Chapter

Eco-Material Selection for Lightweight Vehicle Design

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Abstract

In order for automakers to meet the new stringent environmental policies and to improve fuel efficiency of their vehicles, they started to change the design of their vehicles to be better aerodynamically, to downside their vehicle sizes, thus they can reduce the engine size as well, and to increase the level of the electrification (partial or full electrification) of their fleet vehicles. Lightweight design is another widely used strategy to improve fuel economy of automobiles. Potential lightweight material needs to be cost effective, has the ability to reduce the weight of the vehicle and can meet the functionality requirements. Thus, we need a systematic material selection process that takes into consideration all design aspects such as cost, performance, and environmental impacts. Eco-material selection provides a systematic method for material selection and takes into account material's mechanical properties, cost, and ability to reduce environmental impacts over product's lifetime. This chapter summarizes methods of eco-material selections for automotive structural panels in the body-in-white. A set of numerical and qualitative metrics for eco-material selection will be developed and discussed in this chapter. These metrics cover products' environmental impact, functionality, manufacturability, economic, and societal and safety factors.

Keywords: automotive, body-in-white, eco-material selection, lightweight design, sustainability

1. Introduction

Automakers today work on three major areas to improve the fuel economy of their fleet vehicles. Lightweight design, electrification and advanced powertrain technologies have been widely investigated and adapted by many OEMs (original equipment manufacturers) as the key solutions to improve fuel economy, thus reduce GHG emissions over the vehicle's lifespan. One of the early solutions to improve fuel economy of the vehicles was to reduce their weights and to improve their aerodynamic performance by changing the outer shape of the vehicle. Lightweight design emerged as a strategic solution to reduce the dependency on foreign energy sources after the Arab oil embargo in 1973. Early lightweight vehicle design aimed to reduce vehicle weight by substituting some of the heavy cast iron and steel parts used in vehicles with lighter materials like magnesium and aluminum. Recently advanced high strength steel (AHSS thereafter) and reinforced plastic composite materials emerged as new lightweight materials with a wider acceptance than other expensive materials due to the decreasing trends in their production costs and the new innovations in the manufacturing processes that allow for mass production of these materials. Other lightweight design approaches also include redesigning of the vehicle and downsizing. Some automakers redesigned their cars to reduce aerodynamic resistance and improve fuel economy. In the downsizing approach, the car dimensions and engine size are reduced to save the mass of the vehicle, which require small engines that utilize less amount of fuel per driven mile. One of the key issues encounter lightweight materials is the high cost of these materials compared with the cost of conventional steel used in vehicles, the cost associated with manufacturing these lighter vehicles is nontrivial and could reach $3–22 per kilogram of total weight saved for parts made from aluminum and magnesium and between $11 and $33 for parts made from carbon fiber reinforced plastic, CFRP [1–3]. Cost is not the only challenge that is still facing the lightweight materials such as magnesium and CFRP, and to a lesser extent aluminum, these materials also known of being energy-intensive materials especially in material extraction and manufacturing phases [4–5]. Many researchers focus on the vehicle use phase and under emphasize energy and GHG (greenhouse gas) emissions in the materials extraction and manufacturing of the vehicles which could potentially result in a biased judgment towards favoring these lightweight materials over steel or high strength steel.

If we look at the trend of passenger car weights in the last four decades, we can see that the average passenger vehicle weights declined from about 4035 lb (∼1830 kg) in 1975 to <3200 lb (∼1460 kg) in 1982. Over the same time period, according to the U.S. Environmental Protection Agency numbers, the amount of plastics used in a typical US passenger vehicle increased from about 4.6% in 1980 to about 10–12% today [6]. However, the customer demand shifted their preference in the last few years to the larger and heavier vehicles such as sport utility vehicles (SUVs) and pickup trucks because of their heavy-duty functions. As a result, the average vehicle weight has increased again until it reached about 4150 lb (∼1890 kg) in 2009 [6]. The average weight for new vehicles produced in 2016 was 1830 kg (4035 pounds) as a result of the added weights of electronics and new subsystems in the car. The average new 2016 car weight fell by 23 pounds from 2015 value, and the weight of an average new truck fell by 24 pounds from previous year value (**Figure 1**). However, the new trends in vehicle light-weighting aims at enhancing the vehicle fuel efficiency as well as improving its driving performance while lowering its emissions [6–7]. Many experimental studies found that a 10% reduction in vehicle weight translates into a 5–7% improvement in the vehicle's fuel economy in terms of miles per gallon MPG or kWh per mile [7–9].

Electrification of vehicle drivetrain was proven to be an economic and environmental-friendly solution to overcome the problem of the tailpipe emissions in the congested cities. However, many studies have raised questions on the economics of electric vehicles vs. conventional gasoline powered vehicles and the total environmental impacts when the vehicle uses electricity from power generation plants that uses coal or heavy oil [4]. Electric vehicles that are charged from power grids that associated with larger footprints of the generated electricity (kg $CO_{2\text{-eq}}$/kWh), might not be competitive from the environmental standpoint, thus giving more advantages to the economic petroleum-operated vehicles that have advanced powertrains and higher MPG (miles per gallon).

In this chapter, we will introduce and discuss a systematic eco-material selection method that can be used in the early design phases to screen materials and then

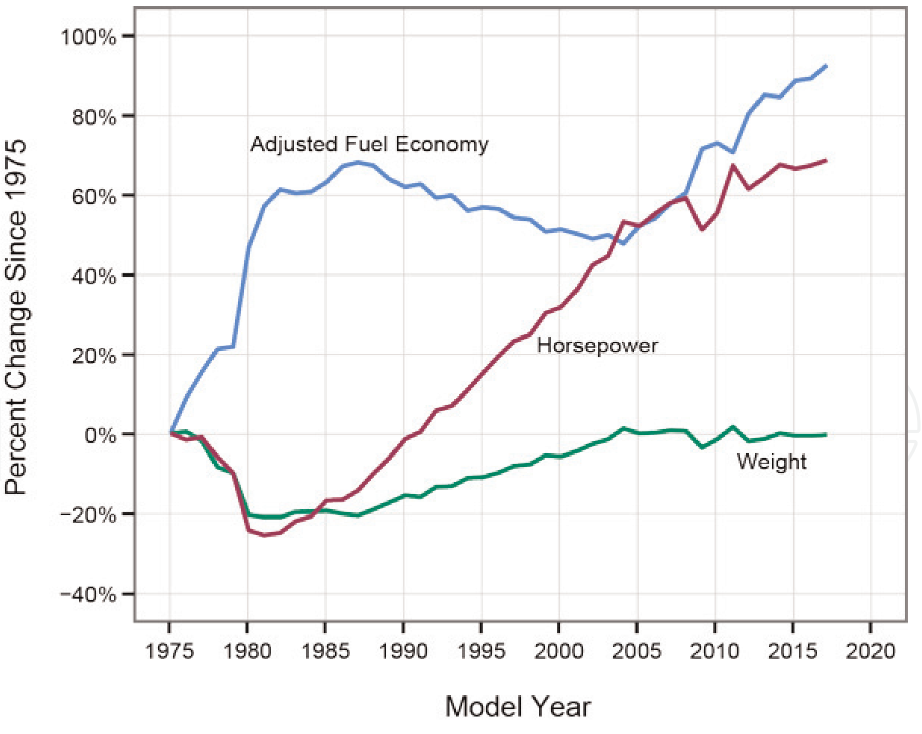


Figure 1.
Change in adjusted fuel economy, weight, and horsepower for model years 1975–2017 (1975 values are: fuel economy 13.5 miles per gallon; horsepower 138 hp; and fuel weight 1830 kg) (image source: Ref. [6]).

select the most suitable candidates that can replace conventional steels in the passenger cars using functionality and mass of the parts as the key requirements in the design, and then expand the selection to include other environmental and economic aspects in the design problem. By following this proposed procedure in the design process, design team could save time and efforts in selecting lightweight materials and make sure they consider all sustainability factors in their part design and selected materials.

