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TEACHING RESOURCES

ADVANCED INDUSTRIAL
CASE STUDIES

Truck Trailer Lightweighting

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First published September 2017

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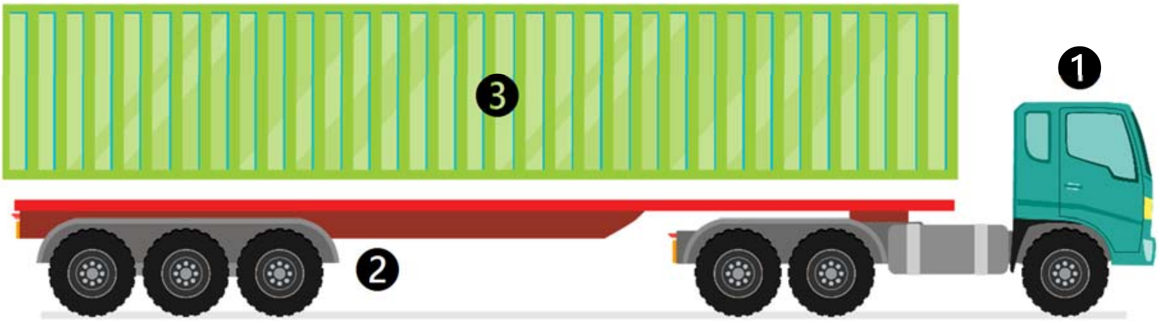
Summary

CES EduPack provides a rational and systematic approach to materials selection which is invaluable to engineering and design. It also supports transparency in this process for the purposes of teaching and training. The available databases enable informed material choices in many specialized areas. In this advanced case study, we focus on materials decisions for transportation in order to reduce energy consumption of heavy goods vehicles.

The results show that a suggested end-grain *Balsa* sandwiched between *Glass Fiber Reinforced Polyester* face-sheets compares well with plywood and hardwood options when it comes to mechanical properties. The mechanical performance is verified independently in three-point bending lab tests. Lightweighting a trailer with the suggested *sandwich panel* decking saves around 300 kg of weight. This comes at a cost, as expected. Eco Audits show that the higher initial energy and economic costs are paid back in less than one year, by reduced fuel costs, in addition to the benefit of a lower CO_2 footprint.

1. What is the scope?

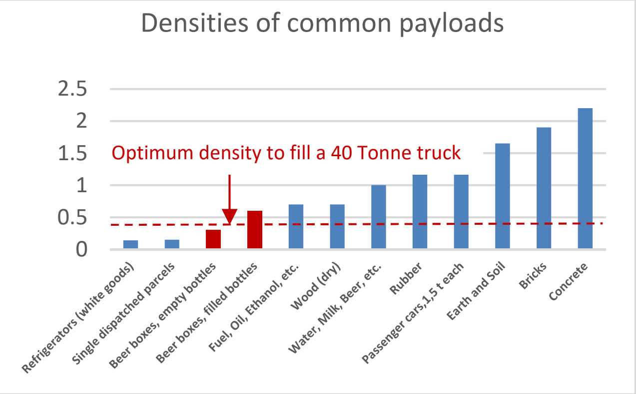
The *Transportation* sector is one of the largest contributors to global greenhouse gas emissions. Road freight is without doubt a major means of goods transportation, and one that is particularly difficult to make fossil-free. There is no indication that its contribution will be reduced in the foreseeable future. Today, Heavy Goods Vehicles (HGVs) over 3.5 tonnes account for almost a quarter of road transport CO_2 emissions, or some 6% of total EU greenhouse gas emissions. This is expected to rise to 8% by 2020 [1].



The different parts of a European-style heavy goods vehicle are ❶Truck, ❷Trailer and ❸Transport load.

It has been noted that we can expect around a 6.5% reduction in fuel consumption just by reducing trailer unladen mass (see above) by 25% [2]. This may seem to be a modest reduction relative to improving logistical factors, such as running full by mass or running full by volume. However, the estimated reduction of 6.5% in fuel consumption from lightweighting is still significant enough to pursue. It has been suggested that reducing the unladen mass of the trailer is probably the easiest of the vehicle design changes to implement, hence this is the main focus of this case study.

