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Life cycle assessment of PU composite shipping container floors compared to conventional wood flooring

This Life Cycle Assessment (LCA) study demonstrates the value of composite floors in ocean container shipping units, where the lighter weight and durability of composites compared to conventional bamboo-wood and plywood floors result in reduced energy use and a smaller carbon footprint. This LCA focuses on a new type of composite container flooring that incorporates fiberglass and polyurethane resin materials. The LCA was performed according to the global standards for conducting LCAs, ISO 14040 and ISO 14044, and was critically reviewed by a panel of independent experts. The study covered the entire life cycle of the floor types, from raw materials extraction to floor manufacturing, transportation between life cycle phases, use in transport on container ships and trucks, floor maintenance and end-of-life. The study included container ships with 6,000 and 12,000 Twenty-foot Equivalent Unit (TEU) capacities. Regarding energy, based on average life time and transportation distance scenarios for a 6,000 TEU ship, the composite floor saves 74.5 gigajoules (GJ) per TEU versus the bamboo-wood floor. Regarding carbon footprint when compared to the bamboo-wood floor under the same scenarios, the composite floor avoids 4.7 t of CO_2-equivalents per TEU. Comparison of an entire 6,000 TEU container ship with composite versus bamboo-wood flooring, the total greenhouse gases (GHGs) avoided amount to 28,200 t of CO_2-equivalents. As expected, the life cycle energy savings and GHGs avoided are relatively lower for a 12,000 versus a 6,000 TEU ship, as the larger capacity ship is more efficient in using less fuel allocated over twice as many containers. Nevertheless, a 12,000 TEU ship with composite flooring versus the bamboo-wood floor saves 57.2 GJ/TEU and avoids 3.4 t CO_2-eq/TEU.

1. Introduction

LCA is a structured, analytical evaluation to determine the environmental impacts of a product across its entire lifespan, or from cradle to end-of-life. The assessment quantifies the inputs (materials, energy) and the outputs (emissions, waste) associated with each life cycle stage of a product, estimates impacts (climate change, resource depletion etc.), and interprets the results to make conclusions, for example, on processes, energy, and materials which contribute most significantly to a product's life cycle. This holistic approach fostered by LCA helps focus efforts on improvements that have the greatest relative impact on the environment.

The scope of this LCA includes quantifying, evaluating and comparing the life cycle energy, GHGs and land occupation associated with three types of flooring used in ocean shipping containers: fiberglass composite, plywood, and bamboo-wood. Although all life cycle stages are covered, this LCA is not a full study since other environmental impact categories (acidification, eutrophication, ozone depletion, smog creation etc.) are not included.

The goal of this study is to provide the container shipping industry and a broader audience with a better understanding of the life cycle energy, carbon footprint and land occupation associated with PU composite versus conventional wood floors, and to identify life cycle stages which have the most significant impacts on the overall life cycle of the three container floor alternatives.

The materials and technology used to create the PU composite flooring are designed to provide a floor with greater strength and durability compared to conventional wood flooring used in container shipping units. Since the composite is a non-porous fiberglass and resin material, the very nature of the composite material makes it stain and breakage resistant. The composite is water resistant,

Fig. 1:
Typical one TEU shipping container

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does not de-laminate, can not be infested with insects that may cause disease and damage structures, and it is highly flame resistant. It was realized that the lighter weight of the composite flooring could have energy and environmental benefits associated with reduced fuel consumption. Alternatively, the lighter weight also provides the possibility of adding more cargo weight up to the maximum payload equal to the standard maximum gross weight.

This study compares two environmental aspects often of interest and relevance to the logistics community: energy use (measured as net calorific value) and GHGs (measured in CO_2-equivalents). In addition, land occupation (land required for cultivation/manufacturing) was estimated for the composite flooring compared to conventional plywood and bamboo-wood.

2. Container unit and floor overview

In the logistics industry, a TEU describes the unit of capacity of an intermodal container with the dimensions 20x8 feet. Intermodal containers are those that can be readily transferred between different modes of transportation such as container ships, trains and trucks. They are typically made of steel except for the flooring, and contain several major parts, including two corrugated sheet steel side walls welded to structural top and bottom side rails and end frames of fabricated steel sections, a corrugated steel wall at one end, and a corrugated or flat steel roof. **Figure 1** shows a typical steel shipping container.

The overall dimensions of the container floor are 5.856x2.320 m. Flooring is attached to the cross members in pieces with screws or bolts. The conventional container floor is made from plywood or bamboo-wood materials. For example, the wood container floors typically are installed in six pieces, each fastened with screws to the steel I-beams on the bottom of the container, with four pieces measuring 2.4x1.16 m and two pieces measuring approximately 1.06x1.16 m. Two types of repair are typically needed: repair of rusted or dented metal walls/roofs, and repair/replacement of the floors. The floor repair process includes cutting out the damaged parts and replacement with new material.