2. Eco-material selection methods

Sustainability is a multidisciplinary approach that encompasses the design for the environment factors (e.g., energy, greenhouse gas (GHG) emissions, and end-of-life, recycling and circular economy analysis), safety and societal factors, and economic factors. Safety and societal factors in the sustainability model focus on safety, health, and wellness of the product from premanufacturing all the way until the retired products being disposed or recycled at their end-of-life stage. Economic factors are costs incurred in the materials and part production and any cost incurred or saved at the end-of-life phase. Automakers use several sustainability models to select materials for auto-bodies. While some of these models focus on the environmental aspects of the material selection process in the early design stages, other models are based on a single portion of the product's life cycle (e.g., energy use or the recyclability of the materials). Some of the popular material selections methods include qualitative and quantitative methods. Artificial intelligence and multi-criteria decision-making methods have also recently emerged as new tools to facilitate the material selection process of the complex design problems where multi-objectives and many constraints can be added simultaneously in one step instead of the tedious, time consuming classical screening and selection process. Below is a brief description of these material selection methods:

1. **Qualitative methods**: qualitative material selection methods have been used as guidelines for eco-material selection (e.g., "choose abundant, non-toxic material if possible," "select cheap lightweight material," etc.). Analysis of material performance requirements is another qualitative method that relies on screening materials based on certain mechanical, environmental, or economic requirements. Performance evaluation can also be expanded to select material based on their manufacturability or their performance in the field [10]. So, the beauty of the qualitative methods comes from their versatility in classifying materials based on their relative performance or functionality, but they cannot be used as the basis in the larger eco-informed decision-making processes when multi-objectives are considered simultaneously or when conflicting goals start to emerge in the design problem.

2. **Quantitative methods**: quantitative approaches are used to rank different materials using specific metrics that derived from numerical material selection process that uses material selection indices as the basis for material screening and selection. The framework of this quantitative material selection process was established by professor Ashby and his colleagues from University of Cambridge, UK. Single environmental indicator or eco-indicator was proposed by Wegst and Ashby [11] to assess materials from the environmental perspective. Ashby [12] extended this single eco-indicator and added energy content indicator to the material selection process. Coulter et al. [13] and, Ermolaeva et al. [14] proposed adding the environmental cost as another measure to assess the relative performance of the candidate materials and how they can do the specified functions at the lowest cost possible.

   Another quantitative method using material selection indices was proposed by Kampe [15]. In this study Kampe developed an energy-based material selection model in which a specific material could be used as a part of the overall decision-making process. Kampe used an expanded version of the Ashby's material selection method to assess materials from the lifetime environmental load perspective. Kampe provided and an example of energy-based material selection of auto body beams, which its main design function is to support a uniformly-distributed load, $\boldsymbol{W}$, along its length without experiencing overload failure. The derived material selection index for this beam can be expressed as $\frac{\sigma_f^{\frac{2}{3}}}{\rho}$. Then Kampe introduced another selection factor to the problem, total energy expenditure, $\boldsymbol{Q}$ to assess materials using a combination of several functionality and mechanical parameters. Kampe extended the classical Ashby's material selection methods by multiplying the derived mass by the energy content per unit mass, $\boldsymbol{q}$. By doing so, Kampe was able to derive a material selection index for a strong beam with low embodied energy which can be expressed as $\frac{\sigma_f^{\frac{2}{3}}}{\rho \cdot q}$. This method could help designers in dealing with multiple design requirements using a quantitative material selection ranking process based on the material selection index.

3. **Decision-making (DM) and artificial intelligence (AI) methods**: multi-criteria decision-making methods (e.g., an analytical hierarchy process, quality function deployment, or material selection numerical ranking methods) have

been used extensively in recent years to facilitate material selection process by including multiple goals and multiple constraints in the design problem (see, for example, [16–18]). On the other hand, AI methods such as neural networks, fuzzy logic, genetic algorithms, and digital logic also emerged as new methods to facilitate the material selection processes especially when exploring large material datasets [19–22]. Both DM and AI methods provide versatile material selection methods that takes into consideration multiple objective functions with multiple constrains and provide designers with and expanded search domain that can include hundreds or thousands of candidate materials.

Besides the abovementioned DM methods, researchers have also used other effective DM methods such as TOPSIS, VIKOR, and ELECTRE. The technique for order preference by similarity to an ideal solution (TOPSIS) method is based on the logic that the chosen alternative should have the shortest distance from the ideal solution and the longest distance from the negative-ideal solution [23]. Vise Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) is very similar to TOPSIS in the logic sequence but differs in the normalization process. VIKOR uses a linear normalization where the normalized values do not depend on the evaluation unit of the criterion, whereas TOPSIS uses vector normalization where the normalized value can change for different evaluation units of a particular criterion [23–24]. The second key difference is the aggregation function in each method, VIKOR uses a function that factors in only the distance from the ideal value and TOPSIS uses the ideal and anti-ideal values [23–24]. While authors of these studies discussed the beauty and limitations of these methods, they concluded their discussion by emphasizing that there is no technique that can be considered the most powerful for any given selection process, rather they presented versatile methods that can simplify the calculations and produce a more reliable result when studying a multi-objectives problem. As a matter of fact, it was reported in many articles that several AI and DM methods could produce different outcomes in ranking a set of alternative materials/decisions, which is partially due to the bias arises when making assumptions or assigning relative scores for certain material selection criteria; thus caution should be practiced when adopting any of these AI or DM methods.

3. Sustainability model for auto-bodies

Sustainability is a holistic approach that takes into consideration all environmental, economic and societal factors of the product. It also covers all lifespan phases from cradle to the grave. In the last few decades, many new terms and buzzwords start to emerge referring to new aspects in the environmental research. However, some of these new aspects are not more than an expansion of the sustainability framework to give more emphasis to the economic and societal related factors. Now, if we want to summarize these research areas, we can definitely place sustainability in the upper level of the hierarchy as shown in **Figure 2**. In the second level we can place economic, environmental and societal aspects of the product. We can also group other research aspects under each of these major sustainability fields, for example, design for environment which goes under environmental pillar of the sustainability also covers other research subareas such as life cycle assessment, design for recycling and dematerialization. Industrial ecology is part of the environmental aspects of the product, which in turn contains models that cover material flow through industry (MFI) and industrial energy (IE) analysis. Economic factors include analysis of the total cost of ownership which covers all cost incurred in the

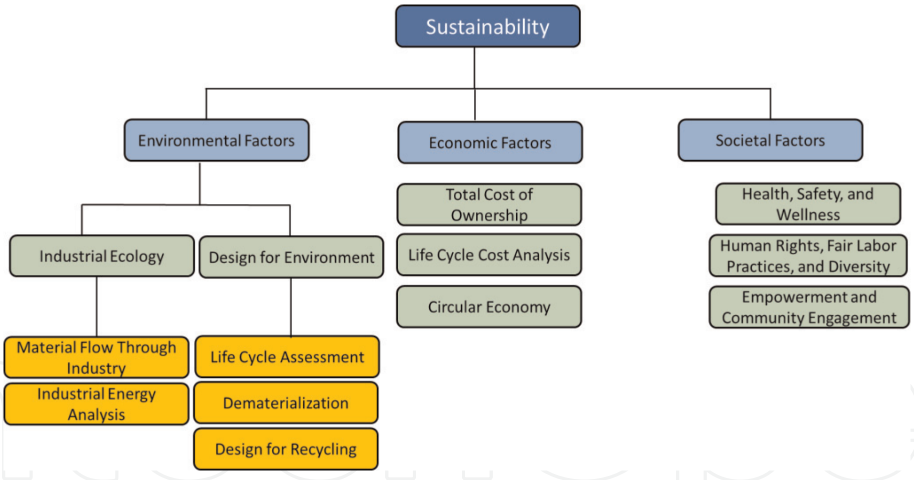


Figure 2.
Sustainability model and its branches.