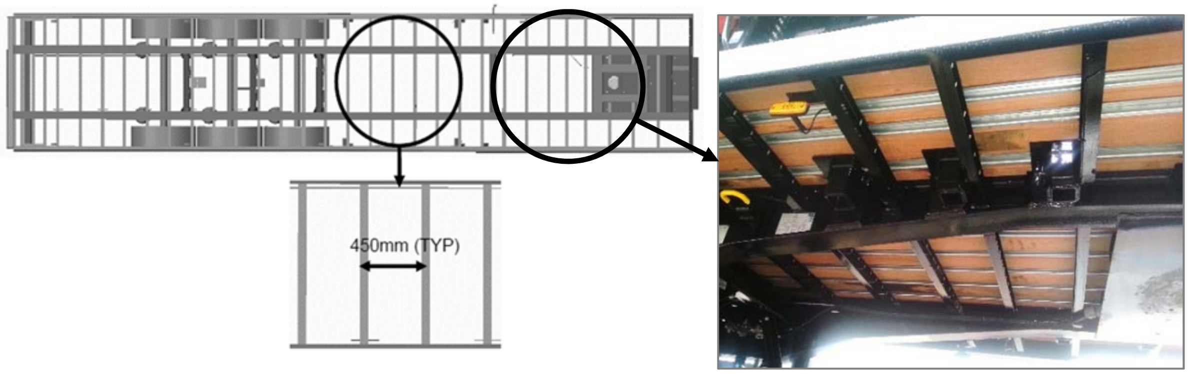
Logistically, the volume of the load is somewhat flexible but the maximum weight is not. The payload may be increased by the weight saved if the trailer weight is decreased. Some typical values of payloads are given in the diagram to the right [3]. The optimum density of the payload is typically somewhere between boxes of filled and empty beer bottles (closer to the empty…). Since the maximum weight of the load may increase by the weight saved on the trailer, the direct energy and emission reductions will come from the mileage of empty load.



The Table to the right shows the approximate weight contributions of major structural components in a 13.6 m flatbed road freight trailer [4], commonly found in Europe and shown in the picture above. It is evident that trailer decking, which is typically made of hardwood or plywood, contributes a significant proportion of weight and is therefore a good target for lightweighting. Using a lightweight deck in trailer design is also a significantly easier way to upgrade the existing fleet, compared to altering the design of steel chassis beams or the running gear. Another lightweighting action that is relatively easy to implement would be changing wheels from steel to aluminium or even CFRP.

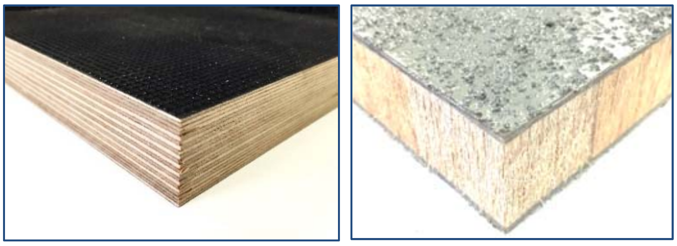
Trailer component	**Approx. mass, kg**	**Approx. mass, %**
Chassis beams and Structure	1800	43
Wheels and tyres (6)	570	7
Running gear system (bogie)	1200	29
Decking	700	17
Scrub plate	150	4

A truck trailer deck commonly complies with the ISO1496 standard for cargo containers, and represents a surface area of approximately 27 m^3 for a 13.6 m trailer, as shown below. The typical thickness is 30 mm.



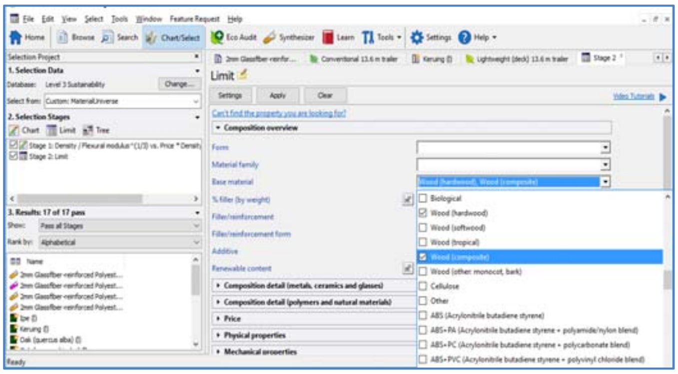
View of the trailer from the top without decking (left) and from underneath, with hardwood decking (right).

The structural configuration of a lightweight trailer deck could take many forms, including monolithic panels, plywood (left image), sandwich and hybrid panels (*e.g.*, balsa-core sandwich panel, right image). The highly cost-driven nature of trailer construction, as well as the geometry of the conventional steel trailer chassis, makes sandwich panels strong candidates for use in this application. A sandwich structure could help increase flexural strength and rigidity, while simultaneously reducing weight. Indeed, the structures of common road freight semi-trailers are strikingly similar to pedestrian bridges, where sandwich panel decks have been mounted on top of steel beams successfully. Sandwich panels are already replacing plywood panels in the side walls of box-type road freight trailers, which is also encouraging for their application to trailer decking.



2. What can you do with CES EduPack?

CES EduPack makes a systematic and comprehensive approach to material selection possible. This is based on the work of Professor Mike Ashby [5] and coworkers. The data and the tools that come with the software enables a proper investigation into alternatives for lightweight decking as well as benchmarking of the options. There are more than 500 types of wood in the advanced Level 3 databases and models for laminated as well as sandwich panel structures in the Synthesizer tool, available in some editions. We will use the Sustainability database, as it contains both the Synthesizer tool for estimating properties of structural hybrids and the enhanced Eco Audit tool for assessment of life-cycle benefits of the lightweight decking.



