Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Politechniki Morskiej w Szczecinie

2024, 77 (149), 47–62
ISSN 2392-0378 (Online)
DOI: 10.17402/596

Received: *28.09.2023*
Accepted: *29.02.2024*
Published: *31.03.2024*

Management of the manufacturing process and exploitation of steel and composite shipping containers. Case study and life cycle assessment analysis

Jacek Wojnowski
https://orcid.org/0000-0002-5880-3506

Maritime University of Szczecin
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: j.wojnowski@pm.szczecin.pl

Keywords: shipping container, composite materials, management, life cycle assessment, transport, green technology

JEL Classification: L61, M11, O14, O32

Abstract

This paper takes the form of a comparative life cycle assessment (LCA) analysis of 40-foot steel and composite containers based on GaBi® software. Reducing greenhouse gas emissions can be undertaken, among other things, by reducing the weight of the container, which is possible if lighter materials with comparable mechanical properties to steel are used. The LCA analysis allowed us to estimate the energy consumed and the amount of greenhouse gases emitted during the production of a steel and composite container. It turned out that the energy consumed in the production of the composite and steel container is practically equal in value, provided that carbon fiber from the polyolefin precursor is used in production. The processes with the highest energy intensity for container production are carbon fiber and COR-TEN A® steel production and processing. Changing the container material from steel to composite would save fuel and greenhouse gas (GHG) emissions into the atmosphere by 5.1 % and 18.3 % for road transportation and sea shipping, respectively.

Introduction

Drewry Shipping Consultant Ltd. reports that, in 2018, the number of 20-foot equivalent units (TEUs) worldwide was over 37 million, with a further upward trend (Song, 2021). Among the most common containers in Europe are steel containers: 20-foot and 40-foot (20' and 40').

The modes of transport with the highest greenhouse gas emissions are water transport and road transport, accounting for 13.5–21.0 % and 69.0–71.0 %, respectively, of total CO_2 emissions (Doukas et al., 2021; European Maritime Safety Agency, 2021). In addition, container ships are responsible for 23 % of total CO_2 emissions from maritime transport (Olmer et al., 2017).

Composite containers have a lower weight than steel containers and do not scatter GPS signals or X-rays, so they can be easily tracked and X-rayed (Plastics Today, 2014; Riley, 2018). Moreover, they have similar resistance to damage, wear and tear, and environmental factors as steel containers and have lower maintenance costs (Magnuson & Wagner, 2007).

Publications have been reported in the literature on the development of lighter, mainly 40-foot containers:

- Steel containers with and without plywood (Doukas et al., 2021);
- Sidewall plate corrugation, 576 kg weight reduction (Obrecht & Knez, 2017);

- Side walls and roof material – steel changed to aluminum or high strength steel, from 175 to 840 kg weight reduction (Buchanan et al., 2018);
- Steel replaced with epoxy-carbon composite, 2868–2928 kg weight reduction (Yildiz, 2019).

Containers with mechanical properties comparable to steel containers can be manufactured from epoxy-carbon composites (Yildiz, 2019). Carbon fibers (CF) are produced as a product of controlled oxidation, carbonization, and graphitization of an organic polymer precursor, e.g., polyacrylonitrile (PAN) (Park, 2018) or polyolefins-polyethylene (Aldosari, Khan & Rahatekar, 2020). The use of polyolefins for CF production reduces production costs by 50 % and also significantly reduces energy intensity, but decreases Young's modulus and tensile strength (Aldosari, Khan & Rahatekar, 2020). Epoxy resins (ER) are a group of resins with excellent mechanical properties and high resistance to weathering, including water (unlike polyester resins, they exhibit the absence of ester groups in the main chain).

There is a gap in the field of container construction and transport: composite containers have numerous advantages and still have considerable potential for development. One of the main advantages is their low weight in relation to classic steel containers. It is becoming important to investigate whether lighter composite containers are indeed more environmentally friendly and more energy favored than steel containers. It is also important to determine whether a significant reduction in the tare weight of a composite container reduces the fuel consumption of a given means of sea and land transport, and to what extent.

Materials and methods

The primary objective of this publication is to determine the impact of a 40' container design (steel or composite) on the fuel consumption of a sea and road transport vehicle carrying a given container loaded with 12 tonnes. At the same time, it is determined which design represents the better solution in terms of environmental impact and energy consumption. The entire layout of the research methods of this study is given in Table 1.

The methodology for conducting LCA analyses covering the entire life cycle of a product – i.e., material production and processing, container assembly, use, container transport, recycling and uncertainties analysis – can be found in the specialized standards PN-EN ISO 14040:2009P and PN-EN ISO 14044:2009P. GaBi® engineering software version 10.6.1.35 with SQLite database is used to qualitatively and quantitatively determine the impact of the container design on the environment and the energy consumed in a given life cycle stage.

Among others, the following has been carried out using LCA: analyses of the fuel consumption of different modes of transport carrying cargo in tare weight containers (Buchanan et al., 2018) and life cycle analyses of carbon fiber composites (Tapper et al., 2020).

Table 1. Research methods in the present work

Issue	Research method source	Description
Shipping container production	LCA based on standards[a] and the author's own work based on research literature	The production stages of a steel container, a composite fiber container based on PAN, and a polyolefin precursor are followed. It is determined which steps in the production of the container are the most energy-intensive and the most harmful to the atmosphere. This is based on energy consumed and GHG emissions into the atmosphere
Shipping container transportation	LCA in GaBi® software and author's own work based on research literature	The fuel consumption of a given means of transport transporting a container of a given type over a given distance is determined. The GHG emissions during the transport of a container over a given distance are also found. It is determined which container construction (lightweight composite or steel) is the most environmentally friendly in terms of greenhouse gas emissions into the atmosphere
Shipping container design	Author's own work	It is determined which container design, relative to the others, produces the greatest savings in GHG emissions into the atmosphere
Entire life cycle of a container of a given design	LCA based on standards[a] and the author's own work based on research literature	The energy consumed and GHG emissions during material manufacture, container production, operation, and recycling are found. Analyses are carried out for the means of sea and road transport
Recycling of shipping container	Author's own work based on the research literature	The energy consumed and GHG emissions of recycling the container are determined

[a] PN-EN ISO 14040:2009P and PN-EN ISO 14044:2009P standards

In this paper, three design cases of 40' shipping containers are presented and described. The steel structure is designated as a "steel shipping container". A composite one is based on carbon fiber from a PAN precursor and is known as a "CFRP shipping container (PAN)" or simply a "composite shipping container (PAN)". Another composite is based on carbon fiber from a polyolefin precursor and is called a "CFRP shipping container (polyolefin)" or a "composite shipping container (polyolefin)".

Production, processing, and transport processes always involve the consumption of a certain amount of energy. The production of containers consumes electrical energy (via the operation of machinery and transport of prefabricated parts on the production line) or thermal energy from the combustion of natural gas (material heating) (Cresco, 2017). The input flows of the analyzed system also include the amount of fuel used to transport containers of a certain design and over a certain distance using a given mode of transport.

The lower limit of system accuracy is established based on the criterion of the detail of the unit processes representing the system. The top-down principle is used. The general case is the process of building a container, the energy consumed for this, and the amount of greenhouse gases released into the atmosphere. At a higher level of detail, the production processes of the prefabricated components from which the container is built are considered, e.g., steel rolling, obtaining an epoxy resin composite, and carbon fabric. The next level of detail will be to consider the energy consumption and atmospheric GHG emissions from the stage of obtaining the construction materials. The material production stage is at the lowest level considered in this publication. The above approach allowed input and output streams to be identified to a good degree while avoiding excessive system growth. On this basis, it is also decided not to consider waste in the production of materials, prefabricated components, and the container itself.

The product of embodied energy (EE) and the weight of the construction material are used as a measure of the energy intensity of each LCA step. The unit of EE is MJ per kg of processed material. EE includes the energy associated with, for example, raw material extraction, processing, and transport (Hammond & Jones, 2011).

The production process of a steel and composite container consists of three stages: materials production, materials processing, and shipping container assembly. At the materials production stage, the obtaining of construction materials is analyzed. In the materials processing stage, the engineering material is processed into a specific semi-finished product. Finally, a container of a specific design is assembled from the semi-finished products.