product starting from material extraction and production, through operation and maintenance and ending with the recycling/reuse/landfilling of the end-of-life product. Life cycle cost analysis is in essence very similar to the total cost of ownership model and attempts to cover all cost associated with the product manufacturing and use. Circular economy is a new term that has gained a wider acceptance in the last few years because it overlaps economic and environmental aspects of the product use and recycling. The idea is to conserve resources by converting all end-of-life products into materials that can be used to make new products.

Eco-materials selection as another branch of the general sustainability model, is considered a multi-criteria decision-making process that starts by collecting and analyzing design requirements and design goals. Then the design engineers establish well-defined and accepted limits for each design requirement and try to classify materials based on their abilities to meet design requirements and perform the function the part is designed for. While finding a unique material that satisfies all design needs is generally difficult, the design team usually tries to compromise between economic, environmental, and societal factors and find a suboptimal set of candidate materials that can fulfil most of the design requirements.

Eco-material selection for auto-bodies is a typical material selection process that usually associated with conflicting objectives on hand, so tradeoffs between these objectives represent, in most cases, the only possible solution designers can use in their design process. For example, lightweight materials such as aluminum and magnesium are known for their ability to reduce energy and emissions in the use phase, but they are expensive and require much energy in the mining and refining processes. Plastic-based composites (CFRP, GFRP) look very appealing when it comes to the density and mass savings, but their manufacturability and cost represent two key challenges that limit their use in the vehicles. These are just two simple example of conflicting objectives the design team usually encounters in the design and material selection phase while they try to narrow down the selection to choose the most practical alternatives.

In this section, we propose a sustainability model for selecting eco-materials for auto bodies that covers most of the environmental, economic, societal, and technical factors in the design process. This sustainability model (**Table 1**) takes many attributes simultaneously and narrow down the selection process to a small group of materials that can meet as many sustainability factors as possible. While this interim model is developed to cover almost all sustainability factors, it can be modified

Environmental	Economic	Societal and safety	Technical/ manufacturability
Resource depletion	Materials cost	Crashworthiness (safety)	Formability
Water pollution	Manufacturing cost	Noise, vibration and harshness	Jointability
Energy consumptions	Operation and maintenance cost	Health and wellness (externalities)	Paintability
Greenhouse gas emissions	End-of-life credit/cost		Durability
Particulate matter pollutants			
Toxic materials			
End-of-life and recyclability			

Table 1.
Sustainability model for eco-material selection for auto bodies.

when needed to include other factors not discussed here. The model focuses on selecting materials that minimize vehicle weight, but it also ensures any material selection conforms to the sustainability holistic approach.

The material selection process should adhere to the sustainability requirements shown above for the selected materials to be considered sustainable. The importance of these factors in the model can be described as follows:

Resource depletion: represents the scarcity of certain materials and how much we consume annually in vehicle production and in the other end uses.

Water pollution: environmental impacts and contaminations into water during material extraction and manufacturing. Chemical or foreign substance that contaminate water could be detrimental to human, plant, or animal health.

Life cycle assessment (LCA): the LCA provides a comprehensive framework to assess materials or products from material extraction all the way to the end-of-life where products can be recycled, reused or landfilled depending on the economic value of the materials/products and environmental regulations in the country where the products end up. Use phase is the most demanding energy and most contributing phase for GHG emission in the typical LCA for vehicles. Besides the traditional LCA that focuses on emission analysis, new sub-topics have been introduced recently to emphasize certain aspects of the life cycle impacts. Examples of these LCA sub-topic include LCEA (life cycle energy analysis), LCIA (life cycle impact analysis to quantify environmental and health impacts), LCC (life cycle cost analysis to assess the ownership cost of the vehicle).

End-of-life and recyclability: retired or end-of-life vehicles can be recycled, reused, or disposed in the landfill. Sending end-of-life vehicles to the landfill means that we are going to lose invaluable resource for recycled materials and will also result in environmental issues such as contaminations of surface and ground water and the loss of the usable land. Recyclability has several metrics (e.g., recycle fraction (ψ); cost of recycling, energy consumption in relative to the energy consumed in producing virgin materials, etc.).

Economic impact factors: Total cost of ownership method represents a comprehensive costing model that takes into consideration material and manufacturing costs, operation and maintenance cost, and end-of-life cost. It also accounts for emissions costs and monetized externalities (health impacts and premature deaths).

Societal factors: two metrics are used to quantify societal factors. First, safety is an indirect measure for material properties (i.e., toughness and yield strength). Second, "health and wellness" is another indirect measure that is governed by:

- Greenhouse gas emissions, particulate matters, and other effluents to the environment, and their expected adverse effects (e.g., acid rain, global warming potential, and ozone depletion).

- Noise-vibration-harshness performance (which is controlled by dynamic stiffness of the BIW structure and damping capacity of joints and material).

Technical factors: this is an extra pillar added to auto-bodies sustainability model to account for technical requirements to manufacture autobodies using certain hard to manufacture materials, or materials that need special manufacturing routes beyond what is available in the auto assembly plants. Four sub-categories can be considered under technical factors: formability (metals vs. plastic composites), joinability (i.e., weldability and ability to join two different materials using common joining process: riveting, bolting, and brazing), and paintability (the level of difficulty for painting multi-material bodies, or bodies made from plastic composites).

Durability (technical): This parameter can be classified under either environmental or technical factors. Nonetheless, durability in the sustainability model overlaps all economic, environmental, and societal factors, thus enhancing the versatility and effectiveness of the sustainability model.

3.1 Material selection indices and eco-material selection process

In the product development process several design iterations are investigated by engineers to decide on which material to use and the required manufacturing routes to make the final product. In this chapter, we discuss eco-material selection process for the primary panels in the body-in-white (BIW). BIW includes several hundred parts but contains a few major structural panels that constitute more than 80–90% of the BIW weight [17, 25]. These major panels are shown in **Figure 3**, and their key design requirements are summarized in **Table 2**.

