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From Resources to Research - A Framework for Identification and Prioritization of Materials Research for Sustainable Construction

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Abstract

In this paper a framework is presented to aid in the identification and prioritization of research projects related to the development of materials for sustainable construction. The framework is based on a holistic ranking of materials' technical, economic and environmental performance as well as the future availability of their respective raw material constituents. The detailed ranking enables a comparison of the strengths and weaknesses of existing as well as newly developed materials. Each of the 27 attributes included in the framework is measured on a precisely defined scale, which is based on literature and expert data, and presented in detail. Thus, an objective and efficient evaluation of individual materials by practitioners and researchers is possible. Combining the evaluation of material performance with the analysis of factors affecting the respective long-term availability, it is possible to focus funding on specific areas and approaches where research and policy measures have the highest probability of providing long-term improvements to the construction industry.

Keywords

Construction Materials, Research Prioritization, Multi-Criteria-Decision-Making, Sustainability, Economics, Resource Availability

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Declarations of interests

None

1 Introduction

Increasing global population and growing rates of urbanization have led to increasing demand for infrastructure worldwide, especially in developing nations [1]. Consequently, the amount of construction materials required by the industry is steadily increasing as well. The construction industry and its supply chain are responsible for over 30% of global greenhouse gas emissions and 36% of global waste production which is estimated at 3.8 billion tons per year [2,3]. Decreasing global resources and noticeable impacts from climate change have strengthened public advocacy of environmental protection measures which are being more and more strictly enforced by governments around the world. As a major source of these impacts the construction industry is moving towards more sustainable construction strategies. An often thought out approach to such strategies is the systematic selection of optimal construction materials. Construction materials have a large effect on the overall sustainability of construction, as their physical and chemical properties largely determine the amount of material required for a certain structure, their lifetime in a given environment and the overall energy consumption during the use phase of the structure [4]. Furthermore, embodied energy of construction materials, arising from their production and transport, can be responsible for 40-60% of the lifetime environmental impact of a structure [5,6]. Therefore, various fields of research are aiming to improve the sustainability of employed construction materials, for instance through the development of new processing techniques or alternative raw material compositions [7–11]. Such research is highly capital intensive. As an example, the US Government funded various materials research programs with over 23 billion $ in 2014 [12]. Furthermore, most projects require years to decades of experimentation and testing to generate significant, robust results. Additionally, the adoption of new materials and technologies in construction is relatively slow compared to other industries [13–16]. Due to this long period between initiation of a research project and industrial application, and the limited funds available to research institutions and also companies, it is essential to evaluate and prioritize individual projects not only according to their potential to improve specific aspects of a material, but also according to the timeframe for which they will provide this benefit, depending on the used materials' future availability. Existing prioritization frameworks do not take these context specific factors into account, as they are mostly focused on ranking research and development projects in a company setting [17–20]. Furthermore, those frameworks which do cover research concerning construction and sustainability require detailed knowledge of individual projects to produce a ranking and thus cannot be used to identify new projects in the early stages of research planning [21,22].

Therefore, in this paper we present a framework intended to aid the process of identifying promising areas for research and development focusing on construction materials and prioritizing them according to their impact on the overall sustainability of the industry, as well as their potential for long-term commercial applicability. The framework is based on a holistic ranking of materials according to their technical, economic and environmental performance in a desired environment and for a wide range of specific applications or components. While there exist multiple frameworks for the ranking and selection of construction materials, they are mainly applicable to very specific material selection problems and also lack any consideration of long term developments [23–27]. In the light of increasing global scarcity of various materials as well as dwindling resource stocks it is however imperative that the long-term future availability of raw materials required for the production of construction materials be included in evaluation methods aiming to improve the sustainability of current construction practices [28–30]. Therefore, the factors affecting the long-term availability of the raw materials required for production of each material are also assessed in the presented ranking. Thus, the framework evaluates each material's potential for long-term usage in construction, and, combined with the evaluation of material performance, identifies the areas where research funding has the highest probability of providing lasting improvements for the industry.

The paper is structured as follows: First, the methodology of the framework is explained, followed by a description of the process used for selecting the appropriate categories and attributes for the material ranking. Next, all attributes, as well as the definitions for their scores, are described in more detail. Finally, a discussion of the framework is presented followed by a conclusion and outlook on further research.

2 Ranking Methodology

In order to identify suitable research areas for the improvement of construction materials, the strengths and weaknesses of individual materials need to be evaluated. Thus, a holistic ranking of materials according to their technical, economic and ecological performance is completed. This requires a great number of factors and aspects to be analyzed. As such, multi criteria decision analysis (MCDA) is employed [31]. Specifically, a straight-forward simple additive weighting process is used to generate a single score for each material from multiple individual, property specific scores. This method is adapted for the presented framework by incorporating two hierarchical levels; categories and attributes. A category consists of multiple attributes. The attributes are the criteria that are evaluated and scored for each material. The stepwise process for applying this framework is shown in Figure 1 and will be shortly described.

The first step consists of defining *the goal of the ranking*. As a material's performance depends on the specific use case, different cases will produce different rankings. Therefore, it is essential to specify the boundary conditions and goal of the ranking to begin with. This includes, for instance, the definition of broad material categories which are to be analyzed and the environmental conditions for which their performance should be ranked. Furthermore, the *timeframe* for the analysis of future availability should be established. This timeframe should not be below 20-30 years as this would severely limit the evaluation of a materials long-term potential.