Database: Level 3 Sustainability

Select from: Custom: MaterialUniverse

☑ Stage 1: Density / Flexural modulus^(1/3) vs. Price * Density

☑ Stage 2: Limit

3. Results: 17 of 17 pass

Show: Pass all Stages

Rank by: Alphabetical

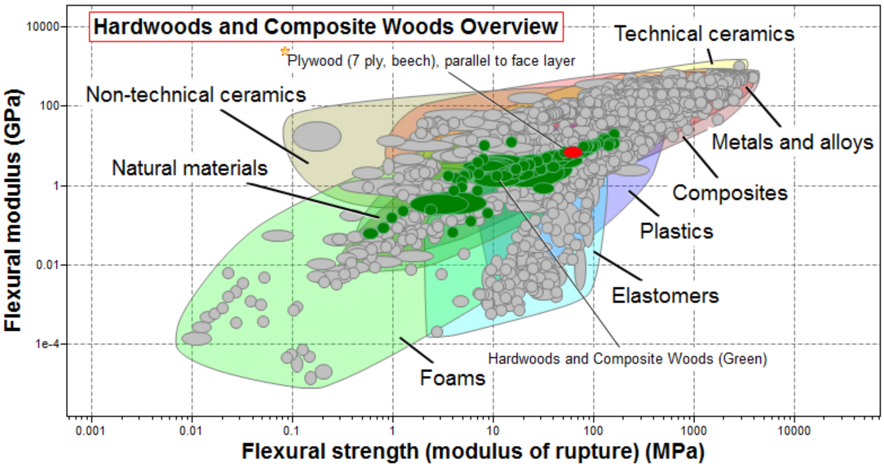
2mm Glassfiber-reinforced Polyest...
2mm Glassfiber-reinforced Polyest...
2mm Glassfiber-reinforced Polyest...
2mm Glassfiber-reinforced Polyest...
Ipe (l)
Kerung (l)
Oak (quercus alba) (l)

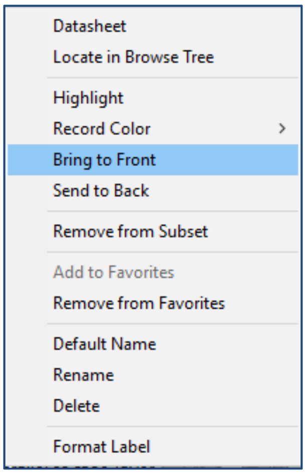
Base material: Wood (hardwood), Wood (composite)

☐ Biological
☑ Wood (hardwood)
☐ Wood (softwood)
☐ Wood (tropical)
☑ Wood (composite)
☐ Wood (other monocot, bark)
☐ Cellulose
☐ Other
☐ ABS (Acrylonitrile butadiene styrene)
☐ ABS+PA (Acrylonitrile butadiene styrene + polyamide/nylon blend)
☐ ABS+PC (Acrylonitrile butadiene styrene + polycarbonate blend)
☐ ABS+PVC (Acrylonitrile butadiene styrene + polyvinyl chloride blend)

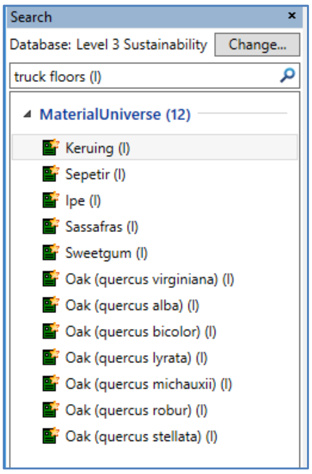
The approach of this study is to find materials that already meet the design requirements and compare these materials with each other and with new candidates. This can stimulate discussions on design decisions in class. We start by considering wood-based materials that are similar to those already used as truck trailer decking. For an initial overview, choose the *MaterialUniverse: All bulk materials* subset after clicking *Chart/Select* in the main toolbar. Then use the filter in the *Limit stage*, where the composition overview allows screening for hardwoods and composite woods (plywood, chipboards etc). This results in nearly 70 realistic wood optioms. An overview plot can now be created by using the *Chart* tool button. Since it is easy to modify or add Chart stages, we start by plotting *Flexural stiffness* vs *Fexural strength* for general mechanical performance.

We will use plywood as a reference for decking, as it is very commonly used. The *Search* function can be used to find ***plywood (7-ply)***, which can be added to *Favourites* by right clicking. Right-clicking also lets you *Label* this record, change *Record Color* for this material to red and use the function to *Bring to Front* for visibility.