For the purpose of this LCA, both container manufacturers and floor manufacturers for all types of floor are assumed to be located in Eastern China. Repair facilities are assumed to be in China for business logistics reasons (e. g. floor raw material availability and labor costs). Since the floors are subject to the greatest wear during use as a result of frequent contact with fork-lift trucks, palets and cargo, damage often occurs that requires floor replacement prior to replacement of the entire steel container.

2.1 Composite floor manufacturing, maintenance, and end-of-life

The fiberglass composite floor is manufactured using a pultrusion process. The key raw material is fiberglass in the form of strands as the reinforcement material, which are combined with lesser amounts of PU chemicals as matrix resins. Before the manufacturing starts, fiberglass strands are pulled manually through an injection box, with 1.5 % of the input fiberglass assumed to be pre-manufactured waste raw material. When the production begins, the strands are continuously pulled through an injection box via a mechanical puller, where they are wetted by the polyurethane liquid resin, which is a mixture of methylene diphenyl diisocyanate (MDI) and a polyether polyol blend.

The polyurethane resin raw materials are stored, mixed, and then piped to the injection box at room temperature. After that, the resin-saturated fiberglass is then pulled through a heated die where pressure and heat cure the resin, creating a flat floor panel. After the panel sections harden, they are cut with saws into desired lengths. The amount of manufacturing scrap is assumed to be 1.5 % of the product manufactured. Ventilation systems collect odors and dust at both the injection box and heated die area, and a vacuum is installed to collect dust at the place where floor panels are cut.

The composite floor is designed to last the entire 20 years life of a container in shipping service. The strength of the composite floor was verified with testing in excess of the requirements of ISO/TC-104-1496.1, as the floor board test was carried out with a test load of 7,260 kg. Regarding service life, tests by a composite floor manufacturer showed that the composite can last many decades, i. e. well beyond the 20 years expected service life of an ocean container. The test results were based on using the composite flooring in truck floors where cargo was repeatedly loaded and unloaded, and the number of loading/unloading cycles for truck service was correlated to that expected for cycles in a container ship. Since the steel part of a container is typically faded, rusted or damaged within 15–18 years of shipping use, the container floor is eventually removed and recycled/reused or landfilled. Thus, even though the composite can last more than 20 years in this analysis, its primary service life is limited by a container shipping service life of 15–18 years.

During its primary service life time, total repairs covering 8 % of the composite floor (1.115 m^2 or 12 ft^2) are assumed. At end of life, it is assumed that 50 % of the composite floor removed from containers will be reused or recycled and the other 50 % will be disposed in a landfill. As a result of its durability, it should be noted that the composite floor can last for decades and find potential use similar to wood floors in many other applications beyond container floors.

2.2 Plywood floor manufacturing, maintenance, and end-of-life

The key raw materials are Apitong wood for laminated plywood layers and urea formaldehyde for the binder. For the purpose of this LCA, it is assumed that all the trees are cut from sustainable tree farms in Southeastern Asia and transported to wood floor manufacturing plants in Eastern China.

Although illegal rainforest harvesting may occur, in this study trees are assumed to be from sustainable tree farms in order to estimate land occupied for cultivation. The sustainable tree farm starts with tree nursing in greenhouses followed by trees planted on farm land and cultivated for a certain number of years before cutting. During this period, nutrients are added and regular maintenance is performed. Trees are then cut and transported to wood floor manufacturers. In the meantime, new trees from nursing greenhouses are planted to replace the old trees. The growth period is assumed to be 15–18 years. The location of wood log production is assumed to be in Southeastern Asia.

After logs are transported to floor manufacturers, they are sawn, shaped, laminated, smoothed, and assembled or glued. Then, the wood floor pieces are transported to shipping container manufacturers and installed. However, the entire floor is replaced at least once during the service life of a container, as the total repaired area assumed is 13.48 m^2, or 99 % of the floor in one TEU. At end-of-life, plywood flooring is removed and either transported to a landfill or burned as an energy source. In this study, it is assumed that 80 % of the plywood floor is land filled and the other 20 % is burned, including repair pieces in both cases.

2.3 Bamboo-wood floor manufacturing, maintenance, and end-of-life

Similar to the plywood floor, bamboo is assumed to be from sustainable bamboo farms. The composition of bamboo-wood flooring is assumed to be 70 % bamboo and 30 % plywood based on data from Kalmar [1]. The cradle-to-gate bamboo manufacturing Life Cycle Inventory (LCI, or compilation of energy, materials and emissions associated with making a product) is based on sustainable practices as described by Vogtländer [2]. In this study of bamboo cultivation processes, gasoline usage is involved but not fertilizer or other materials.

