Journal of Cleaner Production 170 (2018) 1231–1243

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The life cycle assessment of energy and carbon emissions on wool and nylon carpets in the United States

Jaehun Sim [a], Vittaldas Prabhu [b,*]

[a] Industrial & Management System Engineering, Dong-A University, Busan, Republic of Korea
[b] The Marcus Department of Industrial and Manufacturing Engineering, The Pennsylvania State University, University Park, United States

ARTICLE INFO

Article history:
Received 16 February 2017
Received in revised form
29 July 2017
Accepted 22 September 2017
Available online 26 September 2017

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Carpet
Life cycle assessment
Monte Carlo simulation
System dynamics

ABSTRACT

The U.S. textile industry, which includes the carpet industry, is expected to continue to consume a large amount of energy and generate a large amount of carbon emissions. Since the environmental impacts of the carpet industry are expected to grow in the next decade, it is necessary to estimate the energy consumption and carbon emissions generated at each stage of the entire life cycle of carpet to mitigate these environmental impacts. Thus, this study conducts a life cycle assessment of energy and carbon emissions on two types of carpet – a wool carpet and a nylon carpet – from raw material production to recycling and disposal, along with transportation activities. In addition, this study utilizes a system dynamics approach to investigate the impacts of the uncertainty of market share on total energy consumption and total carbon emissions. The results of this study indicate that the production of 0.09 square meter of a carpet tile requires 20.42 MJ of energy and generates 6.35 kg CO_2-e of emissions for the wool carpet, and consumes 25.42 MJ of energy and produces 4.80 kg CO_2-e of emissions for the nylon carpet. To reduce energy consumption, the use stage of a wool carpet and the raw material production stage of a nylon carpet need to made more efficient, while to reduce carbon emissions, the raw material production stage of a wool carpet and a nylon carpet need to be improved.

1. Introduction

Although traditionally considered a labor-intensive industry, the textile industry actually consumes a large amount of energy in its various and complex manufacturing processes (Hasanbeigi and Price, 2012b) and further produces a large amount of carbon emissions to the atmosphere. A subsector of the textile industry, the flooring market is expected to increase from $214.29 B in the year 2014 to $391.38 B in the year 2023 (Transparency Market Research (TMR), 2015), and therefore the energy use and environmental impacts of flooring market products will increase. Since carpet products account for 51% of the total flooring market in the United States (CRI, 2016), the energy consumption and carbon dioxide (CO_2) emissions generated from the carpet product sector is an important part of the evaluation of potential environmental impacts of the overall textile industry. However, to date few studies have investigated the energy consumption and carbon emissions in the life cycle of a carpet.

The life cycle assessment of carpet generally estimates the energy consumption and the carbon emission production in the entire life cycle of carpet – raw material extraction, raw material production, carpet production, carpet installation, and carpet use, as well as carpet disposal and recycling, along with associated transportation activities from the raw material manufacturer site to the recycling and disposal site (Crowley et al., 2010). In the raw material extraction stage, all required energy and produced carbon emissions related to the extraction of a raw material are estimated, along with the transportation activities from a raw material extraction site to a raw material manufacturing or production site. In the raw material production phase, all energy requirements and accompanying carbon emissions in the manufacture of raw materials are analyzed, along with the transportation activities from a raw material manufacturer site to a carpet manufacturer site.

In the next stage, the carpet manufacturing stage, all energy requirements and carbon emissions production related with the production of a carpet are examined, along with the transportation activities from a carpet manufacturer site to a distribution site. In the carpet installation stage, all the required energy use and

* Corresponding author. The Marcus Department of Industrial and Manufacturing Engineering, 310 Leonhard Building, University Park, PA 16802, USA.
E-mail address: prabhu@engr.psu.com (V. Prabhu).

https://doi.org/10.1016/j.jclepro.2017.09.203
0959-6526/

produced carbon emissions in installing carpet are considered, as well as the transportation of the carpet to a customer site. In the carpet use phase, all energy use and carbon emissions during the use and maintenance of carpet are analyzed. In the recycling and disposal stage, all energy use and carbon emissions during the collection and recycling of post-consumer carpet are examined, as well as the disposal of solid waste and transportation from a customer site to a recycling facility site or a landfill site. The total energy use and the total carbon emissions are estimated by summing the energy consumption and carbon emission production at each stage of the entire carpet life cycle.

Since it is necessary to first quantify the environmental impacts of the carpet product to determine where these impacts might be mitigated, this study estimates the energy consumption and the carbon emissions generated from wool and nylon carpets' entire life cycles. While defining the entire life cycle of carpet as a system boundary to fulfill this objective, this study utilizes the attributional life cycle approach, which measures the environmental impact of products based on energy consumption-based emission with average emission intensity data (Brander et al., 2008), while defining one unit of carpet (0.09 m^2) as a functional unit (FU). In addition, this study analyzes the impact of the uncertainty of market share on the total energy consumption and the total carbon emissions from the year 2017 to the year 2030. To analyze the market share uncertainty, this study utilizes the system dynamics approach, which analyzes the nonlinear behavior of a complex system over a certain time period, while investigating the impacts of uncertainty factors on the system (Sterman, 2000).

Despite the importance of the carpet industry, few research studies have addressed the energy consumption and the carbon emission production in the carpet industry during a carpet's entire life cycle. Thus, the objective of this study is to comprehensively investigate the energy consumption and the carbon emissions at each stage of the entire life cycle of a wool carpet and a nylon carpet from a raw material extraction stage to a recycling and disposal stage, while analyzing the influence of the market share uncertainty on the total energy consumption and the total carbon emission production. Environmental managers will be able to use the results of this study as reference data to determine on which stages of carpet's life cycle they need to focus to offset the environmental impacts of carpet products to make a more a sustainable carpet industry.

