore, it is important that engineers develop an open, critical attitude towards such assessments. This paper provides simple, transparent tools and guidelines for sustainable material selection. These tools can be used for both a quick scan of such selections and a verification of assessments performed using other, more complex methods or databases.

2. Materials and Boundaries

In case of a navigation lock gate, 6 material options proved to be applicable in recent projects. They are listed in the first 2 columns of Table 1 below. The other 2 columns specify the most frequently used material grades as assumed for this study. This does not mean, however, that other grades cannot be considered. Figure 2 shows examples of lock gates illustrative for this study and constructed in these 6 optional materials [3, 4].

The lock gates depicted in Figure 2 and the respective providers of their images are:

- a) structural steel, St. Baafs Vijve Lock, Wielsbeke River, Belgium, photo by DMOW;
- b) stainless steel, gate by Deok Sang Co., Korea;
- c) aluminum, Florence, Italy, gate by Polymeccanica Lorenzon;
- d) composite, Goleby Lock in Canal des Vosgues, France, photo by VNF;
- e) reinforced concrete, Amsterdam, Netherlands, photo by MVSA Architects;
- f) timber, Hollandse IJssel Lock, Gouda, Netherlands, photo by R. Daniel.

The analysis was performed for lock gate operation conditions from the medium range of practical applications, in this case according to class III of CVB [5]. The most essential boundary conditions included:

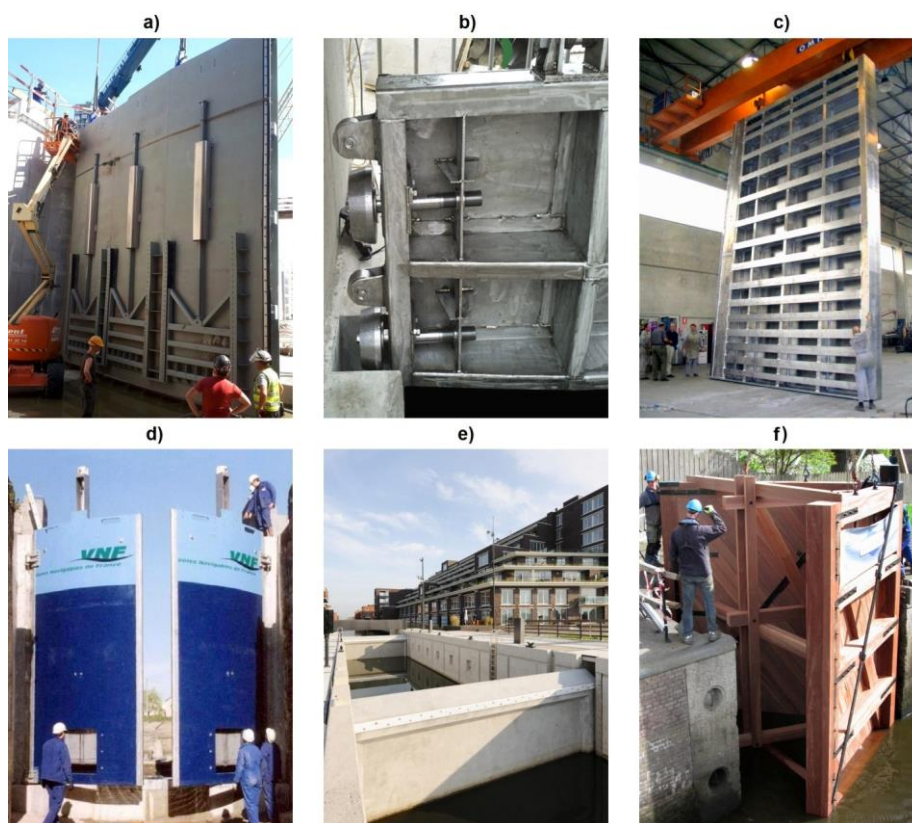
Lock chamber width:	9.00 m
Vessel draft + underkeel clearance:	3.50 m
Lock constant lift:	3.00 m
Type of lock gate:	miter gate
Gate total height:	7.00 m
Gate freeboard:	0.50 m
Width between gate rotation axes:	9.70 m
Gate leaf system width:	5.12 m
Gate leaf total width:	5.40 m
Required gate service life:	50 years

Table 1. Materials of 6 material options for a lock gate as assumed in this study.

Option no.	Material	EU material norm	US material norm
1	Structural steel	EN 10025, gr. S355	ASTM A572, gr. 709
2	Stainless steel	EN 10088, gr. 1.4306	ASTM A240, gr. 316
3	Aluminum	EN 755-2, AW-6061	ASTM B221, 6061-T6
4	Composite	FGRP (Fiberglass Reinforced Polyester)	
5	Reinforced concrete	EN 1992-1-1, class 50 or 60	ACI 318, class 50 or 60 MPa
6	Hard timber	European oak or stronger	American oak or stronger

As mentioned above, the investigation was performed with respect to the three commonly followed sustainability criteria, which are:

- 1) Energy consumption;
- 2) Loads (pollutions) to the environment;
- 3) CO₂ emission (called trendy “carbon footprint”).

**Figure 2.** Examples of lock gates in 6 considered material options as described in Section 2 above.

3. Conceptual Designs

In order to determine the total quantities of materials required, the processes involved etc., conceptual designs of the lock gate were made in all the six materials. As this can be quite laborious, the designers should refrain from falling into

details, which may discourage the analysis. They should, however, identify all environmentally significant processes and conditions at this stage. Balancing between these two objectives requires a good dose of experience and expertise.

Figure 3 presents the conceptual designs of a gate in all the considered materials and for the conditions as specified above. Miter gates comprise two symmetrical leaves, therefore only one leaf is drawn. Cross-sections, spacing of gird-

ers and other dimensions are determined by manual calculations and comparison with operating gates.