The manufacturing process of a steel container consists of producing the material – COR-TEN A® steel, generic steel, and plywood. This is followed by the assembly of the container from semi-finished

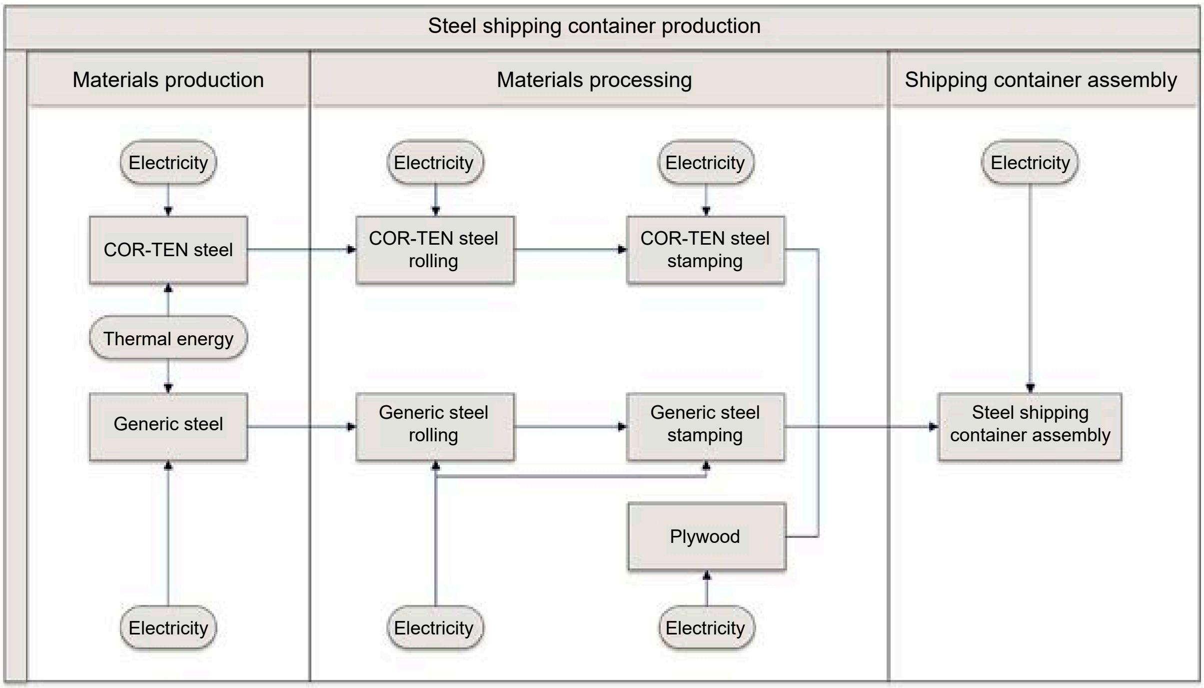

Figure 1. Manufacturing process of a 40' steel container

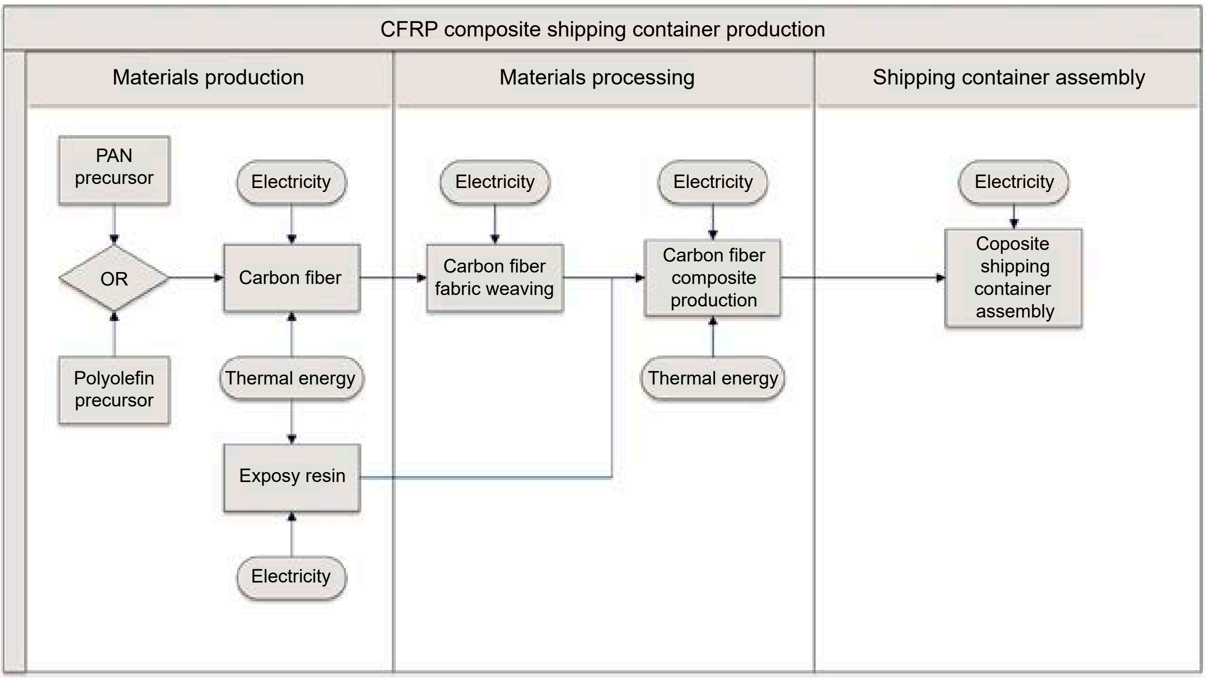

Figure 2. Manufacturing process of a 40' composite container

products (Figure 1). The production process for a composite container is composed of the selection of a precursor for the production of carbon fiber, the production of carbon fiber, and the production of fabric, which is followed by the production of the composite and, finally, the assembly of the container from semi-finished products (Figure 2).

The allocation of electricity and heat energy flows to a given production stage from natural gas is completed as follows (percentage allocation of electrical energy and heat energy in brackets) (Sunter et al., 2015):

1. Production of the steel container
   - Stainless steel (COR-TEN) production (electrical energy: 50 %, heat energy: 50 %);
   - Generic steel production (electrical energy: 50 %, heat energy: 50 %);
   - Stainless steel (COR-TEN) rolling (electrical energy: 100 %);
   - Generic steel rolling (electrical energy: 100 %);
   - Stainless steel (COR-TEN) stamping (electrical energy: 100 %);
   - Generic steel stamping (electrical energy: 100 %);
   - Plywood production (electrical energy: 100 %);
   - Steel shipping container assembly (electrical energy: 100 %).
2. Production of the composite shipping container:
   - Carbon fiber production (electrical energy: 65.3 %, heat energy: 34.7 %);
   - Epoxy resin production (electrical energy: 8.1 %, heat energy: 91.9 %);
   - Carbon fiber fabric weaving (electrical energy: 100 %);
   - Carbon fiber composite (CFRP) production (electrical energy: 40.2 %, heat energy: 59.8 %);
   - CFRP shipping container assembly (electrical energy: 100 %).

The elementary flow of fuel is assigned 100 % to a particular mode of transport. Due to the non-availability of a model of a refinery supplying ships with HFO with a sulfur content of 0.5 wt.%, it is decided to use the fuel with the lowest sulfur content available in the GaBi® software, i.e., 1.0 wt.% S. The remaining parameters are used according to default values from the GaBi® software database, current for the range of years: 2021–2024. The allocation of raw materials is based on literature data (Sunter et al., 2015; Buchanan et al., 2018).

The life cycle impact assessment (LCIA) aims to determine the impact of the inputs and outputs of the analyzed model on the GWP 100 impact category, which is directly the greenhouse effect potential over 100 years due to the negative atmospheric effects of GHGs. Using GHG-specific coefficients, their emissions are converted into CO_2 equivalent. The unit of GWP 100 is t CO_2 equivalent (Solomon et al., 2007).

The following are the input data requirements for the LCIA analysis of this paper:

- Data interval, age of data, and minimum time within which data collection is recommended: the data used in this publication are not older than 2010. The values related to natural gas electricity and heat fluxes are valid for 6 years, i.e., from 2017 to 2023;
- Geographical area analyzed: European Union;
- Technological area analyzed: manufacturing technologies are based on steel sheet rolling, stamping, welding of steel sheets (which is negligible in relation to other manufacturing processes), prefabricated steel and composite container assembly, estimated value, spinning of carbon fiber fabric, and manufacturing of CFRP composite by resin transfer molding (RTM). Structural materials such as steel, plywood, epoxy resin, and carbon fiber are included in the analysis as separate processes;
- Precision: there are no statistical measures in the literature for the data used;
- Completeness and representativeness: the system analyzed in this publication effectively reflects the production of both steel and composite containers (Buchanan et al., 2018);
- Consistency: the LCA methodology is applied uniformly to all stages of steel and composite container manufacture and transport;
- Reproducibility: the information provided in the publication allows for the analysis to be reproduced in any LCA software;
- Data sources: numerical values for unit processes and elementary flows are taken from the literature. In the absence of relevant information in the literature, data publicly available on the internet is used, e.g., carbon fabric weight or EE of COR-TEN A® and generic steel;
- Uncertainty of data sources and model: if the share of, for example, hard coal in electricity production changes, the GWP 100 may change in a given geographical area.