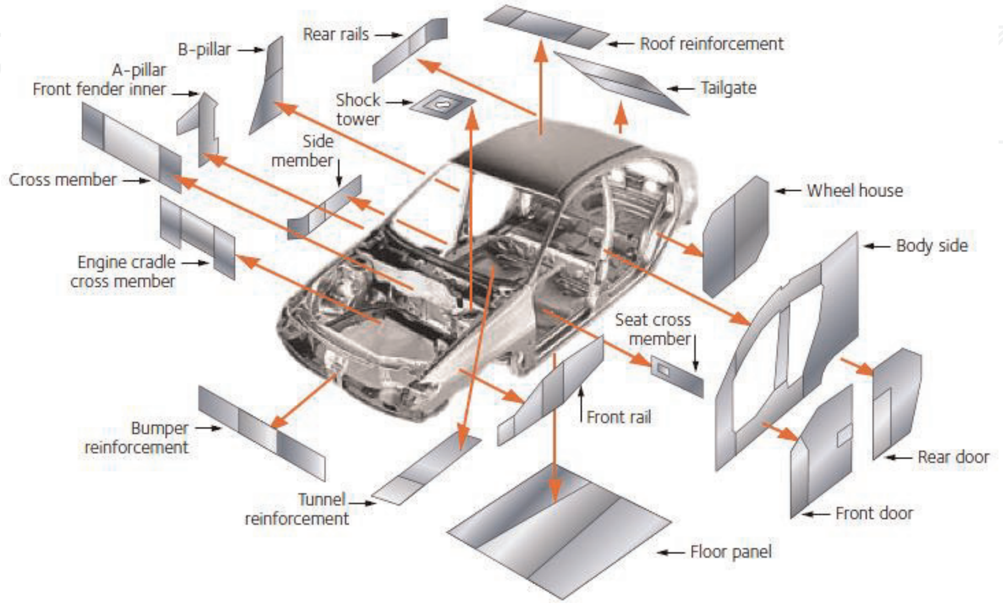


Figure 3.
Body-in-white with closures (courtesy: Ref. [26]).

No.	Panel name	Main design functions
1	Roof	Dent resistance, NVH[†], durability
2	Roof reinforcement	Bending stiffness, NVH, ease of manufacturing
3	Hood (inner)	Bending stiffness, NVH, ease of manufacturing
4	Hood (outer)	Dent resistance, NVH
5	Trunk (inner)	Bending stiffness, NVH, ease of manufacturing
6	Trunk (outer)	Dent resistance, NVH
7	Trunk pan	Strength, NVH, durability
8	Tunnel reinforcement	Strength, NVH, durability
9	Engine cradle	Crashworthiness, temperature performance, NVH, durability
10	Shock towers	Bending stiffness, NVH, durability
11	Splash/fire wall	Temperature performance, NVH, durability
12	Quarter panel	Dent resistance, NVH
13	Front fender	Dent resistance, NVH
14	Door (inner)	Bending stiffness, NVH, ease of manufacturing
15	Door (outer)	Dent resistance, NVH
16	Side members	Bending stiffness, NVH, durability
17	Wheel house	Bending stiffness, NVH, durability
18	A, B pillars	Bending stiffness, NVH, ease of manufacturing, durability
19	Floor pan	Strength, NVH, durability
20	Bumper	Crashworthiness, NVH, durability

[†]NVH = noise, vibration and harshness.

Table 2.
BIW major panels and their main design functions [7, 25].

In the proposed material selection strategy, the objective function for each panel is used to rank the candidate materials based on its closeness to the best candidate, which is calculated numerically using a set of derived material selection indices (discussed in the next section). In most cases, the design objective can be expressed in terms of either maximizing or minimizing a mathematical problem. According to Ashby [12], materials selection indices and material selection charts are powerful tools that can be used to map all engineering materials in one chart and then isolate a subset of materials that meets most of the design objectives. The design problem is usually developed with more than one objective function, which requires plotting design requirements on the selection charts and/or using several sequential charts to screen these materials. In some cases, material selection charts can be designed to handle two or more selection indices in one plot to emphasize the tradeoffs between these objectives. The following sections give some examples of the eco-material selection process for several BIW panels.

3.2 Material selection for bending resistance, lightweight panel

In this section, we will discuss the method of deriving a simple material selection index using Ashby method. For a flat panel subject to a bending force that has a length L, width w, and wall thickness t, subjected to a bending force F (**Figure 4**).

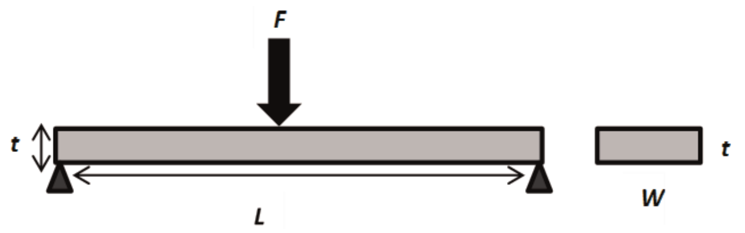


Figure 4.
Simply supported solid rectangular panel under bending force that is designed to withstand certain load without failures.

This panel must not fail under pure bending load, with the objective of minimizing the mass of the panel (m). That is the bending stress on the panel should not exceed its yield stress:

$$\sigma_y > \frac{M \cdot t/2}{I} = \frac{3F.L}{w \cdot t^2} \tag{1}$$

$$I = \frac{w \cdot t^3}{12} \tag{2}$$

where m = mass, w = width, L = length, ρ = density, t = thickness, I = second moment of area, σ_y = yield strength.

In this example, assuming that we have an autobody panel with fixed length and width due to the limitations in the space design, while thickness can be varied to meet the design requirements.

Rearranging Eq. (1), will give us the following equation as a function of the panel thickness:

$$t = \left(\frac{3F \cdot L}{w.\sigma_y}\right)^{1/2} \tag{3}$$

Substituting this in the mass equation $m = A.L.\rho = w.t.L.\rho$, will give us the following:

$$m = (3F.w)^{1/2}(L)^{\frac{3}{2}}\left(\frac{\rho}{\sigma_y^{1/2}}\right) = K.\left(\frac{\rho}{\sigma_y^{1/2}}\right) \tag{4}$$

where $K = (3F.w)^{1/2}(L)^{\frac{3}{2}}$ is constant. As mentioned above, the panel thickness can be varied for the lightweight design. Under this assumption, the mass substitution rate defined in terms of the ratio of the material density and yield strength and can be expressed mathematically as:

$$\frac{m_{LWM}}{m_{ref}} = \frac{\rho_{LWM}}{\sqrt{\sigma_{y,\,LWM}}}\frac{\sqrt{\sigma_{y,\,ref}}}{\rho_{ref}} \tag{5}$$

Where subscript LWM: refers to the lightweight material under consideration, and subscript ref refers to the reference material. Note that alternative assumptions regarding how the cross-sectional dimensions are allowed to vary will produce different results for the substitution rate. Using Eq. (5) and the material yield strength will give us the mass substitution rates for this unit cell in relative to any other material used as a reference. For illustration purposes, Dual Phase 280/600 (yield strength 280 MPa, ultimate tensile strength 600 MPa), was selected as the

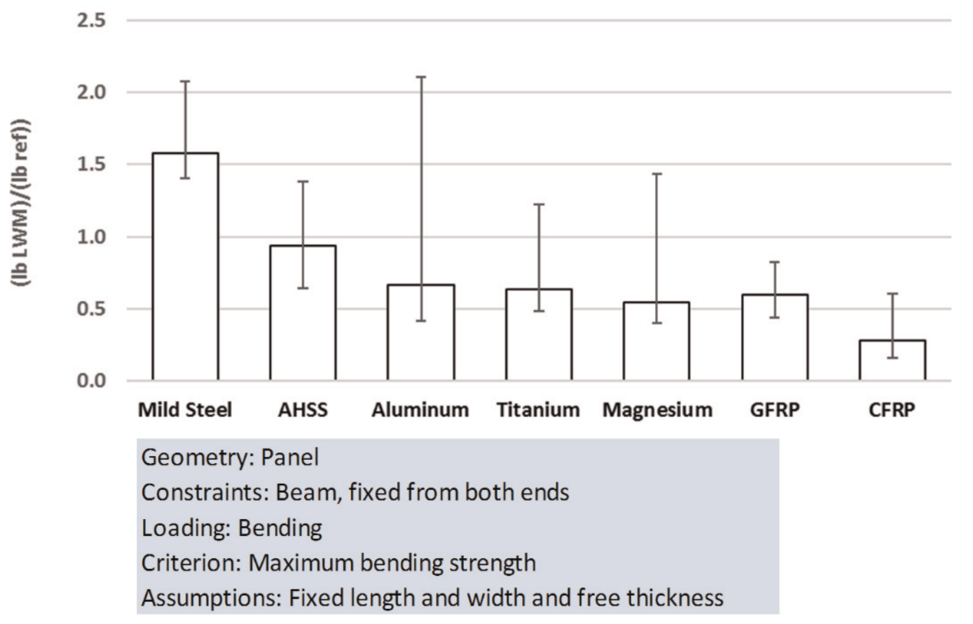


Figure 5.
Average, minimum, and maximum mass substitution rates relative to dual phase 280/600 steel (reference material) (error bar represents min and max).

reference in this example. **Figure 5** provides a comparison of the average, minimum, and maximum substitution rates within each material class. Error bars represent minimum and maximum within each material class.