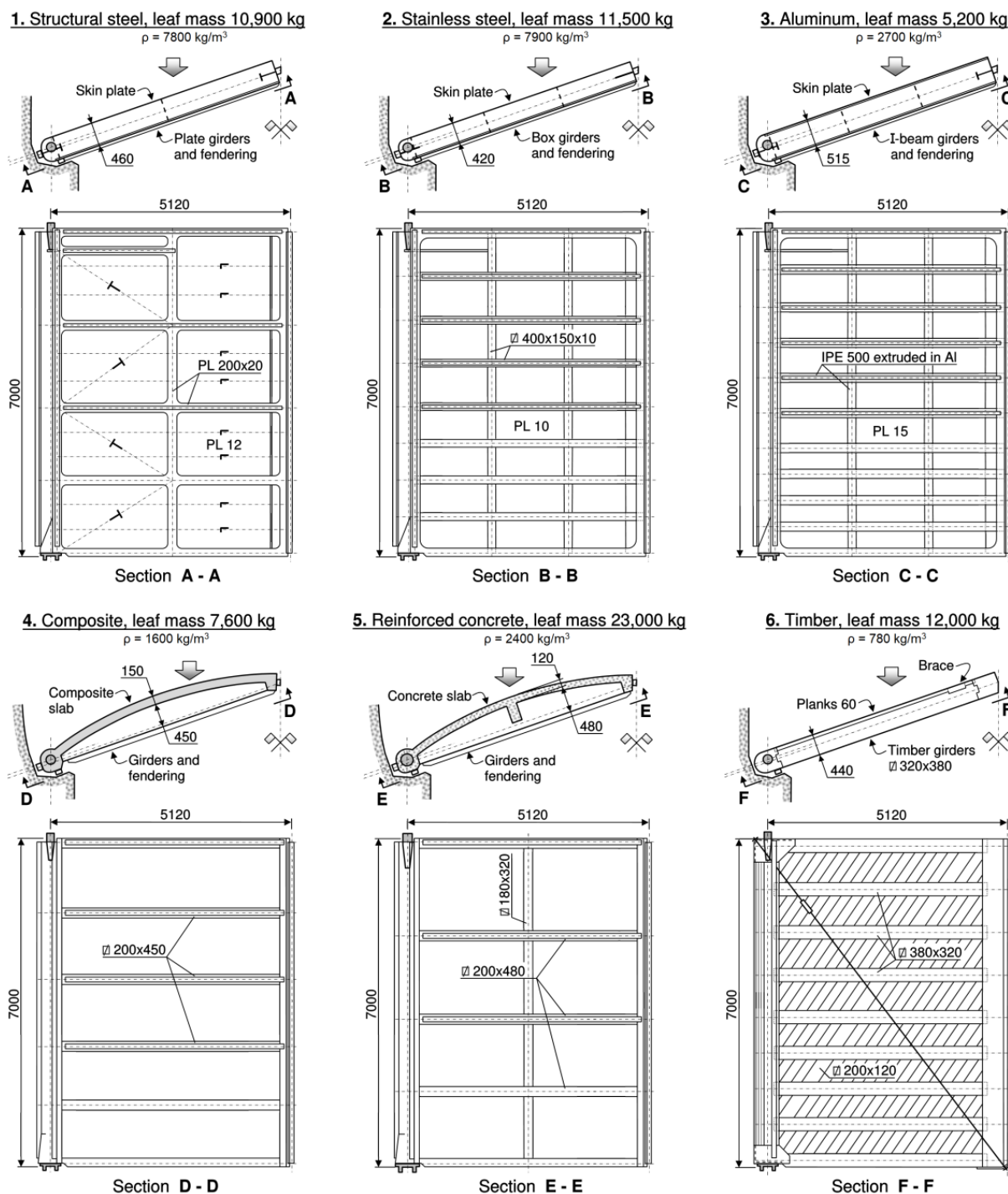


Figure 3. Conceptual designs of a lock gate in 6 considered material options.

The designs allowed to quantify the masses of gate basic materials, as indicated in Figure 3. Obviously, such structures also comprise some other materials, like steel for hinges or rubber for seals. Their quantities are, however, marginal. In a few cases, the environmental impact of those materials was taken into account by a slight modification of data for the basic material.

4. Analysis and Results

4.1. Criterion 1: Energy Consumption

It is not questioned anymore that energy consumption is an

important indicator of sustainability. In case of a navigation lock gate, this indicator should be considered not only for the material choice, but we will now focus on this issue. The analysis begins at data collection on energy input (in MJ/kg) for the fabrication and turn-key delivery of the structure in the 6 materials considered. These data may differ because materials can be obtained and processed in different technologies. Also, some data cover more processes than the other. There is still much arbitrariness in this field. For example, the energy consumption for a steel structure varied from 6 MJ/kg [6] to 46 MJ/kg [7] when a similar analysis was performed by the author for bridge materials [8, 9].

This is frustrating for engineers who, normally, work with precise data. On the other hand, refraining from sustainability analyses for this reason is not a desired attitude. Some encouragement can be drawn from the fact that the available data bases are – despite differences – usually consistent in themselves. High values for, e.g., structural steel, cover the processes like rolling, cutting, machining, surface treatment, welding, transportation, assembly etc. Low values may not cover all such processes. It is advisable to check what the data

set actually covers, and – if possible – to use the data from one source throughout the analysis.

This analysis employs the so-called “exergy method”. The “exergy”, or energy used to obtain the gates from Figure 3, is the sum of energetic value decreases of gate materials in production processes. These decreases represent the capacity of energy to deliver work. A more detailed outline can, e.g., be found in ref. [10, 11]. The concept of exergy makes it possible to speak of energy consumption, while the ‘classical’ energy cannot be consumed, it only changes its form.

The energy consumption data used in this analysis is presented in Table 2. It was delivered by NewProducts [7], then reviewed and slightly modified to reflect the processes associated with hydraulic gates [3, 4]. Exceptions are the data for timber that was derived from G. Wall [12] of the Chalmers University of Technology in Göteborg, Sweden; and some corrections for aluminum from Mahadvi and Ries [6] of the Carnegie-Mellon University in Pittsburgh, USA. The “primary” condition refers to materials from natural resources; the “secondary” condition refers to recycled materials.

Table 2. Energy consumption data for six optional gate materials.

Material	Condition	Used energy value (MJ/kg)	Product exergy value (MJ/kg)
Structural steel (e.g. S235J0)	primary	46	7
	recycled	36	7
Stainless steel (e.g. AISI 316)	primary	69	11
	recycled	54	11
Aluminum (e.g. AlMgSi1)	primary	149	33
	recycled	48	33
Composite (FGRP)	primary	33	6
	recycled	not practiced	
Reinf. Concrete (B50 or B60)	primary	24	4
	recycled	not practiced	
Hard timber (oak or harder)	primary	30	15
	recycled	not practiced	

A detailed discussion of these data goes beyond the scope of this paper. Below are only a few notes:

- 1) All data represent estimates, fine-tuned to reflect the application in hydraulic gates to the best of authors' knowledge. The processes involved are of generally accepted, well-controlled fabrication methods.
- 2) No secondary condition data are provided for composites. Their recycling is difficult, which favors combustion or utilization as a filler in low-tech products.

This can change in the future, as there is much development in recycling.

- 3) The data for reinforced concrete is computed from cement and steel. Gravel, sand, processing etc. are roughly covered by 75% increase of the cement rate. A factor of 1.25 was applied to cover for high strength concrete.
- 4) The data for timber is based on 18 MJ/kg from [12], increased by 2/3 to account for hard timber, fabrication

and delivery. The exergy stored in the product is slightly decreased to account for biological degradation.

