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Citation for the original published paper (version of record):

Poulikidou, S., Schneider, C., Björklund, A., Kazemahvazi, S., Wennhage, P. et al. (2015)
A material selection approach to evaluate material substitution for minimizing the life cycle
environmental impact of vehicles.
Materials & design, 83: 704-712
<https://doi.org/10.1016/j.matdes.2015.06.079>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-173255>

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DOI: 10.1016/j.matdes.2015.06.079

A material selection approach to evaluate material substitution for minimizing the life cycle environmental impact of vehicles

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Abstract

Weight reduction is commonly adopted in vehicle design as a means for energy and emissions savings. However, selection of lightweight materials is often focused on performance characteristics, which may lead to sub optimizations of life cycle environmental impact. Therefore systematic material selection processes are needed that integrate weight optimization and environmental life cycle assessment. This paper presents such an approach and its application to design of an automotive component. Materials from the metal, hybrid and polymer families were assessed, along with a novel self-reinforced composite material that is a potential lightweight alternative to non-recyclable composites. It was shown that materials offering the highest weight saving potential offer limited life cycle environmental benefit due to energy demanding manufacturing. Selection of the preferable alternative is not a straightforward process since results may be sensitive to critical but uncertain aspects of the life cycle. Such aspects need to be evaluated to determine the actual benefits of lightweight design and to base material selection on more informed choices.

Keywords:

Lightweight design, material selection, life cycle assessment, sandwich structures, self-reinforced composites

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1. Introduction

The transport sector accounts for about one third of total energy demand in Europe and is among the major contributors of greenhouse gas emissions [1]. Road vehicles have a considerable share in this. To meet increased regulations and customer requirements for reduced environmental impact, the automotive industry seeks solutions to improve the performance of their fleet especially during the dominant operation stage. Weight reduction is commonly adopted in vehicle design, resulting in

both energy and emissions savings [2, 3]. Weight savings can be realised through material substitution to lightweight materials, such as lighter metals, polymers and composites [4, 5], through use of materials in a more weight efficient manner, for instance as a sandwich structure [6], or through a combination of the two. Lightweight design does, however, have drawbacks. Compared to steel, composite materials such as carbon fibre reinforced polymers (CFRPs) are costly and have higher energy demand during manufacturing [5]. Recycling of composites and sandwich structures is also costly and complicated; since composites consist of two different materials (matrix and reinforcement) and traditional sandwich structures often consist of three (face sheet-, core material and adhesive), separation of the materials is difficult. A relatively new class of composite materials, self-reinforced polymers (SrPs), also called single-polymer or all-polymer, could combine weight savings with high recyclability at end-of-life (EOL), since fibres and matrix are based on the same recyclable polymer [7, 8]. They also exhibit good mechanical properties [9, 10] and may hence be attractive for automotive applications. To assess whether there are any significant unexpected environmental trade-offs over the life cycle, these novel materials need to be assessed using a life cycle perspective. Such an assessment should consider physical, mechanical, and environmental characteristics in an integrated manner [11] and be adopted in standard material selection and vehicle design processes. Such assessments are rarely applied in practice, as vehicle designers primarily consider performance and acquisition cost of the material [12] while environmental performance is rarely prioritised [13, 14]. If performed, environmental assessments are usually done for finalized products, not as an integrated part of the design process [13, 15]. For the automotive industry to meet the challenge of reducing the climate and other environmental impacts, a shift in the material selection paradigm is needed. Eco-design guidelines, e.g. ISO TR 14062 [22], suggest that environmental assessment should be performed in parallel to the traditional product design process and before any final design decision is made. Hence, comprehensive frameworks are needed which ensure that both functional and environmental vehicle performance requirements are considered and balanced. Although rarely applied in practice, several such integrated models for evaluating and selecting materials can be found in literature [3, 5, 16-20]. Simoes et. al. [3] and Witik et al. [5] suggest a thorough environmental and cost analysis. However, design parameters and requirements are not presented as part of a comprehensive material selection model, limiting those studies to an environmental and cost assessment of finished products. Only a few complete frameworks for material selection in a design context based on structural optimization and life cycle environmental assessment techniques have been published [16, 18, 20]. Some of these are prescriptive, for instance concerning the use of preselected environmental indicators or decision making functions. While this may simplify application, there is also a risk that it prevents integration in a company's established material selection process.

1.1 Aim and scope of the paper

An integrated material selection approach is presented in which structural weight minimization is combined with environmental life cycle assessment (LCA), with the aim to allow for systematic evaluation of material alternatives before any final design decision, and to reduce the risk for sub-optimizations and shift of environmental burdens along the different life cycle stages of the vehicle. It builds on previous frameworks and expands their scope especially concerning environmental performance of the materials. Efforts were made to capture critical aspects in vehicle design. The approach was tested on a vehicle design case study. SrP composites were compared to commonly used materials for a particular vehicle component, in order to show how materials for vehicle design can be systematically assessed, but also to provide specific results regarding the environmental performance of SrP composites.

