Year: 2021

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DOI: https://doi.org/10.1016/j.oceaneng.2020.108378

Originally published at:
Kappenthuler, Steve; Seeger, Stefan (2021). Holistic evaluation of the suitability of metal alloys for sustainable marine construction from a technical, economic and availability perspective. Ocean Engineering, 219:108378.
DOI: https://doi.org/10.1016/j.oceaneng.2020.108378

Holistic evaluation of the suitability of metal alloys for sustainable marine construction from a technical, economic and availability perspective

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Abstract

The demand for resilient infrastructure located in marine environments is expected to increase in the coming decade as rapid urbanization of coastal areas continues and industries such as oil and gas, renewable energy generation or aquaculture move further offshore to utilize the extensive amount of resources and space available on the open ocean. Increasing environmental concerns, global scarcity of various materials, as well as dwindling resource stocks have made sustainability considerations a major issue for the construction of such infrastructure. Metal alloys, as one of the most commonly used materials for marine construction, are often the focus of discussions on criticality and are associated with a high environmental impact if produced from virgin mineral resources. In this paper we analyze the long-term potential of five metal types commonly used in marine construction (carbon steels, stainless steels, aluminum alloys, titanium alloys and nickel-copper alloys). By evaluating and ranking these materials' performance according to 27 precisely defined attributes related to durability, economics, sustainability and future availability, we provide a detailed comparison of each material's strengths and weakness. Additionally, by focusing on the identified weaknesses of the individual materials we discuss promising areas of research which support the sustainable use of these metals for marine construction in the long term.

Keywords

Marine Alloys, Sustainable Construction, Research Prioritization, Multi-Criteria-Decision-Making, Economics, Resource Availability

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations of interests

None

1 Introduction

Ocean based industries and activities are major contributors to global economic output and employment. As a key provider of a multitude of societal needs such as transport, leisure, food, energy and minerals, they are essential for the future welfare of mankind. Driven by global megatrends such as population growth, increasing rates of urbanization and climate change adaption, economic activity in the ocean is increasing at a rapid pace through expansion of existing (shipping, fisheries, conventional oil and gas, coastal tourism) and establishment of new (offshore renewable energy generation, deep-sea oil and gas, marine aquaculture, seabed mining) sectors [1–5]. In line with the expansion of ocean-based activities, the demand for infrastructure to support these activities will increase significantly in the coming decades. The selection of suitable material for these constructions will be paramount to ensure an efficient, economic and environmentally friendly expansion, as the physical and chemical properties of a material greatly influence the overall sustainability of a structure [6–8]. Metals have played an important role in marine construction in the past. Due to their high toughness, stiffness and strength they were used extensively for the production of not only large-scale structural components such as ship hulls, support columns for off-shore platforms and pressure vessels, but also for pipelines, tethering attachments and reinforcement of concrete structures [9–11]. Despite the emergence of newer material classes such as ceramics or fiber reinforced polymer composites in the past decades, metals will remain exceedingly important materials for marine infrastructure in the future. Many frameworks have been developed to assess the most optimal materials for the construction of specific components used in marine environments [12–16]. These frameworks evaluate the detailed technical and to a certain extent economic potential of a given material for a specific application. However, the production of metals is associated with large environmental impacts further exacerbating global challenges such as climate change [17]. Furthermore, the raw materials for various metal alloys are non-renewable and can be highly geographically concentrated [18–20]. Considering the impact a lack of availability of central alloys required in marine construction could have on the development of the industry and the time for new alternative material compositions to be developed, tested and introduced into the market, it is essential to identify such supply risks early on and to begin developing mitigation strategies long before supply shortages occur. These issues are almost completely neglected in existing material selection frameworks, as they focus solely on material selection in the present and lack a consideration of long-term developments. To enable a holistic evaluation of a material's suitability, not only today, but also in the long term future, an alternative framework was developed, consisting of 27 attributes designed to rate a specific material’s technical, economic and environmental performance as well as the availability and distribution of the raw material resources required for its production [21]. In this paper the mentioned framework is applied to evaluate the potential of different types of metals and alloys for long-term use in marine construction and to identify the issues, as well as potential solutions, which need to be addressed to enable an environmentally and economically sustainable expansion of marine activities in the future.

The rest of the paper is structured as follows. First the methodology of the ranking applied to the specific case of marine construction is explained and the different metal categories used for the ranking are presented. This is followed by the results of the ranking, which was completed with experts from industry and academia. Based on these results, we discuss research areas that may have a large impact on the overall sustainability of marine construction, as well as a high potential for long-term commercial applicability.

2 Methodology

The framework applied in this paper was developed to aid in the identification and initial high-level prioritization of research projects focusing on the development or improvement of materials for the use in sustainable construction. The theory behind the framework is described in great detail in a previous publication by the authors [21]. In this section, we therefor provide a short overview of the structure of the framework and then focus on the methodological issues related to the application of the framework to the presented case.

2.1 Short description of methodological framework

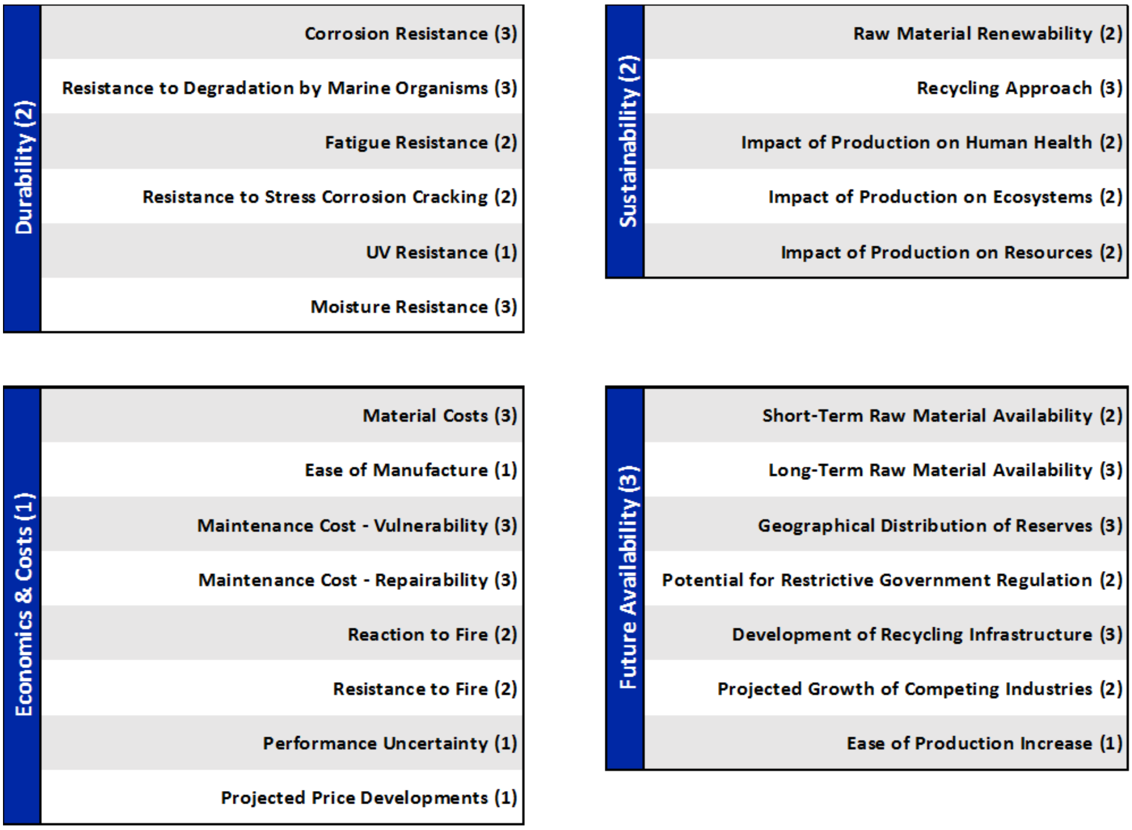
As the goal of the applied framework is to identify and prioritize promising research areas for the improvement of construction materials, the strengths and weaknesses of the evaluated materials need to be assessed in a first step. Therefore, the framework is based on a holistic ranking of each materials’ technical, economic and ecological performance. As this requires a large number of individual properties to be analyzed, multi criteria decision analysis is employed using two hierarchical levels, categories and attributes, where a category consists of multiple attributes and the attributes are the criteria that are evaluated. The categories covered in the framework are Durability (a measure of technical performance), Economics & Costs, Sustainability & Environmental Impact, and Future Availability (evaluation of long-term potential for use). Mechanical stability (another measure of technical performance) is included in the form a *functional unit* that is used to compare the performance of the different materials. For each material the attributes are given a score from 1-5 (1 being the lowest, 5 the highest score). For quantitatively measurable attributes, values where specified for each point along the scale. For attributes that need to be assessed qualitatively the lowest acceptable (1), average (3), and ideal (5) property of a material was described as precisely as possible based on expert discussions and literature data (all scales are shown in Appendix A). The attribute scores are aggregated using a Simple Additive Weighting process to produce a single score for each category. These category scores are then aggregated again using the same process to produce a final material score. The resulting ranking provides a comparison of the individual materials' performance levels, as well as an overview each materials' strengths and weaknesses, which is then used to identify areas where material improvements have a high impact on the overall score of the material [21].

2.2 Goal of Ranking

For this work the *goal* of the ranking is to identify the types of metals that have the highest potential to be used as structural components for sustainable marine construction in the long-term future. Therefore, the attributes developed in the original framework were adapted to measure the performance of the evaluated materials in a marine environment. All attributes and their scale definitions are shown in Appendix A. The Durability attributes are evaluated for exposure in the splash zone. This is the harshest location of exposure for marine construction [9,22]. The individual metals are evaluated without considering any protection methods (ex. coatings). The Future Availability attributes are evaluated for a *timeframe* of 50 years unless stated otherwise in Appendix A. Disposal and Recycling Costs (originally included in the Economics & Costs category) are left out of the ranking as they vary greatly from country to country, are highly process specific, and thus cannot be realistically estimated [23].