3.3 Material selection for stiff, lightweight panel

This example discusses the method for driving a material index for a flat panel, subject to a compressive load. The performance design criterion is maximum stiffness. **Figure 6** shows a schematic of this panel with length L, width w, and wall thickness t, subjected to a compressive force F.

This panel must not exceed certain stiffness, with the objective of minimizing the mass of the panel:

$$S = \frac{C.E.I}{L^3} \tag{6}$$

where $I = \frac{w.t^3}{12}$

where m = mass, w = width, L = length, ρ = density, t = thickness, I = second moment of area, E = Young's modulus of elasticity.

Length and width are assumed to be fixed due to the limitations in the space design, while thickness is assumed to be free. Rearranging equation 6, will give us the following:

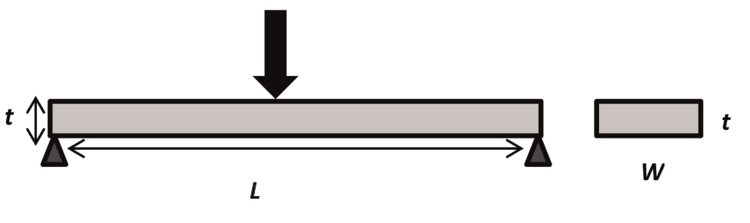


Figure 6.
Simply supported solid rectangular panel under bending force that is designed not to exceed certain deflection.

$$t = \left(\frac{12S.L}{C.E.w}\right)^{1/3} \tag{7}$$

Substituting this in the mass equation ($m = A.L.\ \rho = w.t.L.\rho$), will give us the following:

$$m = \left(\frac{12S.w^2}{C}\right)^{1/3} L^2 \left(\frac{\rho}{E^{1/3}}\right) \tag{8}$$

The component thickness can be varied for the lightweight design. In order to uniquely determine the substitution rate in terms of material properties, an assumption of fixed length and width are adopted and only the panel thickness is allowed to vary. Under this assumption, the mass substitution rate defined in terms of the ratio of the material density and yield strength:

$$\frac{m_{LWM}}{m_{ref}} = \frac{\rho_{LWM}}{\sqrt[3]{E_{LWM}}} \cdot \frac{\sqrt[3]{E_{ref}}}{\rho_{ref}} \tag{9}$$

Where subscript LWM: refers to the lightweight material under consideration, and subscript ref refers to the reference material. Note that alternative assumptions regarding how the cross-sectional dimensions are allowed to vary will produce different results for the substitution rate. Using Eq. (9) and the material properties, the mass substitution rates for this panel can be determined for each of the material specifications relative to any other specification used as the reference. Again, we used dual phase 280/600 steel as the reference material for illustration purposes. **Figure 7** shows a comparison of the average, minimum, and maximum substitution rates within each material class. Error bars represent minimum and maximum within each material class.

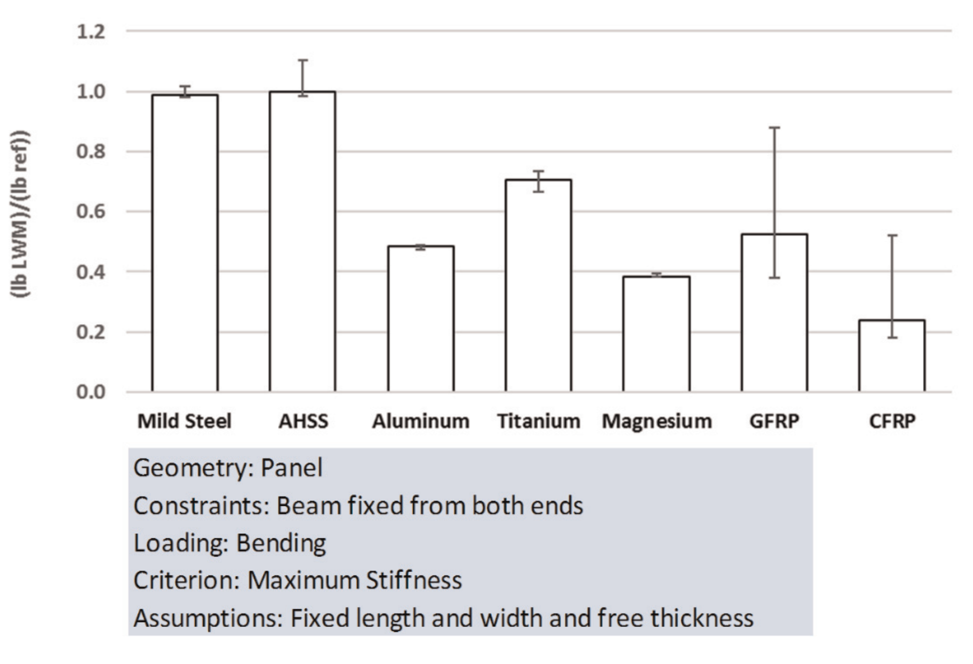


Figure 7.
Average, minimum, and maximum mass substitution rates relative to dual phase 280/600 steel (reference material) (error bar represents min and max).

3.4 Eco-material selection for auto-bodies

In this section, we will discuss an example for deriving a material selection index for a stiff, recyclable, and lightweight panel under bending load. Now let us formulate the design problem using a similar procedure. In this example we have:

Fixed variables: panel, width w and length L are specified.

Objectives: minimize mass, m; and maximize recycle fraction ψ:

Objective function of this problem in this case is a type of the mixed mix-min function, "minimize mass, m and maximize recycle fraction, ψ ($0 \le \psi \le 100\%$)." Now, if we set the objective functions as a minimization problem only, then:

$$m.\left(\frac{1}{\psi}\right) = (A\,L)\,(\rho).\left(\frac{1}{\psi}\right) = (w\,t\,L)(\rho).\left(\frac{1}{\psi}\right) \tag{10}$$

Constraints: stiffness of the panel, S:

$$S = \frac{F}{\delta} \Rightarrow S = \frac{C E I}{L^3} \tag{11}$$

$$I = \frac{w t^3}{12} \tag{12}$$

where m = mass, w = width, L = length, ρ = density, t = thickness, S = stiffness, I = second moment of area, E = Young's modulus.

Variables: **material choice, panel thickness "t" or combination of both**.