2. Life cycle based material selection

The integrated material selection approach was aligned to traditional material selection frameworks that consider material properties and structural weight optimization to derive feasible and weight efficient design alternatives [21]. It adds evaluation of life cycle environmental impact of all feasible material alternatives at an early stage. It consists of five major steps; Definition of design target, Selection of material families and candidate materials, Weight minimization, Life cycle modelling and assessment, and Results analysis and material selection (**Fel! Hittar inte referenskölla.**). Selection of weight minimization models, environmental analysis tools and impact indicators are to be decided by the users. Possible ways to analyse and interpret the results are suggested. Although cost is an important parameter in material selection today, it is not considered in this study.

2.1 Definition of design target; setting requirements and constraints

Design targets are defined by a number of functional (fundamental properties) and non-functional requirements according to the intended application. These requirements need to be fulfilled in a limited design space. A functional requirement of a car roof for instance, is to protect passengers from outdoor conditions and from accidents. In this material selection approach, low environmental impact is also considered a functional requirement of the design target as suggested by Deutz et. al. [23], in order to “extend the definition of functional requirement” from considering only the performance of the product to its life cycle performance. Additionally, properties related to the intended application (vehicle) may also have an influence and restrict the design target. The type of vehicle and operating conditions (including total life time and environmental conditions), legislation as well as corporate requirements are some examples related to the intended application.

Figure 1: Developed framework for life-cycle based materials selection. The dashed lines show processes that are outside the scope of this approach but could be included in the model.

2.2 Selection of material families and candidate materials

Engineering materials can be classified into six families: metals, ceramics, glasses, polymers, elastomers and hybrids [21]. The functions and requirements defined by the design target constrain the selection of certain material families [24]. A front window of a vehicle for instance should be transparent which obviously excludes the use of metals. From the remaining families, a more specific list of properties and constraints (such as application temperature, specific strength or stiffness, manufacturing constraints, regulation requirements etc.) will lead to only a few representative alternatives or material candidates that fulfil the design target [13, 18, 24]. Those materials represent feasible design solutions for the design target and will be used in the consecutive stages of weight minimization and life cycle assessment applied in this approach.

2.3 Weight minimization

Weight minimization is applied to all material candidates in order to derive the lowest optimal mass for the design target. For the weight minimization, constraints such as available space for the part or maximum allowed deformation etc. are defined based on the requirements of the design target. The general constraint optimization problem is formulated as:

$$\text{minimize} \quad f_0(x_{(1:i)}) \quad (1)$$

$$\text{subject to} \quad f_k(x_{(1:i)}) \leq b_k, \quad k = 1 \dots n \quad (2)$$

$$\underline{x}_i \leq x_i \leq \overline{x}_i, \quad i = 1 \dots 5$$

f_0 is the weight function which is a function of the design variables x_i . f_k is the constraint function while b_k represent the constraint values. $\underline{x}$ and $\bar{x}$ define the lower and upper bounds for the design variables x_i . These bounds could be for instance the allowed wall thickness of a structure.

2.4 Life cycle models and assessment

Life cycle models of each candidate material are created and assessed according to [25]. The functional unit (reference measure of the assessment) [26] defines the function and operational life of the design target and remains constant for all design alternatives in order to provide comparable results. Environmental inventory data (inflows of energy and materials and outflows of emissions and waste) are collected for all stages and processes involved, either from generic material databases e.g. [27, 28], suppliers, or manufacturing sites. The potential environmental impact of the design alternatives can be estimated with life cycle impact assessment (LCIA) methods [29] that quantify the impact of resource use and emissions [26]. The most appropriate LCIA method is determined by the availability of data, quality of the model, as well as the aspects that the designer wants to consider. Different software tools are available to facilitate data collection and calculation procedures.

2.5 Results analysis and material selection

In order to fulfil the functional requirement of low life cycle environmental impact, a comprehensive analysis of the results is needed, which may consider the following aspects: (i) total life cycle impact of each material alternative separately and in comparison to the others, (ii) environmental performance of each alternative in different life cycle stages, (iii) trade-offs between life cycle stages or environmental impact indicators and (iv) variations in the design target or properties of the product and its life cycle that may influence the life cycle impact of the material. Selection of the optimal material is case specific, depending on company priorities of trade-offs between functional requirements.

3. Case study: material selection for a truck roof panel

A material selection case study for a truck roof panel is used to test and illustrate the suggested approach. The case study was also used to evaluate the performance of SrP from a lightweight design and environmental perspective. Since this is a theoretical case, specific manufacturers and materials suppliers were not available when conducting the data inventory. The majority of data considered are based on generic databases and literature.

