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Abstract
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Keywords
product design, textile manufacturing, cradle-to-gate, supply chain management, environmental impacts, energy consumption, carbon footprint, sustainable product design, sustainable manufacturing

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Energy and carbon footprint reduction during textile-based product design and manufacturing

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1 Introduction

Integration of sustainability principles into the design of products and manufacturing processes and systems is crucial; it helps decision makers consider environmental, economic, and societal effects. Design has substantial effects on global sustainability. As such, materials, manufacturing processes, transportation, and end-of-life should be considered in the early design stage (Ramani et al., 2010). Pursuing the application of design for environment (DfE) during early product design mitigates environmental impacts and boosts product competiveness (Choi et al., 2008). In economic terms, investing 5–7% of product cost in early design can decrease total cost by 70–80% (Ramani et al., 2010). Sustainability encourages companies to conduct business responsibly by providing information about the potential social impacts from activities across the life cycle of a product (Dreyer et al., 2006).

Due to the existing uncertainties in design, tools and methods are needed to consider all aspects of sustainability. The research herein describes a method to predict the cradle-to-gate energy consumption and carbon footprint during design for global production of consumer goods. The method is applied to evaluate a textile-based product (a backpack). Background motivation and related research is first presented, and the paper concludes with a discussion of the developed method and an examination of the results.

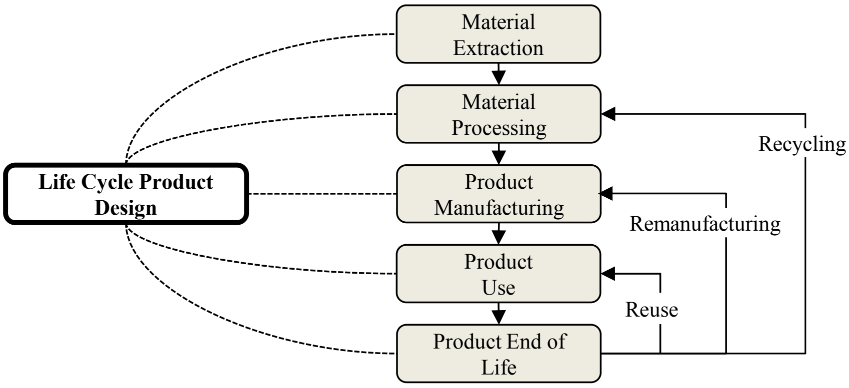
2 Background

Eco-design, or design for environment is a design method that considers environmental impacts, human health, and safety during development of a product, from material extraction to end-of-life (Fiksel, 1993). Occupational and consumer safety, resource protection, pollution prevention, waste reduction, and recyclability are applications of DfE as per Fiksel's (1993) framing of the concept. Reducing carbon footprint and supply chain cost simultaneously during design stage is a recommended use of DfE (Chiu et al., 2010). These authors demonstrated that design decisions can significantly impact total transportation cost and environmental impacts during product manufacturing. Johansson (2002) introduced six areas of concern to improve integration of eco-design in product development: management, customer relationships, supplier relationships, development process, competence, and motivation. Several eco-design methods and tools, along with a discussion of their advantages and disadvantages, are available for designers and decision makers to solve different problems during product design (Fargnoli and Kimura, 2006).

Life cycle engineering (LCE) includes the application of scientific principles in the product design and manufacturing stages to protect the environment and preserve natural resources with special attention given to product cost (Jeswiet and Hauschild 2005). LCE provides a basis for understanding the environmental attributes of each stage of the product life cycle and, consequently, supplies a foundation to decision making before manufacturing takes place (Jeswiet and Hauschild, 2005). In this manner, thoughtful attention should be paid to product redesign to improve environmental, economic, and social performance (Ramani et al., 2010). Life cycle assessment (LCA) is a method that can assist eco-design through the evaluation of product and environment interactions with respect to the energy and material flows through all stages of the product life from cradle-to-grave, including raw material extraction, manufacturing processes, transportation, use, remanufacturing, reuse, recycling, and, ultimately, disposal (Ramani et al., 2010; Hertwich et al., 2000), as shown in Figure 1.

LCA is the most widely used method in comprehensively assessing various environmental impacts, such as energy use and global warming potential (GWP). While LCA is appropriate for a quantitative assessment of environmental impact of products and services, it requires the collection of a wide variety of data. This data collection is time and cost intensive, especially for complex designs (Koffler et al., 2008). LCA has been used as a support tool in an eco-design approach considering the uncertainties of the design stage, and integrating multi-objective optimisation (Yu et al., 2011).

Figure 1 Influence of design on cradle-to-grave product life cycle stages (see online version for colours)



Source: Bohm et al. (2010)

Another challenge faced by designers is the need to shift the framing of product design from being relevant only to the economic aspect to all sustainability aspects (Devanathan et al., 2010). An effort in this direction is a new eco-design methodology that takes advantage of LCA and visual tools to correlate environmental impacts with product function in the early design stage (Devanathan et al., 2010). Such developments can assist designers in more quickly navigating the design space. Various impact assessment methods do exist to support designers in evaluating the potential environmental impacts of their decisions. For example, ReCiPe 2008 is an impact assessment method that is relatively new to practice (Goedkoop et al., 2009). It is based on the integration of prior methods, and considers eighteen midpoint impacts (e.g., ecotoxicity, acidification, and fossil depletion) and three endpoints (i.e., human health, ecosystem quality, and resource availability).

Other eco-design methods have been developed to assist decision making. Eco-design checklists, for example, offer a qualitative tool that uses a list of questions and items to assess a product's environmental impacts at the early design stage (Bovea and Perez-Belis, 2012). Checklists help designers decide whether a product or material is harmful to the environment or not. Different questions can be used that are convenient to answer, such as "what are the significant environmental aspects of the product during its life cycle?" or "which eco-design guideline should be used for the specific product?" (Lee and Park, 2005). This tool is subjective when it is compared to LCA-based tools; and therefore, it is mostly used in the early design stage and requires knowledge and experience (Ramani et al., 2010).