To adapt the ranking to the specified goal, each attribute and category has a corresponding *weighting factor*. Three possible values for the weighting factors are applied, depending on the importance of an attribute or category for the use of a material in the defined environment and application. Attributes with a high, medium or low importance are weighted with a factor of 3, 2, or 1 respectively. This method allows the weights of the different categories and attributes to be easily and quickly adapted to a variety of use cases and timeframes by increasing the weighting factors of essential attributes and decreasing those of less central attributes. Weighting factors can also be established with more sophisticated methods, such as the analytical hierarchy process (AHP), which however are substantially more time consuming.

In a next step a *functional unit* needs to be defined, which is in line with the specified goal. This allows the comparison of materials with widely diverging properties according to the defined performance requirement (ex. ability to carry a defined load). Additionally, according to the application and environment specified, minimal mechanical properties (ex. stiffness, compressive strength, etc.) can be defined in order to *screen materials* and reduce the number of candidate materials introduced into the final ranking [31].

The *scoring of the attributes* is then completed on a 5-point scale, 1 being the lowest and 5 the highest possible score. For each attribute the values of 1, 3 and 5 were defined to represent the following scale:

1. Property or value below the level a material can be considered acceptable
3. Property or value that can be seen as average for a material used in construction
5. Property or value of a hypothetical ideal material

This scale allows not only the comparison of materials included in the ranking amongst each other, but also shows how far each individual material is from an ideal state for each attribute.

The attributes included in the framework are either qualitative or quantitative. For the quantitative attributes values were specified for the points along the scale. For the qualitative attributes the requirements for each of the three mentioned points were described as precisely as possible.

To *calculate the overall score* of a specific material the scores of all four major categories are calculated first. The category scores are computed by dividing the aggregated weighted attributes by the sum of the weighting factors:

$$C_j = \frac{\sum_{i=0}^{n} A_i \times a_i}{\sum_{i=0}^{n} a_i}$$

where C_j is the score of category j, A_i the score of attribute i and a_i the weighting factor of attribute i. These category scores in turn are weighted, aggregated and divided by the sum of the category weighting factors resulting in the final score for each material:

$$M = \frac{\sum_{j=0}^{n} C_j \times c_j}{\sum_{j=0}^{n} c_j}$$

where M is the final score for a specific material and c_j the weighting factor for category j. Following this process the framework produces a final ranking of the selected materials related to the goal specified by the user. Each materials' score for the individual attributes thus highlights its strengths and weaknesses, while the category and final material scores identify the overall most promising materials for a given application.

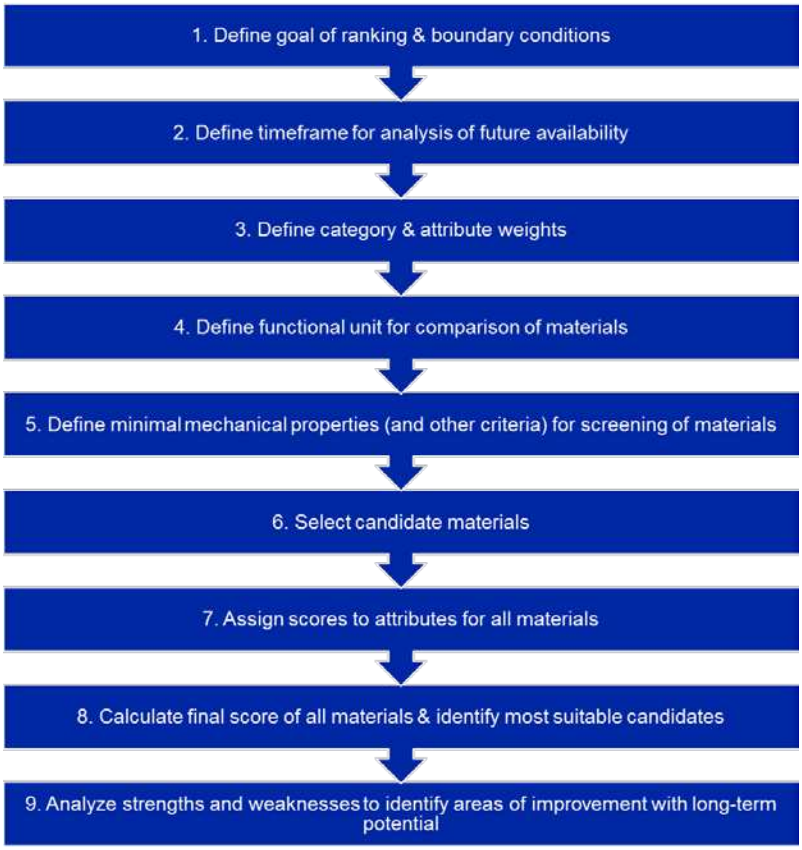


Figure 1: Methodology for application of framework to material selection.

3 Category and Attribute Selection for Framework

To develop a holistic ranking the selection of appropriate categories, attributes and scale values is critical. The categories need to cover all aspects relevant for the current and future use of materials in construction, while not being redundant. The same is true for the attributes contained in each category. Additionally, the attributes and corresponding ranking scales need to be general enough to be applied to a wide range of materials with different behaviors and properties, and at the same time specific enough to allow for a scoring process that is as exact and objective as possible.