3.1 Definition of design target; setting requirements and constraints

The truck roof panel represents the design target of the material selection process. The roof is used by a 40t diesel truck and designed for a life cycle distance of 1 000 000 km (indicated as average life time mileage in [30] for heavy freight vehicles). The roof size is assumed to be 2.2m x 2m with a maximum allowed roof thickness of 100mm and it is designed to fulfil specified functional and safety requirements such as the truck cabin safety test standard ECR29 [31].

3.2 Selection of material families and candidate materials

Representative materials were selected from the material families which could fulfil the design target; metals, hybrids and polymers. Mechanical properties of the selected materials (assumed to be linear elastic up to yield stress) are presented in

Table 1. Steel and aluminium are the most commonly used metals in the vehicle industry. To have the roof as light as possible, steel and aluminium alloys with good mechanical properties are needed. Hence, a dual phase steel DP800 and an Al6061-T6 were selected. Hybrids, such as fibre reinforced polymer composites are also widely used in automotive applications. Commonly used hybrids are carbon or glass fibre reinforced vinyl-ester (C/VE and G/VE respectively). To obtain relatively high stiffness and strength, the volume fractions of fibres in the composite were assumed to be 0.58 vol. % and 0.54 vol. % for the C/VE and

Table 1: Material properties of the selected materials

		Steel [32]	Al [33]	C/VE [10]	G/VE [10]	PET [34]	SrPET [10]
Young's modulus:	E (GPa)	210	68.9	57	27.1	3	7.9
Tensile yield stress:	σ_{yt} (MPa)	570	276	350*	350*	55	100
Compression yield stress:	σ_{yc} (MPa)	570*	276*	350	350	60	60
Density:	ρ (kg m ⁻³)	7800	2700	1600	2100	1350	1350

*assumed to be the same as the tensile or compression stress

G/VE respectively. The SrP composite considered was a self-reinforced polyethylene terephthalate (SrPET) composite. SrPET composite is based on 50% low melting temperature PET (matrix material) and 50% high tenacity PET (fibre material) [10]. Due to the reinforcing fibres, SrPET composite material has higher mechanical properties than the base material PET, but is expected to have higher environmental impact than of base material PET. To investigate if this higher environmental impact is compensated by the lower weight of SrPET, an unreinforced PET was also included in the study.

3.3 Weight minimization

To use the material efficiently the truck roof was designed as a corrugated sandwich panel. To facilitate recycling the panel should consist of the same face sheet and core material. The geometry

of the sandwich panel (**Fel! Hittar inte referenskälla.**) was defined by weight minimization for all materials.

Figure 2: a) Schematic of sandwich beam b) corrugated unit cell

The weight minimization problem was simplified to a corrugated sandwich beam with a length $L=2.2\text{m}$, simply supported edges and with a uniform distributed load $q=22.3\text{kN/m}$. Five design variables were used (Table 2). Bounds were chosen to ensure a manufacturable sandwich structure while limiting the design space without influencing final result. The objective function f_0 is the beam mass per unit width

$$f_0 = \rho L(t_{fc} + t_{ft} + \frac{t_w}{\cos(\omega)}), \quad (3).$$

Table 2: Design variables

x_i	Notation	Description	Bounds
x_1	t_{fc}	face sheet thickness top	0.5 - 20mm
x_2	t_{ft}	face sheet thickness bottom	0.5 - 20mm
x_3	ω	corrugation angle	10 - 80°
x_4	t_w	core member thickness	0.5 - 15mm
x_5	t_c	core height	10 - 90mm

Weight minimization was performed with a constrained nonlinear multivariable optimization function `fmincon` in Matlab R2012b. The Matlab global search algorithm `MultiStart`, which generated 10 000 uniformly distributed starting points within the bounds, was employed to search for a global minimum.

3.3.1 Constraints

The constraints considered were geometrical and stiffness constraints. The geometrical constraint was determined by the available physical space, which defines a maximum allowed sandwich structure thickness of 100mm (sum of face sheets and core thickness). The stiffness constraint defines a maximum roof deflection of 100mm. To ensure that the roof deflection is not exceeding the maximum, the sandwich structure is not allowed to soften. It was assumed that this structural

softening appears when the material yields or buckles. This results in five more constraints. Deflection of a sandwich beam is the sum of deflection due to shear w_s (assumed to appear only in the core) and due to bending w_b resulting in $w=w_s+w_b=0.125qL^2S^{-1}+5/385qL^4D^{-1}\leq 100\text{mm}$ [6] where q is the distributed load, S and D are the shear stiffness and flexural rigidity of the sandwich structure respectively. $S=G_{xz}d^2t_c^{-1}$ where $d=t_{fc}/2+t_c+t_{ft}/2$ is the distance between the centroids of the faces and core shear modulus $G_{xz}=0.5Et_wL_{cm}\sin(2\omega)$ for corrugated core defined by [35] where $L_{cm}=t_c/\sin(\omega)$ is the core member length. The flexural rigidity D of the sandwich structure is defined as:

$$D = \frac{Et_{fc}^3}{12} + \frac{Et_{ft}^3}{12} + \frac{E_{xx}t_c^3}{12} + E(t_{fc}(d-e)^2 + t_{ft}e^2) + E_{xx}t_c\left(\frac{t_c+t_{ft}}{2} - e\right)^2 \quad (4)$$

where the core modulus $E_{xx}=Et_w\cos^3(\omega)t_c^{-1}$ [35] and the position of the neutral axis is

$$e = \frac{Et_{fc}d + E_{xx}t_c\left(\frac{t_c}{2} + \frac{t_{ft}}{2}\right)}{Et_{fc} + E_{xx}t_c + Et_{ft}} \quad (5).$$

The material failure constraint for the top face sheet (compression stress) for materials with linear behaviour is:

$$\sigma_{fc} = \frac{M_x(d-e)E}{D} \leq \sigma_{yc} \quad (6)$$

where $M_x=0.125qL^2$ is the maximum bending moment in the beam. Similarly, material failure for the bottom face sheet (tensile stress) is:

$$\sigma_{ft} = \frac{M_x e E}{D} \leq \sigma_{yt} \quad (7).$$

In the sandwich core, the core members are loaded in tension and compression and therefore the core member material constraint is:

$$\sigma_{cm} = \frac{T_x}{t_c \sin(\omega)} \leq \frac{\sigma_{yc}}{\sigma_{yt}} \quad (8)$$

where $T_x=0.5qL$ is the transverse force in the sandwich beam. The core members and the top face sheet are loaded in compression and can fail by buckling. The buckling constraint for the core member is (assuming pinned ends):

$$\sigma_{cm} \leq \hat{\sigma}_{Bcm} = \frac{\pi^2 Et_w^2}{12L_{cm}^2}, \quad (9)$$

where $L_{cm}=t_c\sin^{-1}(\omega)$ is the core member length. For the top face sheet, the buckling constraint is (assuming pinned ends):

$$\sigma_{fc} \leq \hat{\sigma}_{Bf} = \frac{\pi^2 Et_{fc}^2}{12L_{critf}^2}, \quad (10)$$

where $L_{critf}=2t_c\tan^{-1}(\omega)$ is the length of the top face sheet.

3.3.2 Weight minimization results

Results obtained from weight minimization are listed in Table 3. The table also shows weight savings compared to steel which can be considered as the reference material for the truck roof. As expected, the highest weight saving was achieved by C/VE. Unreinforced PET resulted in a 23% heavier roof.

Table 3: Weight results and corresponding geometry

	Steel	Al 6061	C/VE	G/VE	PET	SrPET
Total Mass (kg)	108.4	64.3	40.0	74.3	133.9	85.1
Weight difference compared to steel (%)	0%	-40%	-63%	-31%	+23%	-21%
t_{fc} (mm)	1.3	1.8	2.2	3.1	8.3	5.4
t_{ft} (mm)	0.5	1.3	0.7	1.0	2.8	1.8
t_w (mm)	0.5	0.8	0.9	1.4	4.5	2.7
ω (°)	63.7	61.9	61.9	64.0	61.2	62.5
t_c (mm)	25.3	31.0	37.7	46.4	83.6	64.5

In all optimal sandwich structures $t_{fc} > t_{ft}$ because the compression loaded top face sheet can buckle which is driving the face sheet thickness difference. Similar as for the top face sheet, the driving constraint for the core member thickness was buckling as well. All sandwich structures reached the maximum allowed deflection showing that the roofs are designed for stiffness. The selected load case is similar to a roll-over accident of a truck. During an accident, material usually gets plastic deformed or fail. In this optimization, the roof deforms only elastically which shows that the mass values are relatively conservative results.

3.4 Life cycle models and assessment

Life cycle models were built of the truck roof, for each material candidate (Figure 3). The functional unit is “one truck roof” with design specifications according to the design target and a life cycle distance of the truck of 1 000 000 km. Results from the weight minimization provided the total mass of the roof and the amount of each material needed. The geographical boundary is Europe, meaning that inventory data was representative for Europe. Transportation of materials and parts were excluded due to lack of data and expected minor impact on results. LCA models were built using the SimaPro 7.3 software [36] and environmental inventory data from the ELCD v2.0 and Ecoinvent v2.0 and databases [27, 28]. Other sources of information, mainly academic publications, were also used. A summary of assumptions is presented below. Details on the process data can be found in the supplementary material of this paper.