The assumptions for the LCA analysis of composite and steel containers represent, in addition to the system boundaries (included above), additional conditions that constrain and frame the modeled system. The following assumptions are made:

- The containers analyzed in this paper are manufactured from new materials. The recycling stage of steel and composite containers and the recycling operations are chosen to be limited to a description, as this is not the main purpose of the publication;
- Analyses are based on the energy supplied to the material/prefabricate during processing;
- The weight ratio of carbon fiber to the epoxy resin used to produce the composite is 58:42 (Sunter et al., 2015);
- The energy and potential costs arising from the maintenance, upkeep, and repair of the container are not taken into account;
- The energy consumed in transporting material between factories or sites within a single factory is not considered;
- For the recycling of the composite container, it is assumed that disassembling the top and bottom (as well as the side walls and cross beams) and breaking it into smaller pieces is achieved with low and negligible energy consumption.

Previous work (Buchanan et al., 2018) gives a life span of 15 years for a steel container; other research (Rodrigue, Comtois & Slack, 2013) indicates that the useful life of a container is in the range of 12–15 years. Composite container lifetimes are not recorded in any online or literature sources. In determining the lifespan, the lifespan of marine structures is relied upon. It is assumed that the required minimum lifetime of marine structures made of composite material is 20–25 years (Choqueuse & Davies, 2014). Of which the value of 25 years applies to structures operating mainly underwater. For the considerations in this study, the lifespan of a steel and composite container is decided to arbitrarily assume 20 years as the limiting lifespan of the container.

The average net weight carried by steel containers in ports in Europe is determined on the basis of data available on the website of the Statistical Office of the European Union for the year 2021 (EUROSTAT, 2021). The net cargo weight value determined is 12 t/FEU.

The LCA analyses are based on two modes of transport – i.e., sea and road. Figure 3 shows a diagram of the analysis conducted in this study. Initially, the type of container must be selected, and then the mode of transport must be chosen. The load is constant and equals 12 tonnes.

First, we consider the ocean container ship MAASTRICHT MAERSK, an ultra-large container vessel (ULCV), IMO: 9780483, MMSI: 219045000, deep sea shipping, DWT = 190,326 t. The number of 40' containers taken on board this container ship is 10284. The capacity utilization factor of the container ship is assumed to be 0.700. The average speed of the container ship is 18.5 knots, the distance covered per day of travel is 822 km, and the annual distance is 280,000 km (Buchanan et al., 2018). Second, an articulated lorry is considered with a 28–34 t gross weight. The vehicle's payload capacity

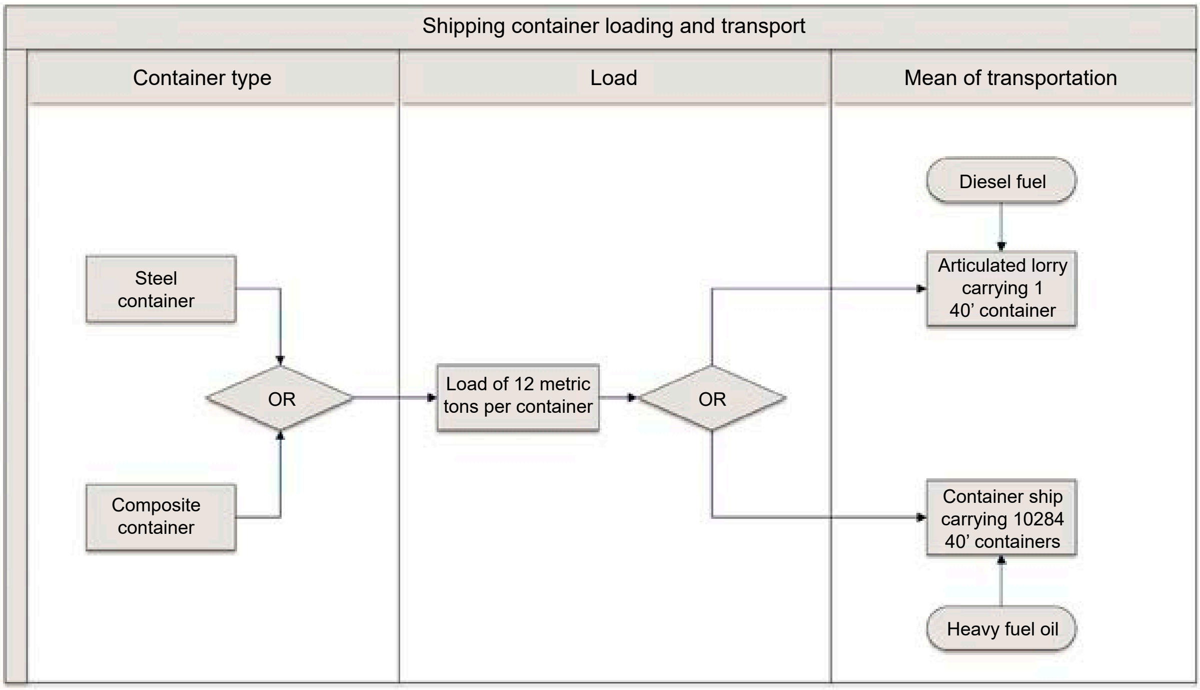

Figure 3. 40' steel and composite container loading and transport

utilization factor is 0.713 for a loaded steel container and 0.583 for a 12 t composite container. Assuming that the average distance traveled by an articulated lorry per day is 400 km, with an average operating time per year of 243 days, the distance traveled by the container per year is 97,200.

This publication adopts a simplified methodology based on the empirical relationship available in GaBi® software, i.e.:

$$\text{Spec diesel tot} = ((\text{Share mw} \cdot \text{Spec diesel mw}) + (\text{Share ru} \cdot \text{Spec diesel ru}) + (\text{Share ur} \cdot \text{Spec diesel ur})) \cdot \text{distance} \quad (1)$$

$$\text{Spec diesel mw} = (183.3 + (273.2 - 183.3) \cdot \text{Utilization}) / (\text{Payload} \cdot 1000 \cdot \text{Utilization}) / 1000 \quad (2)$$

$$\text{Spec diesel ru} = (176.4 + (284.2 - 176.4) \cdot \text{Utilization}) / (\text{Payload} \cdot 1000 \cdot \text{Utilization}) / 1000 \quad (3)$$

$$\text{Spec diesel ur} = (223.0 + (380.2 - 223.0) \cdot \text{Utilization}) / (\text{Payload} \cdot 1000 \cdot \text{Utilization}) / 1000 \quad (4)$$

$$\text{Diesel consumption} = \text{Cargo} \cdot \text{Spec diesel tot} \quad (5)$$

where Spec diesel tot denotes the weighted diesel consumption, in units of kg diesel/kg cargo; Share mw, ru, ur are, respectively, the share of road types on which the articulated lorry travels, i.e., motorway (mw) = 0.7, suburban (ru) = 0.23, and urban (ur) = 0.07; Spec diesel mw, ru, ur are, respectively, the diesel consumption on motorway, suburban, urban, in units of kg diesel/(kg·km); Distance is the distance traveled by the articulated lorry, km; Utilization represents the capacity utilization; Diesel consumption is the diesel consumption when transporting a container with cargo (Cargo), kg. The mass of diesel consumed is then converted into a volume in liters, using a diesel density of 0.845 kg/l.

In this publication, a simplified methodology based on the empirical relationship available in the GaBi® software, which relates fuel consumption to the deadweight tonnage (DWT) of a container ship, has been adopted analogously to determine the fuel consumption of a container ship, i.e.:

$$\text{HFO consumption specific} = ((-5 \cdot 10^{-9} \cdot \text{DWT}^2 + 0.0016 \cdot \text{DWT} + 9.8129) / \text{Utilization}) \cdot \text{Distance} \quad (6)$$

$$\text{HFO consumption} = \text{Cargo} \cdot \text{HFO consumption specific} \quad (7)$$

where HFO consumption represents the fuel consumption of a container ship with a given carrying capacity and cargo carried, in units of kg HFO; Distance is the distance traveled by a container ship with a given DWT, km. The HFO mass is then converted into a volume in liters using an HFO density of 0.900 kg/l.