With these data and the gate weights from Figure 3, the energy consumption as result of the 6 optional material choices is as follows:

4.1.1. Structural Steel Gate

Mass of gate 2 leaves: 21,800 kg. Assumed: 80% primary and 20% recycled steel. Energy consumed Ex_0 on delivery:

$$Ex_0 = 21\,800 \cdot [0.8 \cdot (46 - 7) + 0.2 \cdot (36 - 7)] = 806\,600 \text{ MJ.}$$

50 years' life requires 2 x blast cleaning and painting with transportation. A single service energy impact is estimated by subtracting the energy for an unpainted structure, 31 MJ/kg [11], from that of a painted structure from Table 2. The benefit of delay (20 and 35 years respectively) is approximated by a global reduction factor of 0.75. The energy consumed by maintenance Ex_1 and the total energy consumed Ex are then:

$$Ex_1 = 21\,800 \cdot 2 \cdot 0.75 \cdot (46 - 7 - 31) = 261\,600 \text{ MJ,}$$

$$Ex = Ex_0 + Ex_1 = 1\,068\,200 \text{ MJ.}$$

4.1.2. Stainless Steel Gate

Mass of gate 2 leaves: 23,000 kg. Assumed: 70% primary and 30% recycled steel. Energy consumed Ex_0 on delivery:

$$Ex_0 = 23\,000 \cdot [0.7 \cdot (69 - 11) + 0.3 \cdot (54 - 11)] = 1\,230\,500 \text{ MJ.}$$

Maintenance is limited to cleaning, replacement of worn bushings in hinges and occasional small repairs. Assume Ex_1 as 10% of Ex_0 . This gives:

$$Ex_1 = 0.10 \cdot 1\,230\,500 = 123\,100 \text{ MJ,}$$

$$Ex = Ex_0 + Ex_1 = 1\,353\,600 \text{ MJ.}$$

4.1.3. Aluminum Gate

Mass of gate 2 leaves: 10,400 kg. Assumed 70% primary and 30% recycled aluminum. Energy consumption Ex_0 on delivery:

$$Ex_0 = 10\,400 \cdot [0.7 \cdot (149 - 33) + 0.3 \cdot (48 - 33)] = 891\,280 \text{ MJ.}$$

Maintenance is marginal. Yet, there is concern about mechanical damages when in service. Ex_1 is assumed as equivalent to 2 major repairs, consuming 25% of Ex_0 :

$$Ex_1 = 0.25 \cdot 891\,280 = 222\,820 \text{ MJ,}$$

$$Ex = Ex_0 + Ex_1 = 1\,114\,100 \text{ MJ.}$$

4.1.4. Composite Gate

Mass of gate 2 leaves: 15,200 kg. No recycled material can be used. Energy consumption Ex_0 on delivery:

$$Ex_0 = 15\,200 \cdot (33 - 6) = 410\,400 \text{ MJ.}$$

Maintenance due to ageing is low, but ultraviolet light and mechanical damages cause concern. Therefore, Ex_1 assumed as equivalent to 2 repairs, consuming 25% of Ex_0 :

$$Ex_1 = 0.25 \cdot 410\,400 = 102\,600 \text{ MJ,}$$

$$Ex = Ex_0 + Ex_1 = 513\,000 \text{ MJ.}$$

4.1.5. Reinforced Concrete Gate

Mass of gate 2 leaves: 46,000 kg. No recycled concrete can be used. Energy consumption Ex_0 on delivery:

$$Ex_0 = 46\,000 \cdot (24 - 4) = 920\,000 \text{ MJ.}$$

Maintenance limited to hinges and walkways. Hinges are of concern due to high loads. So is possible damage from vessel impacts and reinforcement corrosion. Therefore, Ex_1 roughly estimated as 15% of Ex_0 :

$$Ex_1 = 0.15 \cdot 920\,000 = 138\,000 \text{ MJ,}$$

$$Ex = Ex_0 + Ex_1 = 1\,058\,000 \text{ MJ.}$$

4.1.6. Gate of Hard Timber

Mass of gate 2 leaves: 24,000 kg. No recycled assumed. Energy consumption Ex_0 on delivery:

$$Ex_0 = 24\,000 \cdot (30 - 15) = 360\,000 \text{ MJ.}$$

50 years' service unreal; gate to be replaced after 30 years. However, cost delay is a benefit, therefore only 50% of Ex_0 assumed to cover the replacement. Additional 10% assumed to cover cleaning and incidental repair. Ex_1 and Ex are then:

$$Ex_1 = (0.50 + 0.10) \cdot 360\,000 = 216\,000 \text{ MJ,}$$

$$Ex = Ex_0 + Ex_1 = 576\,000 \text{ MJ.}$$

4.1.7. Comparison of Energy Consumption

The presented calculations are approximate and often based on 'engineering judgment'. The author's view is that such approach is not only justified but also desired due to the relative, often questionable quality of available data. Yet, it is better to critically apply the available data, and call for its improvement, than to wait until it becomes better, in which case it may never improve.

It may also be questioned why the product exergy values have been subtracted. A short answer is that production processes may not only use but also deliver exergy. More data on this for buildings can be found in ref [13].

The results of the calculations above are summarized in a

graph in Figure 4 [3]. They allow for a few general conclusions as presented below the graph.

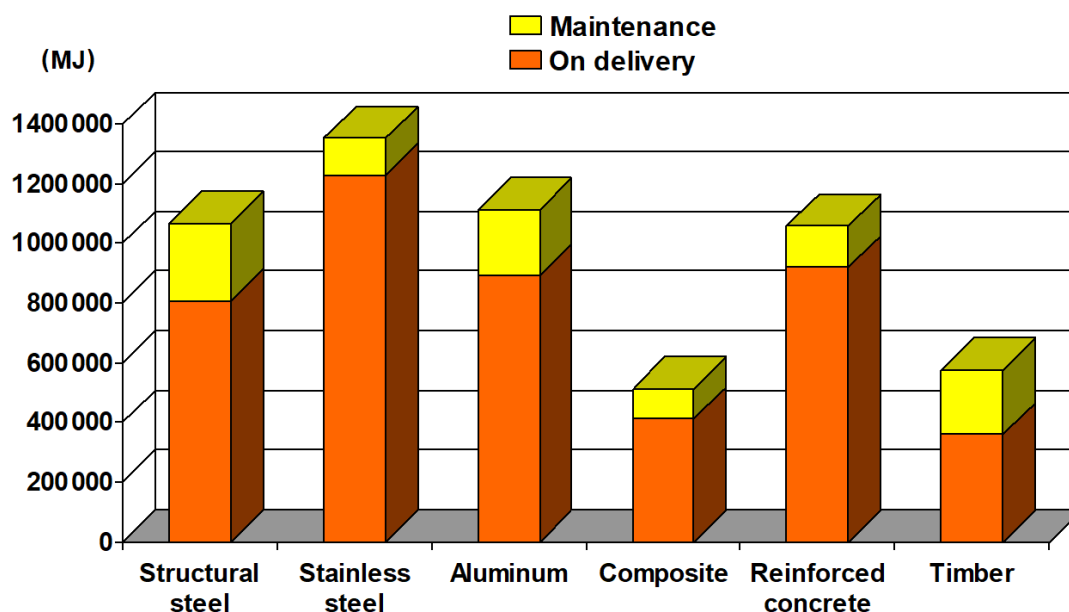


Figure 4. Energy consumption for a lock gate in 6 material options.

- 1) Two gate materials appear to be the most favorable: composite and timber. The first gives the lowest total energy consumption; the latter gives the lowest energy consumed on delivery. However, the difference is small and within the accuracy range of this analysis. Their advantage above the other options is, to the contrary, very clear.
- 2) The middle group covers structural steel, aluminum and concrete. Mutual differences are here also small and possibly within the accuracy range. Yet, this result is remarkable in view of the current practice that favors structural steel. No significant preference for steel can be derived from energy consumption. Also remarkable is that the reinforced concrete gate does not score worse in this group, despite its large mass and energy used in the production of cement.
- 3) The stainless steel option is the worst choice as it “consumes” the most energy. The advantage of low maintenance does not compensate this. This option requires even more energy than the aluminum gate, although the electrolysis of aluminum is a highly energy-consuming process. The reason is the big difference in mass of the two gates compensates.