After harvesting, bamboo is transported to a strip manufacturing facility nearby and sliced into strips. The strips are transported to floor manufacturers and processed there into bamboo-wood flooring. The key processes include rough planing, carbonization, drying, processing strips to beam, and activating glue in an oven. Processing energy is all electricity. The only additive is phenol formaldehyde as glue. Finished floors are transported and installed in the container manufacturer's facilities. Although bamboo-based floors have been used in the container industry for only the past five years, the total repair and end-of-life scenarios are assumed the same as for plywood floors.

2.4 The functional unit TEU

For the purpose of this LCA, the functional unit is one TEU dry cargo container floor (5.856 x 2.320 x 0.028 m) transported by ocean-going ships and trucks at a defined distance and service life. The defined transport distance ranges from 180,000–300,000 km per year on the ocean plus 7,500 km per year on trucks, and the defined service life ranges from 15–18 years. The annual transport distance range was based on input from several shipping company experts.

Since the composite floor is a highly engineered system, it has a weight of 250 kg per TEU with minimal variability. Although the floor area covered by the composite floor is the same as that of the wood floors, the composite floor has an I-bar shaped cross-section, as shown in **figure 2.** Both the composite and wood floors are 28 mm thick, but unlike the composite, the wood floors are of a solid cross-section. The mass of the composite floor is determined from its dimensions, and the material's density of 2,062 kg/m^3.

The reference flow is the mass of material used for each type of container floor. The reference flow is important for quantifying the raw materials, energy, and emissions associated with a given mass of floor material. The mass of the wood floors was obtained from industry literature data, yielding the following reference flow per functional unit for each type of flooring:

- Composite floor = 250 kg
- Plywood floor = 304 kg
- Bamboo-wood floor = 330 kg

3. Product system boundaries

The composite studied is based on production plant data from companies that supply raw materials and companies that manufacture composite floors, as well as literature sources and life cycle inventory databases. Materials and process data (composition, energy consumption, emissions, etc.) for plywood and bamboo-wood floors are from various literature sources. The use phase transportation energy and GHG analyses are based on published industry data for container ships. The life cycle phases include:

- extraction of raw material resources, including cultivation and tree harvesting,
- manufacturing and processing of raw materials,
- container floor manufacturing,
- container floor use in ocean-going container ships and land transport,
- end-of-life for container floors,
- transportation throughout all life cycle phases.

Figures 3 and **4** show the life cycle stages for the composite floor and the plywood/bamboo-wood floors, respectively.

Regarding transportation, this includes material transport from the raw material manufacturing plant to the container floor manufacturing plant, then to the container assembly

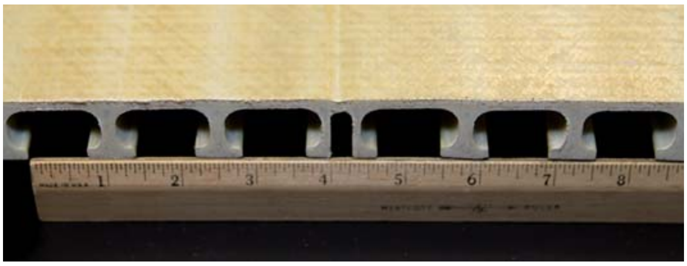


Fig. 2:
Cross sectional view of composite floor (Conforce International)

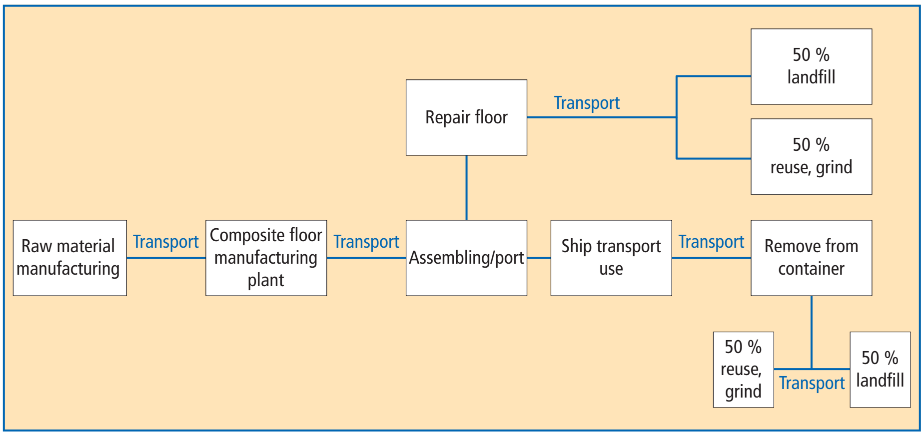
plant. Transportation of floor for disposal is also included in this study. Use phase defined in this study includes ocean ship transportation and truck to transport cargo to customers. Two assumptions are made for assembly and repair locations:

1) The container assembly plant is assumed to be close to the harbour/port, so no transportation is included from assembly plant to harbour.
2) The repair facility is close to the harbour/port and containers are only repaired when they reach the repair facility. Therefore, no transportation between the floor material manufacturing plant and harbour/port is needed for repair materials. Containers are not transported empty to the port for repair purposes only.