2.3 Category and Attribute Weights

All categories and attributes are given a *weighting factor* reflective of their importance for achieving the stated goal (1 = low importance, 2 = medium importance, 3 = high importance). These weights were defined together with industry experts and are shown in Figure 1.



Durability (2)
- Corrosion Resistance (3)
- Resistance to Degradation by Marine Organisms (3)
- Fatigue Resistance (2)
- Resistance to Stress Corrosion Cracking (2)
- UV Resistance (1)
- Moisture Resistance (3)

Sustainability (2)
- Raw Material Renewability (2)
- Recycling Approach (3)
- Impact of Production on Human Health (2)
- Impact of Production on Ecosystems (2)
- Impact of Production on Resources (2)

Economics & Costs (1)
- Material Costs (3)
- Ease of Manufacture (1)
- Maintenance Cost - Vulnerability (3)
- Maintenance Cost - Repairability (3)
- Reaction to Fire (2)
- Resistance to Fire (2)
- Performance Uncertainty (1)
- Projected Price Developments (1)

Future Availability (3)
- Short-Term Raw Material Availability (2)
- Long-Term Raw Material Availability (3)
- Geographical Distribution of Reserves (3)
- Potential for Restrictive Government Regulation (2)
- Development of Recycling Infrastructure (3)
- Projected Growth of Competing Industries (2)
- Ease of Production Increase (1)

Figure 1: Categories and attributes used for ranking (weights)

Since the focus is on sustainable marine construction in the long-term future, immediate economic considerations were seen as less important while future availability was determined to be the most central category.

2.4 Definition of Functional Unit

The *functional unit* (FU) chosen to compare the different metals according to their performance as structural components was related to the materials’ tensile strengths. Thus, it was calculated for each metal how much material would be required for the production of a 1 m long beam with a square cross section that is able to withstand a tensile load of 5000 kN. Consequently, the tensile strength of each metal determines the area of the cross section and thus also the amount of material required (i.e. the FU).

2.5 Material Selection for Ranking

For *Material Selection* existing categorizations of metals used in marine construction were analyzed [9,24–26]. This led to a first selection of broad metal categories, which each include the pure metals as well as the plethora of individual alloys of the specific metal type. The categories commonly used in literature are carbon steels (CS), stainless steels (SS), aluminum alloys (AA), titanium alloys (TiA), nickel-copper alloys (Ni-Cu), magnesium alloys and zinc alloys. After discussion with industry experts it was decided to exclude magnesium and zinc alloys from the ranking. Magnesium and zinc are extremely low on the galvanic series and corrode rapidly in seawater. Consequently, they cannot be used as structural materials in these environments. For each of the remaining metal categories one specific alloy was chosen to represent the entire category. This choice was based on discussions with experts and literature review to identify the alloy that commonly provides a good performance in the marine environment. For the CS, S355J2 (1.0553) was chosen as the representative material as it is a versatile structural steel specified for marine use by various codes such as BS EN 10225:2009. The most commonly used SS are austenitic steels since they are also the cheapest. However, these steels may still corrode in aggressive environments as can be found offshore in the splash zone. Therefore, to reflect more precisely the material used for marine construction, duplex stainless steel grade 1.4462 (X2CrNiMoN22-5-3) was selected to represent the category as it combines the advantages of both austenitic and ferritic stainless steel and is the most suitable material for the use in corrosive environments [27]. For the AA, the 5xxx series containing magnesium as the main alloying element are mainly used for structural applications due to their increased corrosion resistance [28]. Alloy 5083 (AlMg4.5Mn) was chosen as the representative material for this group. The most used TiA for marine environments is grade 5 titanium (3.7165 - Ti6Al-4V). This alloy accounts for around 50% of global titanium alloy production [29]. Finally, for Ni-Cu, Monel K500 (2.4375 - NiCu30Al) is used as the representative material.

2.6 Data Collection

Data for each attribute of all evaluated metals was gathered through discussions with experts, and from technical reports, material databases and scientific literature. The experts were asked to complete the ranking and to explain the reason for each individual score. All scores are discussed in detail in the next section. For each metal at least 3 experts completed the ranking. In general, the average score was chosen as the final score. However, if the scores given by different experts varied by more than 1 point, further investigation into the literature was conducted, which allowed a well informed decision on which score was appropriate. Overall a total of 10 experts from academia and industry participated in the ranking.

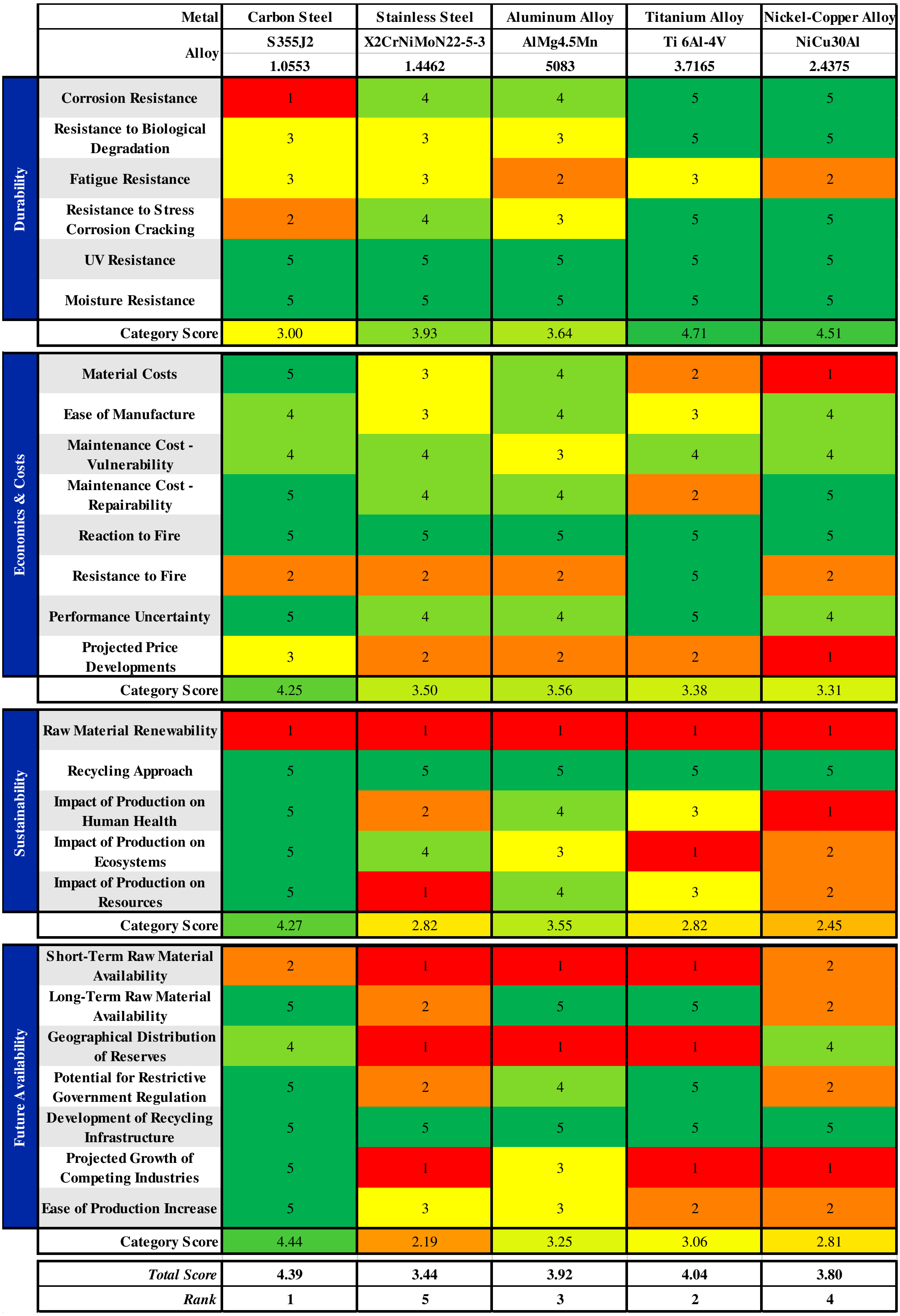
3 Results & Discussion

The individual attribute and category scores are shown in Table 1, providing an overview of each metal’s strengths (values 4-5) and weaknesses (values 1-2). As mentioned, the applied framework evaluates the technical performance of the metals in the form of their durability (i.e. resistance to external physical and chemical impacts), their commercial potential according to their usage costs and anticipated price developments, their overall sustainability (based on renewability, environmental impact (EI) of production, and recyclability) and finally the future availability of the raw materials required for their production which is determined by the global supply and demand situation (for more details [21]).

The highest durability scores are achieved by the corrosion resistant TiA and Ni-Cu followed by SS, AA and finally CS. The economics scores show almost the exact opposite ranking (CS>AA>SS>TiA>Ni-Cu), as the less alloyed metals are cheaper to produce and somewhat easier to manufacture. The same ranking resulted for the sustainability category. While all metals are non-renewable and highly recyclable, the mining and processing of more specialized alloying elements leads to significantly higher EI of production (per FU) for SS, Ni-Cu and to a lesser extent TiA, despite their higher tensile strengths (Appendix B). Concerning future availability, the most critical materials are nickel, chromium and molybdenite leading to low scores for SS and Ni-Cu. In the longer term these alloys (as well as TiA) will furthermore see strongly increasing demand from other industries beside construction, exacerbating potential supply concerns. For AA competition may also be an issue, but this is less certain. No competition or availability shortage is expected for CS.