For the LCIA analysis of steel container production, the following embodied energy values are assumed (the year in which this data is current is indicated in parentheses):

- Fabrication, rolling, and stamping of COR-TEN A® steel are 19.0 MJ/kg (2022) (MakeItFrom.com, 2023), 6.4 MJ/kg (2011), and 5.1 MJ/kg (2011) (Sunter et al., 2015), respectively;
- Manufacturing, rolling, and stamping of structural steel are 38.8 MJ/kg (2022) (Australian Government, 2020), 6.4 MJ/kg (2011), and 5.1 MJ/kg (2011) (Sunter et al., 2015), respectively;
- Plywood (plywood) production is characterized by an EE value of 15.0 MJ/kg (2015) (Sabnis, Mysore & Anant, 2015);
- The EE for rubber and other very lightweight materials, relative to the other materials of the steel container, is assumed to be negligible and equal to zero (2018) (Buchanan et al., 2018).

In the LCIA analysis of the production of the composite container, EE is assumed with the following values:

- Manufacturing carbon fiber from PAN and polyolefin precursors is 870.0 MJ/kg and 190.4 MJ/kg, respectively (2010) (Cresco, 2017);
- The manufacture of carbon fiber fabric is 4 MJ kg, assuming an average fabric weight of 200g/m^2 (1999) (Stiller, 1999);
- Epoxy resin synthesis is 46.6 MJ/kg (2010) (Cresco, 2017);
- Obtaining an epoxy resin-carbon fiber composite by resin transfer molding technology (including vacuum infusion) had a value of 3.2 MJ/kg (2010) (Cresco, 2017).

In previous work (Buchanan et al., 2018), a simplified method of expressing fuel savings via a difference between the fuel consumption of a given means of transport when transporting a heavier and a lighter container (ΔFC) can be found. In addition, the authors of the above work present another parameter, the "fuel reduction value (FRV)" (equation (8)). Its unit is l/(100 km·t) and is the ratio of ΔFC to ΔM (where ΔM is the difference in the weight of the heavier and lighter container), so that:

$$\mathrm{FRV} = \Delta FC / \Delta M \tag{8}$$

The total greenhouse gas emissions during each year of operation are calculated using the formula developed for this article, which is given as follows:

$$\text{GHG emission} = \text{GHG production equivalent} + (\text{Distance traveled annually}/\ 100) \cdot \text{GHG equivalent/100 km} \cdot \text{Exploitation year} \tag{9}$$

where GHG production equivalent is the GHG emission in the production stage of a container, t CO_2 equivalent; Distance traveled annually is the distance traveled by the container per year by the specified means of transport, km; GHG equivalent/100 km is the CO_2 equivalent of the transport of a steel or composite container (PAN, polyolefin) by the respective means of transport as determined by analyses in the GaBi® programme, t CO_2 equivalent/100 km; Exploitation year denotes the year of exploitation of a container.

Results and discussion

Shipping container production stage – energy consumed and environmental burden

The result of the analyses carried out in this study is, firstly, an estimation of the energy consumed in the manufacture of a container of a specific design, i.e., steel, composite (PAN), and composite (polyolefin). The amount of energy supplied to the system is highest for the manufacture of COR-TEN A® steel and equates to 55 GJ. To produce a steel container, a total of 107 GJ of energy must be supplied. The components with the greatest impact on the value of energy supplied to the system are the production of COR-TEN A® steel and its processing – i.e., its stamping and rolling (Figure 4). The marginal energy flows turn out to be rolling, stamping of the structural plate, and assembly of the prefabricated container.

The carbon fiber production technology has the greatest impact on the total energy used to produce a lightweight composite container. CFs based on PAN precursor (870 MJ/kg) are among the most energy-intensive, while CFs based on polyolefin precursor (190 MJ/kg) are much less energy-intensive. The production of carbon fiber from PAN precursor (Figure 5) and polyolefin precursor (Figure 6) consumes 415 GJ and 91 GJ of heat and electricity, respectively. This is followed by the epoxy resin production step, where 16 GJ of energy is consumed.

The energy required to build a steel shipping container (Figure 4) and a composite container with CF based on a polyolefin precursor (Figure 6) are similar in value. This means that, with polyolefin precursor technology, composite containers that are lighter than steel containers could be produced with the same energy input.

The GWP 100 impact category value of the production of a CFRP composite container based on a PAN precursor is approximately four times that

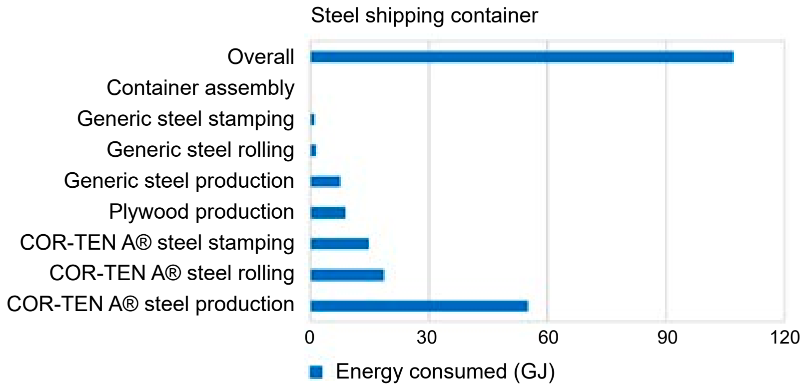

Figure 4. Components of the energy consumed in the production of a 40' steel container

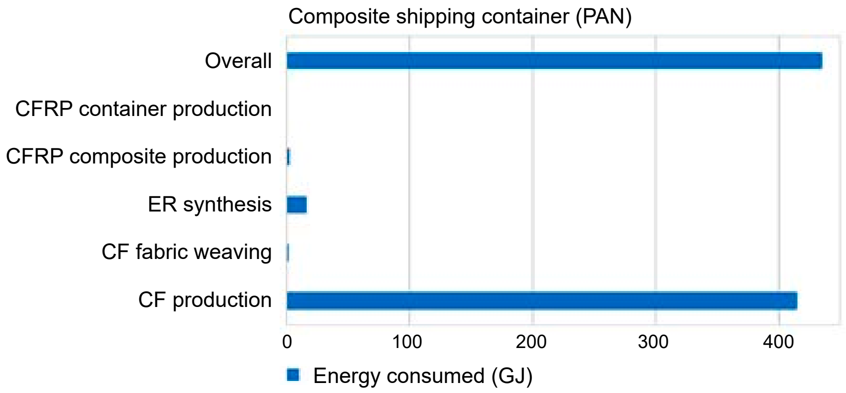

Figure 5. Components of the energy consumed in the production of a 40' CFRP shipping container (PAN)

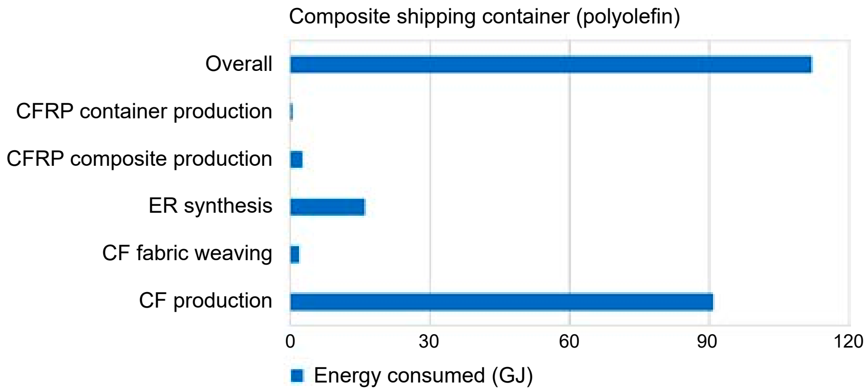

Figure 6. Components of the energy consumed in the production of a 40' CFRP shipping container (polyolefin)

of a container built on carbon fiber from a polyolefin precursor. Changing the carbon fiber precursor from PAN to a polyolefin precursor results in a threefold reduction in the energy intensity of the production stage of the structural material. This is a 75 % reduction in the energy used to produce the container, equivalent to 324 GJ (Figures 5 and 6). Thus, at the cost of producing one lightweight CFRP container from a PAN precursor, four containers can be produced from CF based on a polyolefin precursor.

For a container made from CF derived from a PAN precursor, the carbon fiber process consumes 95 % of the total energy used to produce the composite container (Figure 5). For a container made from CF based on a polyolefin precursor, the value is 81 % (Figure 6). More than four times as much energy has to be used to produce PAN carbon fiber as for the polyolefin precursor. Similarly, the total amount of energy used to produce a container based on PAN-based CF reinforcement is four times that of polyolefin precursor-based CF: 436 GJ and 112 GJ of energy, respectively.