Hence, if we eliminate t and re-arrange the equation, we will get:

$$\frac{m}{\psi} = \left(\frac{12\,S\,w^2}{C}\right)^{1/3} L^2 \left(\frac{\rho}{\psi.E^{1/3}}\right) \tag{13}$$

To maximize this equation, one should choose materials with largest:

$$M = \frac{\boldsymbol{\Psi E^{1/3}}}{\boldsymbol{\rho}} \tag{14}$$

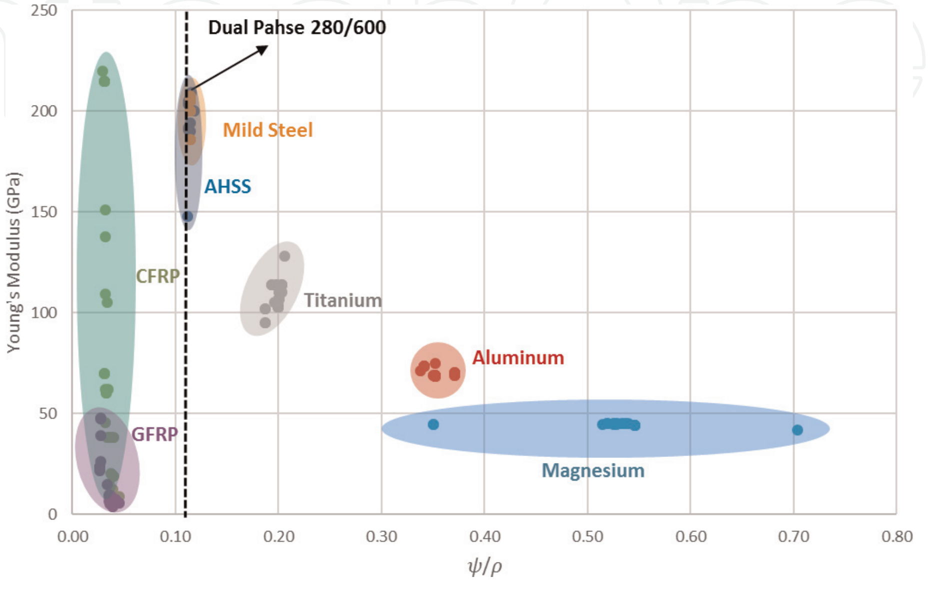


Figure 8.
Materials for stiff, lightweight-recyclable panels (e.g., A-, B-, and C-pillars, inner door and inner hood panels).

So for material 2 to replace material 1, the following equation should be valid:

$$\frac{M_2}{M_{ref}} = \frac{\left(\Psi_2 E_2^{1/3} / (\rho_2)\right)}{\left(\Psi_{ref} E_{ref}^{1/3} / (\rho_{ref})\right)} > 1.0 \quad (15)$$

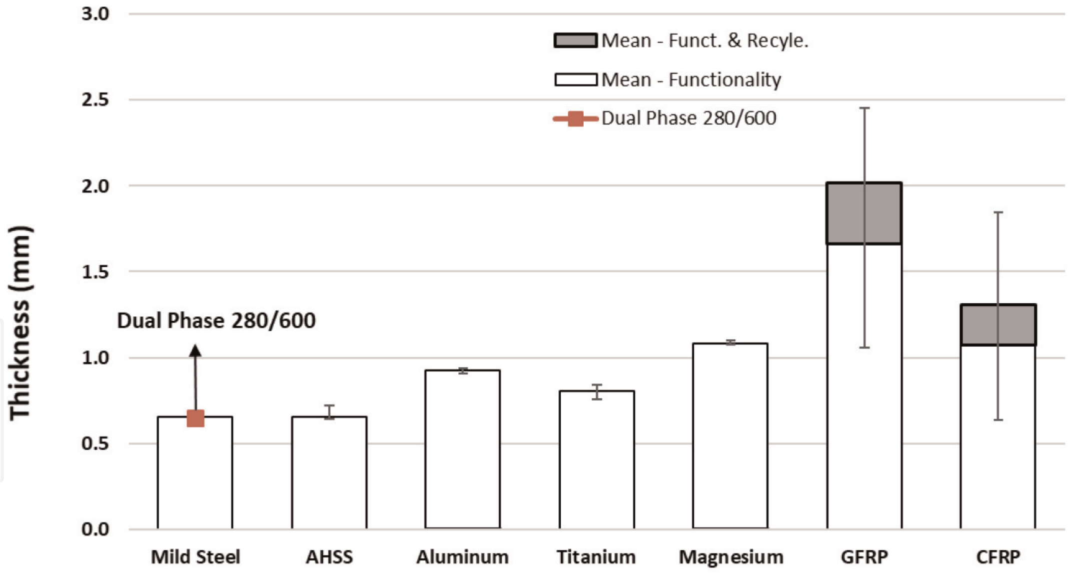
Material selection chart for a stiff, lightweight, and recyclable panel is shown in **Figure 8**. The dashed line in this chart separates materials with a ψ/ρ value >0.1128. These candidate materials such as titanium alloys, aluminum alloys, magnesium alloys, and some types of mild steel and AHSS are considered suitable to replace dual phase 280/600 steel in lightweight stiffness panels. While CFRP and GFRP represent very good candidate materials from the lightweight perspective, their low recyclability could limit their use when recycling is considered in the design requirements.

3.5 Example of material selection for recyclable hood (inner panel)

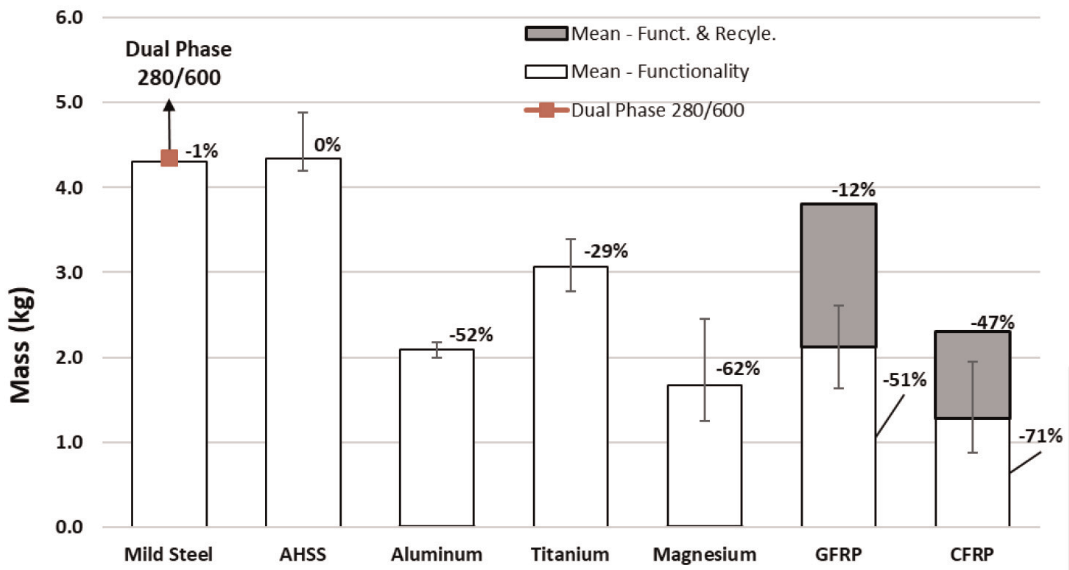
In this section, we will discuss a numerical example for eco-material selection for lightweight hood (inner panel) (**Figure 9**). The main design function for this panel is to withstand certain bending load without failure, so the derived material selection is $M = \frac{E^{1/3}}{\rho}$. However, for ecomaterial selection that combines part's functionality and recyclability, the selection index for light stiff panel becomes $M = \frac{\psi \, . \, E^{1/3}}{\rho}$. The mass of inner panel in the hood is around 4.35 kg and has an average thickness of 0.65 mm. We assumed that reference hood panel is made from dual phase steel (DP steel) with an average yield strength (YS) of 280 MPa and an average ultimate tensile strength (UTS) of 600 MPa. **Figure 8** shows the required thickness based on the functionality of the hood (inner panel) made out of DP steel as a reference material and the corresponding thickness of same panel/part made out from other materials. We also calculated the new thickness for panel made from lightweight materials using functionality and recyclability of the materials (shaded bars).