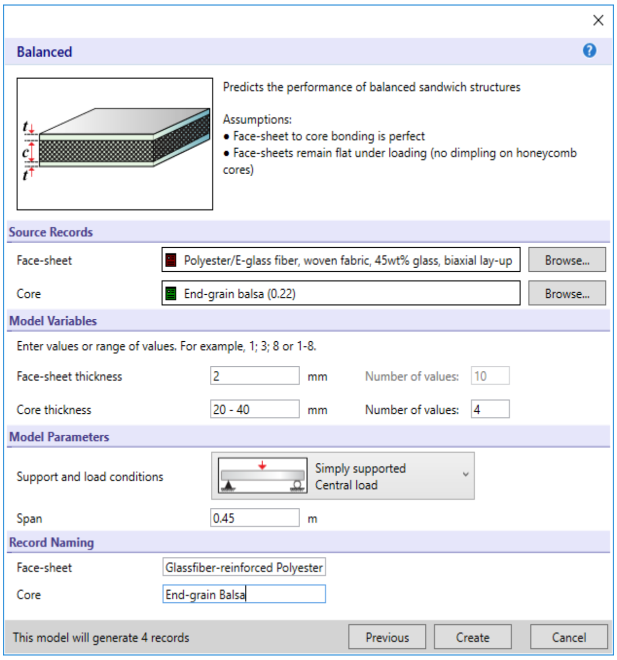
The chart above (with family envelopes) shows that woods, and particularly plywood, perform well in these relevant properties for decking. In the next step, we narrow the selection of woods to include only the ones that actually appear as truck flooring material in the datasheets. A search for ***truck floors*** renders 24 wood and 8 aluminum records. Note that all woods appear twice, since their properties are anisotropic and there are separate records for transverse (across) properties and longitudinal (along). We therefore go back to the Search window and add “(l)”, as shown to the right, in order to eliminate the metals and (inferior) transverse (t) datasheets. This reduces the results to a dozen woods, all used for truck flooring. We then use shift-click to mark all these records and then right-click to *Add to Favourites*. Favourites now contain these 12 materials plus the previously added plywood. Finally, we create and add one more decking option that represent a realistic sandwich panel, as suggested previously.


Search

Database: Level 3 Sustainability

truck floors (l)

MaterialUniverse (12)
- Keruing (l)
- Sepetir (l)
- Ipe (l)
- Sassafras (l)
- Sweetgum (l)
- Oak (quercus virginiana) (l)
- Oak (quercus alba) (l)
- Oak (quercus bicolor) (l)
- Oak (quercus lyrata) (l)
- Oak (quercus michauxii) (l)
- Oak (quercus robur) (l)
- Oak (quercus stellata) (l)


Balanced

Predicts the performance of balanced sandwich structures

Assumptions:
- Face-sheet to core bonding is perfect
- Face-sheets remain flat under loading (no dimpling on honeycomb cores)

Source Records

Face-sheet: Polyester/E-glass fiber, woven fabric, 45wt% glass, biaxial lay-up

Core: End-grain balsa (0.22)

Model Variables

Enter values or range of values. For example, 1; 3; 8 or 1-8.

Face-sheet thickness: 2 mm, Number of values: 10

Core thickness: 20 - 40 mm, Number of values: 4

Model Parameters

Support and load conditions: Simply supported Central load

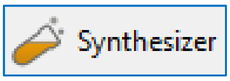
Span: 0.45 m

Record Naming

Face-sheet: Glassfiber-reinforced Polyester

Core: End-grain Balsa

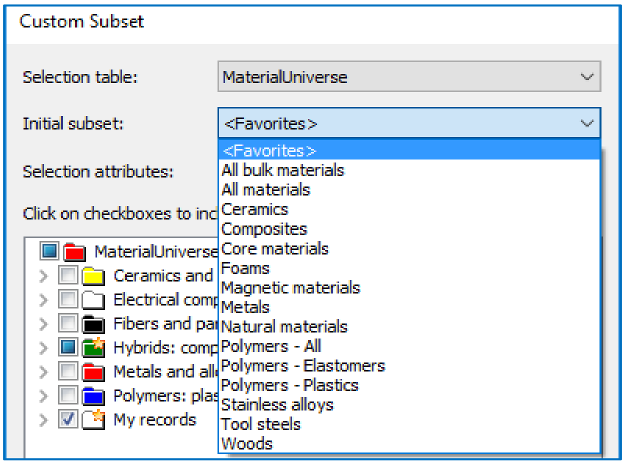
This model will generate 4 records



To generate lightweight deck options, we invoke the Synthesizer tool, available in certain advanced editions of CES EduPack. It provides models to estimate properties for some structural hybrids, such as balanced sandwich panels, that can be visualized. The face material is a ***Glass Fiber Reinforced Polyester***, 45 wt% biaxial lay-up, found under Hybrids… > Composites > Polymer matrix... ***End-grain balsa*** is found under Hybrids… > Composites > Natural material composites > Woods... The load is chosen to be a simply supported panel with a point load, representing a truck. The span is taken from actual trailer data, 0.45 m. The core thickness ranges around actual samples (25.4 mm) tested and reported in research [6]. After filling the *Record Naming*, a datasheet with a number of estimated properties is generated and located in a special folder in the Browse Tree, called *My Records*. This and the 13 Favorite materials can now be plotted and compared thoroughly.