In total, 9.8 t of CO_2 equivalent is emitted during the production of a 40' steel container. The processes with the highest greenhouse gas emissions are the manufacture and processing of COR-TEN A® steel (Figure 7). The manufacture of COR-TEN A® steel accounts for 4.6 t of CO_2 equivalent. Sheet rolling and stamping emit 1.89 t CO_2 equivalent and 1.51 t CO_2 equivalent, respectively. The production of plywood emits 0.90 t of CO_2 equivalent. For the structural steel production stage, it is 0.63 t CO_2 equivalent. In percentage terms, the production, rolling, and stamping of COR-TEN A® steel account for 47 %, 19 %, and 16 % of total GHG emissions, respectively. The figures are 9 % and 7 % for plywood production and structural steel production, respectively. For the rolling and stamping of structural steel and the assembly of the container, the mass of CO_2 equivalents emitted is negligibly small, totaling approximately 0.23 t CO_2 equivalent.

The total CO_2 equivalent value for the production of the lightweight composite container from the PAN precursor is 38.7 t CO_2 equivalent (Figure 8), while that from the polyolefin precursor is 9.7 t CO_2 equivalent (Figure 9). For the composite container, the production of carbon fiber is found to have the largest greenhouse gas impact, with 37.1 t CO_2 equivalent for the PAN precursor and 8.1 t CO_2 equivalent for the polyolefin precursor. In second place is the epoxy resin synthesis process, which emits 1.1 t CO_2 equivalent. The smallest contribution to GHG emissions originates from the manufacture of the carbon fiber fabric, the production of the composite, and the assembly of the composite container, with a total contribution of 0.45 t CO_2 equivalent and a percentage of less than 5 %.

No information on the energy consumed to produce the 40' composite container is reported in the literature. Information on the energy consumed to obtain the 40' steel container is scarce; one literature reference stated that the energy consumed to produce the 40' steel container is 123 GJ (Table 2) (Buchanan et al., 2018). The slight difference in the results of the energy consumed in the production of the steel container from a previous publication (Buchanan et al., 2018) and that determined in this analysis may originate from the EE values that are used in the calculations and the weight of the construction materials used in the construction of the 40' container (Obrecht & Knez, 2017; Buchanan et al., 2018). The EE value of the steel depends on the technological condition, type of steel, manufacturer, and other technological parameters (Hammond & Jones, 2011).

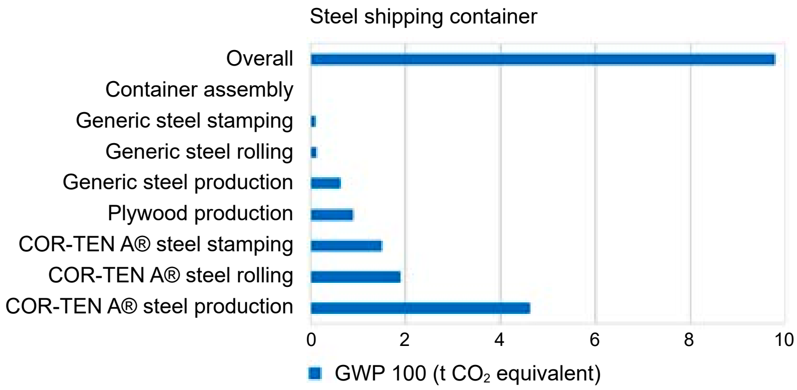

Figure 7. Environmental burden of the production stages of the 40' steel container

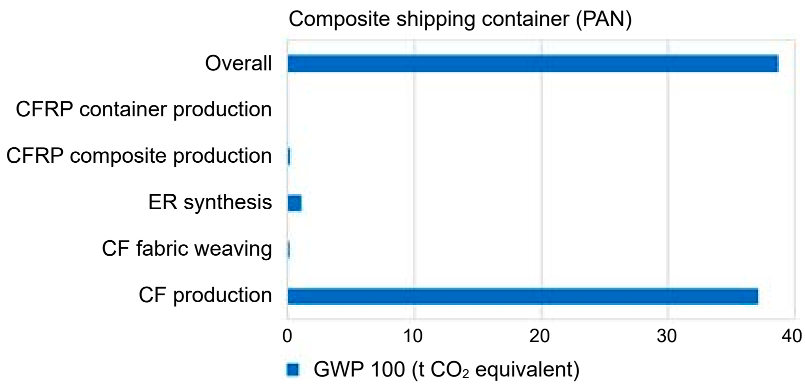

Figure 8. Environmental burden of the production stages of a 40' composite shipping container (PAN)

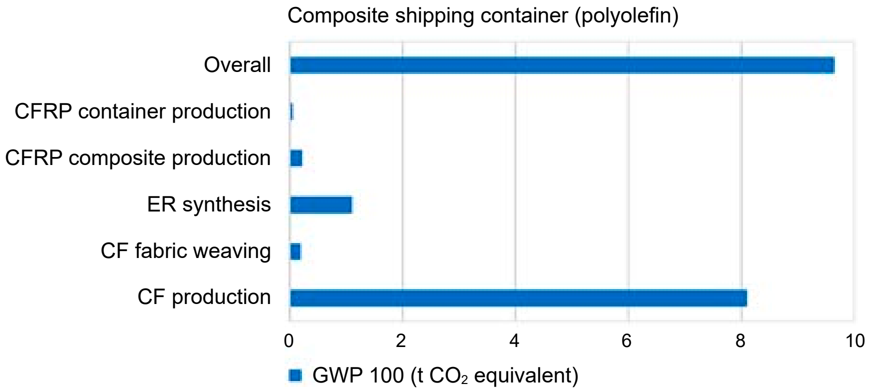

Figure 9. Environmental burden of the production stages of a 40' composite shipping container (polyolefin)

Previous work (Buchanan et al., 2018) reported that the GWP 100 value attributable to the production process of the 40' steel container is equal to 11 t CO_2 equivalent (Table 2). The GWP 100 value associated with the production of the steel container in the present work is 9.8 t CO_2 equivalent. The authors of the aforementioned papers do not comment on the impact of the different stages of steel container production on the final GWP100 value and the energy consumed in the production of the steel container.

Table 2. Energy consumed and GWP 100 emitted in the container production process

Source	Energy consumed, GJ	GWP 100, t CO_2 equivalent
Literature reference (Buchanan et al., 2018)	123	11.0
Steel container calculated	107	9.8
Composite container (PAN) calculated	436	38.7
Composite container (polyolefin) calculated	112	9.7

Container exploitation – fuel consumption and environmental burden

Table 3 shows the results of fuel consumption and greenhouse gas emissions per single container. During the entire transport phase of a steel and composite container by sea transport means, container ship and HFO consumption of 103,481 and 84,567 liters can be expected, respectively (equation (7)). For an articulated lorry, these values are 583,887 and 554,120 liters of diesel fuel (equation (5)), respectively. The reduction in tare weight of the 40' container leads to reduced fuel consumption and reduced GHG emissions into the atmosphere by the container ship. This is a change of 18.3 %. These values are reduced by 5.1 % and 5.0 % for the articulated lorry, respectively.

In a previous paper (Doukas et al., 2021), one can find fuel consumption data for different classes of container ships at four types of ship speed: S (steaming 25 knots), SS (slow-steaming 18 knots), SSS (super-slow-steaming 15 knots), and ES (economical steaming 11 knots). For the slow-steaming speed and the container ship ULCV, the fuel consumption from the aforementioned publication is equal to 3.3 l/100 km per FEU. The one calculated in this paper for a 40' steel container is equal to 1.85 l/100 km per single container. For a light composite container (PAN and polyolefin), it is equal to 1.51 l/100 km per FEU (Table 3).

The fuel reduction per 100 km, resulting from changing the container design to a lighter composite design, leads to a saving of 0.338 liters of HFO per

Table 3. Fuel consumption and environmental burden during the transport of a single container with cargo

Mode of transport	Shipping container design	Fuel consumption, l/100 km	Fuel consumption, l per lifetime	GHG emissions, t CO_2 equivalent per 100 km	GHG emissions, t CO_2 equivalent per lifetime
Container ship	Steel	1.85	103 481	0.0050	277.2
	Composite (PAN)	1.51	84 567	0.0040	226.5
	Composite (polyolefin)	1.51	84 567	0.0040	226.5
Articulated lorry	Steel	30.04	583 887	0.0823	1600.0
	Composite (PAN)	28.50	554 120	0.0782	1520.2
	Composite (polyolefin)	28.50	554 120	0.0782	1520.2

container for a container ship (Table 4). For an articulated lorry, this is a value of 1.524 liters of diesel per 100 km. The fuel reduction factor (FRV) reaches values of 0.118 and 0.531 liters per 100 km·t for the container ship and articulated lorry, respectively.