Two key measures of product environmental impacts are energy consumption and carbon footprint. It is expected that worldwide energy demand and price will continue to increase; thus, determining the total energy consumption of a product during its life helps stakeholders and designers explore new ways to improve energy efficiency (O'Driscoll et al., 2013). Hertwich and Peters (2009) showed that 72% of greenhouse gas (GHG) emissions result from household consumption and related transportation. Figure 2 shows the contributions of various GHG emissions in the USA for 2010. It can be seen that CO_2 accounts for more than three-fourths of total GHG emissions.

GHGs include carbon dioxide (CO2), methane (CH_4), nitrous oxide (N_2O), and halogenated compounds, which can be compared on the basis of carbon dioxide equivalents (CO_2e). Thus, a product carbon footprint can be determined with respect to direct and indirect GHG emissions across the life cycle. The importance of using energy consumption and carbon footprint as

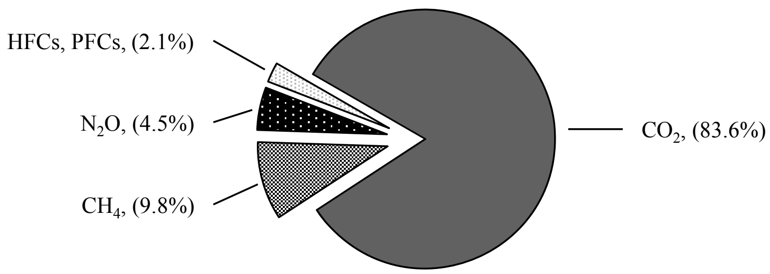
1 environmental impact measures of manufacturing activities
2 as indicators of global climate change, high energy consumption, and health concerns
3 their use in assisting governmental decision makers have been reported widely in the literature (Laurent et al., 2010; Boguski, 2010; Jeswiet and Nava, 2009; Joyce et al., 2010).

By evaluating energy consumption of product manufacturing and supply chain activities, as well as associated CO_2 and other GHG releases during product design, the environmental performance of the product can be improved. Such improvements can provide competitiveness in the marketplace by appealing to environmentally conscious consumers, as well as by reducing operational costs of energy consuming products.

3 Related research

The research herein is an extension of prior work (Alsaffar et al., 2012), which presented a framework to reduce the energy consumption and carbon footprint from the cradle-to-gate perspective by considering product manufacturing and supply chain networks simultaneously. Unit process modelling (UPM) was the primary analysis method applied. To demonstrate the framework, bicycle pedal manufacturing was investigated. The pedal assembly was comprised of ten components using several materials, e.g., steel, aluminium, and plastic. Manufacturing processes included casting, cutting, turning, milling, and drilling.

Figure 2 US greenhouse gas emissions for 2010 based on CO_2e



Source: US EPA (2012)

Efforts considered process flow alternatives for each component, and impact analysis spanned the whole supply chain. Several supply chain network scenarios were assumed to elucidate transportation-related effects. The components with the lowest carbon footprint were selected to achieve the lowest overall cradle-to-gate carbon footprint. It was shown that simultaneous consideration of manufacturing and supply chain processes can impact decision making and improve product life cycle environmental performance in the design stage. The current research undertakes a similar approach with a focus on textile product manufacturing. Work extends the generalised models for underlying materials and components representative of textile-based products. The methodology is described in greater detail in Section 4. The balance of this section discusses related supporting literature.

3.1 Manufacturing process considerations

Sustainable product development requires the analysis of manufacturing processes and supply chain network activities, simultaneously. Thus, the energy consumption and carbon footprint for each process must be considered from cradle to gate. Products require various processes and processing steps to convert raw materials into the final product. The synthetic textile manufacturing process chain starts with the chemical processes to produce polymers, followed by fibre manufacturing, yarn processing, fabric production, and final product manufacturing. Due to the variety of the processes in textile manufacturing, different facilities are needed to produce the finished product; this leads to a large amount of energy use.

Hasanbeigi and Price (2012) provided a review of energy use and efficiency improvement opportunities for major processing activities across the textile supply chain. Other researchers have widely explored these opportunities in the textile industry (Herrmann and Thiede, 2009; Hasanbeigi and Price, 2012; Hasanbeigi et al., 2011), and are not reviewed here. Product design and manufacturing processes need to be studied at the early design stage to understand the economic and environmental aspects simultaneously (Allen et al., 2002).

Manufacturing process-related environmental impacts can be minimised and improved by looking at three categories:

1 process improvement

2 new process development

3 process planning (Ramani et al., 2010).

New process development can lead to replacing conventional manufacturing processes with new processes exhibiting lower environmental impact. New manufacturing processes, e.g. additive manufacturing, may help designers address environmental impacts, in addition to economics, in certain applications. Similarly, a metalworking fluid delivery can be improved by using a water-based fluid or by switching to a gas-based lubrication system (Skerlos et al., 2004). One study found that replacing shot peening and dry turning with laser shock peening and laser assisted turning, respectively, could significantly reduce environmental impacts (Zhao et al., 2010).

Several studies demonstrated potential improvements through process planning using input-output process modelling and optimisation based approaches (Sutherland and Gunter, 2001; Lin and Polenske, 1998; Fang et al., 2011). To improve environmental performance of the textile industry, design phase efforts can focus on decisions that impact manufacturing processes. For instance, energy efficiency solutions in yarn spinning, weaving, wet processing, and fibre production can be developed and implemented (Hasanbeigi and Price, 2012).