Combining the individual scores of each metal using the weighting factors presented in Figure 1 leads to the total scores shown at the bottom of Table 1. Despite having a lower durability than all the other metals, the low cost and EI of production (on a relative scale, the impact is still rather high, when compared with other materials such as timber or concrete) as well as the high future availability results in CS achieving the highest overall score. The second highest ranked material is TiA, mainly due to its high durability. This is followed by AA, Ni-Cu and finally SS. The performance of the individual metals will be discussed in detail in the following subsections.

Table 1: Ranking results including attribute, category and total scores for the analyzed metals



	Metal	Carbon Steel	Stainless Steel	Aluminum Alloy	Titanium Alloy	Nickel-Copper Alloy
	Alloy	S355J2	X2CrNiMoN22-5-3	AlMg4.5Mn	Ti 6Al-4V	NiCu30Al
		1.0553	1.4462	5083	3.7165	2.4375
Durability	Corrosion Resistance	1	4	4	5	5
	Resistance to Biological Degradation	3	3	3	5	5
	Fatigue Resistance	3	3	2	3	2
	Resistance to Stress Corrosion Cracking	2	4	3	5	5
	UV Resistance	5	5	5	5	5
	Moisture Resistance	5	5	5	5	5
	Category Score	3.00	3.93	3.64	4.71	4.51
Economics & Costs	Material Costs	5	3	4	2	1
	Ease of Manufacture	4	3	4	3	4
	Maintenance Cost - Vulnerability	4	4	3	4	4
	Maintenance Cost - Repairability	5	4	4	2	5
	Reaction to Fire	5	5	5	5	5
	Resistance to Fire	2	2	2	5	2
	Performance Uncertainty	5	4	4	5	4
	Projected Price Developments	3	2	2	2	1
	Category Score	4.25	3.50	3.56	3.38	3.31
Sustainability	Raw Material Renewability	1	1	1	1	1
	Recycling Approach	5	5	5	5	5
	Impact of Production on Human Health	5	2	4	3	1
	Impact of Production on Ecosystems	5	4	3	1	2
	Impact of Production on Resources	5	1	4	3	2
	Category Score	4.27	2.82	3.55	2.82	2.45
Future Availability	Short-Term Raw Material Availability	2	1	1	1	2
	Long-Term Raw Material Availability	5	2	5	5	2
	Geographical Distribution of Reserves	4	1	1	1	4
	Potential for Restrictive Government Regulation	5	2	4	5	2
	Development of Recycling Infrastructure	5	5	5	5	5
	Projected Growth of Competing Industries	5	1	3	1	1
	Ease of Production Increase	5	3	3	2	2
	Category Score	4.44	2.19	3.25	3.06	2.81
	Total Score	**4.39**	**3.44**	**3.92**	**4.04**	**3.80**
	Rank	**1**	**5**	**3**	**2**	**4**

3.1 Durability

With the exception of CS, all analyzed metals have a very high Durability rating. All metals are immune to damage from UV radiation and are not affected by moisture (excluding corrosive effects), thus achieving the highest score in these categories. TiA and Ni-Cu are furthermore considered as inherently corrosion resistant (Ni-Cu is often used as protective cladding for marine steel structures) and are also not susceptible to biological degradation and stress corrosion cracking (SCC, see definition in Appendix A) [25,30]. In fact, the only attribute where these metals do not achieve the maximum score is fatigue resistance.

All metals are susceptible to fatigue damage. Nevertheless, their fatigue behavior is well understood and can be predicted rather precisely. Therefore, for metals with a fatigue limit (CS, SS, TiA) structures with an infinite fatigue life can theoretically be designed, if the loads a component will be exposed to during its service life are known (score 3). This is not possible for metals without a fatigue limit (AA, Ni-Cu), which is why these metals have a lower fatigue score (i.e. 2).

The next best metals concerning Durability are SS and AA. Duplex SS perform very well in the marine environment. However, they can still suffer from pitting corrosion. It has been shown that the depth of these pits increases rapidly after initiation but remains constant after a period of several years [31]. Therefore, for thicker stainless steel components this pitting corrosion can be seen as mostly superficial affecting the visual aspects and not the mechanical ones. A lifetime of 50-100 years should be achievable [27]. Nevertheless, since the initiation of corrosion can under certain circumstance lead to failure of a component a score of 4 was assigned. The same score was assigned for AA, which are corrosion resistant due to the formation of a passive oxide layer on their surface. If this layer is damaged localized pitting corrosion can also occur.

For both SS and AA biological attack presents an issue in the form of microbially induced corrosion (MIC). Certain microorganisms can become attached to SS and AA components and give rise to slimy biofilms on the surface. These films can accelerate the initiation of pitting corrosion which can lead to sudden failure of a component (score 3) [32].

Concerning SCC Duplex SS perform better than AA. Both are generally not susceptible to SCC. For AA however certain tempers as well as defects during manufacture can strongly increase SCC susceptibility [33]. Due to this possible susceptibility a score of 3 was assigned. Duplex SS do not exhibit this behavior but are still not completely immune to SCC (score 4).

CS as the lowest ranking metals readily corrode in seawater (score 1), are also susceptible to biological attack in the form of MIC (score 3) and in the past have commonly failed due to SCC mechanisms when used in marine structures without the appropriate maintenance or protection (score of 2) [34].

3.2 Economics and Costs

Concerning Economics and Costs all metals perform well. The main weaknesses are fire resistance and increasing prices in the future. The ranking of the total Economic scores is the same as that of material costs per FU. CS are the cheapest of the analyzed materials followed by AA which cost about 100% more per FU. The more complex Duplex SS, TiA and Ni-Cu are significantly more expensive due in part to the higher content of specialized alloying elements such as chromium, molybdenum or vanadium, and achieved scores of 3, 2 and 1 respectively (The costs per FU for each metal are shown in Appendix B).

Concerning Ease of Manufacture, all metals have similar properties. Larger components such as sheets, rods and bars are produced in a factory for all analyzed metals. Theoretically, any shape or size can be produced. For CS and Ni-Cu, components can easily be resized and joined on-site with simple welding equipment. To a certain extent these components can also be reshaped. Nevertheless, the main design of the component produced in the factory largely determines the final shape that is used on-site (score 4). AA achieved the same score despite the fact that on-site welding of Al components is more difficult than for CS or Ni-Cu, as this disadvantage is compensate by the lower stiffness of AA making it easier to reshape components on-site. SS and TiA were given a lower score, as welding and reshaping on-site is not easily completed (score 3). For SS more caution needs to be given when handling components to make sure the surface isn't damaged or contaminated which would reduce corrosion resistance [27]. Thus, the environment needs to be carefully controlled during casting and also welding, jointing and cutting, necessitating more specialized equipment and better trained personnel. Especially the welding of duplex SS is a big challenge even for trained personnel, making factory conditions much more suitable for manufacture than on-site ones. For TiA the primary and secondary fabrication processes are up to 18 times more costly than when using CS. This is due to the hardness and reactivity of titanium which wears down tools very quickly and requires a slow fabrication process [35]. Thus, it requires expensive specialized equipment for manufacture. Furthermore, it is very difficult to shape TiA components on-site making factory production of the complete final components a necessity.

The Ease of Manufacture of the different metals has a direct consequence on their Repairability. As CS and Ni-Cu can be rather easily be welded the repair of damaged components is possible on-site even to the extent of restoring original mechanical properties (score 5). The same can be done with AA and SS components although more sophisticated equipment and specially trained personnel is required (score 4). For TiA the hardness of the material makes it very difficult to cut out a damaged area before welding on-site. Thus, removal of the entire component and repair in a factory are a more feasible approach (score 2).

Fire resistance is an issue for all unprotected metals except TiA which have an excellent heat resistance (score of 5). The high thermal conductivity of metals leads to a rapid temperature increase throughout the entire component in the case of a fire. If unprotected, they lose their mechanical strength at lower temperatures than those present in an average fire and thus fail under standard service loads. Nevertheless, for any given load it is possible to calculate the time it will take for a specific component to fail in a fire, making the failing behavior predictable (score 2).

All analyzed metals have been used for decades in marine construction and thus have a low performance uncertainty. The difference in individual scores is due to the fact that some metals have been used extensively for larger structural components (CS, TiA score 5), while others are more commonly used for non-structural uses such as pipes, valves, cladding or handrails (SS, AA, Ni-Cu, score 4).

Finally, in the long term, for all metals except CS a significant price increase is expected in the foreseeable future. The main driver for these increases differ from metal to metal. For instance, global aluminum prices are expected to increase by over 30 % by 2030 compared with 2016 [36]. This will have a large effect on the future prices of AA and to a certain extent also for TiA as aluminum is used as an alloying element. The prices for titanium minerals (ilmenite & rutile) are also predicted to increase in the range of 5-15% from 2017-2020. It is expected that suppliers will aim to keep price increases steady but moderate [37]. A critical point for TiA is vanadium. In the near term a price spike is expected for vanadium as demand exceeded supply in 2017. However, as new capacity comes online these prices are expected to stabilize [38,39]. Overall vanadium is only added as an alloying element in small amounts (4% of mass) but will nevertheless influence the final price of grade 5 titanium. For duplex SS, rising prices for raw materials (excl. iron ore) are seen as one of the main restraints for future growth of the industry. Increased use of scrap (which will occur if prices are high) could limit these increases [40]. The highest increase in price is expected for nickel (an alloying element in SS and the main component of Ni-Cu). Due to decreasing production levels and increasing demand from green technologies such as batteries, turbines or electric motors an increase of up to 100% is expected from 2016 to 2030. Furthermore, copper prices are also expected to increase by around 40% in the same timeframe [36]. Thus the lowest value was assigned for Ni-Cu.