3.4.1 Production of raw materials and truck roof manufacturing

Data on raw material acquisition and production were obtained from databases [27, 28]. Production of carbon fibres (CF) was modelled according to [37]. Manufacturing processes for the truck roof

Figure 3: Overview of the life cycle of the different design alternatives. Arrows represent transports while dotted lines show the processes excluded from the study.

were modelled based on the properties of the selected materials. Metal structures go through a sheet rolling and cutting process. To join the structure the solid – state joining process friction stir welding was assumed. The CF and GF composite corrugated structures were manufactured by a 3D fibre weaving process. The woven CF and GF structures were then infused with the vinyl ester resin. For the SrPET sandwich structure, a commingled yarn of PET fibres and PET matrix was used which was consolidated by a hot compaction process. Finally, the unreinforced PET structure was assumed to be manufactured by a PET injection moulding process. Energy requirements of the manufacturing processes are presented in Table 4. Electricity was modelled as average European mix [27, 28]. Waste from cutting of polymer and composite structures was assumed to be 10% of the structures' weight. Thermoplastic polymer process waste was recycled and C/VE and G/VE process waste was assumed to be incinerated in municipal waste incineration facilities, modelled based on [43].

3.4.2 Use phase

The use phase was modelled as operation of a diesel truck of EURO 5 emission standard [44]. Energy use and emissions during the reference life time distance of 1 000 000 km were allocated to the truck roof assuming a linear relationship between weight and fuel consumption, resulting in a fuel consumption of $7.5 \cdot 10^{-6} \text{ l km}^{-1} \text{ kg}^{-1}$ material (which is close to the values estimated by [2]).

3.4.3 End of life (EOL)

EOL treatment is determined by the properties of the materials and available waste management technologies. Recycling of metals from end of life vehicles (ELVs) is well-established with high material recovery rates [5, 45]. Polymers and composites usually end up in the automotive shredder residues (ASR) that is either incinerated or landfilled [46, 47]. However, there are large geographical differences and uncertainties about future practice at EOL. The uncertainties are explored by analysing different treatment alternatives (Table 5). As a reference case, recycling (R) of metals and thermoplastic materials and incineration (I) of thermoset composites were assumed, representing the “best case” of technologies available today. Incineration of all structures (apart from metals) was modelled as a moderate case, and landfill (L) of all structures as a worst case.

Table 4: Energy needs during processing and finishing of the structure

Material candidate	Manufacturing processes	Electricity use (kwh/kg)	Reference
Steel and Aluminium	Sheet rolling	0.14 (Steel) / 0.55 (Alum.)	[38]
	Cutting	0.47	[38]
	Welding	0.47	[38]
C/VE and G/VE	Weaving of the fibres	0.12	[39]
	Resin transfer moulding (RTM)	3.5	[40]
	Cutting	0.4	[41]
PET	Injection moulding	1.48	[42]
SrPET	Commingling and weaving of PET fibres	0.55	[39]
	Hot compaction	1.48*	[42]

*Assuming similar energy requirements as injection moulding

Table 5: List of waste treatment alternatives of

	Steel	Aluminium	C/VE	G/VE	PET	SrPET
Best case (reference)	R	R	I	I	R	R
Moderate case	R	R	I	I	I	I
Worst case	L	L	L	L	L	L

95% recycling efficiency was assumed, while remaining material was landfilled [45]. Benefits of recovered materials were included as avoided burdens, assuming replacement of production of equivalent primary materials. Waste incineration was assumed to produce electricity only (no heat). Although heat recovery from waste incineration is significant in some regions, it is low in the EU as a whole [48]. Electricity production was calculated based on the thermal content of the materials (Table 6) and an average 20% energy efficiency [49]. Benefits of recovered electricity were also included as avoided burdens, using average European electricity mix [28] as the avoided electricity.

3.4.4 Environmental impact assessment

Impact assessment was done using the methods Cumulative Energy Demand (CED) v. 1.08 [29, 51] (unit: MJ), and Global Warming Potential (GWP) [29, 52] (unit: carbon dioxide equivalents, CO₂ eq.),

as implemented in SimaPro [36]. The assessment was limited to these two methods due limitations in the inventory of life cycle data.

Table 6: Incineration and energy recovery data used in the study

Material	Thermal content	Recovered electricity
C/VE	32 MJ/kg [41, 50]	6.4 MJ/kg waste
G/VE	7.5 MJ/kg waste (similar to SMC) [41]	1.5 MJ/kg waste
PET and SrPET	23 MJ/kg waste [43]	4.6 MJ/kg waste

4 Results analysis and material selection of the truck roof

Fel! Hittar inte referenskälla. shows life cycle CED and GWP of the weight minimised truck roof for the different candidate materials. EOL is represented by the reference alternative; EOL appears as a net negative (avoided) impact, due to energy and emissions savings. The heaviest roofs (PET and steel) exhibit the highest life cycle impact both for CED and GWP. The total impact decreases as the structure becomes lighter (especially C/VE and aluminium) and avoided burdens at EOL increase. The SrPET roof may reduce the impact compared to steel by about 10% for CED and GWP. Unreinforced PET on the other hand exhibits higher life cycle impact than steel. The use phase of the truck roof accounts for the largest share of CED and GWP for all design alternatives. For the metal structures it contributes to almost 95% of the total impact, while for the lighter roof (C/VE) its share is lower, around 50% of CED and GWP. The relative importance of the other life cycle phases, especially manufacturing, then becomes relatively more significant. EOL has the lowest contribution to the life cycle impact of all structures. It