Obviously, these conclusions must be viewed together with the assumed design specifications. For wider gates or gates carrying much larger hydrostatic pressure, some material options may prove uneconomic or even infeasible. Also the issues like local availability of materials may play a role. Nevertheless, the analysis indicates that energy consumption can be quantified and used as criterion for sustainability assessment of a structure.

4.2. Criterion 2: Loads to the Environment

In discussions related to climate change, energy consumption can be an indicator of anthropogenic (human-made) emissions of greenhouse gases (GHG), because most energy is still obtained from hydrocarbons. However, it says little about how ‘clean’ or ‘dirty’ the considered material option is, or – in ecological terms – what its ‘loads to the environment’ are. These loads are of a local character.

While assessing such loads, one cannot simply sum up the quantities of polluting substances (called “pollutants”) associated with a material option, because these pollutants are not equally harmful to the environment. What helps are the so-called ‘legal thresholds’ of these substances in, respectively, air, water, and – if relevant – soil. The way to use them in building projects was introduced by Mahadvi and Ries [6]. The first application in infrastructural project was for a pedestrian bridge at the Eastern Scheldt Storm Surge Barrier in the Netherlands [8, 9].

The method makes use of two data sets:

- 1) $B_{m,i}$ [kg/m³], masses of pollutants i emitted in production and processing of 1 m³ of material m . They are recorded as loads to air, water or soil;
- 2) $B_{0,i}$ [kg/m³], legal thresholds of pollutants i in 1 m³ of respectively air, water or soil.

Knowing these data records, the total masses m_m [kg] of gate materials m and their densities ρ_m [kg/m³] makes it possible to compute the total volumes of air V_m^a and water V_m^w polluted up to the legal thresholds (so-called “critical volumes”). The formula for these volumes is [4, 14]:

$$V_m = \frac{m_m}{\rho_m} \cdot \sum_i \frac{B_{m,i}}{B_{0,i}} \quad (1)$$

Let us disregard the stainless steel gate at this point due to its poor performance in terms of energy. Let us also assume that the processes involved are sufficiently controlled, so that

no significant pollutions of soil occur. The emissions $B_{m,i}$ and their thresholds $B_{0,i}$ to be taken into account for the five remaining options are given in Table 3 and Table 4 for pollutions to air and water respectively. These data mainly originate from ref. [6, 15], with a few adjustments by authors to reflect specific applications in hydraulic projects and some recent developments in material technologies.

Table 3. Estimated emissions to air $B_{m,i}$ and $B_{0,i}$ in $[\text{kg}/\text{m}^3]$ for the five material options considered¹⁾.

Pollutant	Struct. steel $B_{st,i}$	Aluminum $B_{al,i}$	Composite $B_{cp,i}$ ²⁾	Concrete $B_{cr,i}$	Timber $B_{tm,i}$	Threshold $B_{0,i}$
CO ₂	$2.56 \cdot 10^3$	$2.10 \cdot 10^4$	$1.03 \cdot 10^3$	$4.95 \cdot 10^2$	$1.78 \cdot 10^2$	$9.0 \cdot 10^{-3}$
CO	$9.58 \cdot 10^1$	$5.15 \cdot 10^1$	1.32	3.48	1.18	$4.0 \cdot 10^{-5}$
CH ₄	5.95	$5.39 \cdot 10^1$	1.21	$9.89 \cdot 10^{-1}$	2.07	$6.7 \cdot 10^{-3}$
N ₂ O	$3.70 \cdot 10^{-2}$	$2.94 \cdot 10^{-1}$	$4.80 \cdot 10^{-3}$	$1.51 \cdot 10^{-2}$	$1.25 \cdot 10^{-3}$	$1.0 \cdot 10^{-7}$
PM Fe/Al ³⁾	$4.40 \cdot 10^{-1}$	1.65	$1.05 \cdot 10^{-1}$	$7.50 \cdot 10^{-2}$	-	$1.0 \cdot 10^{-7}$
PM Si/Ca/org ³⁾	$4.20 \cdot 10^{-2}$	$2.70 \cdot 10^{-1}$	$5.05 \cdot 10^{-1}$	$5.88 \cdot 10^{-1}$	$1.35 \cdot 10^{-1}$	$3.0 \cdot 10^{-7}$
SO ₂	3.28	$1.27 \cdot 10^1$	$2.51 \cdot 10^{-3}$	$2.80 \cdot 10^{-1}$	$1.10 \cdot 10^{-1}$	$1.2 \cdot 10^{-6}$
NO _x	3.08	$2.45 \cdot 10^1$	2.83	1.27	$1.00 \cdot 10^{-1}$	$1.0 \cdot 10^{-5}$
Styrene	-	-	$1.20 \cdot 10^{-1}$	-	-	$8.0 \cdot 10^{-7}$

1) Data mainly collected from ref. [6, 15] with a few adjustments for the reasons identified in this paper.

2) Solid FGRP with E-glass in 20% of volume assumed; actual volume is larger due to partial foaming.

3) PM = particulate matter (dust), here predominately Fe/Al or Si/Ca oxides, organic PM for timber.

Table 4. Estimated emissions to water $B_{m,i}$ and $B_{0,i}$ in $[\text{kg}/\text{m}^3]$ for the five material options considered¹⁾.

Pollutant	Struct. steel $B_{st,i}$	Aluminum $B_{al,i}$	Composite $B_{cp,i}$ ²⁾	Concrete $B_{cr,i}$	Timber $B_{tm,i}$	Threshold $B_{0,i}$
Aluminum	$3.33 \cdot 10^{-6}$	$3.09 \cdot 10^{-5}$	$2.00 \cdot 10^{-6}$	$2.06 \cdot 10^{-7}$	-	$5.0 \cdot 10^{-5}$
Ammonia	$4.58 \cdot 10^{-3}$	$4.23 \cdot 10^{-2}$	$1.10 \cdot 10^{-3}$	$2.38 \cdot 10^{-4}$	$9.16 \cdot 10^{-4}$	$2.2 \cdot 10^{-3}$
Cadmium	$4.57 \cdot 10^{-5}$	$4.28 \cdot 10^{-4}$	$2.10 \cdot 10^{-6}$	$2.73 \cdot 10^{-6}$	$1.30 \cdot 10^{-6}$	$3.5 \cdot 10^{-6}$
Copper	$1.96 \cdot 10^{-8}$	$1.82 \cdot 10^{-7}$	$7.90 \cdot 10^{-4}$	$0.99 \cdot 10^{-9}$	$6.50 \cdot 10^{-5}$	$2.0 \cdot 10^{-4}$
Cyanide	$3.08 \cdot 10^{-4}$	$2.85 \cdot 10^{-3}$	$7.40 \cdot 10^{-5}$	$1.60 \cdot 10^{-5}$	-	$1.0 \cdot 10^{-4}$
Fluoride	$1.03 \cdot 10^{-1}$	$6.49 \cdot 10^{-3}$	$2.00 \cdot 10^{-4}$	$3.51 \cdot 10^{-3}$	$5.20 \cdot 10^{-6}$	$1.5 \cdot 10^{-3}$
Manganese	$6.07 \cdot 10^{-6}$	$5.64 \cdot 10^{-5}$	$3.60 \cdot 10^{-6}$	$3.79 \cdot 10^{-7}$	$1.04 \cdot 10^{-6}$	$5.0 \cdot 10^{-5}$
Mercury	$1.57 \cdot 10^{-4}$	$1.45 \cdot 10^{-3}$	$7.00 \cdot 10^{-7}$	$7.53 \cdot 10^{-6}$	$6.00 \cdot 10^{-9}$	$5.0 \cdot 10^{-6}$
Zinc	1.98	$5.44 \cdot 10^{-2}$	$1.40 \cdot 10^{-3}$	$1.69 \cdot 10^{-1}$	$6.00 \cdot 10^{-4}$	$5.0 \cdot 10^{-3}$
Cobalt	$1.10 \cdot 10^{-3}$	$2.00 \cdot 10^{-4}$	$1.50 \cdot 10^{-2}$	$2.50 \cdot 10^{-4}$	$1.30 \cdot 10^{-7}$	$4.0 \cdot 10^{-4}$