3. Using CES EduPack to compare and Benchmark materials

When making the chart, the Favorites can be selected as a *Custom Subset* in the "Select from:" drop-down menu, which makes them easy to plot. *My records* or the synthesized record therein can be included explicitly in the Custom subset, as shown to the right. A chart is subsequently plotted using the Advanced function button in the *Chart stage* dialog box. This enables a function editor that allows you to specify a performance index for minimum mass, ***M1***, and for minimum cost, ***M2***, respectively. It is a ***Stiffness-Limited Design,*** since we want the deck to deflect as little as possible.



Custom Subset

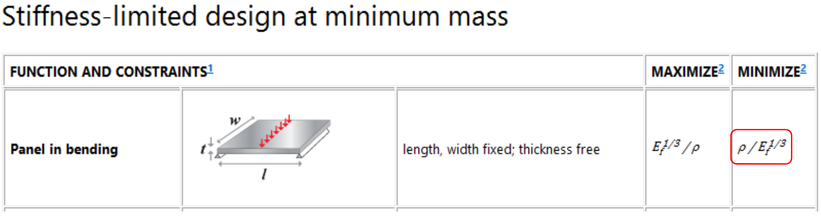
Selection table: MaterialUniverse

Initial subset: <Favorites>

Selection attributes:

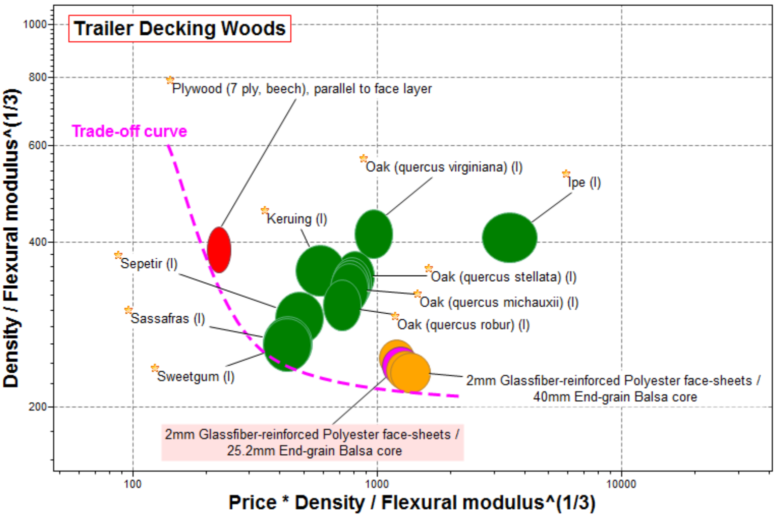
Click on checkboxes to inc

In order to visualize the options, we plot the performance indices for minimum mass and cost, respectively. **The Function** corresponds to a *stiffness-limited design* of a panel in bending, assuming the thickness to be the free variable. **The Constraints** are already considered, since we are primarily looking at a subset of materials already in use. **The Objectives** for the performance are given by the indices found in the Help menu (Help > Quick Start > Material Index).



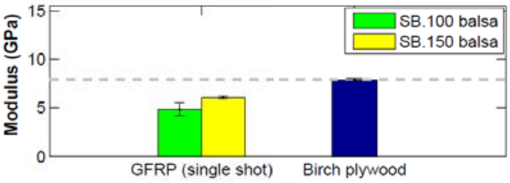
Stiffness-limited design at minimum mass

FUNCTION AND CONSTRAINTS[1]			MAXIMIZE[2]	MINIMIZE[2]
Panel in bending		length, width fixed; thickness free	$E_f^{1/3}/\rho$	$\rho/E_f^{1/3}$