Figure 4: Life cycle CED and GWP of the different truck roofs (life cycle distance 1 000 000 km).

results in a negative value for CED and GWP for the metal and polymer structures due to recycling and recovery of materials. Similarly, electricity recovered from incineration of composite structures leads to avoided impact of CED, while no net savings of GWP are obtained when EU average electricity is the avoided electricity. During manufacturing the most significant processes for both CED and GWP is the acquisition and production of raw materials. Steel is the least energy demanding raw material (Table 7). The lighter materials (aluminium, C/VE and SrPET) use more energy during acquisition and production, thus resulting in greater emissions. SrPET results in slightly higher CED and GWP, despite its lower weight compared to unreinforced PET, since additional manufacturing steps are required. Manufacturing the roof per se represents a lower share of the impact during this stage. Processing of polymer and composite structures is more energy demanding thus resulting in higher GWP compared to metals.

Table 7: Environmental impact during the production of 1 kg of raw materials and for the production of the total amount of material needed for the truck roof

Material	CED (MJ/kg raw mtrl)	GWP (kg CO ₂ eq./ kg raw mtrl)	CED (GJ/total amount of mtrl for the truck roof)	GWP (kg CO ₂ eq./ total amount of mtrl for the truck roof)
Steel	27.9	1.72	3.0	186.5
Aluminium	194.0	12.2	12.5	784.5
C/VE	282.0	13.7	11.3	548.0
G/VE	70.9	3.8	5.3	281.6
PET	78.4	2.7	10.5	361.5
SrPET	114	4.5	9.7	383.0

4.1 Analysing variations during the life cycle of the design target

The environmental assessment entails uncertainties since not all stages of the life cycle are known at this stage in the design process. Trucks or parts of a truck are often used longer than they are designed for e.g. as spare parts for other vehicles [53]. This would increase the operational life of the component, but may also influence how the component will be treated at EOL. In addition, lightweight design is rarely the only strategy for environmental improvements is vehicle design [5]. More efficient engines are developed and alternative fuels may be used. Such uncertainties may influence results and were investigated with sensitivity analyses.

4.1.1 Variations of the operational life of the truck

Figure 5 illustrates the GWP and CED a life cycle distance up to 2 000 000 km, representing a case where the component or the entire truck has a “second life”. At life time zero, only impacts of

manufacturing and EOL are included. Total impact increases with distance, depending on the weight of the design alternatives. From zero distance up to 200 000 km, the metal roofs have a relatively low CED and GWP value, thanks to low impact from manufacturing and avoided impact from recycling. At intermediate distance (500 000 km) the heavy PET roof has the highest impact, while the aluminium roof has the lowest impact. At 1 000 000 km, low use phase impacts of the C/VE roof, due to low weight, has compensated for the high GWP burden of manufacturing compared to the aluminium

roof. Aluminium remains a better alternative in terms of CED mainly due to high savings at EOL. At distance beyond 1 000 000 km, results develop in favour of the lightest C/VE structure.

Figure 5: Influence of life cycle driving distance on CED and GWP for a diesel truck

4.1.2 Variations in energy efficiency or fuel type

More energy efficient engines would reduce the relative importance of the use phase impacts for all studied structures. In Figure 5 this would reduce the gradient of the plotted lines, meaning that all breakeven points between materials would move to larger distance, i.e. the benefits of light-weight materials would be less profound. Use of renewable fuels has a similar influence on GWP. According to the European Renewable Energy Directive (RED) [54], renewable fuels are those that lead to at least 60% reductions of greenhouse gas emissions, and the life cycle GWP impact is significantly reduced. However, more energy demanding fuel production and lower fuel efficiency of ethanol [55] increases the influence of weight on CED, shifting the breakeven points in between materials Figure 5 to an shorter travelled distance. In contrast, the much lower GWP of the ethanol truck significantly reduces the benefit of light-weight materials; high GWP in manufacturing would not be compensated

by the lighter structures during the assumed life time. At 2 000 000 km, a truck roof out of PET would have the same GWP as the much lighter C/VE.

4.1.3 Variations during EOL

Two EOL alternatives were considered in addition to the reference case (Table 5). EOL remains the stage with the lowest contribution in terms of environmental impact, although the life cycle impact of the design alternatives vary between the best and worst EOL alternatives. Recycling of the aluminium, PET and SrPET structures has the potential to save significant amounts of energy and emissions. Such savings were less significant for PET and SrPET when the moderate alternative with incineration was assumed. If all structures are landfilled, total environmental impact increases for all design alternatives. For the metals and thermoplastic structure this increase is more significant since they lose the potential for material recovery. Weight reduction in that case has a significant influence on the results, so that the light C/VE structure would be the best alternative followed by the G/VE and aluminium. These structures are among the ones with the highest impact from manufacturing, but this is compensated earlier than 400 000 km when compared to the heavier but less energy and emission intense steel structure.