3.3 Sustainability and Environmental Impact

Concerning Sustainability the only positive aspects of the analyzed metals is their high recyclability. The recycling rates are above 60% for all metals, which corresponds to the highest score [41–43]. However, none of the raw materials required for production of the individual alloys are from renewable sources, translating into the lowest score for Renewability.

The individual EIs were calculated for the production of 1 FU of the specific metal from 100% virgin materials using data from the Ecoinvent 3.3 database (The individual scores are shown in Appendix B. Information on the individual calculations can be found in Appendix C). CS have the lowest EI for all three categories analyzed (Human Health, Ecosystems, Resources) and thus the highest score for these attributes. This is once again due to the low content of alloying elements. For instance SS and Ni-Cu with the overall highest impact require nickel and for SS also molybdenum, both of which are largely mined as sulfide minerals. The hydrometallurgical processing of these minerals leads to large impact scores from emissions and leaching of the sulfide tailings. Overall, these direct impacts are larger than the indirect impacts from energy production which are significant for the energy intensive production of AA and TiA [17,44]. It must be kept in mind that the EI rankings are based on the relative values of the analyzed material and thus cannot be directly translated into "environmental friendliness" of production.

3.4 Future Availability

The Future Availability scores for all materials are determined by the raw materials required for their production. Table 2 describes the elemental composition of the individual alloys, while Table 3 shows the raw materials from which each element is produced as well as their availability and concentration values.

The overall Future Availability score for CS stands out from those of the other metals. The raw material resources of all raw materials required for the production of carbon steel (Fe, C, Cu) are large and geographically well distributed. Furthermore, the construction industry is the main user of steel and the only competition could potentially come from the automotive industry, which is predicted to grow strongly in the coming decades due to increased demand from developing nations. However, the automotive industry is moving strongly towards more lightweight materials such as aluminum or composites. Therefore, the demand for steel from the automotive industry will very likely be significantly lower than the demand from the construction industry. Concerning manganese, the main alloying element in low carbon steels, the steel industry is the major consumer responsible for around 90% of global demand and therefore this should not lead to a shortage in supply for the construction industry (score 5). Finally, demand growth for steel is slowing down after a period of very strong growth driven largely by China. Many steel producers already have or may soon have significant overcapacities. Some facilities have even been shut down to improve the carbon footprint of producing companies. Therefore, a certain increase in production volumes should be possible with existing facilities. The past surge in demand for steel by China demonstrated that significant production capacity can be added in a very short period of time (score 5) [45–47].

Table 2: Elemental composition of analyzed alloys (based on data from the MaterialUniverse database provided by Granta Design [48])

Metal Class	Specific Alloy	Material Composition in weight %
Carbon Steels	S355J2 / 1.0553	Fe (balance), Mn (1.6), Cu (Max 0.55)
Stainless Steels	X2CrNiMoN22-5-3 / 1.4462	Fe (balance), Cr (22), Ni (5), Mo (3), Mn (2)
Aluminum Alloys	AlMg4.5Mn / 5083	Al (balance), Mg (4.4), Mn (0.7), Cr (0.15)
Titanium Alloys	Ti6Al4V / 3.7165	Ti (balance), Al (6), V (4), Fe (Max 0.4)
Nickel Alloys	NiCu30Al / 2.4375	Ni (balance), Cu (30), Al (2.7), Ti (0.6), Fe & Mn (Max 2)

Table 3: Availability and geographical concentration of raw materials (Calculated with data from 49)

Element	Raw Material	Short-Term Availability (Reserves / Production Ratio)	Long-Term Availability (Resource / Production Ratio)	Geographical Distribution HH-Index of Reserve Concentration
Al	Bauxite	107	286	1538
Cr	Chromite	17	Large	3890
Cu	Copper Ore	37	>300	1678
Fe, C	Iron Ore	60	169.0	1589
Mg	Various	Virtually Unlimited	Virtually Unlimited	Globally Widespread
Mn	Manganese Ore	43	Large	1840
Mo	Molybdenite	66	85	3662
Ni	Laterites (60%) Sulfite deposites (40 %)	35	58	1164
Ti	Ilmenite (89 %), Rutile (11 %)	126	>300	1514
V	Various (often recovered as a byproduct)	4	>300	3246

In comparison the score for SS, the lowest ranking metal type concerning future availability, is greatly affected by the use of nickel, chromium and molybdenum as alloying elements. All three elements either have a limited short- or long-term availability (score 1 and 2 respectively), while chromium and molybdenum reserves are also highly concentrated (score 1). Furthermore, government regulations which have an impact on the production of SS are already in effect. For instance, the government of Indonesia restricted the export of unprocessed nickel ore in order to ensure that the value increasing refining processes are completed in the country in 2014. Furthermore, in the Philippines the government issued an order in 2016 to audit all existing mines in the country to check for environmental compliance and to clamp down on non-sustainable mining practices, reducing output and even shutting down critical operations. These two countries together account for 31% of global nickel production and thus these developments have limited the supply of this crucial raw material on the global market and created substantial uncertainty [50,51]. Further export restrictions exist for other essential raw materials of SS such as chromium and even SS scrap. These export restrictions have a high potential to limit (but not completely restrict) supply of raw materials especially for the European Union, which is responsible for around 20% of global SS production and a much larger percentage of global duplex grade production (score 2)[52]. To add to these issues, the construction industry is only responsible for around 12% of total stainless steel demand (this includes all grades) and demand from competing industries is expected to increase strongly (score 1). The major concern comes from a strong expected growth of the renewable energy and electro mobility sectors that would lead to large demand increases for nickel and also molybdenum. Kleijn et al. estimated the increased metal supply that would be required under different energy scenarios and came to the conclusion that nickel output would have to increase by 50-250% and molybdenum output by 30-100% to meet the rising demand from the energy sector alone [53]. Even if supply security can be achieved, increasing the production of duplex SS will only be possible with large capital investments (score 3). As most facilities which currently produce duplex SS do not have large overcapacities, new facilities will need to be constructed. If these facilities are to be built in countries that are currently not yet producing duplex SS, careful technology transfer will be required, as the process for producing these high quality materials is significantly more complicated than those used to produce austenitic SS or CS.

For AA the main bottleneck concerning availability are globally highly concentrated chromium reserves (score 1) combined with existing export restrictions mentioned before (as it is only a minor alloying element in the 5xxx series a value of 4 was assigned to Potential for Government

Regulation). For the production of the AA themselves there is no real competition for raw materials as 95% of globally produced bauxite is used for metallurgical processes [54]. However, next to construction, transport is a major end-use sector for the globally produced AA. Both sectors account for around 25% of total demand. Increase in demand from the construction of lighter weight vehicles is expected to outweigh the increase in demand from the construction sector. Currently global AA production is more or less at full capacity and further investments in new mines and production facilities are ongoing. If production increase can keep up with demand growth competition for supply should be limited (due to the uncertainty a value of 3 was assigned) [44,55]. Concerning Ease of Production Increase, the mentioned high level of capacity at which global aluminum production is currently running means that new mines and processing facilities would need to be built requiring large, long term investments, in order to increase global production levels (score 3).

The Future Availability of TiA suffers mainly from the high concentration of vanadium resources (score 1) as well as Demand from Competing Industries (score 1) and to a lesser extent the high investments required to increase global production levels (score 2). The main competing industry for the production of TiA is the use of titanium in pigments. 91% of mineral supply is consumed for production of TiO_2 pigments, while only around 6% are used for the production of metallic products. As the construction industry is also only a minor user of TiA, the number and size of competing industries is significant. The largest end-use sectors for TiA are aerospace, chemical processing and power generation. Demand from the aerospace industry is expected to increase significantly due to increasing production of commercial aircraft and also increasing titanium content of new aircraft. However, future titanium prices are still expected to be determined largely by the level of demand from pigment producers as the largest users of this element [56–58]. Another issue is the use of high purity vanadium as a major alloying element in Ti-6Al-4V. Only around 4% of global vanadium production is used in titanium alloy production. The major user is the steel industry responsible for 93 % of vanadium consumption. The demand for these steels is expected to grow due to increasing construction activities specifically in China [38]. Furthermore growth in the green technology sector is expected to drive demand for vanadium redox batteries (specifically renewable energy and electric vehicles). By 2020 it is expected that the production of such batteries could consume about 30% of global vanadium production [39]. Concerning Ease of Production Increase, the global titanium sponge production is currently running at around 70% capacity. Due to an oversupply in the last years as well as environmental concerns some plants were closed down or decreased production rates [57]. Consequently, to a certain extent it would be possible to increase titanium production by reactivating plants that were shut down and running existing ones at full capacity. However, for an increase to significantly higher production levels large investments will be required as titanium production is a very expensive process were return on capital is measured in decades and not years [59]. Furthermore, new primary mines will most likely also be required, not only for titanium, but also for vanadium which requires further investments along the entire value chain. Currently, the global high purity vanadium production required for the use in titanium alloys is running at full capacity and demand is expected to exceed supply already in 2017 [38].

Ni-Cu, as the second lowest ranked metals concerning Future Availability, suffer from the same issues as the SS due to the use of nickel as the main material component (low short- and long-term availability, government regulation restricting supply and high competition from other industries). A significant advantage Ni-Cu have over SS is that they don’t require chromium or molybdenum as an alloying element and thus have a relatively well distributed resource base (score 4). Concerning the Competition from Competing Industries (score 1) the main use of nickel is for SS production (67%) and the main use of Ni-Cu is for the aerospace industry. Future demand is expected to increase substantially due to growing demand from energy generation, transport and food processing. As nickel producers are currently decreasing production capacity in reaction to a strong oversupply in the past years, increasing production would to a certain extent be possible by reopening closed facilities and increasing capacity of running ones. However, a ramp-up of the mostly old and deep mines would require a long time and significant investments. Furthermore, it is expected that existing capacity even with reopening of mines will need to be significantly expanded to meet future demand. As no new high-grade deposits have been discovered in a long time lower grade deposits will need to be developed, mostly in more remote regions, requiring significant investments and having higher environmental concerns [53,60].