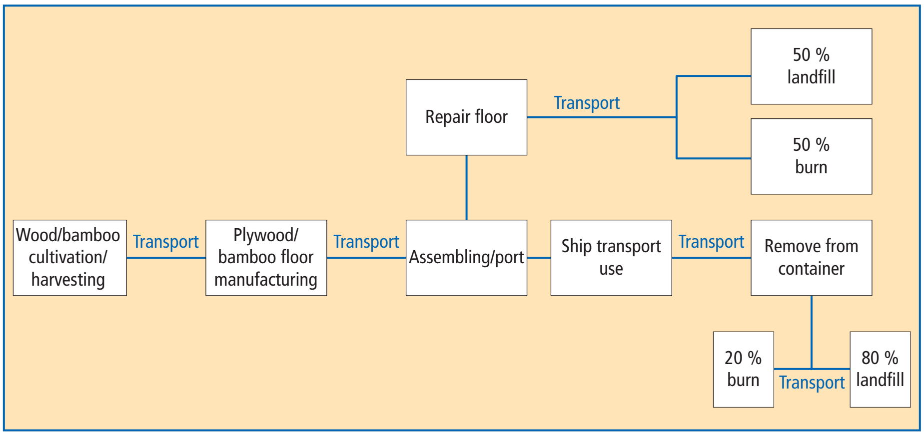
The following phases and materials are excluded from the system boundary of this study:

- Human labour, construction and maintenance of plant facilities and equipment.
- Top coating/varnish of wood container floors, which is relatively minimal. Plywood floors often are not coated but bamboo-wood floors are typically coated. Since the coating is just under 1.1 % of the total bamboo-wood floor mass, it is not a significant contributor to the life cycle.
- Mechanical fasteners (steel), adhesives and sealant used during assembly and installation, assumed to be the same for all three types of floor.
- Floor installation and removal (negligible electric power for drilling/insertion and acetylene/propane torch for removal, applied to all types of floor).
- Packaging material for all floor types (wooden pallets with wrapped boards are scrapped eventually; environmental impacts are negligible compared to the overall life cycle).

▼ ***Fig. 3:*** *Life cycle flow diagram for composite floor*



▼ ***Fig. 4:*** *Life cycle flow diagram for plywood / bamboo-wood floor*



3.1 Technological, geographical, and time coverage

Regarding technological coverage, plant site specific data were provided by a composite manufacturer. MDI and polyol data are derived from a study by the American Chemistry Council [3], as this is recent data and similar technology for resin raw materials is used globally. German plant data from the GaBi database [4] is used for fiberglass manufacturing, as data from China is not available. Cradle-to-gate data represents hardwood harvesting and flooring manufactured in the USA and China. The bamboo-wood floor is a combination of bamboo and plywood. Bamboo data represent bamboo and Strand Woven Bamboo (SWB) floor manufacturing in Western European countries. For any primary data which could not be collected, secondary literature sources are used. Background inventory data sets from recognized databases are utilized for raw materials and other ancillary or process materials, such as the production of chemical feedstocks, fuels such as natural gas and electric power, or regional grid mixes.

Regarding geographical coverage, all three kinds of floors are assumed to be produced in Eastern China. Since LCI data are not available in this region, it is assumed that current manufacturing processes, technology and background data such as electricity generation and natural gas production in China is the same as North America or Western Europe. For the composite floor, MDI and polyol data represent the USA average. Western European data is used for fiberglass and bamboo manufacturing. Hardwood planting and flooring manufacturing data from the Inland Northwest and the Northeast-North Central regions of the USA are representative for plywood container floors. In addition, US background data such as electricity generation and natural gas production are used wherever technically relevant.

Regarding geography and energy consumption for key raw materials used in making the composite floor, MDI and polyol plants are designed, built and operated in China with similar technology and processes used in the USA (but with newer/more efficient MDI plants in China), so the energy consumption for such operations in China would be expected to be less or similar to those in the USA. Since the fiberglass supplier in China has modern plants that are significantly larger than those on which the data are based (Germany, 2005), it would be expected that the energy consumption per unit of fiberglass produced in China is likely to be less than the European average based on smaller, older plants. Overall, the energy to produce the composite floor in China is expected to be less than or about equal to that required in the USA or Europe.