5 Discussion and conclusions

The need for a systematic comparison during material selection and substitution in order to reduce life cycle environmental impact of products has been stressed by many [3, 5, 18]. This paper presents an integrated material selection approach for vehicle design that combines weight minimization and environmental life cycle assessment and its application to a hypothetical material selection case study for a truck roof. The case study also served to assess the environmental performance of SrPET, representing a novel material which needs to be assessed from a life cycle perspective before it can be widely applied in automotive applications. The results show significant weight savings of composite materials. Aluminium remains a competent lightweight alternative, with low life cycle environmental performance and high recyclability. SrPET was among the lightest design alternatives. It had a lower life cycle environmental impact than the steel roof and almost the same as the G/VE roof. From a holistic vehicle design perspective, where recycling regulations need to be fulfilled (e.g. the ELV directive [56]), SrPET can be a good substitution alternative to non-recyclable composites while energy consumption and emissions during the use phase are still reduced. Operation remains the stage with the highest environmental impact for all structures, even for light weight design alternatives. Since operation impacts directly depend on fuel consumption, they can be reduced if the efficiency of the engine is improved, or impact of the fuel is reduced. Based on the sensitivity analyses performed, variations in the use phase were shown to have considerable influence on the

potential environmental savings that lightweight design can offer; long life cycle driving distances are needed to get the full advantage of lightweight design. As the impact of the use phase decreases with lightweight design, manufacturing becomes relatively more important. C/VE and SrPET have energy demanding manufacturing. However, manufacturing of composite materials, especially new materials such as SrPs, is less mature compared to metals and improved process efficiency may lead to additional energy savings in the future. EOL only has minor contribution on the life cycle impact of the studied vehicle component but cannot be neglected. The selection of the preferable material alternative may vary depending on available EOL treatment. Recycling is a preferable alternative since closed material loops are necessary when sustainable development is aimed for. The results indicate that high recyclability can compensate for slightly heavier components. However, lightweight design should be prioritised when EOL practices are uncertain, or for non-recyclable materials.

The study showed that weight minimization and LCA can be performed in a systematic and integrated manner during the design and material selection process. The suggested approach assists in moving from (partly) ad-hoc processes often seen today [13, 15, 23], to more informed and systematic decision making processes. This reduces the risk for sub-optimizations and shift of the environmental burdens along the different life cycle stages of the product. Material selection however, is rarely a straightforward process. In practice, the selection of the best alternative depends on more parameters in addition to environmental impact and weight; leading to a multi-criteria assessment [16, 18]. Designers must define decision criteria and handle trade-offs between the different parameters. For the suggested approach to be widely implemented in practice, the necessary information, tools, and expertise need to be in place. This requires multidisciplinary groups including among others designers, material specialists and environmental experts, but also procurement or sales representatives. Such groups exist in vehicle manufacturing companies but rarely work in an integrated manner during material selection [13]. A systematic procedure may facilitate communication and collaboration among different groups during product development, the lack of which was often seen as barrier for implementation of eco-design practices [57, 58].

Acknowledgements: This work was performed within the Centre for ECO² Vehicle Design at the Department of Aeronautical and Vehicle Engineering, Royal Institute of Technology, KTH with financial support from the Swedish Agency for Innovation Systems (VINNOVA).

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Supplementary material

Table A1: Inventory data for modelling the life cycle of the truck roof panel.