1) Data mainly collected from ref. [6, 15] with a few adjustments for the reasons identified in this paper.

2) Solid FGRP with E-glass in 20% of volume assumed; actual volume is larger due to partial foaming.

The data for composite was received by the author from DSM Resins, a market leader in this field at the time of the research [8]. The data for timber is averaged from the author's

market survey. This explains small traces of various wood preservatives (copper, fluoride, zinc, cobalt), while normally no more than one of them is used in a particular timber batch.

In this case, the pollution by dust (particulate matter, PM) is split into two types that normally represent higher and lower risk to human health. This is authors' arbitrary division with some rough estimations for the sake of simplicity. It is also common to split the PM emissions depending on the size of dust particles rather than their chemical contents [6]

The dichotomous division into pollutants to air and water in Tables 3 and 4 can be questioned as well, as some pollutants are emitted to both air and water. Assigning them into one of these media follows other research [6], and – occasionally – the authors' engineering judgment. One can also dispute the referred "legal thresholds" in both tables. Such thresholds significantly vary per country and per specific surrounding. They can, for example, be different for surface water, ground water and waste water; or for air in urbanized areas and in vulnerable natural environments.

However, despite these arbitrarinesses, the proposed assessment method has two important advantages:

- 1) It brings the emission data of qualitatively different pollutants into the same units. This makes it possible to sum them up, which gives an objective environmental assessment of the considered material options.
- 2) By incorporating legal thresholds, the method is founded on law. This is of tremendous value as it protects the assessments from aggressive lobbying, practiced in environmental disputes nowadays.

The emission estimations from Tables 3 and 4 and the lock gate masses and densities from Figure 3 can be used in formula (1). This gives the critical volumes of polluted air V^a and water V^w for, e.g., the structural steel gate as follows:

Polluted air:

$$V_{st}^a = \frac{m_{st}}{\rho_{st}} \cdot \sum_i \frac{B_{st,i}}{B_{0,i}} = \frac{2 \cdot 10\,900}{7800} \cdot \left(\frac{2.56 \cdot 10^3}{9.0 \cdot 10^{-3}} + \dots + \frac{3.08}{1.0 \cdot 10^{-5}} \right) = 29.71 \cdot 10^6 \text{ m}^3$$

Polluted water:

$$V_{st}^w = \frac{m_{st}}{\rho_{st}} \cdot \sum_i \frac{B_{st,i}}{B_{0,i}} = \frac{2 \cdot 10\,900}{7800} \cdot \left(\frac{3.33 \cdot 10^{-6}}{5.0 \cdot 10^{-5}} + \dots + \frac{1.1 \cdot 10^{-3}}{5.0 \cdot 10^{-3}} \right) = 1.446 \cdot 10^3 \text{ m}^3$$

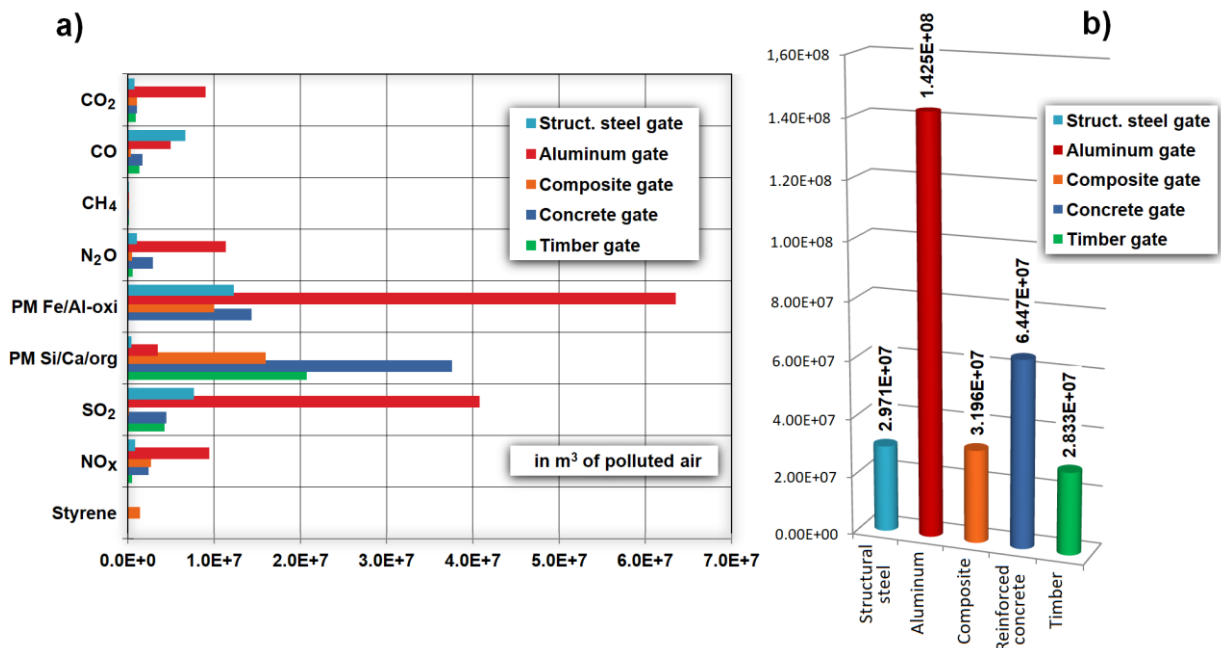


Figure 5. Emissions to air for a lock gate in 5 optional materials: a) per pollutant; b) in total critical volumes of polluted air.