The impact of a different energy grid mix in China compared to the USA/Europe on GHG emissions is not possible to assess at this time due to lack of data availability. Regarding geographical location and energy consumption/GHG emissions associated with wood floor manufacturing, no data are available on these manufacturing processes in China. Therefore it is not possible to determine the impact on life cycle results for wood floors based on differences in local energy grid mix and practices in China versus those in Europe and the USA. However, given that the use phase transportation energy consumption and GHG generated is significantly greater than the energy used in making the floors, differences in embodied energy/associated GHG would not be expected to impact the overall life cycle results significantly.

Regarding time coverage, primary data were obtained from a polyurethanes raw material supplier and a composite floor manufacturer for their current operational activities and were representative for the year 2010. LCI datasets published in 2010 by Corrim [5] are used for Cradle-to-Gate plywood floor manufacturing. Inventory data for energy and material inputs of the SWB manufacturing process are based on data published in 2010 by Vogtländer [2] and assumed to be current. The data from Vogtländer together with the above-mentioned plywood manufacturing data are used for bamboo-wood floor.

3.2 Key use phase assumptions

In addition to the functional unit dimensions and mass values, key assumptions for the LCA and especially the use phase (transport on container ship) include the container floor life time or service life, the annual distance that containers are transported, and the composition of the bamboo-wood floors. The data are summarized in **table 1.**

As shown in **table 2,** information on average energy consumption and GHG emissions per metric ton cargo per km travelled were collected for two selected groups of the CMA-CGM fleet from data published on shippingefficiency.org [6].

These representative transportation distances and service life lengths, as well as data on reported energy consumption, are used to determine the use phase energy savings and carbon footprint (GHGs) avoided by the composite floor compared to a plywood floor and a bamboo-wood floor of the composition noted.

3.3 LCIA methodology and impact categories

Considering data of primary interest to the companies involved and concerns among decision-makers in the industry and the general public, energy consumption, global warming and preservation of natural resources (i. e. primary forests) are selected as relevant midpoint impact categories.

Energy consumption is a measure of resource depletion. Net calorific value (lower heating value) is reported in this study. The difference between higher heating value and lower heating value is that the latent heat of vaporization of water is not taken into account in lower heating value. Efficiencies in energy conversion (e. g. power, heat, steam, etc.) are taken into account. The unit of measurement is megajoules (MJ).

Global Warming Potential (GWP) is used as a measure of the global warming or climate change effect of GHG emissions, such as CO_2, methane, and nitrous oxides. These components increase the absorption of radiation emitted by the earth, magnifying the natural greenhouse effect. The GWP estimated in this study is based on the US EPA TRACI impact assessment methodology [7]. The characterization factor of global warming is kg CO_2-equivalent.

Land use is the measure of amount of land required to produce a certain amount of product and associated environmental impacts. It includes impacts on biodiversity and the life support function of the biosphere. In addition, agricultural or non-agricultural land use can be addressed in LCA studies. However, in this study, the impact of land use is limited to the amount of land occupied for cultivating trees and manufacturing flooring. Therefore, the term land occupation is more appropriate to express results associated with estimating land occupied for cultivation and manufacturing.

3.4 Data sources and collection

The key data sources used in this study include primary data from a composite floor manufacturer (Conforce International, Inc.), manufacturing sites which produce polyurethane raw materials (Bayer MaterialScience LLC plant sites), the Corrim report by Puettmann [5] of hardwood floor manufacturing, the SWB production in Western Europe [2], the GaBi LCI database that includes Ecoinvent data [4], and associated literature.

Regarding data collection, a survey sheet for pultrusion process data was sent to the composite floor manufacturer to obtain gate-to-

▼ ***Tab. 1:*** *Key use phase assumptions and bamboo-wood composition*

Items	*Data*	*Source*
Container floor lifetime	*15–18 years*	*Conforce International, Inc.*
Transportation distance on ship	*180,000–300,000 km/year*	*Conforce International, Inc.*
Bamboo-wood floor composition	*70 % bamboo-wood, 30 % hardwood*	*Kalmar Industries*

gate onsite energy consumption, emissions and transportation data. The energy and emissions data were averaged based on several days of operation at the composite floor manufacturing operation.