Reducing the energy consumption and related carbon footprint of conventional metal manufacturing processes has been an area of intense focus (Nava, 2009; Gutowski et al., 2006). Haapala et al. (2004) studied a set of manufacturing processes, e.g., sand casting, bending, welding, and laser cutting, for the production of large steel products. The objective was to estimate materials and energy use and associated wastes using a spreadsheet tool. A recent study by Dietmair and Verl (2008) described an approach to determine the energy consumption of production equipment and demonstrated the method for the milling process. Similarly, Diaz et al. (2011) investigated the energy consumption of the milling process by measuring the material removal rates and studying the power demand to find and characterise the energy consumption. According to a review of engineering research in sustainable manufacturing, fundamental aspects include metric definition and decision making, which are key tasks at the early design stage (Haapala et al., 2013).

Researchers have established a method to analyse manufacturing processes and quantify related energy consumption based on LCA, known as unit process life cycle inventory (UPLCI) in the US and as the cooperative effort on process emissions in manufacturing (CO2PE!) in Europe (Kellens et al., 2012a, 2012b; Overcash and Twomey, 2012). According to these methods, energy consumption and carbon footprint in product manufacturing processes can be evaluated by using research literature, tools, software, or experiments. For instance, Alsaffar et al. (2011) looked at how changes in the design of a three-ring binder affected manufacturing and supply chain impacts. The study was assisted using LCA software (SimaPro), and compared eight three-ring binder design alternatives. It was found that transportation impacts were low compared to material and manufacturing impacts. The same characteristic was found when applying a process-based approach for bicycle pedal manufacturing (Alsaffar et al., 2012).

3.2 Supply chain considerations

Due to globalisation, products are often assembled in one location, while components may originate from geographically dispersed locations. Thus, supply chain considerations are as important as manufacturing processes in determining product impacts. Total cost and environmental impact reduction for transportation of raw material to the manufacturing companies and transportation of the final products to the customers are concerns of academic and industry researchers. Recently, Ilgin and Gupta (2010) reviewed 540 peer-reviewed papers to examine the current research progress in environmentally conscious manufacturing and product recovery (ECMPRO). They focused on four phases of the product life cycle: design, supply chain networks, remanufacturing, and disassembly. Another review of the sustainable supply chain management literature by Seuring and Müller (2008), referenced 191 published papers from 1994–2004. They identified two different strategies, i.e., for supply chain management risk and performance and for sustainable products.

Carbon emissions, which result from a product supply chain, have been identified as a threat to the global warming (Sundarakani et al., 2010). Carbon footprint can be measured and compared for different supply chain modes and networks. For instance, rail transport has been shown to have a 3–9% lower carbon footprint than other transportation modes (Ibbotson and Kara, 2011). Chiu et al. (2010) investigated a product design framework based on a graph theory optimisation methodology combined with LCA, which accounted for cost and carbon footprint at the product development phase. Their approach was applied to minimise the cost and carbon footprint of a global supply chain for bicycle manufacturing. Bevilacqua et al. (2011) performed a study on the effect of different supply chain networks on the carbon footprint of textile product manufacturing (a wool sweater). With the help of Monte Carlo simulation, variations of transportation type, combinations of transportation type and route, and selection of suppliers were explored to assess supply chain carbon footprint.

Understanding the environmental consequences of the transportation motivates decision makers to integrate supply chain considerations into product design decisions. In this stream of research, efforts focus on addressing how different supply chain transportation modes and routes affect energy consumption and related carbon footprint. Since textile product manufacturing requires multiple production processes at different locations, many supply chain alternatives can be defined by a single product design. In the following section, this complexity will be addressed, as well as the product manufacturing processes considered in the development of the research methodology.

4 Research methodology

Simultaneous consideration of manufacturing processes and supply chain design alternatives is pursued to reduce the cradle-to-gate energy consumption and related carbon footprint for textile-based products. While prior studies have applied standard LCA tools to analyse textile product manufacturing processes or supply chain networks independently, the present work is the first known study to develop and apply a comprehensive process-based modelling approach to assess these simultaneously. The intent is to explore the energy consumption and related carbon footprint and the existing tradeoffs between different product designs and supply chain networks.

Eastlick and Haapala (2012) proposed the general steps to choose the most sustainable design alternative as follows:

1. generate the design alternatives
2. choose the sustainability metrics
3. determine and evaluate the relative importance of metrics
4. generate alternative rankings
5. compare and contrast the alternatives.

In the approach developed and applied herein, the steps to analyse the environmental impacts of textile-based product manufacturing processes and supply chain alternatives are as follows:

1. disassemble the backpacks
2. determine the component compositions, masses, and dimensions
3. create the supply chain network including modes and distances
4. collect supply chain and manufacturing process data from technical literature
5. conduct environmental impact assessment

6 interpret and compare results.

Two backpacks were selected for product dissection, or disassembly, to determine their components and material composition (Figure 3). The selected backpacks are made from similar materials, but vary in design. While the first backpack (backpack 1) had wheels, two handles (carry and pull), and four compartments; the second backpack (backpack 2) had no wheels, one handle (carry), and three compartments. After dissection, the mass and dimensions were measured for each component in the finished product, as well as recording the material type. Then, for each fabric piece, the maximum overall length and width dimensions were noted. These dimensions were used to estimate the size of the sheet of fabric from which each piece was cut. The masses of the fabric sheets and plastic components were calculated and aggregated for each material type.

Figure 3 Disassembled view of backpack 2 (see online version for colours)

Next, an arbitrary supply network was created. Figure 4 shows the major nodes of a textile product supply chain network for product a composed of i materials; the suppliers (S_j) of materials, fibre, fabric, and components; supplier warehouses (W_j); small distribution centres (DS_k); large distribution centres (DL_k); and the final product manufacturer (M). Nodes of the supply chain are connected by links, which represent different transportation modes and distances. It can be assumed that bolts of fabric and plastic components are produced by independent suppliers. These will be shipped to the manufacturing company for cutting, sewing, and finishing.

In addition to the geometry, designers can specify different materials from which to construct a backpack; material decisions define the part masses, supply chain networks, and resulting energy consumption and carbon footprint. New manufacturing processes having less environmental impact and end-of-life management strategies for the finished product, such as recycling, can also be considered in the design stage. Four primary materials are typically used to produce backpacks, including polyester, polypropylene, nylon, and polyethylene. Raw material suppliers are located in various locations globally, but primarily in Asia.