3.5 Improving Material Performance

By analyzing the weaknesses of each material discussed in the previous sections in combination with its overall future availability, it is possible to roughly determine the research areas and approaches that have the highest probability of providing long-term benefits to the industry. For this, the low ranked attributes (scores 1-2 in Table 1) which have a high weight are analyzed and, where possible, existing approaches are discussed.

For carbon steels the main weak points are Corrosion Resistance (weight 3), to a certain extent Fire Resistance (weight 2) and the high EI of Production (weight 2). For all other metals the high EI of production also presents a reason for concern. However, the main weak points lie in a low long-term availability (weight 3, for SS & Ni-Cu) or high concentration (weight 3, for SS, AA and TiA) of specific alloying elements, as well as strong competition from other growing industries (weight 2, for SS, TiA and Ni-Cu). Further, a factor reducing the overall attractiveness of TiA and Ni-Cu is price (weight 3).

Concerning CS, multiple approaches are already broadly employed to increase their corrosion resistance such as sacrificial anodes, or various kinds of organic and inorganic coatings. Further research in this area is well warranted, as carbon steel presents the best option from the sustainability and availability perspectives for all the metals and an increase in Corrosion Resistance would significantly increase the Durability and overall score of this material. However, it is essential to evaluate the Economics, Sustainability and Future Availability of the desired protection method to ensure that the addition of a coating or anode does not significantly decrease individual scores of the carbon steel. Most coatings contain an organic component which has been produced either from petroleum or natural gas. The use of these non-renewable resources will slightly reduce the Resources to Production Ratio Score (i.e. long-term availability) from 5 to 4 [61]. As for all products containing petroleum derived organic substances, the development of bio-based alternatives presents an interesting option for ensuring long-term availability and potentially increasing sustainability of production.

Another aspect to consider for protective coatings is that they often contain active substances which prevent the initiation of corrosion if the barrier formed by the coating is damaged. The future availability, as well as the potential environmental impact of large scale use of these substances also needs to be taken into account prior to investing in the development of new coatings. For instance, coatings containing cerium nanoparticles have been shown to provide significant corrosion inhibition to steel substrates [62]. Cerium reserves are however geographically highly concentrated (HHI of ca. 2250) and the use of such coatings would reduce this score for steel components from 5 to 2 [49]. Furthermore, the extraction of cerium from mined ore is complicated and cost-intensive leading to a number of severe environmental issues [63]. Finally, it must also be taken into account that a certain amount of cerium will leach into the environment during the lifetime of the coated component. The toxicity of cerium oxide nanoparticles is a topic of intensive investigation and initial results currently point towards the possibility of adverse effects on multiple organisms [64,65]. Therefore, it may be the case, that extensive use of these particles in sensitive marine environments is prohibited by governments in the future, further reducing the overall score of this improvement strategy. A more promising approach (from a resource and environmental perspective) are thermally sprayed aluminum coatings which are often employed for corrosion protection of submerged steel components [66,67]. Looking at the availability scores for aluminum (the element, produced from bauxite) in Table 3 it can be seen, that availability or concentration does not present an issue. The EI of aluminum production still needs to be taken into account, as well as the potential impact of aluminum leaching into the environment. Although higher aluminum concentration have been found to have adverse effects on certain marine organisms, it is suspected that the increase in dissolved aluminum caused by leaching from offshore structures will remain well below this level due to dilution effects [68,69].

As mentioned, another main weakness of all analyzed metals is the high EI of production. The sources of these impacts are direct solid, liquid and gaseous emissions occurring during mining and processing as well as indirect emissions stemming from the production of energy and reagents required for these steps [17]. Concerning the process of resource extraction (i.e. mining and separation of metals from minerals) there are a number of possibilities to reduce these impacts. For instance, the energy required for the mining operations could be provided from renewable sources such as bio based fuels or electricity (from wind, solar power etc.). Another approach is the development of more environmentally friendly, bio-based or biodegradable chemicals as well as the use of specialized microbes for the extraction of the desired metals [70–73]. However the only true solution to decreasing the EI of metal production is to eliminate the need for mining and processing of new virgin raw materials by significantly increasing recycling rates and moving further towards to a closed loop economy [41]. Increasing recycling rates will furthermore also mitigate the availability concerns of essential alloying elements for AA, TiA and Ni-Cu, such as chromium, nickel or vanadium.

A major challenge in the recycling of metal alloys is the efficient separation of the individual alloy types and alloying elements as well as complete removal of contaminants from the scrap metal [74–78]. Technologies that efficiently separate different scrap automatically according to various physical and chemical properties present promising improvements for the recycling of all metals. Examples are near infrared spectroscopy, x-ray diffraction/fluorescence, laser induced breakdown spectroscopy or 3D-imaging techniques [74,79]. These technologies are essential, as a proper separation of individual alloys before the actual recycling step minimizes the amount of different elements (i.e. impurities) in the scrap metal, greatly improving the quality of the recycled alloys [80,81]. Nevertheless for certain impurities are almost impossible to separate completely and thus need to be removed as part of the recycling process. For example, for AA the main contaminant which reduces the quality of the recycled alloy is iron. Iron content can be managed by mixing end-of-life scrap with less contaminated scrap, obtained during the manufacture of AA products (cut-offs, shavings etc.), or primary aluminum [74]. Also for TiA the removal of iron (Fe) and oxygen (O) impurities in scrap material presents the largest barrier to improving the recycling rate. Again, higher quality scrap (containing lower concentrations of Fe and O) is diluted with highly pure titanium sponge (which is produced from virgin materials) to ensure sufficient quality of the recycled alloy. Lower quality scrap is used to produce ferrotitanium, an alloying element used for the production of certain steels [77]. Thus, by reducing the Fe and especially O content of TiA scrap the need for additional virgin material and down-cycling could be reduced. Technologies for removal of these contaminants are mostly still in the fundamental stage of research [82–87]. If further development proves successfully, they could have a high commercial potential.

Consequently, the development of recycling processes which remove certain contaminants, along with on-line analytical methods for the separation of different metal alloys present high-potential research areas, which could greatly improve the economics and sustainability of metal recycling.

4 Conclusion

In this paper a newly developed material selection framework is applied to analyze the long-term potential of different metal types for use in sustainable marine construction. The results provide a detailed overview of each material’s strengths and weaknesses related to their Durability, Economics, Sustainability and Future Availability. Overall carbon steels achieved the highest score followed by titanium alloys, aluminum alloys, nickel-copper alloys and finally stainless steels. For the lower ranked alloy types the higher Durability scores could not compensate for the Future Availability concerns of various specialized alloying elements (ex. Ni, Cr, V, Mo). The main weakness of carbon steels is their low corrosion resistance, which however is compensated by a low price and high availability. Based on these results a number of research areas which may improve the performance of these materials in the future could be identified. The critical research areas identified were the development of environmentally friendly protective coatings for carbon steels and improved separation and recycling technologies, in order to minimize contaminants in the recycled materials, for all metal alloys. While many such technologies already exist, they are currently still uneconomical on a large scale. Further investments into their development may in the long-term enable a significantly more sustainable use of metals not only in marine construction but also for all other areas of application.

Appendix A: Attributes and Scales

Table A.1: Durability Attributes and Scales used for Ranking

Attribute	1	3	5
Corrosion Resistance	Structural damage to material from corrosion in less than 10 years in splash zone in average ocean water	No structural damage to material after 50-75 years in splash zone in average ocean water	No structural damage to material from corrosion after 100 years in splash zone in average ocean water
Resistance to Biological Degradation	Material is highly susceptible to attack from marine organisms and is fully degraded over time (loses mechanical strength)	Marine organisms do not directly attack or degrade the material but can accelerate other degradation processes	Material is immune to degradation or accelerated degradation by marine organisms
Fatigue Resistance	Material does not have a fatigue limit and also exhibits unpredictable fatigue behavior	Material has predictable fatigue behavior and a fatigue limit	Material is extremely resistant to fatigue thus this is not a concern for the design of structures
Resistance to Stress Corrosion Cracking	Material is very susceptible to stress corrosion cracking which leads to highly increased speed of degradation and loss of mechanical properties	Material may suffer from stress corrosion cracking after longer exposure to salt water and higher wave & wind forces (storm levels)	Material is immune to stress corrosion cracking
UV Resistance	Material is highly susceptible to damage from atmospheric UV radiation and is completely degraded over time	Surface layer of material is degraded by exposure to atmospheric UV radiation, but strength reduction is limited	Material is not affected by UV radiation
Moisture Resistance	Material is degraded by moisture and loses all mechanical strength for instance through leaching or swelling	Mechanical properties of material are reduced when it becomes saturated with moisture, but stabilize at a certain point. This behavior is predictable and reversible	Mechanical properties of material are not affected by moisture absorption