In a first step a review of the literature was conducted to identify the attributes which were previously used in construction and engineering related MCDA material rankings and sustainability assessments [23,24,31–44]. Although these frameworks are mostly case specific, attributes could be grouped into three major categories: technical performance, economics, and sustainability and environmental impact. Each category covers an area that is essential for the potential of a material to be used in sustainable construction.

The technical performance of a construction material is determined by two main factors; its mechanical properties and its durability. The mechanical properties of a material determine the way in which a structure can be designed with it and vice versa, meaning a specific structural design requires certain minimal mechanical properties for each of its components. As these properties, such as Young's modulus, tensile/compressive strength or fracture toughness, are precisely measurable, they can be used to define constraints for potential candidate materials [31]. Consequently, mechanical properties are used for screening of candidate materials in this framework and are not included as an individual category.

Once a material meets the minimal mechanical requirements for a component in construction, the further technical performance is determined by the time the material retains these properties in a given environment; i.e. its durability. Durability is difficult to predict and is determined by a materials resistance to chemical and physical external influences or impacts such as corrosion or biological degradation. These impacts are highly dependent on specific environmental conditions. For individual construction environments, the detailed assessment of a material's durability provides information on the specific resistances which would need to be improved to increase the lifetime and therefore the technical performance of the material.

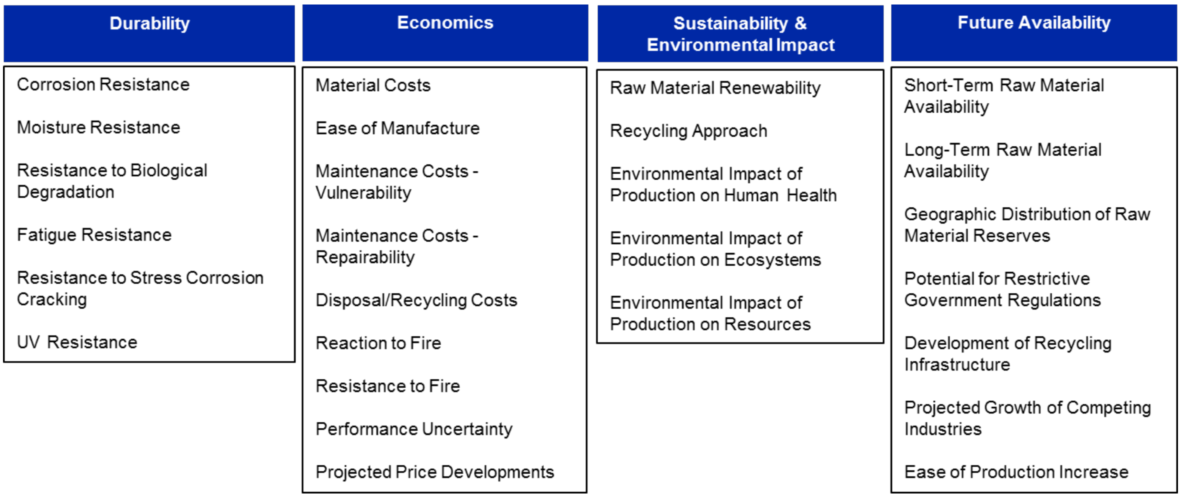
For the evaluation of the commercial potential of a certain material for use in the construction industry the costs involved with using the material also needs to be analyzed. This includes not only the actual lifecycle costs (from purchasing, construction and maintenance to disposal) but also the indirect costs associated with the various risks involved. Furthermore, a projection of the future price of the material is need to assess its competitiveness in the long-term.

Next to the technical and economic potential, the assessment of the environmental impacts associated with the use of a given material is necessary to ensure that material developments not only aim to improve mechanical or physical properties, but also contribute to increasing the overall sustainability of the construction industry. For existing materials this provides crucial information on developments that are needed if continued large scale usage of the material is to be sustainable. For potential research and development projects, it enables a rough assessment of the sustainability of the proposed approach early in or even before the actual material development process.

These three categories evaluate the potential performance of a material in the present. However, in light of the increasing dynamics of global change, such as population growth and industrialization pushes (esp. in emerging countries), leading to an ever-increasing scarcity of various resources and materials, a consideration of future availability is essential for evaluating the long-term potential of a given material development project. If this is neglected, it may be the case that a new material, which at the beginning of development achieved a high score in all the previous categories, may become unsuitable for use in construction by the time it reaches the market, as certain raw materials employed in its production are no longer readily available or have become substantially more expensive. Thus the evaluation of future availability allows an efficient distribution of resources to projects that have a high probability of long-term commercial applicability.

Literature on criticality assessment was reviewed to identify the attributes required to cover this category [45–51].

In a final step, through discussions with experts from industry and academia, the previously identified attributes were adapted and additional attributes were added to enable the coverage of all aspects necessary to achieve the goals intended for the presented framework. This resulted in the 4 categories and 27 attributes shown in Figure 2.