Major suppliers were identified in Japan, Thailand, Vietnam, South Korea, and Taiwan. Materials must be transported to the various manufacturers and distribution centres. The distribution centres are assumed to be located in Japan, Vietnam, and China. Locations and distances were determined with the assistance of a major outdoor gear manufacturer and using online tools (Patagonia, 2013). Table 1 shows possible supply chain alternatives, raw material suppliers, distributions, distances, and transportation modes.

Table 1 Supply chain network alternatives

Alternative	*From*	*To*	*Distance (km)*	*Air*	*Road*	*Road/rail*	*Rail*	*Deep sea*
1	Tokyo, Japan	Yamaguchi, Japan	824.3		x	x	x	
	Yamaguchi, Japan	Kagoshima, Japan	258.1		x	x	x	
	Kagoshima, Japan	Shanghai, China	807.4					x
	Shanghai, China	Guangdong, China	1,212.2		x	x	x	
2	Tokyo, Japan	Guangdong, China	2,891	x				
3	Seoul, South Korea	Guangdong, China	2,352.9					x
4	Bangkok, Thailand	Da Nang, Vietnam	862.2		x	x	x	
	Da Nang, Vietnam	Guangdong, China	928.5					x
5	Bangkok, Thailand	Guangdong, China	1,811.3		x	x	x	
6	Ho Chi Minh City, Vietnam	Guangdong, China	1,522.2	x				
7	Ho Chi Minh City, Vietnam	Da Nang, Vietnam	607.3		x	x	x	
	Da Nang, Vietnam	Guangdong, China	928.5					x
8	Ho Chi Minh City, Vietnam	Guangdong, China	2,146		x	x	x	
9	Taipei, Taiwan	Guangdong, China	797	x				x

Figure 4 outlines several modes and routes for materials and parts to follow from the initial supplier to the final product manufacturer. For instance, to transport polyester fibre from Tokyo, Japan to Yamaguchi, Japan, three different modes are available (i.e., road, rail, or a combination of both), but to transport polyester fibre from Kagoshima, Japan to Shanghai, China, only one option is available (deep-sea container). Thus, different supply chain scenarios can be explored in terms of sustainability performance, as demonstrated below. It is noted that the final destination of all piece-parts is Guangdong, China.

Figure 5 shows the backpack manufacturing process flow. Raw material processing, fibre manufacturing, fabric manufacturing, and transport of the materials and parts are considered. To produce a backpack, four different materials are usually needed, as mentioned above. Each material production route starts with raw material manufacturing. Then different process flows, such as fibre production, are applied. Fabric production (e.g., knitting) is the final step to produce the raw materials to produce a backpack (aside from the plastic and metal components). To create and assemble shaped fabric panels, different types of cutting and sewing operations are needed.

Figure 4 Schematic of supply chain network alternatives for textile product manufacturing

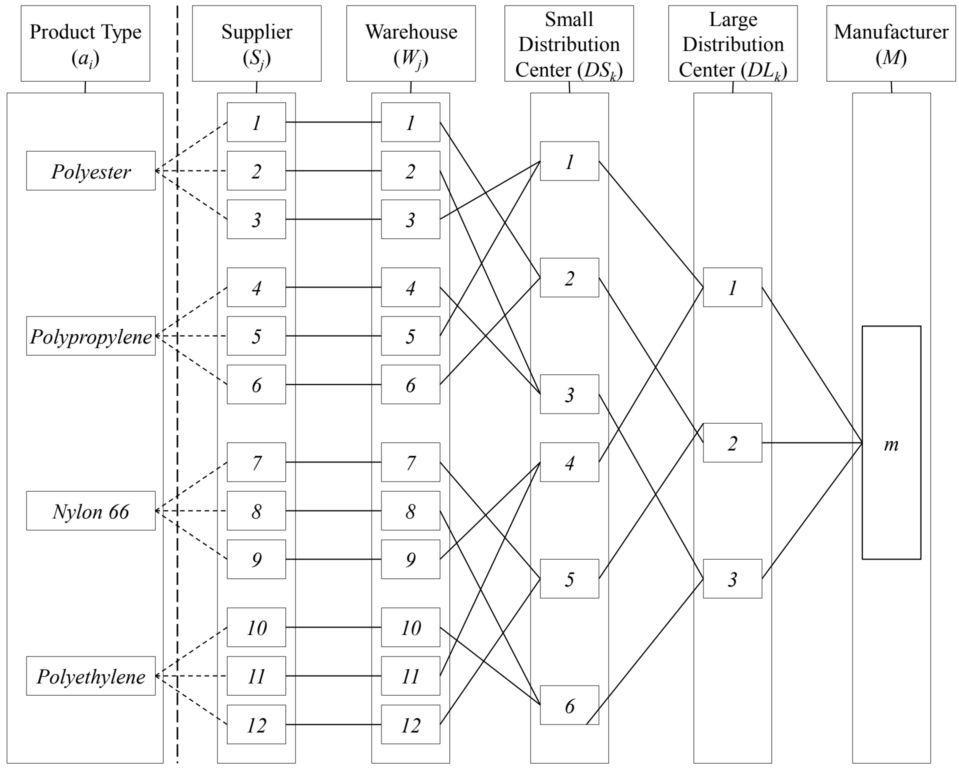
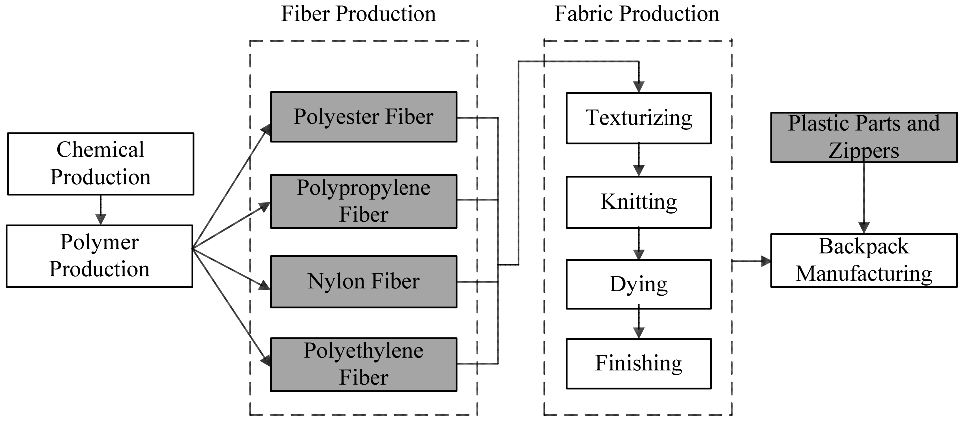