Table A.2: Economics & Costs Attributes and Scales used for Ranking

Attribute	1	3	5
Material Costs	Material cost [$/FU] lie above the 80th percentile of all materials evaluated	Material cost [$/FU] lie in between the 60th and 40th percentile of all materials evaluated	Material cost [$/FU] lie in the 20th percentile of all materials evaluated
Ease of Manufacture	Material is very difficult to form into diverse shapes, can only be manufactured in a factory, requires specialized , expensive equipment and is limited to certain sizes and geometries	Material can be formed into almost any shape and size, with specialized equipment in a factory	Material can be formed into almost any shape, without expensive specialized equipment on site by less experienced personnel
Maintenance Cost - Vulnerability	Material is easily damaged and fractures propagate easily through the material	Either material is easily damaged but damage remains local or material is more difficult to damage but fractures propagate easily	Material is very difficult to damage and damage remains local and does not spread easily
Maintenance Cost - Repairability	Material once damaged cannot be repaired but needs to be replaced completely	Material can be repaired on-site, but original mechanical properties or durability cannot be achieved	Material can be easily repaired on-site by less experienced personnel without removal to restore original mechanical properties
Disposal & Recycling Costs	The disposal (landfill or incineration) of material waste or scrap is done by specialized companies that charge a fee for the process	Material waste or scrap can be given away for free to a recycling company, or can be disposed of free of charge	Material waste or scrap has a significant value and can be sold to other industries or recycling companies
Reaction to Fire	Material burns readily and contributes to fire falling into class E & F according to EN-13501-1	Material falls into Class C according to EN-13501-1	Material is completely fireproof falling into class A1 & A2 according to EN-13501-1
Resistance to Fire	Material losses mechanical properties in fire rapidly due to increase in temperature (t < 30 min, softening or degradation) and strength loss is difficult to calculate as it burns irregularly	Mechanical properties of material decrease in fire due to decomposition of surface layer. Increasing the cross-section increases time to collapse. This process is accurately predictable through calculations	Mechanical properties of material are not affected by heat from fire and material is not degraded
Performance Uncertainty	Material has not yet been used in construction for the specified use and environment. A high risk is associated with using it for the first time	Material has been used for smaller scale applications in other industries in the specified environment	Material has been extensively used for large scale structures in construction for the specified use and environment. Regulations and codes exist based on long term experience
Projected Price Developments	Price for material expected to increase by over 100% in the foreseeable future	No changes in price to be expected in the foreseeable future	Price for material expected to decrease by over 100% in the foreseeable future

Table A.3: Sustainability & Environmental Impact Attributes and Scales used for Ranking

Attribute	1	3	5
Raw Material Renewability	0-25 % of raw materials are renewable	50-75 % of raw materials are renewable	100 % of raw materials are renewable
Recycling Potential	Material has very low recycling rates in construction leading to most demolition waste being brought to landfill or being incinerated	Material when used in construction is mostly downcycled into material that can be further used in the construction industry	Material is recyclable with little to no preprocessing and can be recycled to use instead of virgin material and has very high recycling rates when used in construction
Environmental Impact of Production on Human Health	ReCiPe Endpoint impact score [EIP/FU] of material production on human health above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on human health in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on human health in 20th percentile of all materials evaluated
Environmental Impact of Production on Ecosystems	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems in 20th percentile of all materials evaluated
Environmental Impact of Production on Resources	ReCiPe Endpoint impact score [EIP/FU] of material production on resources above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on resources in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on resources in 20th percentile of all materials evaluated

Table A.4: Future Availability Attributes and Scales used for Ranking

Attribute	1	3	5
Short Term Availability of Raw Materials	Raw material reserves/production ratio below 25 years	Raw material reserves/production ratio between 50-75 years	Supply large to unlimited so that data on reserves is not exactly available or reserves to production ratio over 100 years
Long Term Availability of Raw Materials	Raw material resources/production ratio below 50 years	Raw material resources/production ratio between 100-125 years	Supply large to unlimited so that data on resources is not exactly available or reserves/production ratio over 150 years
Geographic Distribution of Reserves	Herfindahl-Hirschmann-Index of raw material reserves larger than 2500	Herfindahl-Hirschmann-Index of raw material reserves from 2150-1850	Herfindahl-Hirschmann-Index of raw material reserves below 1500
Potential for Restrictive Government Regulation	Regulations limiting the supply of raw materials will be implemented in the near future or are already in place and strongly limit the availability of raw materials	Uncertain whether regulations limiting access to raw materials will be implemented, but the possibility exists	No realistic reason for governments to regulate usage of material or raw material in the foreseeable future
Development of Recycling Infrastructure	Recycling infrastructure will not develop significantly in the next 50 years leaving landfilling or incineration as the main disposal option for material	Recycling infrastructure will develop to a certain extent increasing recycling rates. However downcycling is expected to remain the only viable option	Infrastructure will develop strongly in the next 50 years leading to high recycling rates (> 75 %) of material that can replace virgin material or recycling rate is already at this level today
Projected Growth of Competing Industries	Construction is only responsible for a small share of material's total demand and demand from competing industries is expected to exceed current supply levels in the next 50 years	Along with other industries the construction industry is a major consumer of the material. As demand increases it is possible that competition for resources between these industries increases	The construction industry is the largest driver of demand for the material and demand from competing industries will become/remain insignificant compared to supply levels in the next 50 years
Ease of Production Increase	Increase in production would require extensive investments into new facilities and the development of new production or manufacturing technologies	Increasing production would require new facilities or adaption/expansion of existing facilities with limited investments	Production could be significantly increased with existing infrastructure (mining, processing facilities etc.)

Appendix B: Functional Unit

Table B.1: Mass, Price and Environmental Impact Points per Functional Unit

Metal Type	Specific Alloy	kg/FU	Price [$/FU]	Environmental Impact [Pt/FU]			
				Human Health	Eco-systems	Resources	Total
Carbon Steels	S355J2 / 1.0553	70.0	48.4	5.5	1.8	11.1	18.3
Stainless Steels	X2CrNiMoN22-5-3 / 1.4462	49.1	309.0	174.9	7.9	126.2	309.0
Aluminum Alloys	AlMg4.5Mn / Alloy 5083 H111	53.4	108.7	24.5	10.3	21.4	56.1
Titanium Alloys	Ti 6Al-4V GR5 / 3.7165	23.8	491.7	37.9	15.8	22.3	76.1
Nickel Alloys	NiCu30Al / 2.4375	55.4	783.8	197.8	15.1	111.3	324.2

Appendix C: Life Cycle Assessment Data

For each material in the ranking the environmental impact of production (cradle-to-gate) was calculated using data from the econinvent 3.3 database adapted with data from recent literature. As the goal was to calculate an average impact of production, the global market process for each material was used (excl. impact from transport). To reflect the production of the specified alloy, the individual transformation processes used in the global market processes, were adapted to result in the desired alloy composition. The final impact scores were calculated according to the ReCiPe 1.13 (Hierarchist) method.

C.1 Carbon Steel S355J2 / 1.0553

Original Files

Steel, low-alloyed {GLO}| market for | Alloc Def, U

Steel, low-alloyed {CA-QC}| steel production, electric, low-alloyed | Alloc Def, U

Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Def, U

Steel, low-alloyed {RER}| steel production, electric, low-alloyed | Alloc Def, U

Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Def, U

Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Def, U

Adaptions

Removed Ferrochromium, high carbon, 68 % {GLO} market for

S355J0 does not contain any chromium so not required as raw material

Removed Ferronickel, 25 % Ni {GLO} market for (was 0.045 kg)

S355J0 does not contain nickel so not required as raw material

Increased content of Ferromanganese, high-coal, 74.5% Mn {GLO} market for (was 0.015278 kg) 0.021 kg/kg required to achieve Mn content of 1.6% in final alloy

Removed Molybdenite {GLO} market for (was 0.00059649 kg)

S355J0 does not contain molybdenum so not required as raw material

Increased manganese emissions to air (was 6.05E-7 kg)

8.5 E-7 kg/kg required to keep percentage constant with input of manganese

Removed chromium emissions to air (was 1.85E-7 kg lognormal sd 5.2866

No chromium input

Other waste, energy and input sources do not have a large effect on the final impact scores and where therefore left at the same values as before.

C.2 Stainless Steel X2CrNiMoN22-5-3 / 1.4462

Original Files

Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U

Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8 | Alloc Def, U

Steel, chromium steel 18/8 {RoW}| steel production, converter, chromium steel 18/8 | Alloc Def, U

Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Alloc Def, U

Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium steel 18/8 | Alloc Def, U

Adaptions

Decreased Ferronickel 25 % Ni {GLO} market for (was 0.32 kg)

> 0.2 kg/kg required to scale to final nickel content of 5%

Increased Ferrochromium, high-carbon, 68 & Cr {GLO} market for (was 0.26471)

> 0.3235 kg/kg required for final chromium content of 22%

Added Ferromanganese, high-coal, 74.5 % Mn {GLO} market for

> 0.021 kg/kg required to achieve the desired content of Mn which was estimated to be the same as in CS

Added Molybdenum trioxide {GLO} production

> 0.045 kg/kg MoOx is required for 0.03 kg/kg content of molybdenum in final product (stochiometric calculation)

MoOx is smelted to ferromolybdenum which is added to steel. However no ferro-molybdenum process exists.

Increased waste manganese emissions to air (was 6.05E-7 kg)

> 8.5 E-7 kg/kg required to keep percentage constant with input of manganese

Increased chromium emissions to air (was 1.81 E-7 kg)

> 2.26E-7 kg/kg required to keep percentage constant with input of chromium

Other waste, energy and input sources do not have a large effect on the final impact scores and where therefore left at the same values as before.

C.3 Aluminum Alloy AlMg4.5Mn / Alloy 5083

Original Files

Aluminium alloy, AlMg3 {GLO}| market for | Alloc Def, U

Aluminium alloy, AlMg3 {RER}| production | Alloc Def, U

Aluminium alloy, AlMg3 {RoW}| production | Alloc Def, U

Adaptions

Decreased Chromium {GLO} market for (was 0.00305 kg)

0.0015 kg/kg required to achieve final chromium content of 0.15%

Increased Manganese {GLO} market for (was 0.00508 kg)

0.007 kg/kg required to achieve final manganese content of 0.7%

Increased Magnesium {GLO} market for (was 0.0305 kg)

0.044 kg/kg required to achieve final magnesium content of 4.4%

Decreased Aluminum, cast alloy {GLO} market for (was 0.965 kg)

0.947kg/kg required to achieve final aluminum content of 94.7%

Other waste, energy and input sources do not have a large effect on the final impact scores and where therefore left at the same values as before.