From functionality perspective (i.e., stiffness), magnesium and aluminum alloys can offer more than 50% in weight savings and some types of GFRPs and CFRPs can save on average 51 and 71%, respectively (**Figure 10**). Titanium provides modest weight savings with an average weight reduction of 29% in relative to the dual

Figure 9.
Hood inner panel (source of picture: Ref. [27]).



(a)



(b)

Figure 10.
New inner hood panel thickness (a), and mass (b) using eco-material selection index for recyclable stiff panel in relative to the panel made from dual phase 280/600 steel. Note 1: shaded bars represent the difference in thickness and mass if the materials are selected based on their stiffness and recyclability. Note 2: percentages represent calculated mass saving in relative to a hood (inner panel) made from dual phase 280/600.

phase steel. Since our derived material selection indices go beyond classical functionality selection and consider sustainability factors, then we may need to consider recyclability when we select candidate materials to replace dual phase in the hood inner panel. Now, if we look back at the thickness and mass saving charts in **Figure 10**, we can see slight changes (in the range of 0–2%) in the values for steels, AHSS, aluminum, magnesium and titanium which have recycle fraction that exceed 90% in most case. CFRP and GFRP are known for their poor recyclability at the end of the life, so we assumed that recycle fraction is 50% for these composite materials. Upon incorporating these recycle fractions in the thickness and mass calculations, we found that these materials start to look less appealing from the “functionality and recyclability” perspective. That is, their low recyclability divert the selection toward more recyclable materials that have the ability to reduce the panel weight and have good recyclability at the same time.

If we want to rank those materials that can meet functionality and recyclability requirements, then we can consider other factors such as cost or manufacturability and add them to the design problem as new constrains. By doing so, we expect aluminum to have better advantage in terms of manufacturability and cost if compared with magnesium and titanium alloys.

4. Qualitative material selection

As mentioned previously in Section 2, that some sustainability factors are qualitative in nature and can be used in their natural units or can be quantified using certain transformation methods. For example, corrosion resistance of material is a qualitative parameter and materials can be classified as having high, medium, or low corrosion resistance. Similarly, wear resistance can be also expressed qualitatively. An example of these simple scaling systems is shown in **Figure 11a** which can be used to rank materials based on their yield strength and resistance to saltwater (as a result of the salt used to melt the snow on the roads). This chart has five scales along x-axis: very poor, poor, average, good, and very good, and yield strength along the y-axis. This type of qualitative charts can help guide design engineers in selecting loadbearing, corrosion resistance materials. A good example of such application is floorpan and some other parts in the chassis. Alternatively, engineers can plot two durability characteristics in a single chart to learn more about relative performance of the candidate material or group of materials (**Figure 11b**). Material selection chart shown in **Figure 11b** can be used to assess relative performance for materials that in contact with the hot parts in the engine and can be affected from saltwater. Examples of such panels include firewall or floorplan parts that are in contact with the exhaust pipes and subject to contact to the saltwater from the roads.

On the other hand, the absence of a well-established scientific method to quantify some of the societal factors (i.e., safety and health and wellness) and technical factors (formability, weldability/joinability and ability to be paint) also shows the need for design team to have those qualitative charts that help them understand the relative performance of these materials in the material screening during the early design phases.

There are some sustainability factors that can be expressed in a mixed quantitative/qualitative way depending on the function of the part and the material properties. For example, safety can be expressed in many ways such as the resistance of the part to permanent deformation (yield strength) or based on the assessed crashworthiness of the whole vehicle. While yield strength is an intrinsic material property, it seems that crashworthiness is a mixed design function that factors material properties (yield strength, toughness, etc.) and the part design parameters (e.g., shape and geometry of the part). The complexity of the sustainability factors in this case does not mean we cannot derive a sustainability material selection index to facilitate material selection in the early design stages, rather it should simplify the eco-material selection process. In this study, we define safety from a material selection perspective as the material property that plays a key role in determining crashworthiness if a vehicle is involved in any accident including minor crashes. By doing so, safety is assumed to have strong relationship with yield strength and the material toughness. Similarly, health and wellness can be defined as the material characteristics that interfere with human health and quality of the air. A simple function of health and wellness should include the amount of emissions released to the

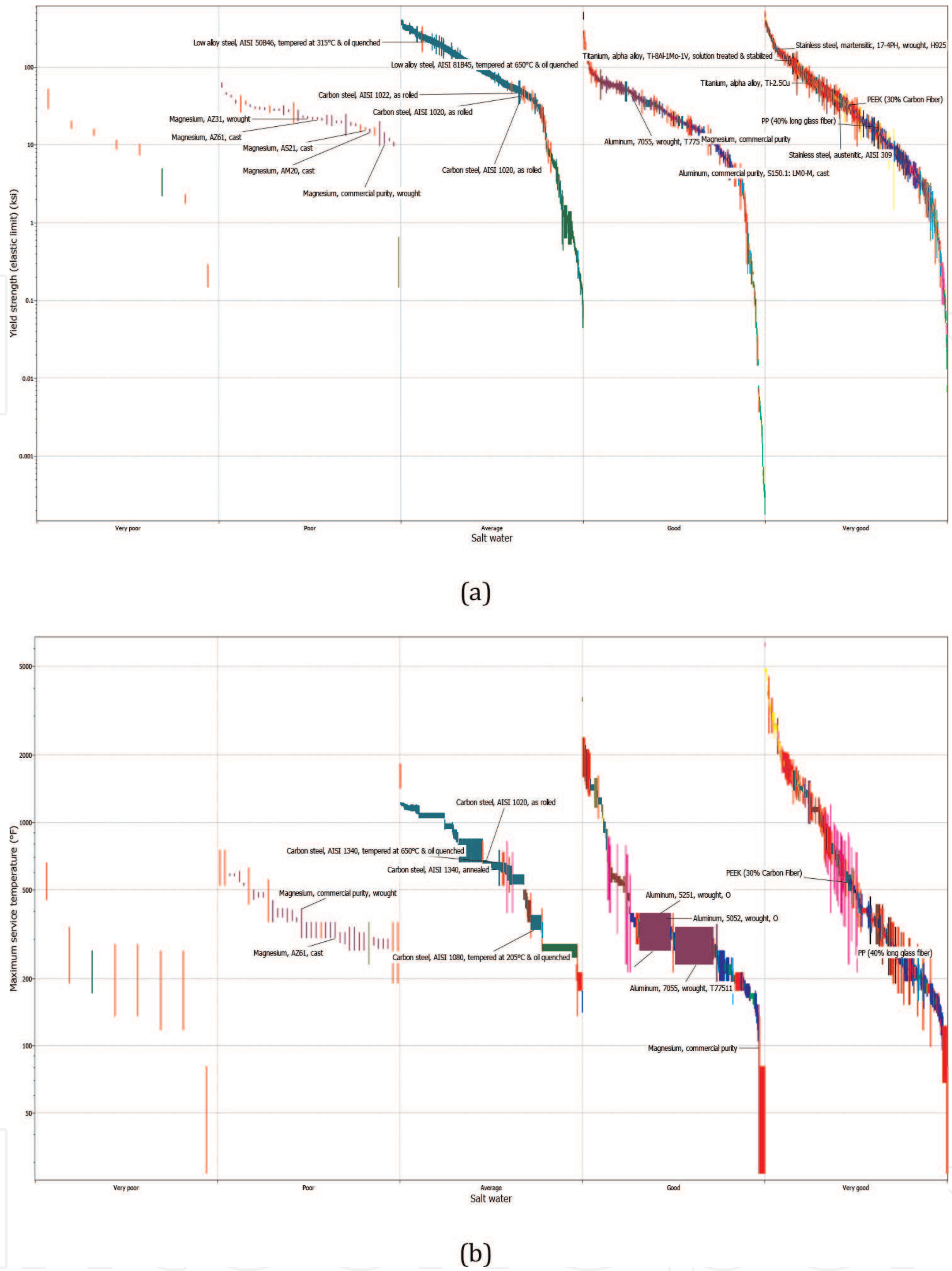


Figure 11.
Example of scaling method for (a) corrosion resistance (in saltwater) for stiff materials, and (b) material selection chart with combined durability selection criteria for corrosion resistance and maximum service temperature.