Durability

- Corrosion Resistance
- Moisture Resistance
- Resistance to Biological Degradation
- Fatigue Resistance
- Resistance to Stress Corrosion Cracking
- UV Resistance

Economics

- Material Costs
- Ease of Manufacture
- Maintenance Costs - Vulnerability
- Maintenance Costs - Repairability
- Disposal/Recycling Costs
- Reaction to Fire
- Resistance to Fire
- Performance Uncertainty
- Projected Price Developments

Sustainability & Environmental Impact

- Raw Material Renewability
- Recycling Approach
- Environmental Impact of Production on Human Health
- Environmental Impact of Production on Ecosystems
- Environmental Impact of Production on Resources

Future Availability

- Short-Term Raw Material Availability
- Long-Term Raw Material Availability
- Geographic Distribution of Raw Material Reserves
- Potential for Restrictive Government Regulations
- Development of Recycling Infrastructure
- Projected Growth of Competing Industries
- Ease of Production Increase

Figure 2: Categories and Attributes for Evaluation of Construction Materials

4 Attribute Scale Definitions

4.1 Durability

To be able to assess the durability ratings of all candidate materials correctly, a good understanding of the exact conditions of the specified construction environment is paramount. The scales for the rating of each attribute shown in Table 1 need to be applied with consideration of these conditions.

Table 1: Ranking scales of Durability attributes

ATTRIBUTE	1	3	5
CORROSION RESISTANCE	Structural damage to material (in form of defined component) from corrosion in given environment in under 10 years	Structural damage to material (in form of defined component) from corrosion in given environment in 50 – 75 years	Structural damage to material (in form of defined component) from corrosion in given environment after 100 years, or immune to corrosion
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
RESISTANCE TO BIOLOGICAL DEGRADATION	Material is highly susceptible to attack from organisms present in given environment and is fully degraded over time (loses mechanical strength)	Organisms present in given environment do not directly attack or degrade the material but can accelerate other degradation processes	Material is immune to degradation or accelerated degradation by organisms present in given environment
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 the defined environment. Degradation and loss of mechanical strength are moderately accelerated	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

4.1.1 Corrosion Resistance

Corrosion is one of the main mechanisms of damage affecting massive amounts of infrastructure globally [52,53]. Therefore, the ability of a material to resist corrosive action either from the atmosphere, seawater or other sources (ex. deicing salts) is paramount for the durability of a structure and needs to be considered carefully.

The corrosion resistance required of the employed material will depend on the desired lifetime of the structure in the environment in which it is situated. Turning this relationship around it is possible to rate the corrosion resistance of a material according to its expected lifetime in a given environment. The minimal achievable lifetime considered was 10 years, as structures that deteriorate in a shorter time can be considered as a waste of resources. An average lifetime for most infrastructure is around 50 years, while long term infrastructure such as tunnels or bridges are built with lifetime requirements of 100 years and more [54,55]. Although the estimation of lifetime is somewhat imprecise, especially for lifetimes exceeding 50 years [56], this measure allows a quick assessment of a materials corrosion resistance by a person with a certain amount of experience in the use of a specific material without the need for complex modeling of corrosion processes. If necessary the lifetimes assigned to the different scores can be adapted to evaluate more specific components with significantly different requirements.

4.1.2 Moisture Resistance

Infrastructure is inevitably exposed to varying levels of moisture ranging from differences in humidity to full wetting and drying cycles due to rain or tidal action for coastal and marine structures. The absorption of moisture can lead to a strong reduction of mechanical properties in certain materials or even full deterioration over time. Clearly the ideal material is not affected by moisture in anyway. However, for some materials the reduction in mechanical strength caused by full saturation with moisture is predictable and if the component is dried the mechanical properties return to their original values. For such materials it is possible to design components with desired strength under given conditions. If this is not possible a material must be protected from large variations in moisture or cannot be used in a variety of environments.

4.1.3 Resistance to Biological Degradation

Depending on the environment in which a material is employed it will be exposed to different sources of biological attack. Bacteria, insects, fungi and other organisms can feed on certain materials or produce and excrete substances which cause extensive damage, potentially leading to failure of a component. Ideally materials are not affected or attacked by biological sources. In some cases, the material itself is not directly attacked but the presence of specific organisms in combination with other external sources can accelerate degradation processes. An example for this behavior is the microbial introduced corrosion of metals where the presence of certain bacteria can alter the physico-chemical properties of the environment at the material's surface thus enabling or accelerating corrosion [57]. As such processes are slower than direct degradation this was set as the neutral point along the scale from full immunity to high susceptibility to biological attack.

4.1.4 Fatigue Resistance

Dynamic loading, i.e the exposure to fluctuating mechanical forces, can cause fatigue damage in certain materials which ultimately reduces their mechanical strength and may lead to failure at loads far below critical levels. Therefore, the fatigue resistance of construction materials needs to be carefully assessed during the design phase. The fatigue behavior of materials can be measured with so called stress cycle (S/N) or *Wöhler* curves. However, since the exact performance of a material depends strongly on the exact experimental parameters being used it is hard to compare *Wöhler* curves from different experiments [58]. Therefore, a more widely applicable qualitative scale was used. For materials which are known to suffer from fatigue a predictable fatigue behavior can be used to specify the lifetime of a component under given dynamic loads. If a material has a fatigue limit any loads below this fatigue limit will never lead to failure. Thus a material with a known fatigue limit can be designed for unlimited fatigue life by increasing the diameter or thickness of a component. Ideally however a structure can be designed with only the amount of material required to carry the maximal defined static load for a desired application and no additional resources need to be used to account for potential fatigue damage.