C.4 Titanium Alloy Ti 6Al-4V GR5 / 3.7165

Original File

Titanium, primary {GLO}| production | Alloc Def, U

Dataset includes production of Ti-sponge from $TiCl_4$ and Mg and the remelting of the sponge with the vacuum arc process. Alloying elements are added after sponge formation.

Adaptions

Decreased Magnesium {GLO} market for (was 0.016 kg)

0.01424 kg/kg required to achieve titanium content of 89% final product

Decreased Titanium tetrachloride{GLO} production (was 4 kg)

3.56 kg/kg required to achieve titanium content of 89% final product

Added Aluminum, primary, ingot {RoW} production

0.06 kg/kg required for final aluminum content of 6%

In reality the aluminum is added as powder, but no better aluminum input was found

Added Iron pellet {GLO} market for

0.004 kg/kg required for final iron content of 0.4%

Vanadium impact is added separately to the values calculated with the process described above

According to the Idemat Database from TU Delft production of 1 kg V causes 4.158 Pt of damage with the Recipe method (Human Health 1.91736; Ecosystems 0.83728; Resources 1.40351)

4% percent of vanadium in the final alloy lead to an additional 0.16623 points of damage (HH 0.07669; Ecosys 0.03349; Res 0.05614)

C.5 Nickle-Copper Alloy NiCu30Al / 2.4375

Original Files

Iron-nickel-chromium alloy {GLO}| market for | Alloc Def, U

Iron-nickel-chromium alloy {RER}| production | Alloc Def, U

Iron-nickel-chromium alloy {RoW}| production | Alloc Def, U

Adaptions

Removed Iron Scrap, sorted, pressed {GLO} market for Alloc, Def, U (was 0.474 kg)

No extra addition of iron necessary

Increased Nickel, 99.5 % {GLO} market for alloc Def, U (was 0.32 kg)

0.65327kg/kg required for final nickel content of 65%

Removed Ferrochromium, high-carbon, 68 % Ct {GLO} market for (was 0.309 kg)

No chromium present in Monel K 500

Added Copper {GLO} market for

0.3 kg/kg required for final copper content of 30%

Added Titanium primary {GLO} market for

0.006 kg/kg required for final titanium content of 0.6%

Added Aluminum primary, ingot {IAI Area, EU27 & EFTA/GLO} market for

0.027 kg/kg requried for final aluminum content of 2.7%

Added Ferromanganese, high-coal, 74. 5 % Mn {GLO} market for

0.02 kg/kg added for the maximum final iron and manganese content of 2% present in the alloy

Increased nickel emissions to air (was 7.07E-7 kg)

1.44E-6 kg/kg to keep percentage constant in relation to input of nickel

Removed chromium emissions to air (was 1.25E-6 kg)

No chromium in Monel K 500

5 References

[1] OECD. The Ocean Economy in 2030. Paris: OECD Publishing; 2016.

[2] European Ocean Energy Association. Oceans of energy - European Ocean Energy Roadmap 2010 - 2050. Brussels; 2009.

[3] Hein JR, Mizell K, Koschinsky A, Conrad TA. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. Ore Geology Reviews 2013;51:1–14. https://doi.org/10.1016/j.oregeorev.2012.12.001.

[4] Jansen HM, van den Burg S, Bolman B, Jak RG, Kamermans P, Poelman M et al. The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. Aquacult Int 2016;24(3):735–56. https://doi.org/10.1007/s10499-016-9987-y.

[5] Kappenthuler S, Seeger S. Addressing global environmental megatrends by decoupling the causal chain through floating infrastructure. Futures 2019. https://doi.org/10.1016/j.futures.2019.04.007.

[6] Harris DJ. A quantitative approach to the assessment of the environmental impact of building materials. Building and Environment 1999;34(6):751–8. https://doi.org/10.1016/S0360-1323(98)00058-4.

[7] Huberman N, Pearlmutter D. A life-cycle energy analysis of building materials in the Negev desert. Energy and Buildings 2008;40(5):837–48. https://doi.org/10.1016/j.enbuild.2007.06.002.

[8] Thormark C. The effect of material choice on the total energy need and recycling potential of a building. Building and Environment 2006;41(8):1019–26. https://doi.org/10.1016/j.buildenv.2005.04.026.

[9] Reuben RL. Materials in Marine Technology. London: Springer London; 1994.

[10] Reddy DV, Swamidas ASJ. Essentials of Offshore Structures: Framed and Gravity Platforms. Hoboken: CRC Press; 2013.

[11] Valdez B, Ramirez J, Eliezer A, Schorr M, Ramos R, Salinas R. Corrosion assessment of infrastructure assets in coastal seas. Journal of Marine Engineering & Technology 2016;15(3):124–34. https://doi.org/10.1080/20464177.2016.1247635.

[12] Igwemezie V, Mehmanparast A, Kolios A. Materials selection for XL wind turbine support structures: A corrosion-fatigue perspective. Marine Structures 2018;61:381–97. https://doi.org/10.1016/j.marstruc.2018.06.008.

[13] Thakker A, Jarvis J, Buggy M, Sahed A. A novel approach to materials selection strategy case study: Wave energy extraction impulse turbine blade. Mater. Des. 2008;29(10):1973–80. https://doi.org/10.1016/j.matdes.2008.04.022.

[14] Cicek K, Celik M. Selection of porous materials in marine system design: The case of heat exchanger aboard ships. Materials & Design 2009;30(10):4260–6. https://doi.org/10.1016/j.matdes.2009.04.027.

[15] Giaccobi S, Kromm FX, Wargnier H, Danis M. Filtration in materials selection and multi-materials design. Materials & Design 2010;31(4):1842–7. https://doi.org/10.1016/j.matdes.2009.11.005.

[16] Rashedi A, Sridhar I, Tseng KJ. Multi-objective material selection for wind turbine blade and tower: Ashby’s approach. Materials & Design 2012;37:521–32. https://doi.org/10.1016/j.matdes.2011.12.048.

[17] Norgate TE, Jahanshahi S, Rankin WJ. Assessing the environmental impact of metal production processes. Journal of Cleaner Production 2007;15(8-9):838–48. https://doi.org/10.1016/j.jclepro.2006.06.018.

[18] Graedel TE, Harper EM, Nassar NT, Nuss P, Reck BK. Criticality of metals and metalloids. PNAS 2015;112(14):4257–62. https://doi.org/10.1073/pnas.1500415112.

[19] Gordon RB, Bertram M, Graedel TE. On the sustainability of metal supplies: A response to Tilton and Lagos. Resour. Policy 2007;32(1-2):24–8. https://doi.org/10.1016/j.resourpol.2007.04.002.

[20] Tilton JE, Lagos G. Assessing the long-run availability of copper. Resour. Policy 2007;32(1-2):19–23. https://doi.org/10.1016/j.resourpol.2007.04.001.

[21] Kappenthuler S, Seeger S. From resources to research—a framework for identification and prioritization of materials research for sustainable construction. Materials Today Sustainability 2019:100009. https://doi.org/10.1016/j.mtsust.2019.100009.

[22] Alexander M. Marine Concrete Structures: Design, Durability and Performance. Cambridge, MA: Woodhead Publishing; 2016.

[23] Frijia S, Guhathakurta S, Williams E. Functional unit, technological dynamics, and scaling properties for the life cycle energy of residences. Environ Sci Technol 2012;46(3):1782–8. https://doi.org/10.1021/es202202q.

[24] Ashby MF. Materials Selection in Mechanical Design. 5th ed. Burlington, MA: Butterworth-Heinemann; 2016.

[25] Dexter SC. Handbook of oceanographic engineering materials. New York, Chichester: Wiley; 1979.

[26] Powell C, Francis R. The corrosion performance of metals for the marine environment: A basic guide / edited by Carol Powell & Roger Francis. Leeds: Maney; 2012.

[27] Baddoo NR, Burgan BA. Structural Design of Stainless Steel; 2001.

[28] Davis JR. Alloying: Understanding the basics / edited by J.R. Davis, Davis & Associates. Materials Park, Ohio: ASM International; 2001.

[29] Titanex GmbH. Titanium Grade 5 / 23 / ELI. [August 23, 2017]; Available from: http://shop.titanex.com/PDFs/Grade_5_23_ELI.pdf.

[30] De CP. Use of titanium and its alloys in sea-water service. High Temperature Materials and Processes 1993;11(1-4):61–96.

[31] Krouse D, Laycock N, Padovani C. Modelling pitting corrosion of stainless steel in atmospheric exposures to chloride containing environments. Corrosion Engineering, Science and Technology 2014;49(6):521–8. https://doi.org/10.1179/1743278214Y.0000000221.

[32] Liengen T, Basseguy R, Feron D, Beech I (eds.). Understanding biocorrosion: Fundamentals and applications. 1st ed. Amsterdam: Woodhead Publishing; 2014.

[33] Jones RH. Stress-corrosion cracking: Materials performance and evaluation / edited by Russell H. Jones. Materials Park: ASM International; 2017.

[34] Moan T. Life-cycle assessment of marine civil engineering structures. Structure and Infrastructure Engineering 2011;7(1-2):11–32. https://doi.org/10.1080/15732471003588254.

[35] Sŏng S-m, Younossi O, Goldsmith BW. Titanium: Industrial base, price trends, and technology initiatives / Somi Seong, Obaid Younossi, Benjamin W. Goldsmith ; with Thomas Lang, Michael Neumann. Santa Monica, CA: RAND Project Air Force; 2009.

[36] World Bank. World Bank Commodities Price Forecast 2017; 2017.

[37] Hope M. Mineral Sand Forecasts; 2017.

[38] Ametek. Master Alloys and Titanium Raw Materials - The Dog Wagging the Tail. Amsterdam; 2017.

[39] Perles T. Vanadium Market Outlook; 2013.