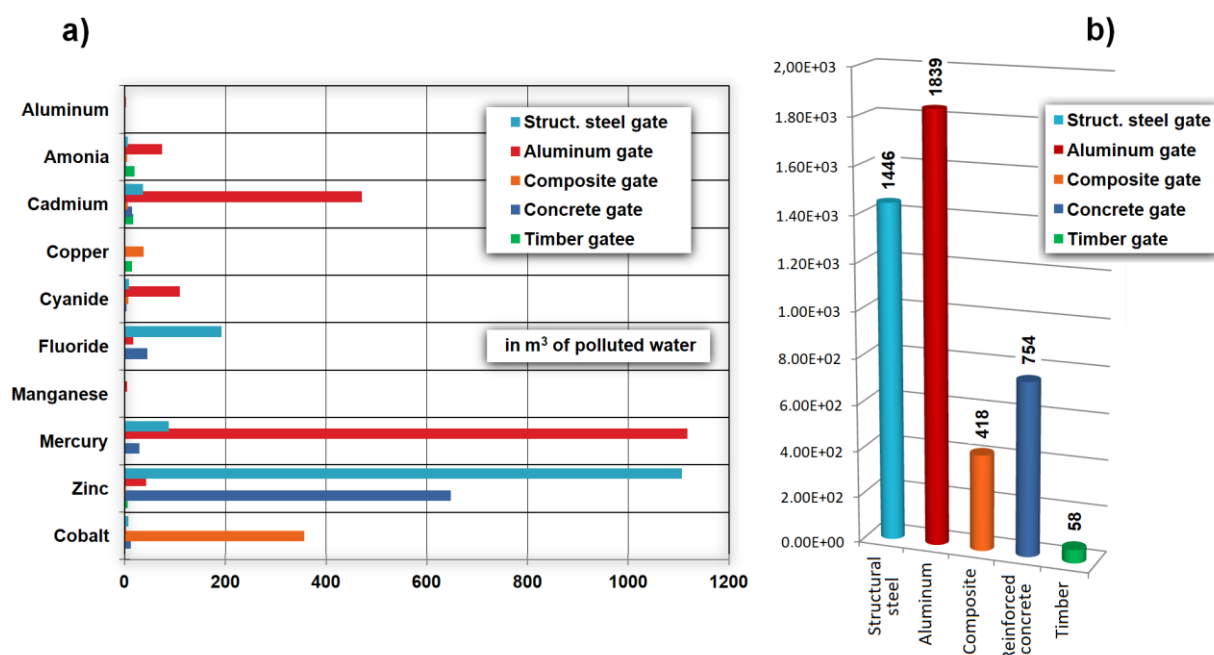


Figure 6. Emissions to water for a lock gate in 5 optional materials: a) per pollutant; b) in total critical volumes of polluted water.

Such calculations can most conveniently be performed in spreadsheets. Figures 5 and 6 present the graphic rendering of the results for the five material options considered [3]. Graphs (a) in both figures show how the lock gates perform when split into particular pollutants. The column charts (b) present the global comparative performances of these lock gates in cubic meters of, respectively, air and water polluted up to the legal thresholds.

Note that these graphs not only help to choose ‘clean’ materials for the structure. They also point to very specific pollutants that determine the scores, indicating which of them are more and which less significant. This not only makes the analysis transparent, which is desirable considering the interests and emotions of various material suppliers. It also shows the industry where to seek an improvement for a particular material option. After all, sustainable material choice for a structure is a common challenge for all parties involved in construction projects. It is not easy to remain unbiased or to withhold the pressures of various lobbies when dealing with this challenge. The authors hope that the presented approach will help engineers to achieve this goal.

Some readers with the engineering background may feel discouraged by the approximate character of pollution data in the performed calculations. Nevertheless, this analysis still allows for a few general conclusions:

- 1) It is possible to objectively assess a number of optional structural materials in terms of emissions to the environment. This possibility exists for any structure, including a hydraulic gate. The available databases are still of low precision and often controversial, but they continue to improve.
- 2) In loads to air, three gate materials represent ‘clean’

choices: timber, steel and composite. This is also their preferred sequence, although the differences are small and possibly within the accuracy range. Concrete gate falls in the middle. Aluminum gate is the ‘dirtiest’ choice due to the high emission of dust and SO₂.

- 3) In loads to water, the timber gate is an undisputed winner. Its resulting emissions are 7 times lower than those of a composite gate, the second best. Concrete gate takes the third place, while aluminum and steel gates perform the worst. For the steel gate, this mainly results from zinc emissions. An improvement in processing of galvanized scrap would enhance this score.
- 4) The graphs in Figures 5 and 6, unlike in the energy analysis, do not account for gate maintenance and lower emissions when recycled materials are used. These two factors can be particularly considerable for steel and aluminum. One can roughly assume that their aggregated impact is neutral for steel. It would, however, enhance the score of aluminum.

4.3. Criterion 3: CO₂ Emissions

The attention of politics, technology, science and media focuses at present on the anthropogenic emission of carbon dioxide (so-called ‘carbon footprint’) as the factor that drives the climate change. The authors do not entirely agree with this view, but the demand is clear and needs to be addressed in this discussion.

CO₂ is the first on the list of greenhouse gases (GHGs). According to the Kyoto Protocol [16], there are six gases on this list. The most significant for the current analysis are the first three gases, which also includes methane CH₄ and nitrous

oxide N₂O. The other three are compounds of fluoride, nearly not emitted in the processes under consideration.

The considered three gasses have different Global Warming Potential (GWP) ω , as indicated in Table 5. GWP is an indicator how much heat a mass unit of GHG traps in the atmosphere over a specific period in relation to what carbon dioxide (CO₂) does. Therefore it is appropriate to compare the equivalent emissions of these gases, denoted CO₂e, for the five lock gate material options in this study. We again disregard the stainless steel gate at this stage.

Table 5. Global warming potential ω of the three main GHGs per weight unit.

Greenhouse gas, GHG		Global warming potential, ω
CO ₂	Carbon dioxide	1
CH ₄	Methane	25
N ₂ O	Nitrous oxide	298

The demand for ‘carbon footprint’ assessments gave rise to a variety of software that allows quantifying the emissions of GHGs. For an engineer, an issue with this software is, however, that it is hardly verifiable and is not fine-tuned to specific projects. Nevertheless, it is advisable to make use of such software, albeit in a critical common-sense approach. Examples from the Netherlands are the “CO₂ performance ladder” and “DuboCalc” [17]. In the United States, the LEED rating

system for building projects [18] is popular. It rates the CO₂ emissions in terms of GWP.

The data already presented in this paper also enables such a rating. The emissions of three GHGs from Table 5 and the lock gate masses and material densities from Figure 3 give the emitted CO₂e mass m_m (2) for material option m :

$$m_m^{\text{CO}_2\text{e}} = \frac{m_m}{\rho_m} \cdot \sum_i (\omega_i \cdot B_{m,i}) \quad (2)$$

where i is the subsequent GHG from Table 5.

For example, for the structural steel gate:

$$\begin{aligned} m_{st}^{\text{CO}_2\text{e}} &= \frac{2 \cdot 10\,900}{7800} \cdot \sum_i (1 \cdot 2.56 \cdot 10^3 + 25 \cdot 5.95 + 298 \cdot 3.7 \cdot 10^{-2}) \\ &= 7\,154.87 + 415.74 + 30.82 = 7\,601.43 \text{ kg} \end{aligned}$$

The equivalent CO₂e masses for the other four material options were computed in the same way. However, this calculation does not account for recycled material and for gate maintenance. These aspects are significant for the gates of steel and aluminum. Therefore, an increase of 50% was estimated for steel, and a decrease of 33% was estimated for aluminum. For the other materials, the impact of maintenance and recycled material was considered to be neutral. The timber gate will need to be replaced after 30 years. This was taken into account by a 50% emission increase, on the same ground as in the estimates of energy consumption (see Section 4.1). The calculations resulted in CO₂e emissions as depicted in the column diagram in Figure 7.