3.5 Allocation, cut-off criteria, and data quality

Allocation of energy and environmental burdens is based on the mass of raw materials in the manufacturing process, e. g. the mass of MDI and HCl (co-product of MDI) in the MDI production. Regarding container floor manufacturing, since there is no co-product, no allocation is needed. At the end-of-life, landfilled materials (e. g. 50 % of container floors) are transported to a landfill and landfill burdens are allocated to the floor product. Since reused/recycled materials (e. g. 50 % of the composite floor) will be used for other products, environmental burdens from reuse/recycle processing are thus allocated to another product system. Thus, only burdens associated with transportation to the reuse/recycling center are allocated to container floors.

The reason for allocating transportation to the reuse/recycling facility is that container floors have to be either sent to landfill (or also to an incinerator in the case of wood floors) or to a recycling facility. Thus, the transportation to a recycling facility should be allocated to container floor just as transportation is allocated to floor sent to a landfill or incineration facility.

For mass/energy, a flow less than 1 % of the cumulative mass/energy from reliable estimates of inputs into the LCI model may be excluded. For example, if GHGs of one flow (emissions for a process) are over 1 % of the total GHGs, it is included. The sum of the neglected material flows may not exceed 5 % of mass, energy or GHGs. The process to apply these cut-off criteria is to test the 1 % mass cut-off rule first, then before excluding any flow, the energy and GHGs criteria are also tested. One flow can be excluded only if it has met all criteria (less than 1 % of mass, energy, GHGs). Lastly, a check is made of the sum of mass flows to assure they do not exceed 5 % within each of the categories.

The “pedigree matrix” by Weidema [8], which rates data quality using defined criteria for each characteristic, is used for assessing the inventory data source quality. Data quality is assessed according to five characteristics: “reliability”, “completeness”, “temporal correlation”, “geographic correlation”, and “further technological correlation”.

Each characteristic is divided into five quality levels with a score between 1 and 5, with 1 being the highest quality and 5 the lowest. Uncertainty analysis can be conducted with the data quality scores, but limitations of this uncertainty analysis method should be noted:

- missing data is not taken into account,
- model approach appropriateness is not assessed,
- human errors during modeling are not assessed.

3.6 End-of-life options

End-of-life options for the three types of floors are summarized in **table 3.** 50 % of the composite floor is transported to a grinding facility and processed for recycling and use by secondary customers. Energy to grind the composite floor and transportation to secondary customers are not allocated to the first life of the composite floor since these burdens are allocated to the next product system. Thus, only energy and GWP factors for transportation to the grinding facility are included in the system boundary.

For the plywood and bamboo-wood floors, 20 % by weight is assumed to be burned and used to recover energy with an efficiency of 50 %, which means only 10 % of the embodied energy the in plywood/bamboo-wood floors can be recovered. However, since 20 % of the mass is burned, the GWP factor is calculated based on 20 % of the floor mass. The other 80 % of plywood and bamboo-wood goes to a landfill site.

In order to study the uncertainties in end-of-life options (landfill vs. recycling or burning), a sensitivity analysis was done for the end-of-life phase. Two extreme scenarios (100 % recycling or burning versus 100 % landfill) are calculated for each type of floor to show the impact of end-of-life options.

The transportation of container floors at their end-of-life is assumed to be with a 22 t payload truck. The energy consumption is 0.9338 MJ/(1,000 kg km) and the GWP factor is 0.0653 kg CO_2-eq/(1000 kg km). For the composite floor, the average distance is assumed to be 250 km to the landfill/reuse facility. For plywood/bamboo-wood floors, the average distance to the landfill/incineration facility likewise is assumed to be 250 km.

4. Life cycle impact assessment (LCIA) results

The summary of the LCIA results presented in this section is based on the scenarios:

1) Life time average transportation distances on ocean-going ships and inland truck transportation are 4,050,000 km and 123,750 km, respectively and
2) The end-of-life scenario is 50 % landfill, 50 % recycling for the composite, and 80 % landfill, 20 % burning for plywood/bamboo-wood floor. Results for energy and GHGs for two types of container ship

Nominal capacity (TEUs)	Adjusted GWP factor (kg CO_2-eq/t/km)	Cradle-to-gate energy (MJ/t/km)
5,782	0.01493	0.1862
11,388	0.01072	0.1330

Tab. 2: Average energy consumption and GWP factors for selected container ships

Mass fraction	Composite floor	Plywood/bamboo-wood floors
End-of-life options	50 % landfill 50 % recycled	80 % landfill 20 % burned to recover energy (50 % energy recovery efficiency)

Tab. 3: End-of-Life options for composite and wood flooring

capacities (6,000 and 12,000 TEU) are presented in **figures 5–8.** The delta of energy and GHGs in the figures are based on one floor used in one TEU, excluding freight and steel container, for scenarios noted above.