[40] ASD Reports. Duplex Stainless Steel Market - Global Forecast to 2021. [October 12, 2017]; Available from: https://www.asdreports.com/market-research-report-372979/duplex-stainless-steel-market-global-forecast.

[41] UNEP – International Resource Panel. Recycling Rates of Metals – A Status Report; 2011.

[42] Bowyer J, Bratkovich S, Fernholz K, Frank M, Groot H, Howe J et al. Understanding Steel Recovery and Recycling Rates and Limitations to Recycling; 2015.

[43] Polmear IJ, St. John D, Nie J-F, Qian M. Light alloys: Metallurgy of the light metals. Amsterdam: Butterworth-Heinemann; 2017.

[44] Liu G, Bangs CE, Müller DB. Stock dynamics and emission pathways of the global aluminium cycle. Nature Clim Change 2013;3(4):338–42. https://doi.org/10.1038/nclimate1698.

[45] Morfeldt J, Nijs W, Silveira S. The Future of Global Steel Production; 2013.

[46] OECD. Steel raw materials: DSTI/SU/SC(2011)2, 70th Steel Committee Meeting. Paris; 2011.

[47] World Steel Association. Global steel industry: outlook, challenges and opportunities. Istanbul; 2017.

[48] Granta Material Intelligence. MaterialUniverse materials data. [November 14, 2018]; Available from: http://www.grantadesign.com/products/data/materialuniverse.htm.

[49] U.S. Geological Survey. Mineral Commodity Summaries 2017; 2017.

[50] Glencore. Nickel Market Developments; 2016.

[51] Selby M. Nickel Production and Supply: Market Implications; 2017.

[52] Pothen F, Goeschl T, Löschel A. Strategic Trade Policy and Critical Raw Materials in Stainless Steel Production. Mannheim; 2013.

[53] Kleijn R, van der Voet E, Kramer GJ, van Oers L, van der Giesen C. Metal requirements of low-carbon power generation. Energy 2011;36(9):5640–8. https://doi.org/10.1016/j.energy.2011.07.003.

[54] Flook R. Bauxite & Alumina 2015 - Non-metallurgical market review; 2015.

[55] Fog K. Hydro - Capital Markets Day 2016 - Market Outlook; 2016.

[56] McCOy D. Titanium Minerals Market. Miami; 2017.

[57] Gehler S. World Titanium Sponge Supply Situation; 2017.

[58] Hohne-Sparboth T. An outlook for titanium metal; 2017.

[59] Verkhnaya Salda Metallurgical Production Association. Titanium Raw Materials in Russia and Around the World; 2006.

[60] Mistry M. Nickel: Creating Sustainability in the Long Term. Berlin; 2012.

[61] BP. BP Statistical Review of World Energy 2018; 2018.

[62] Montemor MF. Functional and smart coatings for corrosion protection: A review of recent advances. Surface and Coatings Technology 2014;258:17–37. https://doi.org/10.1016/j.surfcoat.2014.06.031.

[63] Zhou B, Li Z, Chen C. Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies. Minerals 2017;7(11):203. https://doi.org/10.3390/min7110203.

[64] Koehlé-Divo V, Cossu-Leguille C, Pain-Devin S, Simonin C, Bertrand C, Sohm B et al. Genotoxicity and physiological effects of CeO2 NPs on a freshwater bivalve (Corbicula fluminea). Aquat Toxicol 2018;198:141–8. https://doi.org/10.1016/j.aquatox.2018.02.020.

[65] Sendra M, Blasco J, Araújo CVM. Is the cell wall of marine phytoplankton a protective barrier or a nanoparticle interaction site? Toxicological responses of Chlorella autotrophica and Dunaliella salina to Ag and CeO2 nanoparticles. Ecological Indicators 2018;95:1053–67. https://doi.org/10.1016/j.ecolind.2017.08.050.

[66] Momber AW, Plagemann P, Stenzel V. Performance and integrity of protective coating systems for offshore wind power structures after three years under offshore site conditions. Renewable Energy 2015;74:606–17. https://doi.org/10.1016/j.renene.2014.08.047.

[67] López-Ortega A, Bayón R, Arana JL. Evaluation of protective coatings for offshore applications. Corrosion and tribocorrosion behavior in synthetic seawater. Surface and Coatings Technology 2018;349:1083–97. https://doi.org/10.1016/j.surfcoat.2018.06.089.

[68] Golding LA, Angel BM, Batley GE, Apte SC, Krassoi R, Doyle CJ. Derivation of a water quality guideline for aluminium in marine waters. Environ Toxicol Chem 2015;34(1):141–51. https://doi.org/10.1002/etc.2771.

[69] Kirchgeorg T, Weinberg I, Hörnig M, Baier R, Schmid MJ, Brockmeyer B. Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment. Mar Pollut Bull 2018;136:257–68. https://doi.org/10.1016/j.marpolbul.2018.08.058.

[70] Behera SK, Mulaba-Bafubiandi AF. Microbes Assisted Mineral Flotation a Future Prospective for Mineral Processing Industries: A Review. Mineral Processing and Extractive Metallurgy Review 2017;38(2):96–105. https://doi.org/10.1080/08827508.2016.1262861.

[71] Hidalgo T, Kuhar L, Beinlich A, Putnis A. Kinetic study of chalcopyrite dissolution with iron(III) chloride in methanesulfonic acid. Minerals Engineering 2018;125:66–74. https://doi.org/10.1016/j.mineng.2018.05.025.

[72] Laitinen O, Hartmann R, Sirviö JA, Liimatainen H, Rudolph M, Ämmälä A et al. Alkyl aminated nanocelluloses in selective flotation of aluminium oxide and quartz. Chemical Engineering Science 2016;144:260–6. https://doi.org/10.1016/j.ces.2016.01.052.

[73] Norgate T, Jahanshahi S. Reducing the greenhouse gas footprint of primary metal production: Where should the focus be? Minerals Engineering 2011;24(14):1563–70. https://doi.org/10.1016/j.mineng.2011.08.007.

[74] Capuzzi S, Timelli G. Preparation and Melting of Scrap in Aluminum Recycling: A Review. Metals 2018;8(4):249. https://doi.org/10.3390/met8040249.

[75] Nakamura S, Kondo Y, Nakajima K, Ohno H, Pauliuk S. Quantifying Recycling and Losses of Cr and Ni in Steel Throughout Multiple Life Cycles Using MaTrace-Alloy. Environ Sci Technol 2017;51(17):9469–76. https://doi.org/10.1021/acs.est.7b01683.

[76] Reijnders L. Conserving functionality of relatively rare metals associated with steel life cycles: a review. Journal of Cleaner Production 2016;131:76–96. https://doi.org/10.1016/j.jclepro.2016.05.073.

[77] Takeda O, Okabe TH. Current Status of Titanium Recycling and Related Technologies. JOM 2018;78:1. https://doi.org/10.1007/s11837-018-3278-1.

[78] Nakajima K, Daigo I, Okada K, Koike S, Nansai K, Matsubae K et al. Bottlenecks in material cycle of nickel. Matériaux & Techniques 2016;104(6-7):604. https://doi.org/10.1051/mattech/2017011.

[79] Cesetti M, Nicolosi P. Waste processing: new near infrared technologies for material identification and selection. J. Inst. 2016;11(09):C09002-C09002. https://doi.org/10.1088/1748-0221/11/09/C09002.

[80] Lu X, Matsubae K, Nakajima K, Nakamura S, Nagasaka T. Thermodynamic Considerations of Contamination by Alloying Elements of Remelted End-of-Life Nickel- and Cobalt-Based Superalloys. Metall and Materi Trans B 2016;47(3):1785–95. https://doi.org/10.1007/s11663-016-0665-2.

[81] Ohno H, Matsubae K, Nakajima K, Kondo Y, Nakamura S, Fukushima Y et al. Optimal Recycling of Steel Scrap and Alloying Elements: Input-Output based Linear Programming Method with Its Application to End-of-Life Vehicles in Japan. Environ Sci Technol 2017;51(22):13086–94. https://doi.org/10.1021/acs.est.7b04477.

[82] Fang ZZ, Middlemas S, Guo J, Fan P. A new, energy-efficient chemical pathway for extracting Ti metal from Ti minerals. J Am Chem Soc 2013;135(49):18248–51. https://doi.org/10.1021/ja408118x.

[83] Moon B-M, Seo JH, Lee H-J, Jung KH, Park JH, Jung H-D. Method of recycling titanium scraps via the electromagnetic cold crucible technique coupled with calcium treatment. Journal of Alloys and Compounds 2017;727:931–9. https://doi.org/10.1016/j.jallcom.2017.08.129.

[84] Taninouchi Y-k, Hamanaka Y, Okabe TH. Chlorination-Volatilization Behavior of Titanium Metal Scraps during Recycling Using Reaction-Mediating Molten Salt. Mater. Trans. 2016;57(8):1309–18. https://doi.org/10.2320/matertrans.M-M2016818.

[85] Okabe TH, Taninouchi Y-k. Recycling Titanium and Its Alloys by Utilizing Molten Salt. In: Chaubal P, Reddy R, Pistorius PC, Pal U, editors. Advances in Molten Slags, Fluxes, and Salts: Proceedings of the 10th International Conference on Molten Slags, Fluxes, and Salts 2016. Cham: Springer International Publishing; 2016, p. 751–760.

[86] Reitz J, Lochbichler C, Friedrich B. Recycling of gamma titanium aluminide scrap from investment casting operations. Intermetallics 2011;19(6):762–8. https://doi.org/10.1016/j.intermet.2010.11.015.

[87] Kang J, Okabe TH. Removal of iron from titanium ore by selective chlorination using TiCl4 under high oxygen chemical potential. International Journal of Mineral Processing 2016;149:111–8. https://doi.org/10.1016/j.minpro.2016.02.014.