4.1.5 Resistance to Stress Corrosion Cracking

In this framework stress corrosion cracking is defined as the combined effect of mechanical stresses and chemical attack in the specified environment. This attribute is included since some materials' resistance to for instance moisture or corrosion damage is determined by the integrity of the surface layer. Small cracks which may occur due to mechanical loading can strongly decrease a materials resistance to environmental damage. Since it is impossible to specify quantifiable values for this attribute, due to the fact that a variety of different materials and damage mechanisms are covered, a qualitative ranking was seen as the only viable approach.

4.1.6 UV Resistance

Most large scale structures will be exposed to atmospheric radiation, mostly UV rays stemming from the sun. Some materials can lose mechanical strength with prolonged exposure to UV radiation due to photo-oxidative cleaving of the chemical bonds in the surface layer. If the UV rays are only able to penetrate a short distance into the material, the reduction in strength of a component is limited. Thus, it is possible to use excess material to account for the expected reduction. If not, the material needs to be protected from UV rays since failure will definitely occur after a certain time. However, it must be considered that even limited UV radiation induced micro- or nanolesions at the surface of a material will have negative impacts on other durability attributes.

4.2 Economics

This category covers the lifecycle costs involved with using a specific material in construction. Despite being a major cost factor for residential buildings, energy usage is not included in this framework, as these costs are mainly determined by the overall construction design and cannot be assessed on the material level. These scales of the economic attributes are shown in Table 2.

Table 2: Ranking scales of Economic attributes

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 and size, 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
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 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 loses 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	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 50% in the specified timeframe	No changes in price to be expected in in the specified timeframe	Price for material expected to decrease by over 50% in the specified timeframe

4.2.1 Material Costs

The costs considered here are those for purchasing of the construction material from a producer on the market. As materials from different chemical groups (ex. metals and plastics) have highly different properties, costs need to be measured relative to a FU which defines the desired performance of the materials. As there is no clear way to specify ideal or unacceptable costs the scores are based on the percentile in which a specific material lies amongst all materials evaluated. Thus, the ranking of a material is dependent on the other materials evaluated. If for a specific scenario it is clear at which level costs are acceptable and unacceptable, the scales can be changed to reflect these considerations.

4.2.2 Ease of Manufacture

Ease of Manufacture scores the ability to manufacture a variety of components for use in construction from a material and also indirectly measures the costs associated with this process. These costs include cost of machinery, labor and transport to the construction site. In order to cover all these factors and a wide variety of potential applications, Ease of Manufacture is measured on a qualitative scale. If a material cannot be readily formed into different shapes then the range of applications for which it can be used is reduced, which reduces the score. Additionally, if the size of individual components is limited, joining will be necessary for the construction of large components, which is often done manually and increases the costs of construction [32]. Joints furthermore can present structural weak points which can increase a structures vulnerability. Therefore, size limitations reduce a materials score. Finally, if specialized equipment or a well-trained work-force is required this will increase the costs for machinery and labor. Although fabrication in a factory may be cheaper for certain materials than on-site fabrication (especially in countries were labor costs are high) the transport costs for the larger and heavier prefabricated components will be higher. Therefore the ability to shape a material into components of any shape and size in a factory was set as the middle point in the ranking scale. The ability to shape the material onsite is applicable to many parts of the world where large scale factories are not present. As these are the areas where most demand for construction is expected in the coming decades this property was set as the ideal case [1].

4.2.3 Maintenance Costs – Vulnerability, Repairability

As the detailed establishment of individual maintenance regimes is beyond the scope of this framework, the measure of maintenance cost is assessed qualitatively. Therefore, the measure was split into the two attributes; Vulnerability (i.e. how often maintenance needs to be completed) and Repairability (i.e. how much each act of maintenance costs on a relative scale).

Vulnerability is determined by the ease with which damage can be initiated through mechanical forces and the ease with which this damage can propagate through the material. The scales were defined by combining these two properties with the center being a material that is resistant in one area but not the other.

The location where repairs can be undertaken (i.e. ease of repair) and the extent to which original mechanical properties can be restored when repairs are completed, were combined to measure repairability. The costliest option involves removal of the entire component either for off-site repair in a factory or complete replacement. On the other hand, the quickest and most likely cheapest option is to repair damages, such as fractures, on-site. Ideally this can be done by unspecialized workers with standard equipment to the extent that the original mechanical properties are restored.

4.2.4 Disposal and Recycling Costs

As disposal and construction waste is one of the largest existing waste streams on a global level, the costs associated with the end-of-life processing of a material are an essential part of the overall life cycle costs [59]. As the exact costs of disposal and recycling vary greatly from country to country depending on local laws and infrastructure this attribute is scored on a rather broad, qualitative scale. This scale ranges from expensive disposal (done by specialized companies which charge for service) through free disposal up to the ideal point where material scrap or waste has a value and can be sold.

4.2.5 Reaction & Resistance to Fire

The behavior of material in cases of fire was included in the economic category due to the consideration that this behavior determines how much material needs to be used, and how much additional money needs to be spent on fire protection and prevention systems as well as insurances in order to meet applicable fire safety codes. This behavior can be measured by two different attributes: The reaction of a material to fire (i.e. its flammability behavior and tendency to start a fire) and the resistance of the material to fire and heat (i.e. how long it can retain its mechanical properties in the heat of an already existing fire) [60].