Table 4. Fuel consumption and FRV value for two modes of transport

Mode of transport	ΔFC, l/100 km	FRV per container, l / (100 km·t)
Container ship	0.338	0.118
Articulated lorry	1.524	0.531

An earlier publication (Buchanan et al., 2018) reported that a reduction in the weight of the container carried by 618 kg (20 % reduction in container weight) results in a reduction in HFO fuel consumption of the container ship by 0.52–0.55 l/100 km. In the present study, a reduction in the tare weight of the container by 2868 kg (more than 78 % reduction in weight) is associated with a reduction in the fuel consumption of the container ship by only 0.338 l/100 km (Table 4).

Previous work (Buchanan et al., 2018) indicates that the fuel consumption of the 2250 FEU container ship "Panamax Max" per container is 6.2 l/100 km. The present study indicates a fuel consumption of 1.85 l/100 km by a ULCV container ship per 40' container. This is due to economies of scale, for which the fuel consumption per container is lower for more containers carried by a container ship.

For an articulated lorry, recent research (Buchanan et al., 2018) reported a fuel consumption saving in the range of 1.80–1.90 l/100 km with a container weight reduction of 840 kg. In the present study, a reduction in the tare weight of the container by 2868 kg (more than 78 % weight reduction) is associated with a reduction in fuel consumption ΔFC of only 1.524 l/100 km for the articulated lorry (Table 4). In the aforementioned publication, the authors report a fuel consumption of 36.80 l/100 km for a 40' steel container on an articulated lorry with a 22.7 t payload. In the calculations in this paper, consumption in the order of 28.50 and 30.04 l/100 km is encountered (Table 3) for a light composite container and a 40' steel container, respectively. The differences in the results found in the aforementioned paper may have their origin in an overestimation of ΔFC or an underestimation of ΔM. It is also important to note that the publications differ in the geographical area from which the data are taken. In the above publication, the analyses are carried out using data from the USA; in this publication, it is from the EU. Consequently, the characteristics of the means of transport in the areas mentioned may differ. In the case of the ULCV container ship analyzed in this publication, a reduction in fuel consumption ΔFC of well over 0.34 l/100 km can be expected with a 78 % reduction in the tare weight of the container.

The FRV per 40' container is 0.118 l/(100 km·t) for container ship transport and 0.531 l/(100 km·t) for road transport. Comparable research (Buchanan et al., 2018) shows slightly higher values of 0.179 l/(100 km·t) for a container ship and 0.617 l/(100 km·t) for road transport. This fact is puzzling, as such a significant reduction in the tare weight of a container should be associated with significantly greater savings in fuel used for transport and FRV for the particular mode of transport analyzed in this publication. Such a difference can be traced back to the fuel consumption calculation methodology of the GaBi® software used by the author of this publication and GREET, which is used by the authors of the previous paper (Buchanan et al., 2018). The fuel consumption of a given means of transport depends on a number of factors, including the fuel consumption model used (which relates the key quantities), the weight of the load, the use of the loading capacity of the means of transport, the distance traveled, and the specific fuel consumption per unit weight of the load transported. It should be borne in mind that the values used in the models are often averages and approximations; hence, differences in fuel consumption may result.

The matter of savings and fuel consumption can be put into perspective. Over the entire lifecycle of a 40' container, 18,914 liters of HFO can be saved per container (Table 3). This amount of fuel can be used for the additional distance the container can travel by sea transport. With an HFO consumption of 1.51 liters/100 km for a light-composite container, it is estimated that a single container could be transported an additional 1,252,514 km over its entire lifecycle. For road transport, the savings in diesel fuel amount to 29,629 l. Hence, with a fuel consumption of 28.5 l/100 km, a container can be transported an additional 103,965 km with respect to a steel container. The load in the containers remains constant and equal to 12 t.

During the operating phase, various amounts of GHG emissions are produced due to the different masses of cargo carried. The graph of the dependence of GHG emissions as a function of years of operation is linear. By considering the differences between the two, it is possible to determine which solutions are the least carbon-intensive and after what time the "CO_2 equivalent savings" of a given solution will be returned relative to other solutions (Table 3).

Based on the analysis of the graph (Figure 10), it can be concluded that the GHG "savings" between the GHG emissions of a steel container and a lightweight composite container (polyolefin) will increase linearly over time. The difference between the "savings" in emissions during the operation of a lightweight composite (PAN) container and a steel container decreases linearly, which means that at some point in the container's lifetime, there will be a turnaround in the amount of GHG emitted by the transport of the lightweight composite (PAN) container relative to the steel container. More precisely, a composite container (PAN) relative to a steel container will "pay for itself" after 11 years if transported by container ship, and after 7 years if transported by articulated lorry. The solution of using a composite container (polyolefin) is always more economical than a composite container (PAN). This is due to the lower energy intensity of the polyolefin CF manufacturing process.

Over a 20-year lifetime and as a result of using a composite container (polyolefin) in place of a steel container, approximately 50.77 t CO_2 equivalent per container can be saved for sea transport and 79.80 t CO_2 equivalent for road transport.

It has been calculated that, for the ULCV container ship considered in this paper, the reduction in GHG emissions resulting from a 78 % reduction in container tare weight is 0.9 kg CO_2 equivalent/100 km per single container. The earlier work (Buchanan et al., 2018) reports a reduction in the mass of emitted GHGs of 2.5 kg CO_2 equivalent per 100 km per single container, which is more than double. This is puzzling, as container ships with higher payloads should achieve greater reductions in CO_2 equivalent emitted to the atmosphere. Such a significant difference in GHG emission reductions can be traced back to both the input values and the mathematical model of the GREET 1 program used by the authors of the aforementioned paper.

Cumulative values of the LCA of the container – energy consumed and environmental burden

The results of the analyses for the various stages of the LCA are shown in Tables 5 and 6. The total energy consumed and the environmental burden consist of the following stages of the container's life cycle: production of the construction material, manufacture of the container, operation

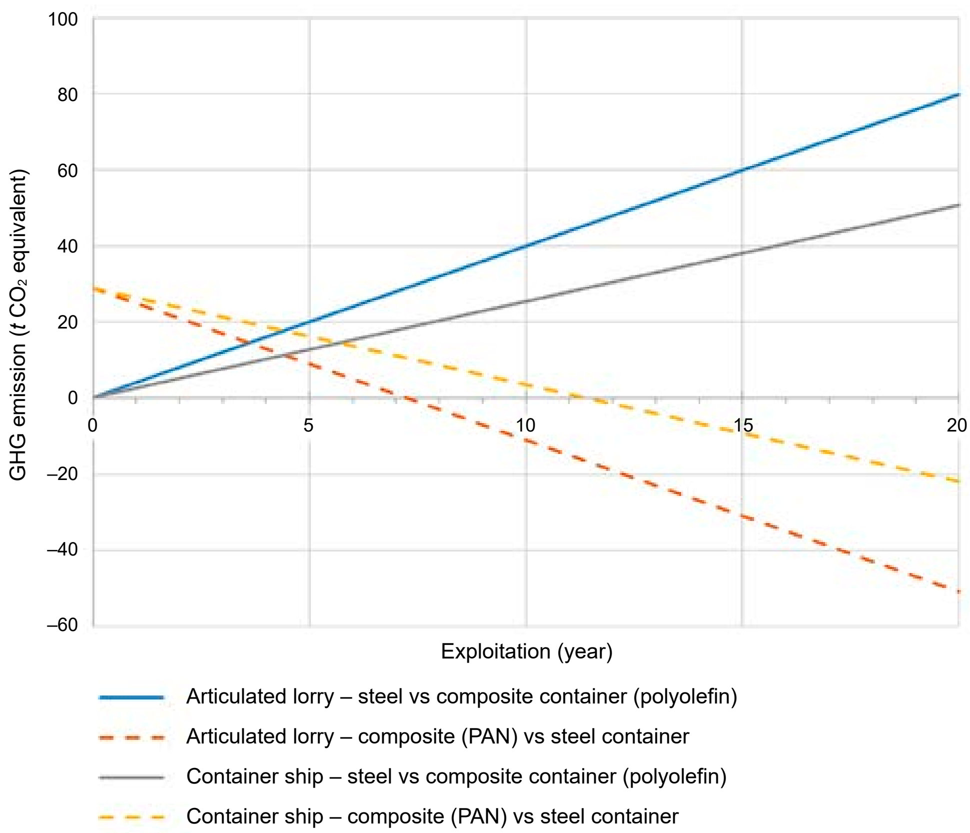

Figure 10. Greenhouse gas savings

Table 5. Energy consumed and environmental burden in the various stages of the LCA of a shipping container of a particular design and mode of sea transport

Container ship						
Impact category	Shipping container design	Material production	Container fabrication	Exploitation	Disp or rec[a]	Overall
Energy consumed, GJ	Steel	71.0	36.0	4042.0	3.80	4152.8
	Composite container (PAN)	431.1	4.5	3074.8	0.25	3510.7
	Composite container (polyolefin)	107.0	5.0	3074.8	0.25	3187.1
GWP 100, t CO_2 equivalent	Steel	6.2	3.6	277.2	5.70	292.7
	Composite container (PAN)	38.2	0.5	226.5	0.03	265.2
	Composite container (polyolefin)	9.2	0.5	226.5	0.03	236.2

[a] Disposal or recycling.