Figure 5 Backpack manufacturing and textile production process flow



To find energy consumption and carbon footprint of backpack manufacturing, several studies from literature have been reviewed. Thus, the quality of results is dependent on data quality and availability. A single backpack is selected as a functional unit. The studied system boundary includes material extraction, material processing, manufacturing operations, and transportation. Use and end-of-life phases are excluded. Since backpacks are non-energy consuming, and do not consume resources or create wastes, the use phase is not considered.

5 Energy consumption and carbon footprint analysis

Finding the environmental impacts of each material and component can be time consuming, and the results are dependent upon the data quality and availability. The supporting data is gathered from the literature and the analysis is based on data collected for two different backpack designs.

5.1 Supply chain network

There are a myriad of feasible supply chain network alternatives available for material and component production and transport. The carbon footprint (CF) of the supply chain network for material or component *i* can be calculated using equation (1), where mi is the mass of material or component *i* to be transported, d_n is the distance using transportation mode *n*, and α_n is the average emission factor for transportation mode *n*.

$$CF_i = m_i * \sum_n d_n * \alpha_n \tag{1}$$

Similarly, the energy consumption (EC) of the supply chain network for material or component i can be calculated using equation (2):

$$EC_i = m_i * \sum_n d_n * \beta_n \tag{2}$$

where β_n is the average energy conversion factor. Common values for α_n and β_n are in Table 2, which assumes transport energy is from direct fuel combustion, and not electrical energy.

Table 2 Average emissions and energy conversion factors for various transportation modes

Transport mode	*Emission factor (g CO_2e/t–km)*[a]	*Energy factor (MJ/t–km)*[b]
Road	62	2.426
Rail	22	0.209
Intermodal road/rail	26	1.317
Deep-sea container	8	0.160
Air freight	602	6.900

Notes: [a]McKinnon (2003) and [b]Davis et al. (2013).

Two different supply chain networks were chosen arbitrarily from among all the possible alternatives. Selected supply chain alternatives, origin locations, distribution centres, distances, transportation modes, and fabric and components transported are described in Table 3. For supply chain alternative A, all fabrics and components originate from Tokyo, Japan, while for alternative B, they come from different countries. The final destination is Guangdong, China, where the backpack manufacturing company is located. Tables 4 and 5 present the energy consumption and carbon footprint results for each backpack design variant for supply chain alternatives A and B, respectively. Regardless of the backpack design, it can be seen that total energy consumption and carbon footprint of supply chain alternative B is greater than alternative A. Air freight dominates other transportation modes due to the higher energy and emissions conversion factors.

Table 3 Two supply chain network alternatives for backpack production

Alternative	*Leg*	*From*	*To*	*Distance (km)*	*Transport mode*	*Component production by material type*
A	1	Tokyo, Japan	Yamaguchi, Japan	824	Road	All materials
	2	Yamaguchi, Japan	Kagoshima, Japan	258	Rail	
	3	Kagoshima, Japan	Shanghai, China	807	Deep-sea container	
	4	Shanghai, China	Guangdong, China	1,212	Intermodal road/rail	
B	1	Tokyo, Japan	Yamaguchi, Japan	824	Rail	Polyester
	2	Yamaguchi, Japan	Kagoshima, Japan	258	Intermodal road/rail	
	3	Kagoshima, Japan	Shanghai, China	807	Deep-sea container	
	4	Shanghai, China	Guangdong, China	1,212	Road	
	5	Bangkok, Thailand	Da Nang, Vietnam	862	Rail	Polyethylene
	6	Da Nang, Vietnam	Guangdong, China	928	Deep-sea container	
	7	Taipei, Taiwan	Guangdong, China	797	Deep-sea container	Nylon 6
	8	Tokyo, Japan	Guangdong, China	2,891	Air	Polypropylene

Table 4 Backpack transportation impact analysis results for supply chain alternative A

Backpack	*Leg*	*Component mass (g)*	*Energy consumption (MJ)*	*Carbon footprint (g CO_2e)*	*Total energy consumption (MJ)*	*Total carbon footprint (kg CO_2e)*
1	1	1,837	3.67	90	6.94	0.2
	2	1,837	0.10	10		
	3	1,837	0.23	20		
	4	1,837	2.93	60		
2	1	496	0.99	30	1.87	0.05
	2	496	0.02	3		
	3	496	0.06	3		
	4	496	0.79	156		

Table 5 Backpack transportation impact analysis results for supply chain alternative B

Backpack	*Leg*	*Component mass (g)*	*Energy consumption (MJ)*	*Carbon footprint (g CO_2e)*	*Total energy consumption (MJ)*	*Total carbon footprint (kg CO_2e)*
1	1	518	0.08	10	8.15	0.6
	2	518	0.17	3		
	3	518	0.06	3		
	4	518	1.52	39		
	5	916	0.16	17		
	6	916	0.14	7		
	7	119	0.01	1		
	8	284	5.66	494		
2	1	359	0.06	7	1.74	0.06
	2	359	0.12	2		
	3	359	0.05	2		
	4	359	1.05	27		
	5	43	0.01	1		
	6	43	0.01	1		
	7	85	0.01	1		
	8	9	0.18	16		

5.2 Raw materials processing

Four raw materials were identified as the key materials in constructing backpacks: polyester, polypropylene, nylon, and high density polyethylene. Polyester is the most popular man-made fibre in textile manufacturing (Hasanbeigi, 2010; Laursen and Hansen, 1997). Cherrett et al. (2005) conducted an ecological footprint analysis of three different fibres including cotton, hemp, and polyester. Results showed that polyester fibre manufacturing is the most energy intensive among the three. The total energy consumption of manufacturing polyester fibre is 104,479 MJ/t (Cherrett et al., 2005).