Life cycle stage	Amount	Modelled as	Comment	
Raw material input				
Steel (Steel DP800)	119.2 kg	Steel, low-alloyed, at plant/RER		
Aluminium (Aluminium alloy Al6061)	70.7 kg	Aluminium, primary, at plant/RER		
Carbon fibres (CF)	30 kg	Customized model for CF production according to [37]	Poly-acrylonitrile fibres (PAN), used as raw material. Weight fraction of fibres in composite: 68%. Customized model based on Ecoinvent process data. Process data of PAN fibres based on ELCD datasets.	
Vinyl ester (VE)	14.4 kg (CF) 22 kg (GF)	Epoxy resin, liquid, at plant/RER	Due to data limitations epoxy resin is used to model VE	
Glass fibres (GF)	59.7 kg	Glass fibre, at plant/RER S	Weight fraction of fibres in the composite: 73%	
PET	148 kg	Polyethylene terephthalate, granulate, amorphous, at plant/RER		
SrPET	100 kg	Polyethylene terephthalate fibres (PET), via dimethyl terephthalate (DMT), prod. mix, EU-27		
Manufacturing processes				
Steel	Hot rolling	119.2 kg	Hot rolling, steel/RER	
	Cutting	10.8 kg	Customised dataset based on: Milling, steel, average/RER	Cutting modelled as milling. Amount of cut material was removed. Process waste 10%. Process waste is recycled.
	Welding	5.42 kg	Customised dataset. <i>Energy used:</i> Electricity, medium voltage, production RER, at grid/RER	Amount of welded material 5% of mass of the structure. Energy used for friction stir welding of steel assumed to be similar to milling (0.474kwh/kg)
Aluminium	Sheet rolling	70.7 kg	Sheet rolling, aluminium/RER	
	Cutting	6.43 kg	Customised dataset based on: Milling, aluminium, average/RER	Cutting modelled as milling. Amount of cut material removed from dataset. Process waste was 10%. Process waste is recycled.
	Welding	3.21 kg	Same as for steel	Same as for steel
C/VE and G/VE	Weaving of CF / GF	30 kg 59.7kg	Customised dataset. <i>Energy used:</i> Electricity, medium voltage, production RER, at grid/RER	Electricity: 0.12kwh/kg [39]
	Resin transfer moulding (RTM)	44 kg 81.7kg	Customised dataset. <i>Energy used:</i> Electricity, medium voltage, production RER, at grid/RER	Electricity: 3.56 kwh/kg [40]
	Cutting	4 kg 7.43kg	Customised dataset. <i>Energy used:</i> Electricity, medium voltage, production RER, at grid/RER	Amount of cut material 10% of mass of the structure. Energy use for cutting 0.4 kwh/kg [41]. Cut material is incinerated.
PET	Injection moulding	148 kg	Injection moulding/RER	The process creates 1 kg of waste that is assumed to be recycled

	Cutting	13.4 kg	Customised dataset. <i>Energy used:</i> Electricity, medium voltage, production RER, at grid/RER	The amount of cut material is 10% of mass of the structure. The energy use for cutting was 0.4kwh/kg [41]. Cut material is recycled.
SrPET	Commingling and weaving of PET fibres	100 kg	Customised dataset. <i>Energy used:</i> Electricity, medium voltage, production RER, at grid/RER	Electricity: 0.55kwh/kg [39]. Process creates 6.4 kg of waste, assumed to be recycled.
	Hot compaction	93.6 kg	Injection moulding/RER	Hot compaction assumed to have the same energy intensity as injection moulding
	Cutting	8.51 kg	Same as for PET	Same as for PET
Use phase				
	Diesel truck operation	1 000 000 km	Operation, lorry >32t, EURO5/RER	Dataset modified based on weight of each structure. Energy use and emissions during operation according to the dataset.
End of life stage				
Recycling	Steel	102.9 kg	<i>Scraping:</i> Iron scrap, at plant/RER <i>Avoided burden:</i> Pig iron, at plant/GLO	95% of structure is recycled [45]. The rest 5% (5.4 kg) is landfilled.
	Aluminium	61 kg	<i>Scraping:</i> Aluminium scrap, old, at plant/RER. <i>Avoided burden:</i> Aluminium, primary, liquid, at plant/RER	Same as for steel. 3.2 kg of Al. are landfilled.
	PET	127.2 kg	<i>Energy use for scrapping:</i> Electricity, medium voltage, production RER, at grid/RER. <i>Avoided burden:</i> Polyethylene terephthalate, granulate, bottle grade, at plant/RER	Energy use for scrapping: 0.6kwh/kg 95% of structure is recycled. The rest 5% (6.7 kg) is landfilled.
	SrPET	80.8 kg	Same as for PET	Same as for PET. 4.25kg of SrPET is landfilled.
Incineration	C/VE	40 kg	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH. <i>Energy recovery:</i> Electricity, production mix RER/RER	Dataset modified to include avoided burden. Energy recovery: 6.4MJ/kg waste. Weight shown here considers weight of the structure and process waste created during manufacturing
	G/VE	74.3 kg	Same as for C/VE	Dataset modified to include avoided burden. Energy recovery: 1.5MJ/kg waste [41].
	PET	133.9 kg	Disposal, polyethylene terephthalate, 0.2% water, to municipal incineration/CH. <i>Energy recovery:</i> Electricity, production mix RER/RER	Dataset modified to include avoided burden. Energy recovery: 4.6MJ/kg waste
	SrPET	85.1 kg	Same as for PET	Same as for PET
Landfill	Steel	108.4 kg	Disposal, steel, 0% water, to inert material landfill/CH	
	Aluminium	64.3 kg	Disposal, aluminium, 0% water, to sanitary landfill/CH	
	C/VE	40 kg	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH	
	G/VE	74.3 kg	Same as for C/VE	
	PET	133.9 kg	Disposal, polyethylene terephthalate, 0.2% water, to sanitary landfill/CH	
	SrPET	85.1 kg	Same as for PET	