environment from cradle to grave (i.e., in all mining and manufacturing processes involved in production and use of the vehicle, and ultimately the recycling or landfilling of the retired parts made from these materials). Thermal performance here represents a qualitative metric that measures relative performance of certain materials in a high temperature environment, especially those parts near or in contact with the engine block where temperatures could easily reach 100°C or more [28]. While classical sustainability models have three pillars to cover environmental, economic and social factors, we still believe that a good sustainability model for auto-bodies should also take into consideration extra technical factors (i.e., forming, welding and joining, and painting) which describe the manufacturability

	Durability			Societal		Technical		
Material	**Corrosion resistance**	**Thermal performance**	**Wear resistance**	**Health and wellness (NVH[§])**	**Crash-worthiness[§§]**	**Forming**	**Joining**	**Painting**
Dual phase steel 280/600	Avg.	VG	VG	Avg.	G	G	VG	VG
Mild Steel	Avg.	VG	VG	Avg.	G	G	VG	VG
AHSS	Avg.	VG	VG	Avg.	VG	Avg.	G	VG
Aluminum alloys	G	VG	Avg.	VG	P	G	Avg.	VG
Magnesium alloys	P	VG	Avg.	VG	P	Avg.	Avg.	G
Titanium alloys	VG	VG	Avg.	Avg.	VG	Avg.	Avg.	G
CFRP	VG	Avg.	G	P	VG	VG	G	VG
GFRP	VG	Avg.	VG	P	P	VG	G	VG

Key: very poor (VP), poor (P), average (Avg.), good (G), and very good (VG). Source of data: [25, 29–30].
[§]NVH is function of vehicle stiffness and material damping properties.
[§§]Crashworthiness is function of yield strength and toughness the material.

Table 3.
Scales for some qualitative material selection criteria for several material classes used in making autobodies [17, 25].

of different materials considered in the complex eco-material selection problems. Unfortunately, these technical factors have neither well-established material selection indices nor any material selection charts that designers can use for screening and sorting purposes. For these reasons, we propose using a scale that has five classes (very poor, poor, average, good, and very good) to evaluate the relative performance of candidate materials from the manufacturability perspective. The ratings provided in **Table 3** were collected from different sources (e.g., [29–30]) and should be used with caution and only provide guidelines to assist engineer in the material selection process.

5. Impact of light-weighting on the life cycle assessment of the vehicle

In this section we will study the impact of using lightweight materials on the greenhouse gas GHG emissions over the vehicle's lifetime. **Table 4** summarizes key lightweight design parameters including curb weight and percentage weight reduction assuming a steel-intensive body design as the base case in this analysis. We can say that most lightweight materials including aluminum alloys, magnesium alloys and carbon fiber reinforced plastics are associated with higher values of GHG emission in the material extraction and refining. Manufacturing phase accounts for about 2–4% of the total LCA emissions, so it has low impact on the overall LCA. End-of-life credits indicate that recyclable materials are more favored from LCA perspective because they can save energy upon recycling when the vehicle is retired. Use-phase is the most contributing source of GHG emissions in the vehicle's

Powertrain	**Internal combustion engine**				
Car type (base)	**Mid-size car**				
Material	**Conv. steel**	**Adv. steel**	**Al**	**Mg**	**CFRP**
Potential weight saving (%)[1]	0	19%	30%	37%	37%
Estimated curb wt. (lb)[2]	3370	2729	2359	2123	2123
Estimated Curb wt. (kg)	1528	1238	1070	1024	1024
$/kg saved in vehicle weight[3]	$ –	+ $ 0.50	+ $ 5.00	+ $ 6.50	+ $ 10.00
Fuel Economy (MPG)[4]	34.40	39.68	43.54	46.42	46.42
GHG Emissions (metric tons of $CO_{2\text{-eq}}$)[5]					
Pre-manufacturing	4.29	4.29	5.51	13.13	13.13
Manufacturing	1.74	1.74	1.70	1.81	1.81
Use	69.77	60.49	55.12	51.70	51.70
End-of-life[6]	−1.18	−1.18	−3.33	−10.00	0
Total LCA GHG (metric tons)	74.62	65.34	59	56.64	66.64
Percent Reduction	0	−12%	−21%	−24%	−11%

[1]*From Ref. [1].*
[2]*Assuming a steel-intensive vehicle as the base case.*
[3]*Estimates based on values from [1, 5, 8].*
[4]*Using values from U.S. EPA (Ref. [6]) and adjusted for lightweight designs assuming 6% improvement in vehicle's fuel economy (mile/gallon) for 10% reduction in the vehicle weight [7–9].*
[5]*Based on values from several sources, see, for example, [1–5, 8–9, 17].*
[6]*Assuming 90% recycle fraction for steels, 95% for aluminum and magnesium and 0% for CFRP.*

Table 4.
Impacts of lightweight materials on the GHG emissions from the vehicle's life cycle.

lifespan. The good news is that the higher emissions of the lightweight materials in the pre-manufacturing and manufacturing phases will be compensated for in the use phase. As we can see in **Table 4**, magnesium and aluminum perform better than plastic composites from the LCA perspective. When it comes to the cost, advanced high strength steels are more favored. Unfortunately, CFRP tends to be less favored from both cost and ease of manufacturing perspectives, thus should be considered with those facts in mind in the design process.

6. Conclusions

Many solutions have been adopted in the recent decades to reduce the environmental burdens associated with the production and use of passenger vehicles. Downsizing, design modifications, electrification and lightweight design are among the most common methods used by automakers. Recently, eco-material selection was emerged as a supporting methodology for lightweight design. Eco-material selection process represents a versatile material selection process that combines two or more of the design parameters in the problem formulation, and thus provides a better way of dealing with multi-criteria material selection problems. Other material selection methods may focus on environmental impacts associated with the production, the use phase, or the end-of-life phase. Historically, less emphasis has been given to economic or societal parameters in the discussion of lightweight materials and more emphasis was given to the environmental impacts. To get a balanced approach for eco-material selection, we proposed a holistic design for sustainability (DFS) model for material selection for the major structural panels in the auto-body. This holistic model covers all environmental, economic, safety and societal factors alongside with the technical challenges in manufacturing of the lightweight materials. Unfortunately, the integration of all sustainability aspects in the design process tends to complicate material selection process and requires proper knowledge of relative importance of the design functions and material selection criteria. Design for sustainability model with the aid of the materials selection indices and material charts offer good tools that can help designers screen and rank materials using their relative performance in the early conceptual design stage.

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