The negative values in **figures 5–8** indicate where the wood floors use less energy and emit less GHG in their life cycle compared to the composite floor. The positive values show where the composite uses less energy and emits less GHG in its life cycle compared to the wood floors. The net total results for one floor on a 6,000 and 12,000 TEU ship can be seen, where the values are stated as net values by adding up the use, end-of-life, and repair stages.

Although the fuel savings associated with the flooring account for approximately 0.5–1 % in relation to the fuel used on a container ship, there are nevertheless energy savings and carbon emissions reduced as a result of the lighter composite flooring compared to wood.

Regarding energy savings for one floor on a 6,000 TEU ship **(fig. 5)** based on the average life time, transportation distance and end-of-life scenarios, the composite saves 74.5 GJ/TEU vs. the bamboo-wood floor and 43.7 GJ/TEU vs. the plywood floor. When it comes to carbon footprint **(fig. 6),** the GHGs prevented by using the composite floor are 4.7 t CO_2-eq/TEU vs. the bamboo-wood floor and 2.6 t CO_2-eq/TEU vs. the plywood floor.

Considering energy savings for one floor on a 12,000 TEU ship **(fig. 7)** based on the average life time, transportation distance, and end-of-life scenarios, the composite floor saves 57.2 GJ/TEU vs. the bamboo-wood floor and 32.1 GJ/TEU vs. the plywood floor. Regarding carbon footprint **(fig. 8),** the GHGs prevented are 3.4 t CO_2-eq/TEU vs. the bamboo-wood floor and 1.7 t CO_2-eq/TEU vs. the plywood floor.

4.1 Land occupation

Land occupation, or land required for manufacturing facilities and tree cultivation in this estimate, is normally categorized as an impact category, e. g. Impact 2002+ defines land occupation as a midpoint impact category. Land occupation is estimated based on assumptions and data listed in the original LCA report [9], where the calculations are described in detail. The estimate is based on a composite floor plant producing 250,000 TEU per year for 20 years versus the land required for sustainable cultivation of plywood and bamboo-wood needed for that same TEU volume and time span. If non-sustainable practices (illegal harvesting) were used, the amount of land required for tree growth would be expected to be even greater. **Table 4** summarizes the land occupation results for each floor type. As seen from the tabulated results for the same amount of container floors (250,000 TEU per year) for a 20 year period, the plywood floor requires more than 100,000 times the land required by the composite, and the bamboo-wood floor requires over 45,000 times more land compared to the composite. These results are not surprising given that the composite floor requires relatively small areas of land for manufacturing plants, compared to land needed for cultivation of trees for wood products.

Fig. 5: *Composite vs. wood floor cradle-to-EOL energy comparisons for a floor on a 6,000 TEU container ship*

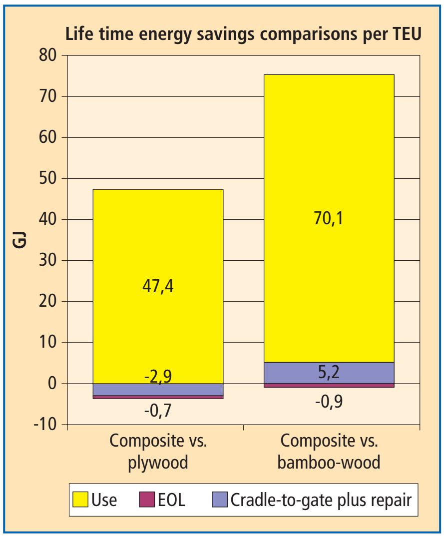


Fig. 6: *Composite vs. wood floor cradle-to-EOL GHG comparisons for a floor on a 6,000 TEU container ship*

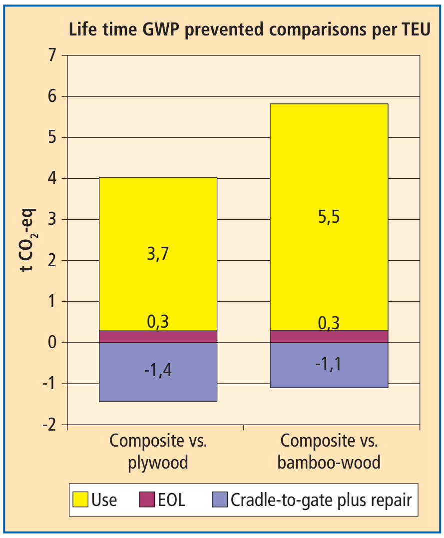


Fig. 7: *Composite vs. wood floor cradle-to-EOL energy comparisons for a floor on a 12,000 TEU container ship*