Concerning fire reaction, there exists European fire reaction classification system (EN-13501-1) which assigns one of the following 7 classes of fire reaction to construction materials based on a number of tests: A1 – no contribution to fire growth at any stage; A2 – no significant contribution to fire growth; B – very limited contribution to fire growth; C – limited contribution to flashover; D – contribution to flashover; E – significant contribution to flashover, and F – products for which there is no data, or products failing to achieve class E [60,61]. The class in which a material falls, determines the application for which it can be used in accordance with further European regulations. As classes A1 and A2 describe non-combustible products they were set as the highest value in this framework. Materials falling in classes E & F can be considered unacceptable, as costly, additional protection methods need to be implemented to ensure the fire safety of a structure.

Fire resistance is measured in this framework as a combination of a materials ability to retain its mechanical strength during a fire and the predictability of strength loss if it should occur. A standard fire reaches temperatures of 1000 °C after 60 min [62]. Ideally a material will not be affected by these temperatures and retain its full mechanical properties indefinitely in a fire. The worst case is represented by a material that losses all mechanical strength in a fire in a short period of time regardless of its shape and burns at an unpredictable rate. Such a material will require extensive additional fire protection measures for instance through coatings or sprinkler systems to comply with fire regulations. Due to the unpredictability of the combustion process the use of the material will also involve higher risks and thus higher insurance costs. In between these two extremes is a material which losses mechanical strength at a predictable rate in a fire through degradation of its surface layer. Thus, it is possible to increase the time in which a component made from this material retains a minimum level of strength in a fire by increasing the cross section of the component.

4.2.6 Performance Uncertainty

When evaluating the potential for use in construction, a material’s stage of development and level of industry adoption must be considered. For instance, for materials which have just left the development stage little experience exists for the use in specific environments. Such materials may have improved properties, however due to a lack of established codes or regulations the risks associated with their use in construction can be relatively high. This increased risk translates into increased costs incurred, for instance, through higher interest rates on borrowed capital or higher insurance costs.

4.2.7 Predicted Price Developments

All previous attributes are related to the performance of a material in the present. However, to assess the economic sustainability of using a material in construction the long term, price developments need to be considered as well, since this will influence the future usage of the material. Price predictions are surrounded with a high amount of uncertainty and this uncertainty increases in line with the prediction horizon. Nevertheless, it is possible to estimate the direction and magnitude of change to a certain degree. Changes in the range of 50 % from today's levels were set as the two end points of the scale as changes exceeding these levels would have a significant impact on material usage in construction [63].

4.3 Sustainability & Environmental Impact

In this framework the sustainability assessment is limited to the production of a material and the disposal. The use phase is not included since impacts occurring during this phase are only marginally dependent on the material, with specific design options and use cases as the major influences. All scales are shown in Table 3.

Table 3: Ranking scales of Sustainability & Environmental Impact attributes

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 APPROACH	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 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

4.3.1 Raw Material Renewability

Renewability of a material is measured in this framework by the proportion of raw materials required for production which can be considered renewable. Even if a material achieves a good score for this attribute, it is essential to look at the actual supply chain in detail, to determine whether a material is produced not only from renewable but also sustainable sources.

4.3.2 Recycling Approach

Concerning disposal, the main factor influencing the sustainability of a material is the extent to which waste can be reintroduced into the material production cycle thus eliminating the need for additional raw material extraction and the associated impacts. The recycling potential of a material is determined by the chemical composition and structure as well as existing recycling infrastructure. In this framework Recycling Approach is rated according to the way in which a material is disposed of or recycled at the end-of-life when it is used in construction. The worst option in this respect is disposal by landfilling or incineration, as the raw materials used for production of the material are usually unrecoverable. To date a growing amount of construction waste is downcycled (esp. in Europe) meaning that the material is reused in a different function with a lower value than the original virgin material [64]. This point was set as the middle of the rating scale. The ideal case is full recycling where the raw materials of a material can be separated and re-introduced into the production process to substitute virgin raw materials thus reducing the pressure on resources.

4.3.3 Environmental Impact of Production – Human Health, Ecosystems, Resources

In this framework the full environmental impact of production is considered by conducting an LCA of the evaluated materials. The scope of this LCA ranges from raw material extraction until production of the final construction material (cradle-to-gate). The environmental impact of production can be calculated using for instance the ecoinvent database and a compatible program such as SimaPro [65]. An internationally accepted calculation method is the ReCiPe method, which calculates a single endpoint score from all defined inputs and outputs of the LCA thus combining a multitude of existing metrics (ex. energy usage, emissions, resource depletion). This endpoint score is composed of the three individual scores for impact on human health, ecosystems and resources [66]. As impact scores are intended to be used for comparison and have no absolute meaning the proposed ranking scale is the same as for the costs, with materials being ranked according to the percentile in which their impact scores lie after all materials have been evaluated. To make these impact scores comparable they have to be calculated relative to the defined FU.