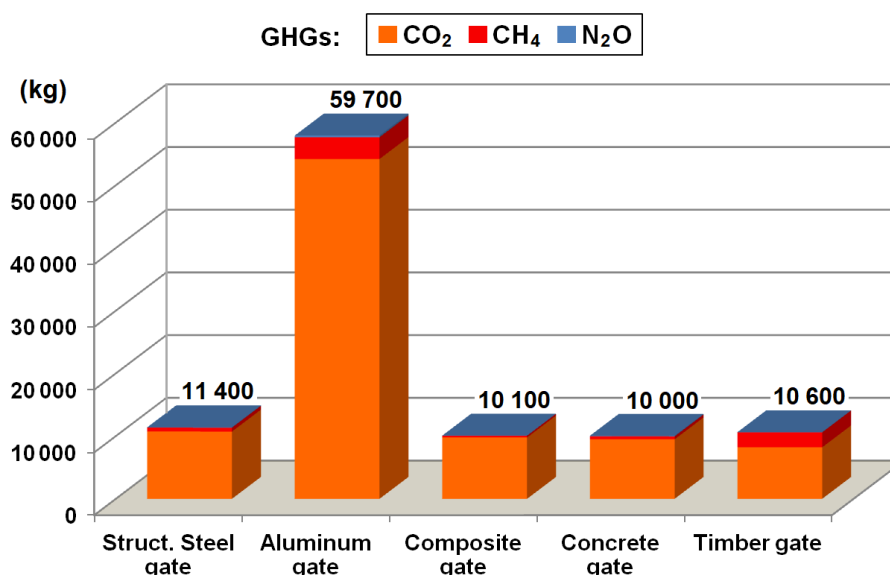


Figure 7. CO₂e emissions for a lock gate in 5 material options.

These results may seem somewhat surprising. It could be expected that the aluminum gate would emerge as the largest

“emitter” of GHGs. After all, the analysis of both the energy and pollution to air also gave this gate the most unfavorable

position on the list. However, it was not expected that the difference would be that high. The aluminum gate alone delivers more GHGs to the environment than all the other options taken together. The CO₂e emissions (“carbon footprints”) of those other options are comparable, with mutual differences within the accuracy margin of this analysis.

At present, drawing more conclusions from this analysis seems premature. There are two reasons for this:

- 1) Although demanded, ‘carbon footprint’ assessments are still disputable. Time will tell whether they earn a permanent place in engineering practice.
- 2) The data for such assessments is inconsistent. It depends on local technologies and conditions, and is sensitive to commercial and other manipulations.

5. Supplementary Notes

The discussion above does not exhaust the topic of sustainable material selection for a structure. The three criteria of sustainability, as identified in the beginning of this paper, can obviously be investigated with more precision. Moreover, there also exist environmental issues that are not directly covered by these criteria. A survey by the World Economic Forum (WEF) identified many such issues in sustainability statements of the main market players [19, 3]. It classified them into 10 groups, as shown in the graph in Figure 8, redrawn from ref. [19]. The columns indicate the numbers of interviewed market players that targeted these issues.

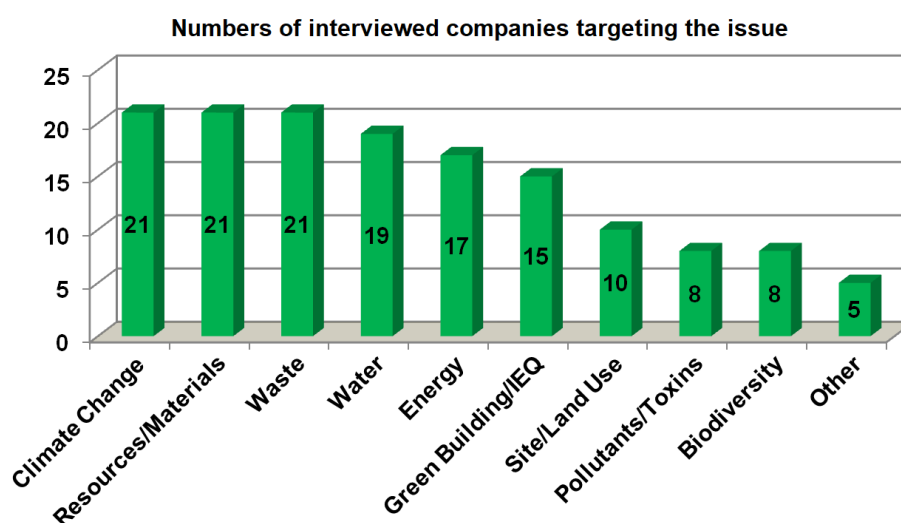


Figure 8. Environmental issues targeted in company principles.

However, the three discussed criteria are probably the main sustainability concerns of the world engineering community nowadays. This paper gives evidence that it is possible to objectively assess the environmental impact of construction material choices in view of these three criteria.

The above does not preclude that such assessments remain more approximate for complex structures, like a navigation lock gate, than for items of mass production with defined life cycles. The complexity of navigation lock gate design has been illustrated by the authors with, as an example, the large gates of Belgian sea locks [20, 21]. Therefore, these assessments should be carried out by experts in design, construction and management of structures. Omissions and incorrect estimations of materials or processes involved may result in serious miscalculations.

A potential trap is also the bureaucratization of the assessments. While an improvement of data is always desired, experience shows that a prescriptive character of assessment methods and data is not. It leads to lagging behind the actual developments, does not help the assessor’s motivation, and

encourages uncritical or even manipulative approach.

Despite common concerns, the investigated criteria are qualitatively different. In the next step, one can consider assigning them weighting factors in order to receive an unambiguously best material in terms of sustainability. Moreover, sustainability is not the only criterion of material choice, so another set of weighting factors may then be needed to justify this choice. These steps are often economic or even political rather than technology-driven. Therefore, they have not been further discussed in this paper.

6. Conclusion of the Case Study

Nonetheless, the obtained results are strongly in favor of a wooden lock gate. This deserves two comments:

- 1) The analysis was performed for a lock gate of moderate sizes and loads. Any extrapolation to higher sizes or loads must be done with care, as it can result in cross-sections that may not be available in hard timber species.

- 2) The source of material was, so far, not an issue, although it matters a lot whether the used timber has been harvested in a sustainably managed forest, or by forest depletion. The latter should, obviously, be discouraged.

Photos in [Figure 9](#) show a navigation lock gate of the author's design [\[22\]](#) and in sizes comparable to those in this

study. It was fabricated from timber harvested in Brazil under the FSC (Forest Stewardship Council) certificate, which is a recommended practice in The Netherlands. This certificate is widely seen as an unbiased evidence of sustainable forest management. Also the gate in [Figure 2f](#) was delivered with such a certificate, see photo (a) in [Figure 10](#).