Keoleian et al. (2012) performed LCA studies for various materials and processes in the greenhouse gases, regulated emissions, and energy use in transportation (GREET) model developed by Argonne National Laboratory. The total energy consumption of polypropylene resin production is 66,129 MJ/t (Keoleian et al., 2012). Two types of nylon (nylon 6 and nylon 66) are available and selected based on tenacity, a measure of a fabric's ability to resist tearing. It is assumed that nylon 6 is used in backpack production. The total energy consumption of nylon 6 resin production is 97,362 MJ/t (Keoleian et al., 2012). The other components of the backpacks are assumed to be made from high-density polyethylene. High-density polyethylene has a large strength to density ratio. The total energy consumption of polyethylene resin manufacturing processes is 67,248 MJ/t (Keoleian et al., 2012).

To calculate carbon footprint, the amount of electricity required must be determined and the relevant country identified. The emissions conversion factor for electricity generation is dependent on the sources (e.g., coal power or hydropower) needed to provide energy to the electrical grid, which vary by geographic location (Table 6). As the same processes are used, the energy consumption for alternatives A and B are assumed to be equal, though they may vary from supplier to supplier in reality. Because of the different sources of energy for the electrical grid in each location, however, the effect on carbon footprint results are demonstrated. The carbon footprint of alternative B is larger than alternative A for each backpack, similar to what was found for the transportation results.

Table 6 Carbon footprint conversion factors for selected countries

Country	*CF factor (g CO_2e/kWh)*
China	867.81
Japan	488.93
Taiwan	738.56
Thailand	598.65

Source: Hill et al. (2012)

Table 7 Raw material processing impacts for the two supply chain design alternatives

Backpack	*Materials*	*Component mass (g)*	*Energy consumption (MJ)*	*Carbon footprint (kg CO_2e)*	
				Alternative A	*Alternative B*
1	Polyester	518	54.14	7.3	7.3
	Polypropylene	284	18.40	2.8	2.8
	Nylon 6	119	12.81	1.7	2.6
	Polyethylene	916	67.85	9.2	11.3
	Total	1,837	155.45	21.0	24.0
2	Polyester	359	37.50	5.1	5.1
	Polypropylene	9	0.60	0.1	0.1
	Nylon 6	85	9.17	1.2	1.9
	Polyethylene	43	3.19	0.4	0.5
	Total	496	50.49	6.8	7.6

Table 7 summarises the raw material processing energy consumption and carbon footprint for the two backpacks and two supply chain alternatives. It should be noted that energy consumption includes electricity generation from a variety of sources as defined by the electrical grid, which in turn impacts carbon footprint.

5.3 *Fibre manufacturing process*

After producing the raw material, the next step of the backpack manufacturing is polyester and nylon fibre production. Yarn spinning is the most energy consuming process of fibre manufacturing, using 72% of the process energy in the form of electricity (Koç and Kaplan 2007). Thus, only the yarn spinning process is considered in estimating the energy consumption and carbon footprint of fibre manufacturing. Koç and Kaplan (2007) calculated the total energy consumption of the yarn spinning process for different yarn counts (linear density). Assuming that the yarn count is 20 tex (grams per 1,000 metres) for combed weaving yarn used for backpack fabric, the total spinning energy consumption is 3.64 kWh/kg of yarn (Koç and Kaplan, 2007). The carbon footprint will vary based on the associated energy generation profile for each supplier location.

5.4 Injection moulding process

In this study, it is assumed that the accessory parts used are made of polypropylene and polyethylene. The main manufacturing process is injection moulding, which uses polypropylene (PP) and polyethylene resins as raw input materials to produce the final parts. The injection moulding process steps include heating the PP or polyethylene resin, injection of molten resin to the mould, cooling the mould with water, and ejecting the final product (Keoleian et al., 2012).

Table 8 Fibre and component production impacts for the supply chain design alternatives

Backpack	*Materials*	*Component mass (g)*	*Energy consumption (MJ)*	*Carbon footprint (kg CO_2e)*	
				Alternative A	*Alternative B*
1	Polyester	518	6.79	0.9	0.9
	Polypropylene	284	1.9	0.3	0.3
	Nylon 6	119	1.56	0.2	0.3
	Polyethylene	916	16.90	2.3	2.8
	Total	1,837	27.35	3.7	4.3
2	Polyester	359	4.70	0.6	0.6
	Polypropylene	9	0.06	0.1	0.1
	Nylon 6	85	1.12	0.1	0.2
	Polyethylene	43	0.79	0.1	0.1
	Total	496	6.68	0.9	1

It should be noted that the total calculated energy consumption and carbon footprint excludes the resin manufacturing and transportation, and is calculated in raw materials processing section. The total energy consumption for polyethylene injection moulding is 16.7 MJ/kg, and the total energy consumption of injection moulding of PP is 6.7 MJ/kg (Keoleian et al., 2012). Table 8 summarises the results for fibre and component manufacturing processes for the two backpacks and two supply chain alternatives.