4.4 Future Availability

Availability is determined by supply and demand. Therefore this category contains attributes determining supply and demand of the material itself as well as the raw materials required for its production. For all attributes, except those measured quantitatively (availability of raw materials and geographic distribution), the timeframe for which predictions need to be made is defined by the user in the first step of the framework.

Regardless of their total content in the final material, all raw materials are essential for its production. Therefore for the rating of the future availability attributes, each attribute needs to be evaluated for all raw materials present in a respective material. The final score for the material is equivalent to the lowest score of the evaluated raw materials (i.e. the bottleneck). The scales for the future availability attributes are shown in Table 4.

Table 4: Ranking scales for Future Availability attributes

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 resources/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 in the specified timeframe, but the possibility exists.	No realistic reason for governments to regulate usage of material or raw material in the specified timeframe
DEVELOPMENT OF RECYCLING INFRASTRUCTURE	Recycling infrastructure will not develop significantly in the specified timeframe, leaving landfilling or incineration as the main disposal option for material	Recycling infrastructure will develop, increasing recycling rates. However downcycling is expected to remain the only viable option.	Infrastructure will develop strongly in the specified timeframe, 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 specified timeframe	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 specified timeframe
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 mature technologies	Production could be significantly increased with existing infrastructure (mining, processing facilities etc.)

4.4.1 Availability of Raw Materials – Short-term, Long-term

Although there is much debate on the use of reserve and resource measures for the prediction of material availability [46,48,50,67,68] no better quantitative measure has been proposed in literature to date. Therefore, the future availability is measured by the reserve to production and resource to production ratios of the respective material's raw materials. The data on global production levels, reserve and resource bases can be obtained via the U.S. Geological Service (USGS) or industry specific sources. The definitions for reserves and resources can be described as follows: Reserves are mineral deposits that have been more precisely defined in terms of mineral content and that can be economically extracted using todays technologies. Resources are known mineral deposits that have yet to be fully characterized, or that present technical difficulties or are uneconomic to extract [69]. The issue with these measures is that the reserves are highly dependent on current market prices and technologies. Therefore, if the reserves are used up, the price of the commodity will rise and thus new resources will be turned into reserves extending the "lifetime" of the raw material. Consequently, two separate availability attributes are incorporated into this framework. The assessment of availability via the reserves/production ratio presents a more short term evaluation, since today's price levels and technologies are considered, while the resource/production ratio measures availability in the longer term as it allows for price changes and technological developments [28]. This is also the reason for the different time values assigned for the specific scores.

4.4.2 Geographic Distribution of Reserves

From a political perspective supply can be influenced by export restrictions and unrest or conflict in producing countries [48,49]. These risks are exceptionally high, when existing material reserves are highly concentrated in a small number of countries. As in the Report on Critical Raw Materials for the EU, concentration is measured in this framework through the Herfindahl-Hirschman-Index (HHI) [49,70]. The index can be calculated for each raw material using country specific reserve data obtained for instance from the USGS or industry sources [69]. The score values are based on the assessment by the U.S. Department of Justice which considers a market with an HHI of less than 1,500 to be a competitive marketplace, an HHI of 1,500 to 2,500 to be a moderately concentrated marketplace, and an HHI of 2,500 or greater to be a highly concentrated marketplace [71]. To keep the number of attributes which need to be assessed manageable, there is no distinction made between the supply risk due to possible export restrictions and political instability or a lack of governance in the producing countries. A high concentration is assumed to be representative of a high risk for the none-producing countries.

4.4.3 Potential for Restrictive Government Regulation

Government regulations aiming at reducing environmental impacts or stabilizing local economies can affect the demand for certain production practices or also uses of materials. Thus, even if resources would be available it may not be legal to use, produce or purchase a certain material. As the exact effect of government regulations on raw material availability is difficult to quantify this attribute is qualitatively measured according to the probability of regulations being implemented and the extent to which these regulations limit the availability of a specific raw material. Regulations to be considered can range from tariffs that raise prices, through export restrictions to bans and prohibitions.

4.4.4 Development of Recycling Infrastructure

The supply of raw materials is not only determined by the reserves and resources which are available for exploitation but also by the level of recycling enabling substitution of virgin material with existing material stocks. The future development of recycling infrastructure is measured in the same way and along the same scale as the Recycling Approach of a material in the Economics category. However, in this case, level and type of disposal/recycling which is projected to be achieved in the specified timeframe is relevant. Increases in recycling levels can occur due to new technological developments enabling a better separation of raw materials or simply through changing policies and practices which improve the recycling system. Materials which already today have high recycling levels can be assumed to remain at such high levels.

4.4.5 Projected Growth of Competing Industries

In order to fully assess the future availability of a material for the construction industry, expected demand from other industries needs to be taken into account as well. As a scenario-based assessment of the projected developments of all demand side industries is beyond the scope intended for this framework, the scale for this attribute is described qualitatively. In a first step, the competing industries for all raw materials of the evaluated material and the material itself need to be identified. Market reports on these industries as well as scientific papers on demand projections for individual raw materials can be used to assess how future demand from these individual industries compares to current and predicted supply levels. Next to the comparison of this demand and supply the position of the construction industry among the consuming industries needs to be assessed, as a stronger position of an individual industry (i.e. responsible for majority of demand) will ensure better access to scarce raw materials [72].