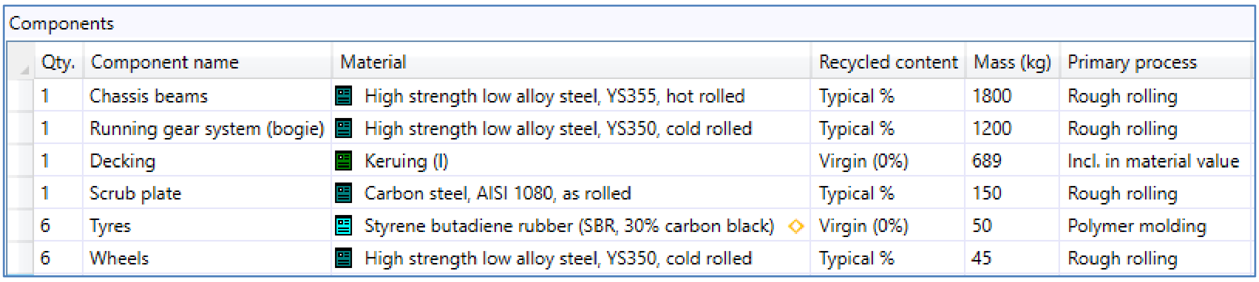
In the chart to the left, we have plotted ***M1*** = Density / Flexural Modulus ^ (1/3) on the Y-Axis and ***M2*** = Price * Density / Flexural Modulus ^ (1/3) on the X-Axis. The comparison shows that *Plywood* is, indeed, the cheapest option per bending stiffness. Common hardwoods, such as *Keruing* and *Oak* have comparable mass performance but are more costly. The *sandwich panels* that were synthesized, are estimated to be the lightest options but also more expensive than, *e.g.*, *Oak*. Both *Plywood* and the *sandwich panels* are at the Pareto front (Trade-off curve) indicated in the chart using the *Annotation* tools. The 25.2 mm balsa core sandwich (shaded) appears to be a good compromise, as a thicker core is more expensive and a thinner core is denser.

The quality of the estimated material property data of the sandwich panel is good, as indicated by test data on a very similar (1-inch core) system, shown below. The sandwich panel indicated above gives an estimated bending stiffness, E_f, of 4.47-6.36 GPa (synthesized datasheet), which is in close agreement with real measurements of an equivalent system (*yellow bar*, 2 mm GFRP/25.4 mm End-grain SB 150 Balsa/2 mm GFRP). The datasheet of *7 Ply Beech Plywood*, gives E_f =6-9 GPa also compare well with the tested birch plywood, shown in the test data (*blue bar*) [6].



4. Eco Audit of a lightweight unladen truck trailer

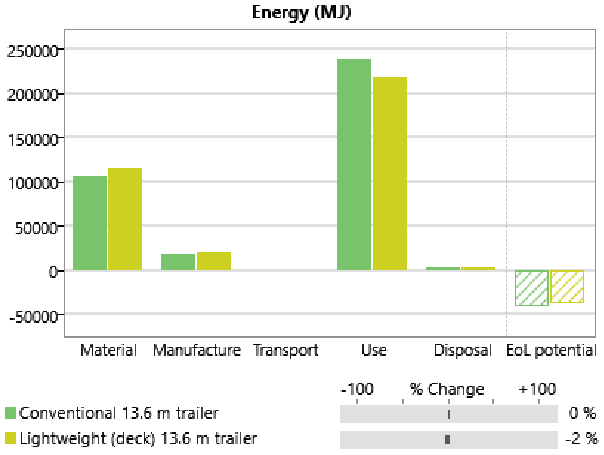
By replacing a few structural components, significant reductions in mass can be achieved. We have used the Enhanced Eco Audit tool to investigate the life-cycle benefits of moderate lightweighting, in comparison to a standard trailer. Simplified Bill of Materials (BOM) for these cases are given below, first the reference trailer with hardwood decking:

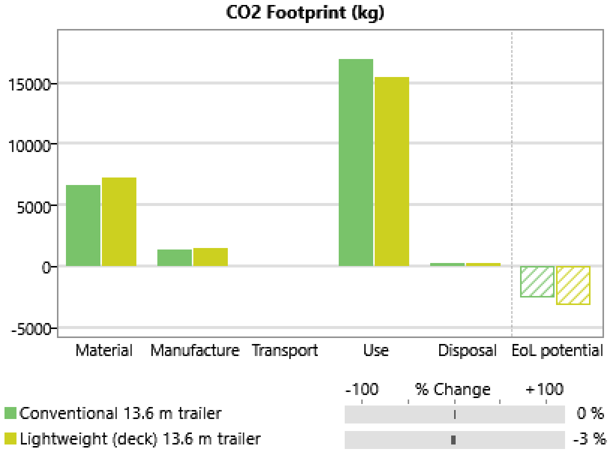


Components

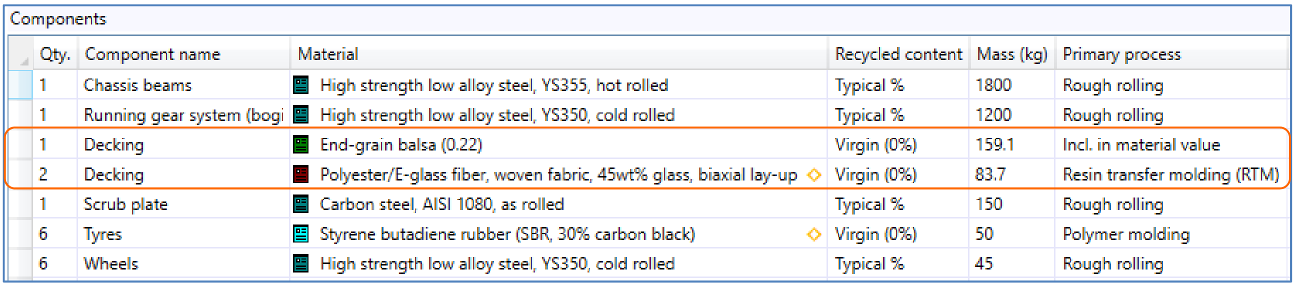
Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process
1	Chassis beams	High strength low alloy steel, YS355, hot rolled	Typical %	1800	Rough rolling
1	Running gear system (bogie)	High strength low alloy steel, YS350, cold rolled	Typical %	1200	Rough rolling
1	Decking	Keruing (l)	Virgin (0%)	689	Incl. in material value
1	Scrub plate	Carbon steel, AISI 1080, as rolled	Typical %	150	Rough rolling
6	Tyres	Styrene butadiene rubber (SBR, 30% carbon black) ◇	Virgin (0%)	50	Polymer molding
6	Wheels	High strength low alloy steel, YS350, cold rolled	Typical %	45	Rough rolling

The Eco Audit summary charts for Energy and CO_2 footprint *in Europe* are shown below. The dark green bars represent the reference trailer. If the mobile use phase is set to: 1 year, 200 km per day, 300 days / year by 32-tonne commercial diesel truck, the materials represent 29% of the total life-energy of the trailer and the use phase 65% the first year. As can be seen, there is a close relationship between the energy use and the CO_2 emissions. The weight of a conventional decking ranges from 606 kg (plywood) to 689 kg (keruing), using a thickness of 0.030 m and area of 27 m^2. As usual, eco-data has much greater uncertainty than mechanical.





The moderate lightweight case is represented by the yellow/light green bars, above. The BOM for this case reflects a 330 kg sandwich panel decking as possible material replacement, resulting in a weight reduction by approximately half. It can be seen in the Eco Audit above that the gains made in the use phase (also 200 km per day, 300 days first year) more than offsets the increase in energy use during the material production and manufacturing phase. In total, the lightweighting results in an estimated 2-3% less energy and CO_2 footprint. And this is based on only 1 year of use. If 5 years use is assumed, the estimated reduction is higher: 7%.



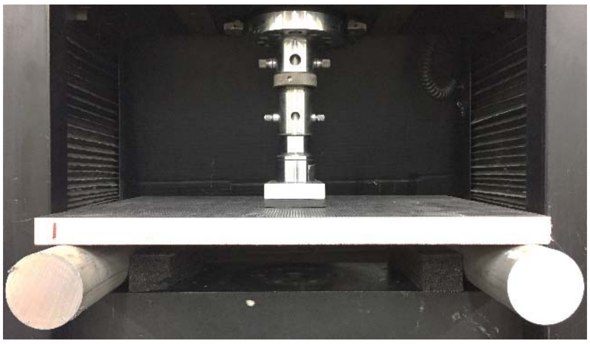
Components

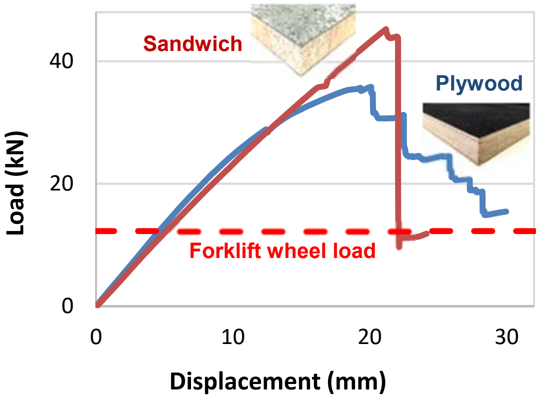
Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process
1	Chassis beams	High strength low alloy steel, YS355, hot rolled	Typical %	1800	Rough rolling
1	Running gear system (bogi	High strength low alloy steel, YS350, cold rolled	Typical %	1200	Rough rolling
1	Decking	End-grain balsa (0.22)	Virgin (0%)	159.1	Incl. in material value
2	Decking	Polyester/E-glass fiber, woven fabric, 45wt% glass, biaxial lay-up ◇	Virgin (0%)	83.7	Resin transfer molding (RTM)
1	Scrub plate	Carbon steel, AISI 1080, as rolled	Typical %	150	Rough rolling
6	Tyres	Styrene butadiene rubber (SBR, 30% carbon black) ◇	Virgin (0%)	50	Polymer molding
6	Wheels	High strength low alloy steel, YS350, cold rolled	Typical %	45	Rough rolling

5. Analysis and reality check

In this Advanced Industrial Case Study, we have departed slightly from the traditional materials selection methodology, screening and ranking of a large number of materials. This systematic methodology is mainly used when selecting a material for a new product. In the Truck trailer lightweighting case, we are predominately interested in improving an existing material in a fixed application, which represents a *constrained design*. We passed the screening by simply restricting the choice to existing materials and used these to benchmark a new candidate, suggested by research. In plotting the objectives in conflict, we assumed the thickness to be a free design parameter, which is not strictly the case if the geometry is nearly fixed. In addition to benchmarking the suggested hybrid structure visually in the chart, we must therefore verify that the mechanical properties at the given thickness are sufficient.