5.5 Fabric manufacturing

The steps in fabric production are weaving and wet processing, which includes preparation, dyeing, printing, and finishing. The amount of electricity needed for weaving preparation, such as automatic winding, classical wending, and warping, is 2.3 MJ/kg, which is negligible compared to wet processing (Koç and Çinçik, 2010). The average electrical energy and fossil fuel required for weaving are 21 MJ/kg and 13 MJ/kg, respectively (Visvanathan et al., 2000). The average amount of electricity and fuel for wet processing, including dyeing and finishing, provided by Visvanathan et al. (2000) are 45.4 MJ/kg and 70 MJ/kg, respectively.

Consequently, it is concluded that the total energy consumption needed for fabric manufacturing is 151.5 MJ/kg. Table 9 summarises results of fabric manufacturing processes for the two backpacks and two supply chain alternatives. The total energy consumption and carbon footprint of the fabric manufacturing processes dedicated to polyester and nylon 6 for each backpack are shown. The primary driver for variation in fabric manufacturing carbon footprint is due to the nylon fabric, which is sourced from Japan for alternative A and from Taiwan for alternative B. Since Taiwanese electricity has a larger carbon footprint, a larger carbon footprint is reflected in backpacks produced using supply chain alternative B.

Table 9 Fabric manufacturing impacts for the two supply chain design alternatives

Backpack	*Materials*	*Component mass (g)*	*Energy consumption (MJ)*	*Carbon footprint (kg CO_2e)*	
				Alternative A	*Alternative B*
1	Polyester	518	78.46	10.6	10.6
	Nylon 6	119	18.08	2.4	3.7
	Total	637	96.53	13	14.3
2	Polyester	359	54.34	7.4	7.4
	Nylon 6	85	12.90	1.7	2.6
	Total	444	67.24	9.1	10

5.6 Textile product assembly

Textile product manufacturing and assembly includes cutting, sewing, and finishing (i.e., ironing and pressing, and packaging). Due to a lack of published information, apparel manufacturing is used to represent backpack manufacturing (Franklin Associates, Ltd 1993). The energy requirement for final product manufacturing, assembly, and packaging of polyester product is 24 MJ/kg (Franklin Associates, Ltd 1993).

Table 10 shows the results for final manufacturing, assembly, and packaging of the two backpack design variants. It can be noted that only sewn fabric parts are included in this calculation; the parts attached to the final product by gluing are excluded. Process energy information was available for polyester product manufacturing, and it is assumed that final product manufacturing using nylon 6 requires the same amount of energy. Supply chain alternatives are not considered for final backpack manufacturing as both backpacks will be produced at the same location (Guangdong, China).

Table 10 Energy consumption and carbon footprint of manufacturing and assembly

Backpack	*Materials*	*Component mass (g)*	*Total energy (MJ)*	*Carbon footprint (kg CO_2e)*
1	Polyester	518	12.45	3
	Nylon 6	119	2.87	0.7
	Total	637	15.32	3.7
2	Polyester	359	8.62	2.1
	Nylon 6	85	2.05	0.5
	Total	444	10.67	2.6

Table 11 Overall energy consumption and carbon footprint for production of two backpack design variants for supply chain alternative A

Manufacturing and transportation activities	*Backpack 1A*		*Backpack 2A*	
	Energy consumption (MJ)	*Carbon footprint (kg CO_2e)*	*Energy consumption (MJ)*	*Carbon footprint (kg CO_2e)*
Raw material processing	155.45	21	50.49	6.8
Component manufacturing processes (fibre, plastic parts)	27.35	3.7	6.68	0.9
Fabric manufacturing	96.53	13	67.24	9.1
Backpack assembly	15.32	3.7	10.67	2.6
Transportation	6.94	0.2	1.87	0.05
Total energy consumption	301.59	-	136.95	-
Total carbon footprint	-	41.6	-	19.45

Table 12 Overall energy consumption and carbon footprint for production of two backpack design variants for supply chain alternative B

Manufacturing and transportation activities	*Backpack 1B*		*Backpack 2B*	
	Energy consumption (MJ)	*Carbon footprint (kg CO_2e)*	*Energy consumption (MJ)*	*Carbon footprint (kg CO_2e)*
Raw material processing	155.45	24	50.49	7.6
Component manufacturing processes (fibre, plastic parts)	27.35	4.3	6.68	1
Fabric manufacturing	96.53	14.3	67.24	10
Backpack assembly	15.32	3.7	10.67	2.6
Transportation	8.15	0.6	1.74	0.06
Total energy consumption	302.8	-	136.82	-
Total carbon footprint	-	46.9	-	21.26

Tables 11 and 12 summarise the energy consumption and carbon footprint of manufacturing backpacks 1 and 2 for supply chain alternatives A and B. As expected, the differences in mass and materials used between the two backpack design variants caused a disparity in the predicted manufacturing and supply chain energy consumption and carbon footprint. Since the total weight of the backpack 1 design is approximately four times that of the backpack 2, it exhibited higher environmental impacts due to materials processing and transportation.

Total energy consumption of the backpack 1 is only twice the level of backpack 2, however. By normalising on a per unit mass basis, the energy consumptions to produce Backpacks 1 and 2 are 160.4 MJ/kg and 272.1 MJ/kg, respectively. Similarly, normalised carbon footprints of backpacks 1 and 2 are 10.4 kg CO_2e/kg and 21.2 kg CO_2e/kg, respectively.