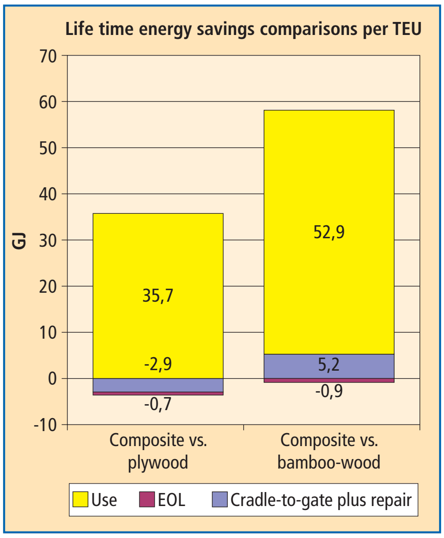
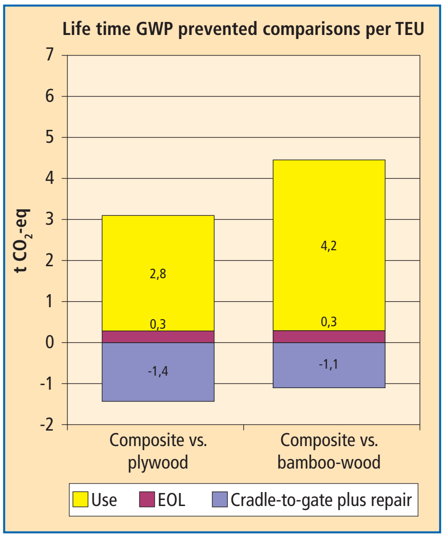


Fig. 8: *Composite vs. wood floor cradle-to-EOL GHG comparisons for a floor on a 12,000 TEU container ship*



4.2 Uncertainty analysis

In order to assess the effect of uncertainties in floor mass and transportation distance on use phase energy savings and GHG prevented for the composite vs. alternative wood flooring, a Monte Carlo analysis was conducted. Monte Carlo simulation is a recognized stochastic modelling technique often used in LCA studies, as it can predict the combined effect of uncertainties in key variables on the results. Based on random sampling of the selected input variables in this study (floor mass and transportation distance), the simulation calculates the distribution of output results (energy savings and GHG prevented).

The weight of the composite floor is constant at 250 kg/TEU, as the composite is an engineered flooring manufactured with standard formulations and process controls. In the case of wood flooring options, however, there may be mass variations associated with the type of wood used, formulation, and processing methods. The mass values used in this study for the plywood and bamboo-wood floors are consistent with values published in studies performed by the Container Owners Association [10]. However, to account for wood floor mass variation, minimum and maximum floor mass values for the wooden floors were determined based on input from independent experts with experience in the container shipping industry, and an alternative scenario using a bamboo-wood floor mass of 311 kg/TEU was evaluated, as this value was based on field measurement studies by one of the critical reviewers of this LCA.

Tab. 4: *Land occupied in manufacturing composite and wood floors (250,000 TEU/year for 20 years)*

Floor type	**Land occupied (m^2)**	**Ratio of wood flooring vs. composite floor**
Composite floor	*8.090×10^4*	*–*
Plywood floor	*9.500×10^9*	*1.174×10^5*
Bamboo-wood floor	*3.725×10^9*	*4.604×10^4*

Tab. 5: *Confidence intervals of sample means of energy savings and GHG prevented*

Confidence Intervals (α=0.001)	**6,000 TEU**		**12,000 TEU**	
	Energy (GJ)	**GHG (t CO_2-eq)**	**Energy (GJ)**	**GHG (t CO_2-eq)**
Composite floor vs. plywood floor	*41.56 44.10*	*2.40 2.59*	*29.54 31.38*	*1.53 1.67*
Composite floor vs. bamboo-wood floor	*46.76 51.22*	*2.74 3.07*	*36.93 40.33*	*1.82 2.07*

Due to lack of information in container floor weight distribution, uniform distributions of floor weight are assumed for both types of floor. Details of the Monte Carlo analysis and associated statistical analysis are provided in the original LCA report [9]. The results in **table 5** show that with a 99.9 % confidence interval, even the lower bounds of the means for energy savings and GHG prevented are far greater than zero. The results thus show large probabilities of superiority of the composite floor in terms of energy savings and GHG prevented.

5. Conclusions

In summary, the use phase is the most significant phase of the life cycle, as the energy savings and GHGs prevented result from the lighter weight of the composite floor versus the heavier wood floors. Even though the composite floor may require more energy compared to wood floors in manufacturing (as shown in the comparison for plywood floors in this study), the composite floor saves significantly more energy and prevents GHGs in the use phase due to its lighter weight. Similarly, even though the wood flooring sequesters carbon dioxide in the cultivation phase, the lighter weight of the composite flooring results in reduced fuel use (and less associated carbon emission) compared to the wood floor alternatives.

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