Table 6. Energy consumed and environmental burden in the various stages of the LCA of a shipping container of a particular design and mode of road transport

Articulated lorry						
Impact category	Shipping container design	Material production	Container fabrication	Exploitation	Disp or rec[a]	Overall
Energy consumed, GJ	Steel	71.0	36.0	21412.9	3.80	21523.7
	Composite container (PAN)	431.1	4.5	20321.2	0.25	20757.1
	Composite container (polyolefin)	107.0	5.0	20321.2	0.25	20433.5
GWP 100, t CO_2 equivalent	Steel	6.2	3.6	1600.0	5.70	1615.5
	Composite container (PAN)	38.2	0.5	1520.0	0.03	1558.7
	Composite container (polyolefin)	9.2	0.5	1520.0	0.03	1529.7

[a] Disposal or recycling.

using the specified means of transport, and disposal of the container. The term “material production” refers to the production of COR-TEN A® steel, structural steel, and plywood (steel shipping container) and the production of CF and ER synthesis (composite shipping container). “Container fabrication”, on the other hand, refers to the rolling and stamping of COR-TEN A® steel and structural steel and the assembly of the container; for the composite container, it refers to the production of carbon fabric, the manufacture of the composite, and the assembly of the composite shipping container.

The total amount of fuel consumed during the transport of the container is converted into energy units using publicly available data: 1 kg of HFO corresponds to 40.4 MJ of energy, while 1 kg of diesel is 43.4 MJ.

In the case of maritime and road transport, the steel container has the highest total energy intensity, while the composite container (polyolefin) has the lowest. The amount of CO_2 equivalent emitted to the atmosphere is of a similar nature, with most GHGs emitted during the lifetime of a steel container, followed by a composite container (PAN) and the least for a composite container (polyolefin).

In general, the 20-year life cycle stage has the greatest impact on the total energy consumed during the container’s life cycle and environmental burden. For a container ship, this is 97.3 %, 87.6 %, and 96.5 % of the cumulative energy intensity for the steel, PAN composite, and polyolefin precursor-based composite container, respectively.

For the means of road transport, the share of energy consumed when transporting a container is 99.5 %, 97.9 %, and 99.5 % for the steel, light composite (PAN), and light composite (polyolefin) containers, respectively. The GWP 100 values for shipping and the three design variants are 94.7 %, 85.4 %, and 95.9 %, while the GWP 100 values for articulated lorry are 99.0 %, 97.5 %, and 99.4 %, respectively. The total energy consumed and the GWP 100 value over the lifecycle are least influenced by the disposal and assembly stages of a container with a specific design.

Although the 40' steel container design is the most common for sea and road transport, it is the most environmentally damaging. In relation to steel 40' containers, the lightweight composite container (polyolefin) proves to be the design with the lowest GHG emissions to the atmosphere and the lowest energy intensity. Changing the 40' container design from steel to lightweight composite reduces the energy intensity over the container's lifetime – including the operational phase – by 965.7 GJ for the container ship and 1085.1 GJ for the articulated lorry.

Recycling/downcycling of steel and composite shipping container

Information on the recycling of a classic 40' steel container can be found in an earlier publication (Buchanan et al., 2018). The authors of this paper indicate that the energy requirement for recycling a 40' steel container is equal to 3.8 GJ, assuming that 90 % of the materials are reprocessed. The recycling of structural steel and COR-TEN A® steel releases 5.7 t of CO_2 equivalent greenhouse gases (value calculated from source (GHK, 2015)).

In the case of fiber-reinforced carbon-fiber epoxy composites, with today's state of the art, it is not possible to talk about recycling but only about downcycling. This consists of pre-cutting the larger components, breaking them into 50–100 mm pieces, and then grinding them into approximately 10–0.05 mm pieces using suitable equipment. The epoxy-carbon composite in this form can be processed by the following techniques: pyrolysis (30 MJ/kg), mechanical downcycling (0.3 MJ/kg), fluidized bed process (6 MJ/kg), and solvolysis process using supercritical water (83.6 MJ/kg) (Shehab et al., 2021).

Of the composite waste management technologies mentioned in the introduction, mechanical downcycling is the most economical and needs the least investment (Shehab et al., 2021). At the same time, it is the most understood and developed technology. The amount of energy used to recycle an 822 kg composite container is calculated as approximately 0.25 GJ, which is negligible compared to the recycling energy of a 40-foot steel container of 3.8 GJ. The mechanical recycling of the composite container will only produce 25 kg of CO_2 equivalent.

According to previous work (Cunliffe, Jones & Williams, 2003), ER during pyrolysis at high temperatures from 350 to 800 °C can be decomposed into a gaseous part (e.g., methane, hydrogen, and ethane/ethene) and a liquid/solid, oily/waxy part (pentane, benzene, ethyl acetate, and methanol). These substances are not involved in the direct resynthesis of the epoxy resin. Therefore, it is not possible in this case to speak of the recycling of composite containers properly as for steel.

Uncertainties in the LCA analysis of steel and composite containers

Due to the lack of precise literature data on the variability (e.g., standard deviation) of EE values of materials and processes and GWP100, a quantitative assessment is not undertaken. Only qualitative indications of what factors may play a significant

Table 7. Uncertainties in the LCA analyses conducted in this study

LCA stages	Model uncertainty	Scenario uncertainty	Parameter uncertainty
General and impact assessment	Approximate container lifecycle model	Data from the GaBi® database	Data without relevant statistical measures
Construction materials production	Model and assumptions for the production of structural materials	Allocation of energy Selection of construction materials Choice of manufacturing routes for structural materials (e.g., carbon fiber from PAN or polyolefin)	Allocation of electrical and heat energy Embodied energy of construction materials
Construction materials processing and container assembly	Model of the production of construction materials (e.g., stamping, rolling of steel, and CFRP production) and assembly of a container	Selection of specific processing routes for metals (e.g., stamping and rolling), non-metals, and polymers (e.g., plywood and cRTM) Choice of container manufacturing method	Electrical and heat energy allocation Embodied energy for the construction materials Mass of construction materials used
Load	Assumptions for the load of a container	Estimating the average load per container	Average container load calculated from averaged Eurostat data
Exploitation of a container	Fuel consumption model based on the GaBi® software	Fuel consumption dependent on the case study	Fuel consumption based on the gross weight of a container, distance traveled, and payload factor
Recycling and downcycling	Recycling/downcycling model for the composite container	Choice of recycling/downcycling technology for the composite container	The recycling/downcycling technology of the composite container has a significant impact on energy consumption

role in interpreting the results of the LCA analyses of this study are given.

An earlier publication (Clavereul, Guyonnet & Christensen, 2012) shows how to determine the uncertainty of the determination of the quantities obtained in the LCA analysis. Uncertainties are divided into three categories: uncertainty of the model, uncertainties resulting from the chosen and analyzed scenario, and uncertainty of the parameters determined in the LCA analysis (Table 7). Model uncertainty refers to the mathematical model on which the LCA analysis is based.

Conclusions & further research

Production of carbon fiber from polyolefins has advantages: low production cost, lower energy intensity of the process, and more environmentally friendly technology. Weaknesses of using polyolefins to produce carbon fiber include the need to crosslink polyolefins due to their linear structure (Aldosari, Khan & Rahatekar, 2020). Based on the information above, it can be concluded that it is possible to modify and optimize the process of obtaining carbon fiber, which is the most energy-intensive step in the production of a CFRP composite container. This could lead to a significant reduction in the price of a composite container compared to a steel container.