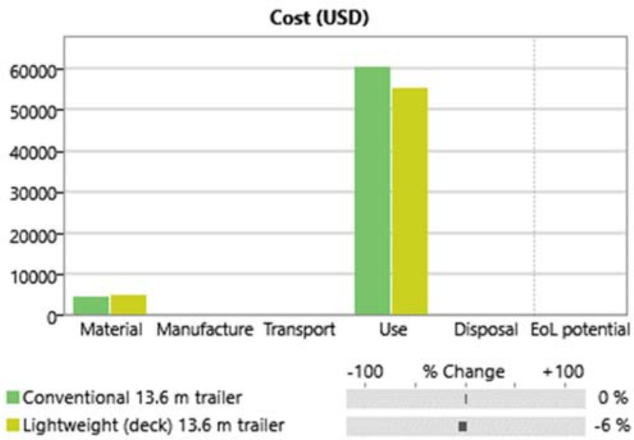
Sandwich panels with woven Glass Fiber Reinforced Polyester and an end-grain balsa has been found to be the most advantageous material combination in terms of both raw material cost and mechanical performance. These panels can be fabricated using a single shot fabrication technique and are approximately 45% lighter than conventional plywood trailer decking. The properties of the fixed thickness (around 30 mm) sandwich panel has been tested under controlled conditions using three-point bending tests at room temperature [6].





The ISO 1496 standard prescribes a scenario resulting from the wheel load of a fork lift. The load is indicated by a dashed red line in the diagram above [6]. As can be seen, the sandwich panel passes the test, surpassing the plywood sample that represents a currently used decking, before failure occurs, confirming the safety.

As the trade-off plot in *Section 3* shows, the sandwich panels are significantly higher in cost per stiffness than the alternatives, as measured by the performance index ***M2***. It is not easy to estimate how much more expensive it is in relation to the fuel savings resulting from the mass reduction. One way to have a quick estimate of the cost benefits, is to look at the *Cost Audit*, supplied optionally by the Enhanced Eco Audit.



A rough idea of the savings in a life-cycle perspective is given in the Eco Audit (more detailed data can be extracted from the Eco Audit report supplied by CES EduPack). It confirms that the Hybrid structure is more expensive in materials cost and manufacturing but, that the total cost remains nearly the same (-1%) due to lower fuel costs. Over a 5-year period, the saving is estimated to 6%, as can be seen to the left. The country of use in the Eco Audit will affect the fuel prices so, for example, if USA is selected instead of Europe, the fuel costs decrease, reversing the economic benefit over the first year (+2%). For 5 years, though, the total economic benefit is 5%.

6. What does CES EduPack bring to the understanding?

CES EduPack is an excellent resource for teaching the design process, working with interactive visual tools. The educator can easily show how to make good materials decisions and students can explore ways to select and assess materials in realistic projects. Our A*dvanced Industrial Case Studies* are intended to inspire and guide product development, provide necessary knowledge and facilitate the understanding of the subject.

In this case study, CES EduPack suggests the following conclusions on truck trailer lightweighting:

- The Sustainable Development database has a large number of specialized materials and data organized into useful subsets, we have successfully explored *woods* for trailer decking. It also provides advanced tools that were particularly useful in this case.
- The *visualization tools* quickly let us have an overview of material properties to compare different options for truck trailer decking, showing, for example, that plywood is a very competitive alternative.
- The *synthesizer tool* could be used to create estimated data for new sandwich panel options, suggested by research, and this could be benchmarked against existing materials in use.
- The Enhanced *Eco Audit* helped us to estimate the life-cycle benefits of the new hybrid panel in terms of *Energy*, *CO_2 footprint* and *Cost*. One should be aware of large uncertainties of eco-properties.

The results show that the suggested End-grain Balsa sandwiched between Glass Fiber Reinforced Polyester face-sheets compares well with plywood and hardwood options when it comes to mechanical properties. This is verified independently in three-point bending tests. A lightweight trailer with Aluminum alloy wheels and the suggested sandwich panel decking has around 300-400 kg less unladen weight that plywood or hardwood. This comes at a cost, as expected. Eco Audits show, however, that the higher initial energy and economic costs are paid back in less than one year, by cheaper fuel bills, in addition to lower CO_2 footprint.

Acknowledgements

This work was based partly on research produced in collaboration with the Engineering Department of the University of Cambridge, funded by the Centre for Sustainable Road Freight and by the Engineering and Physical Sciences Research Council (Grant Reference EP/K00915X/1).

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