Figure 6 Energy consumption for backpack manufacturing and supply chain networks

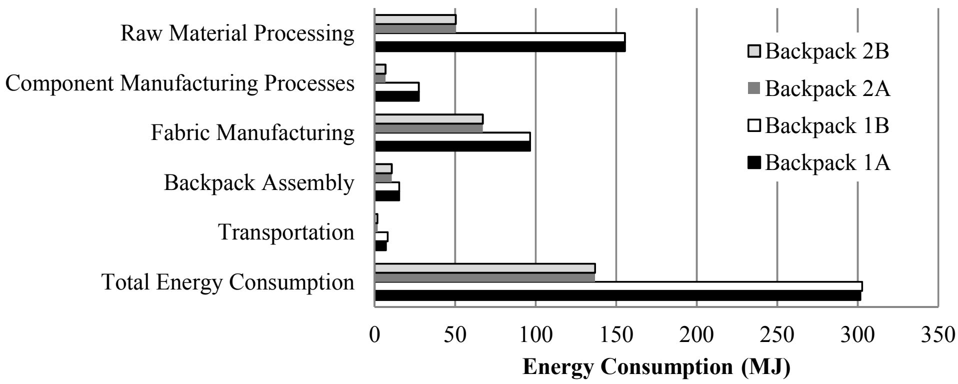


Figure 6 presents a comparison of the energy consumption for the major manufacturing processes for each backpack design. An evident difference between backpacks 1A and 1B are due to transportation energy consumption, which are 6.9 and 8.2 MJ, respectively. For backpack 2, the respective transportation energy consumptions for alternatives A and B are estimated to be 1.87 and 1.74 MJ, respectively. The reduction over backpack 1 is largely due to omission of air transport.

It can also be seen that supply chain alternative B results in an increase in transportation energy consumption for backpack 1, while it is reduced for backpack 2, a disparity due to the variation in materials and components used. It can be noted that manufacturing energy will be the same for each supply chain alternative, due to the use of the same manufacturing process set for a single backpack design.

Figure 7 Carbon footprint for backpack manufacturing and supply chain networks

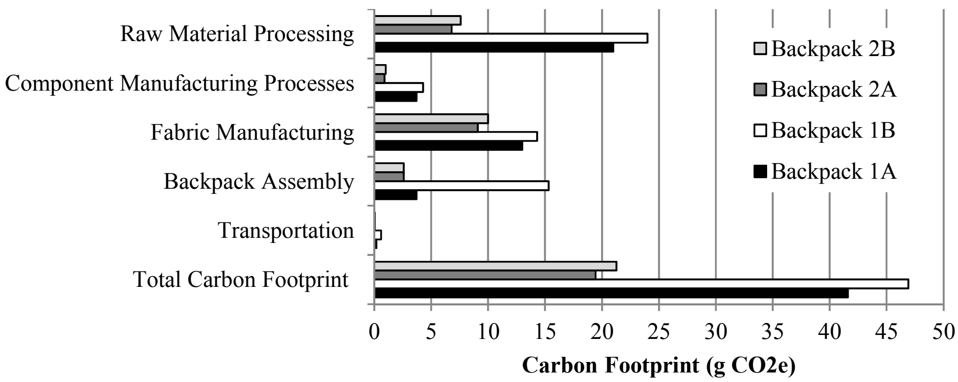


Figure 7 presents the carbon footprint for backpack manufacturing processes and transportation activities for each backpack scenario. Backpack 1B has the largest carbon footprint. For backpack 1A and 1B, the raw material processes dominate the other processes in terms of carbon footprint. For backpack 2A and 2B, however, fabric manufacturing processes have larger carbon footprints than other processes. For each backpack scenario, the carbon footprint of manufacturing dominates that of transportation. In general, supply chain alternative B has a larger carbon footprint than alternative A.

6 Summary and conclusions

This study reported the integration of sustainability principles into the design of products, manufacturing processes, and relevant supply chain networks to assist decision makers, specifically for textile-based products. Two backpacks with variant designs were selected to investigate the effect of design decisions on the environmental impacts of product manufacturing and supply chain activities. The energy consumption and carbon footprint of these activities were evaluated from raw material extraction to assembly of the final product. Raw material extraction, materials processing, manufacturing operations, and transportation for each backpack material and component were considered. Information gathered from previous studies is utilised to assist with the environmental impact assessment undertaken in this research. Two different supply chain alternatives with various points of origin, distribution centres, distances, and transportation modes were considered for each backpack's materials and components.

In the studied case, the carbon footprint due to transportation was found to be low (0.2–1.2%) compared to manufacturing, which demonstrates the importance of understanding the direct influence of product design on manufacturing processes and equipment. In other cases, however, the supply chain may have a greater effect on carbon footprint, and should be considered. As expected, it was found that air transport carbon footprint dominated that of other transportation modes due to a large emissions factor. For backpack 1, the total manufacturing and transportation carbon footprint was three times greater for alternative B than alternative A. It was found that 30% of the carbon footprint was due to fabric manufacturing for backpack 1, while it contributed to half of the carbon footprint for backpack 2. Fabric manufacturing carbon footprint was primarily driven by wet processing, which uses fossil fuel-based thermal energy for steam and heat.

This resulting work of the research is the first known study to apply a process-based approach to simultaneously analyse the manufacturing and supply chain energy consumption and carbon footprint for textile-based products, which can assist industry practitioners during early product design. Different product design and manufacturing alternatives can be explored in the context of supply chain configuration and associated energy consumption and carbon footprint. Moreover, the general approach can be extended to analyse different material types used in the textile industry. The method presented is a generally applicable approach, and the backpack case study is an illustrative example of this approach. The life cycle inventories constructed and the modelling results will facilitate future studies for the textile industry. This data and information was previously not compiled or available from an individual source. Data gathering from many disparate sources is an activity to which practitioners can devote little time.

The general approach described can be applied to evaluate any product. The supply chain and process models reported, however, are applicable to a more limited number of textile-based products – specifically those that use polyester and nylon fabrics and/or plastic components. These may include jackets, hand bags, gear bags, and other outdoor products, in addition to backpacks. The transportation, polymer processing, and yarn production processes can be applied to any polyester or nylon textile product, while fabric production processes would vary depending on the type of material used and final product.

Future research should consider the effect of a low mass-to-volume ratio for some textile products on transportation environmental impacts. Calculated impacts may underestimate the actual impact for low density products, which are volume-limited, rather than mass-limited for transport. Future studies can apply the methodology presented herein along with known supplier and manufacturer data to generate more accurate results for specific studies. Finally, the cradle-to-gate analysis approach can be extended to consider the entire textile product life cycle by modelling distribution, use, and end-of-life treatment processes and activities, which are also influenced by the product design.

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