4.4.6 Ease of Production Increase

If a certain material is seen to be superior to others for the use in construction (be that due to economic, environmental or availability considerations) it may be the case that demand levels increase rapidly in short period of time. Therefore, it is essential to evaluate how a significantly higher demand level could be met in the future. The rating is based on the amount of time and capital which would be required to increase the production of the evaluated material to multiples of today's levels. This is determined by the overcapacities that are currently present in the industry and the maturity of the raw material acquisition and material production technology. Mature industries with high levels of overcapacities could quickly react to increasing demand simply by ramping up production in existing facilities or by reopening facilities that were shut down due to cost reasons. Mature industries without overcapacities would be able to meet demand by increasing production capacity with new facilities and raw material acquisition operations. Despite the fact that this would require significant investments the risks associated with these are known and clearly calculable due to the maturity of the technologies. Finally the largest barrier to increasing production to global levels is faced by new materials that are currently only produced in small amounts in specialized markets. If increasing production requires a scale-up of the manufacturing process significant investments will be required. The development of such new technologies is also surrounded with a high level of mostly unquantifiable risk.

5 Discussion

There are multiple possibilities for applying the presented framework. The most basic application is the evaluation of existing materials, which have been readily adopted by the construction industry, according to their performance in relation to a defined use case. The resulting ranking identifies those materials which are most promising and at the same time allows a comparison of the tradeoffs involved in choosing one over the other. A first prioritization of research and development areas can be done by analyzing the weighting factors of the low scoring attributes of highly ranked materials. Focusing on improving attributes that are considered more important for the defined application will consequently provide the most value to the industry. As future availability is also evaluated it can be clearly analyzed, whether a specific material will also in the future have a high economic potential. Thus, the previously identified research areas can be evaluated according to their long-term potential as well.

It is also possible to introduce newly developed materials into the ranking and compare them with the more established construction materials. Such an evaluation can demonstrate whether a material, which was developed for a specific purpose, is technically, economically, or environmentally superior to existing materials or if certain aspects need to be further improved before it can compete with them.

Finally, the same can be done at the beginning of a material development project. This can for instance be a project that was set up after analyzing existing materials' weaknesses. Even though the properties of the final material need to be estimated (as it doesn't exist yet), the framework requires the detailed evaluation of the future availability of all constituents employed in the planned production process. Thus, it is possible to gauge early on if the developed material will be usable on a global scale in the long term future, giving a clear picture on whether it is economically sensible to invest extensive funds in the material's development.

Next to material development the ranking provided by the framework also serves to identify policy measures which contribute to increasing the sustainability of construction practices. For instance, if a material is currently disposed of mainly via landfill, despite there being a better option (for instance downcycling) the result will be a high discrepancy between the "Recycling Approach" and "Development of Recycling Infrastructure" scores. This clearly indicates that policies aimed at educating users about the improved process are required to increase the materials end-of-life recycling rate. Another example is a newly developed material with an improved "Durability" and/or "Sustainability" rating but a lower "Performance Uncertainty" score. This demonstrates, that extensive effort by governments or other institutions will be required to overcome the regulative and risk related barriers to enable the material's adoption in the construction industry.

As such the framework serves as a first step to identifying and prioritizing the focus areas of research projects and policy measures and provides a rough evaluation of the long-term potential of specific material development projects. The framework, however also has a number of shortcomings. First of all, despite being defined as clearly as possible, the assessment of qualitative attributes remains partly subjective [31]. Therefore, it is essential to consult different sources of information (experts or literature reports) and discuss diverging opinions before establishing a final score [37]. Second, the level of specificity with which use cases can be defined is limited, as the attributes are measured on a broad scale, in order to enable a comparison of completely different material types. For specific material selection problems more appropriate, and precisely measurable attributes need to be defined. Furthermore, for immediate construction in the present an analysis of future developments is superfluous. Finally, the framework does not provide information on the feasibility and exact cost calculations of specific projects. A more detailed evaluation of identified projects or policies needs to be conducted before funds are actually committed.

6 Conclusion & Outlook

The development of improved materials is an essential strategy for increasing the sustainability of global construction practices. The sheer number of existing materials along with the variety of areas and approaches available for their improvement, lead to a plethora of potential research and development projects. To ensure an effective distribution of resources to projects with not only a high, but also long-lasting impact on the construction industry, it is necessary to carefully evaluate and prioritize the individual projects. The framework presented in this paper enables the identification and first, high level prioritization of such projects by evaluating their potential impact on a defined area of construction as well as their long-term commercial potential. This is achieved through a holistic ranking of individual materials' potential for long-term usage in construction, according to their technical, economic and environmental performance as well as the future availability of their raw material constituents. Next to the identification and prioritization of potential research directions the framework enables a comparison of the performance of newly developed materials or planned material developments with existing materials established in the industry.

A first application of this framework executed by the authors for a large set of different materials is underway. However, that study is beyond the scope of this paper. Here it is intended to present the detailed structure of the framework as well as the considerations behind the individual attributes and scores. As the rating scales used for the individual attributes are precisely described based on literature and industry sources, subjectivity in the ranking of qualitative attributes is limited and an efficient evaluation of individual materials is possible. Application of the framework by practitioners and researchers to further materials, will lead to the development of a growing materials database, which can quickly provide crucial information on impactful material development directions, policy options and criticality issues, not only for research institutions and governments but for the entire construction industry.

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