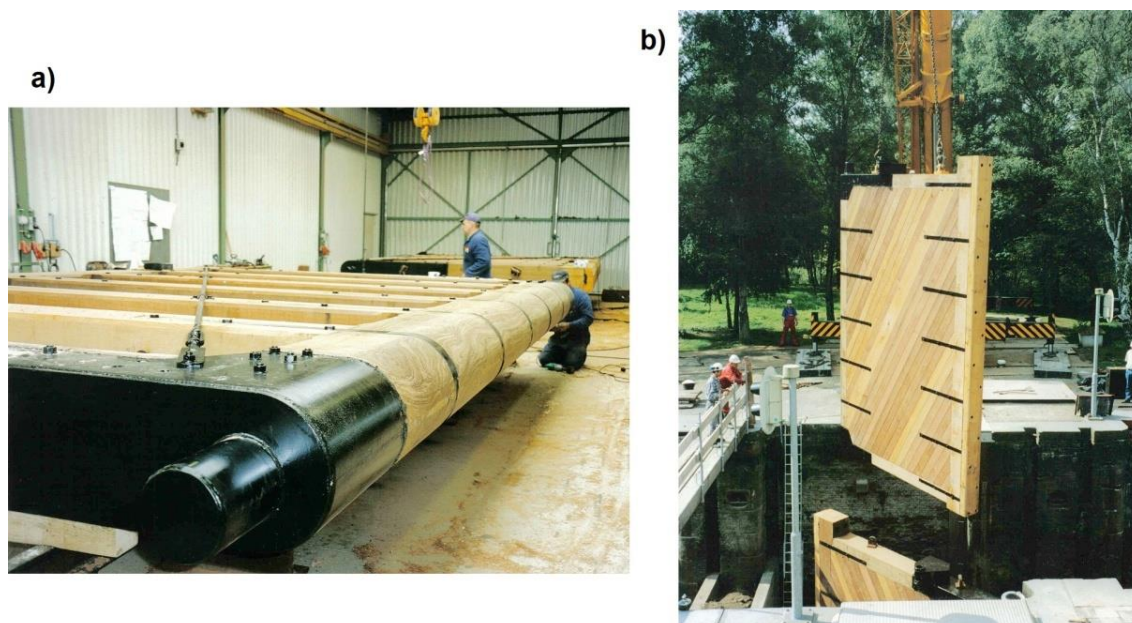


Figure 9. Lock gate in Wilhelmina Canal, Tilburg, Netherlands, photos R. Daniel: a) in fabrication; b) installation on the site.

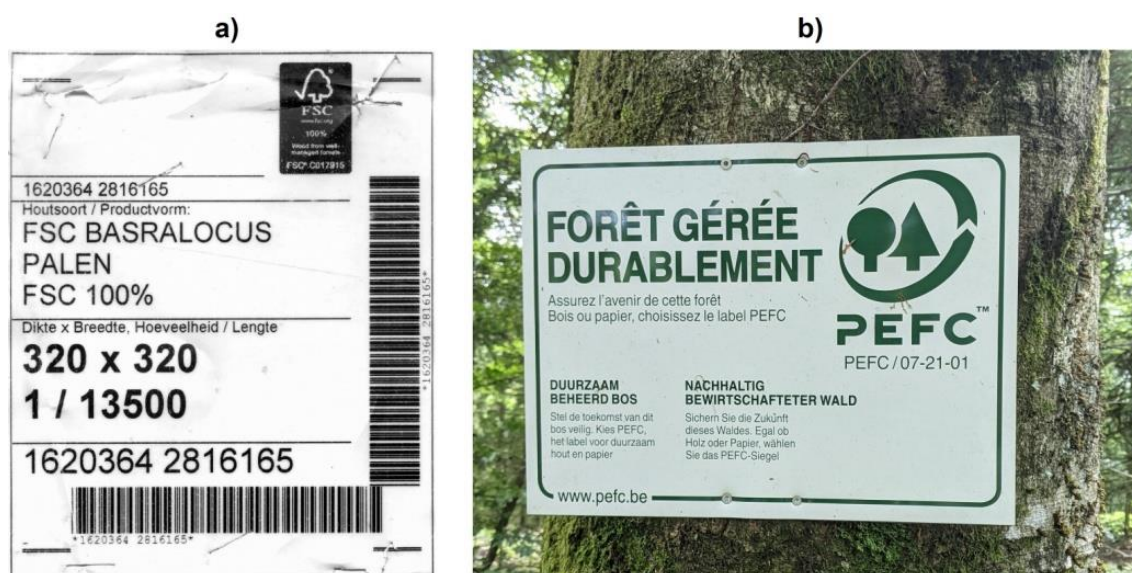


Figure 10. Certificates of sustainable forest management, photos R. Daniel: a) from gate depicted in [Figure 2f](#), The Netherlands; b) in the forests of Ardennes, Belgium.

In Belgium, the Regional Government of Flanders consistently requires that timber in public infrastructure projects be supplied with either FSC or PEFC quality mark, the latter shown in photo (b) in [Figure 10](#). Equivalent certificates are

only acceptable if sustainable forest management can be ensured [\[23, 24\]](#).

In Western Europe – particularly in The Netherlands and in Belgium – one of the favored timber species for structures of

long service life requirement, is Azobé (Figure 11). It comes from the forests of Central Africa, and has a high elasticity module ($18\,600\text{ N/mm}^2$), bending strength, and compressive strength (respectively 157 and 72 N/mm^2) [25]. The characteristic values are slightly lower when multiple sample tests are performed with Bayesian determination for entire population [26]. The environmental disadvantages of Azobé are long shipping distances and limited availability from sustainably managed forests.



Figure 11. Tropical timber at storage yards of Wijma BV in Kampen, The Netherlands, photo R. Daniel.

Therefore, customers are tempted to purchase this timber without a certificate, which brings the risk of environmental damage. This practice is, unfortunately, not exceptional on the world market of timber; and it is of concern to various parties. The issues of sustainable forest management – or wider, sustainable management of any resource – are complex. While such a management is desirable, it cannot be denied that the welfare of the so-called ‘global West’ was partly obtained by natural resource depletion all over the world. The severe conditions of material procurement, as repeatedly imposed nowadays, are often seen by “global South” as an obstacle and attempt to preserve the Western economic dominance. The moral shadows of this go beyond the subject of this paper. Encouragement can be found in the growing support for sustainable forest management also in the Western countries themselves, Photo (b) in Figure 10 gives an example of this.

Abbreviations

CVB	Commission of Navigation Managers, Netherlands
FGPR	Fiberglass Reinforced Polymer
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
GWP	Global Warming Potential ω
LCA	Life Cycle Analysis (or Assessment)

LEED	Leadership in Energy and Environmental Design
MJ	Mega-Joule (energy unit, $1\text{ MJ} \approx 0.278\text{ kWh}$)
DMOW	Department of Mobility and Public Works, Belgium
PEFC	Program for Endorsement of Forest Certification
VNF	Voies Navigable de France
WEF	World Economic Forum

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Author Contributions

Ryszard A. Daniel: Conceptualization, Formal analysis, Investigation, Validation, Visualization, Methodology, Writing – original draft.

Ivar Hermans: Resources, Formal analysis, Investigation, Visualization, Project administration, Writing – review & editing.

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Data Availability Statement

The data supporting the outcome of this research has been reported in this paper, including the utilized sources. In some cases, this the data was modified – if necessary by estimation – to take account of specific issues or latest developments. This has also been reported in the paper.

Conflicts of Interest

The authors declare no conflicts of interest.

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