Based on the analyses in this paper, the following conclusions can be obtained:

- In the field of container transport, there is great potential for new solutions. Composite materials are one of them. The strengths of such a solution can be the low weight of the construction material and the very good strength parameters of the composite material similar to steel (Yildiz, 2019);
- Composite materials, despite their great potential, have not yet gained recognition in container construction. Based on an analysis of the GWP 100 index and the amount of fuel saved during the operational phase, it can be concluded that containers made from an epoxy-carbon composite on a polyolefin precursor can be an excellent alternative to the commonly used steel containers;
- At the cost of one steel container, a lightweight composite container (polyolefin) can be produced. This applies to both the energy consumed in production and the environmental burden of GWP 100;
- The results are significantly influenced by, among other things, the geographical area of data collection, the processing technology, the averaged value of the input parameters and streams, and the approximations/rounding of the determined quantities. The contribution of some production processes to the final value of energy used to produce a container is small, and these processes may have been omitted from the LCIA analyses;
- The ΔFC and FRV values determined by the author of this publication for sea and road transport are similar and/or slightly lower compared to those reported previously (Buchanan et al., 2018). An explanation for these differences may be the sensitivity of the results to the method used to determine fuel consumption;
- The fuel savings from using the lighter 40' container design are significant, amounting to 18,914 liters of HFO and 29,629 liters of diesel per container over its lifetime;
- If a lighter container design is used, it is possible to save GHGs emitted into the atmosphere by 50.77 t CO_2 equivalent in maritime transport per container and 79.80 t CO_2 equivalent in road transport;
- Potential applications of the results of the LCA analyses include the optimization of processes related to the manufacture and operation of lightweight containers made of composite materials. The results will also be able to inform discussions on the environmental impact of new technologies in the field of transport containerization.

This article covers a number of issues: the manufacture and processing of steel and polymeric materials, life cycle analysis, the impact of container technology on the various stages of the life cycle (their GWP and the energy absorbed in each stage), the impact of container technology on the weight of the container itself, the resulting savings in the fuel consumed by the means of transport carrying the container, and the reduction in GHG emissions into the atmosphere resulting from the reduced weight of the container. An in-depth and detailed analysis of each of the above-mentioned issues could provide an important starting point for subsequent publications.

Nevertheless, it seems most interesting to analyze the final stage of the container's life cycle, which is recycling. The values of GWP, energy absorbed or recovered, and mass of GHG emitted into the atmosphere during the recycling process of a steel container, let alone a composite container, are practically absent from the literature. In an era of considerable industrial development and new technologies, reducing the carbon footprint of the product-container, also during its use, should be one of the priority research directions.

References

1. Aldosari, S., Khan, M. & Rahatekar, S. (2020) Manufacturing carbon fibres from pitch and polyethylene blend precursors: a review. *Journal of Materials Research and Technology* 9 (4), pp. 7786–7806, doi: 10.1016/j.jmrt.2020.05.037.
2. Australian Government (2020) *Your Home*. [Online]. Available from: https://www.yourhome.gov.au/materials/embodied-energy [Accessed: 29.03.2023].
3. Buchanan, C.A., Charara, M., Sullivan, J.L., Lewis, G.M. & Keoleian, G.A. (2018) Lightweighting shipping containers: Life cycle impacts on multimodal freight transportation. *Transportation Research Part D* 62, pp. 418–432, doi: 10.1016/j.trd.2018.03.011.
4. Choqueuse, D. & Davies, P. (2014) Durability of Composite Materials for Underwater Applications. In: Davies, P.; Rajapakse, Y.D.S. (eds) *Durability of Composites in a Marine Environment*. Springer Dordrecht.
5. Clavereul, J., Guyonnet, D. & Christensen, T.H. (2012) Quantifying uncertainty in LCA-modelling of waste management systems. *International Journal of Environment and Waste Management* 32, pp. 2482–2495, doi: 10.1016/j.wasman.2012.07.008.
6. Cresco, J. (2017) *Bandwidth study on energy use and potential energy saving opportunities in U.S. carbon fiber reinforced polymer manufacturing*. [Online]. Available from: https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-carbon-fiber-reinforced-polymer-composites-manufacturing [Accessed: 29.03.2023].
7. Cunliffe, A., Jones, N. & Williams, P. (2003) Pyrolysis of composite plastic waste. *Environmental Technology* 24 (5), pp. 653–663, doi: 10.1080/09593330309385599.
8. Doukas, H., Spiliotis, E., Jafari, M.A., Giarola, S. & Nikas, A. (2021) Low-cost emissions cuts in container shipping: Thinking inside the box. *Transportation Research Part D: Transport and Environment* 94, pp. 1–15, doi: 10.1016/j.trd.2021.102815.
9. European Maritime Safety Agency (2021) *Facts and figures: the EMTER report*. [Online]. Available from: https://www.emsa.europa.eu/damage-stability-study/items.html?cid=14&id=4515 [Accessed: 28.03.2023].
10. EUROSTAT (2021) [Online]. Available from: https://ec.europa.eu/eurostat/databrowser/view/mar_mg_am_pvh/default/table?lang=en [Accessed: 29.03.2023].
11. GHK (2015) *A study to examine the benefits of the End of Life Vehicles Directive and the costs and benefits of a revision of the 2015 targets for recycling, re-use and recovery under the ELV Directive. Birmingham: GHK & Bio Intelligence Service*. [Online]. Available from: https://ec.europa.eu/environment/pdf/waste/study/annex7.pdf [Accessed: 29.03.2023].
12. Hammond, G. & Jones, C. (2011) *Embodied Carbon. The Inventory of Carbon and Energy* (*ICE*). [Online]. Available from: http://www.emccement.com/pdf/Full-BSRIA-ICE-guide.pdf [Accessed: 29.03.2023].
13. Magnuson, S. & Wagner, B. (2007) *Composite Materials Touted for Securing Shipping Containers. National DEFENCE: 2007*. [Online]. Available from: https://www.nationaldefensemagazine.org/articles/2007/7/1/2007july-composite-materials-touted-for-securing-shipping-containers [Accessed: 29.03.2023].
14. MakeItFrom.com (2023) EN 1.8945 (S355J0WP) *Weathering Steel*. [Online]. Available from: https://www.makeitfrom.com/material-properties/EN-1.8945-S355J0WP-Weathering-Steel [Accessed: 29.03.2023].
15. Obrecht, M. & Knez, M. (2017) Carbon and resource savings of different cargo container designs. *Journal of Cleaner Production* 155 (1), pp. 151–156, doi: 10.1016/j.jclepro.2016.11.076.
16. Olmer, N., Comer, B., Roy, B., Mao, X. & Rutherford, D. (2017) *Greenhouse gas emissions from global shipping, 2013–2015*. [Online]. Available from: https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf [Accessed: 29.03.2023].
17. Park, S.J. (2018) *Carbon Fibers*. 2nd Ed. Springer, doi: 10.1007/978-981-13-0538-2_8.
18. Plastics Today (2014) Composites could revolutionize shipping containers. [Online]. Available from: https://www.plasticstoday.com/composites-could-revolutionize-shipping-containers [Accessed: 29.03.2023].
19. Riley, T. (2018) *Composites are Taking Cargo Transportation to New Depths and Heights. Market Scale 2018*. [Online]. Available from: https://marketscale.com/industries/aec/composites-are-taking-cargo-transportation-to-new-depths-and-heights/ [Accessed: 29.03.2023].
20. Rodrigue, J.P., Comtois, C. & Slack, B. (2013) *The Geography of Transport Systems*. 3rd Ed. Taylor & Francis Group, doi: 10.4324/9780429346323.
21. Sabnis, A., Mysore, P. & Anant, S. (2015) Construction materials-embodied energy footprint-global warming; interaction. *Proceedings of the Structural Engineers World Congress*.
22. Shehab, E., Meirbekov, A., Amantayeva, A., Suleimen, A., Tokbolat, S. & Sarfraz, Sa. (2021) Cost modelling system for recycling carbon fiber-reinforced composites. *Polymers* 13, 4208, pp. 1–20, doi: 10.3390/polym13234208.
23. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tingor, M.M.B. & Miller, H.L.J. (2007) *Climate Change 2007*. The Physical Science Basis.
24. Song, D.P. (2021) A literature review. Container shipping supply chain: Planning problems and research opportunities. *Logistics-Basel* 5 (2), pp. 1–26, doi: 10.3390/logistics5020041.
25. Stiller, H. (1999) Material Intensity of Advanced Composite Materials. Wuppertal Papers.
26. Sunter, D., Morrow, W.I., Cresco, J. & Liddell, H. (2015) The manufacturing energy intensity of carbon fiber reinforced polymer composites and its effect on life cycle energy use for vehicle door lightweighting. *Proceedings of the 20th International Conference on Composite Materials*.
27. Tapper, R.J., Longana, M.L., Norton, A., Potter, K.D. & Hamerton, I. (2020) An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fibre reinforced polymers. *Composites Part B: Engineering* 184, pp. 1–10, doi: 10.1016/j.compositesb.2019.107665.
28. Yildiz, T. (2019) Design and analysis of a lightweight composite shipping container made of carbon fiber laminates. *Logistics-Basel* 3 (3), pp. 1–20, doi: 10.3390/logistics3030018.

Cite as: Wojnowski, J. (2024) Management of the manufacturing process and exploitation of steel and composite shipping containers. Case study and life cycle assessment analysis. S*cientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Politechniki Morskiej w Szczecinie* 77 (149), 47–62.