2. Literature review

Since few research studies have investigated the energy consumption and carbon emissions of the carpet industry, relevant studies on the broader textile industry are reviewed here to analyze the energy consumption and carbon emissions in the life cycle of textile products. Energy is an important factor in the textile industry, in that it directly influences the textile production cost (Hasanbeigi et al., 2012a) and is largely related to carbon emission production. Several studies assess the energy consumption in the textile industry, for example in the case of China (Peng et al., 2015), Columbia (Martínez, 2009), Germany (Martínez, 2009), India (Palanichamy and Sunda Babu, 2005), Iran (Hasanbeigi et al., 2012a), Taiwan (Hong et al., 2010), and Turkey (Kemal, 2004; Ozturk, 2005).

In addition, some studies focus on specific processes of the textile industry. For instance, the energy consumption amounts of different yarns are investigated in the spinning process (Koç and Kaplan, 2007), while the energy consumption amounts of selected woven fabrics are analyzed in the wet-processing (Koç and Çinçik, 2010). Since a significant amount of energy is consumed during the life cycle of textile products, some studies consider the energy utilization of solar renewable energy (Abdel-Dayem and Mohamad, 2001; Munner et al., 2006) and waste-related renewable energy (Zabaniotou and Andreou, 2010; Kandilli and Koclu, 2011) to decrease the environmental impacts in the textile production stage. Although these research studies analyze the energy consumption of the textile industry in various countries, they do not consider the environmental impact of the textile industry in terms of carbon emissions.

As in other industries, the life cycle assessment methodology has been applied to estimate the energy consumption and carbon emissions of textile products from raw material extraction to recycling and disposal. For instance, some documents indicate the energy requirements of various types of carpets – 306 MJ for Perma-tile modular carpet (Atlas Carpet Mills, 2016), 1430 MJ for non-PVC carpet tile (Shaw Industry Group Inc, 2012), 209.94 MJ for modular carpet (Interface, 2011), 171.3 MJ for modular carpet with post-costumer recycled yarn (Interface, 2009), and 458.6 MJ for Westbond carpet tile (Forbo Flooring, 2013) – during their entire life cycle. With respect to the raw material production stage, some studies conduct the life cycle assessment of various fabric materials – acryl, cotton, elastane, nylon, polyester, viscose, and wool – to evaluate and compare their environmental impacts (Kalliala and Nousianen, 1999; Dahllöf, 2004; Allwood et al., 2006; van der Velden et al., 2014). For instance, the study of Barber and Pellow (2006) considers New Zealand merino wool, demonstrating that on-farm activities contribute about 50% of the total energy consumption and 66% of the total carbon emissions in the wool fiber production.

Several studies conduct a life cycle assessment of the textile production phase (Collins and Aumônier, 2002; Steinberger et al., 2009; Tobler-Rohr, 2011; Walser et al., 2011; Baydar et al., 2015). In addition, life cycle assessment studies of clothing demonstrate that the use stage accounts for the largest portion of energy consumption and carbon emissions during the entire life cycle of clothing (Collins and Aumônier, 2002; Steinberger et al., 2009). In the recycling and disposal stage, several studies demonstrate that energy saving and carbon emission reduction in the cotton production and cotton fiber manufacturing stages can be achieved by recycling cotton from second-hand clothing (Morley et al., 2006; Woolridge et al., 2006). However, most life cycle assessment studies focus only on the energy consumption in some important stages of the entire textile life cycle. In the case of carpet recycling, several studies demonstrate the potential of carpet waste as a recycled raw material, without considering energy consumption or carbon emission production (Mihut et al., 2001; Wang, 2006; Vaidyanathan et al., 2013).

Although the textile industry is energy intensive, a review of the relevant literature on this industry indicates that most of the research studies focus on one particular stage of the entire life cycle of a textile product. Furthermore, there has been little research to estimate the energy consumption and the carbon emission production during the entire life cycle of carpet. Thus, it is worthwhile to analyze two common types of carpets – a wool carpet and a nylon carpet – to understand the energy consumption and the carbon emission amounts at each stage of the entire life cycle of a carpet.

3. Methodology and results

Using the attributional life cycle approach, this study analyzes the energy consumption and the carbon emissions of two types of carpet – a wool carpet and a nylon carpet – from the raw material extraction, the yarn production, the carpet production, the carpet installation, the carpet use, and the carpet recycling and disposal, along with all the related transportation activities, from a raw material production site to a recycling facility or a land fill site. To exemplify the proposed methodology, the developed system dynamics model is further applied to the United States carpet market from 2017 to 2030, while considering the entire life cycle of two types of carpet from raw material extraction to carpet recycling and disposal. For comparison sake, this paper uses the year 2017 for its examples. With respect to cut-off criteria, this study does not consider any type of raw material that is less than one percent of the total mass.

3.1. Life cycle assessment for a wool carpet

A wool carpet is a textile floor covering product, and typically consists of a wool facing, polymer backing and limestone filler (Lippiatt, 2007). A wool carpet is a nature-friendly carpet that accounts for 10% of the global face fiber market (Subbiah, 2008) and 1% of the United States carpet market (Carpet Buyers Handbook (CBH), 2016). Since wool fiber is made from a recyclable natural material, wool carpet is considered to be one of the most environmentally friendly floor covering products available. This study investigates the energy consumption and the carbon emission production of 0.09 m^2 of a wool carpet tile as a functional unit (FU) during its entire life cycle. Since the U.S. carpet demand is expected to be 1.24 B m^2 in the year 2017 (Freedonia, 2014), the expected demand is predicted to be 12.42 M m^2 (138 M FU) for wool carpet.

3.1.1. System boundary of wool carpet

As shown in Fig. 1, the life cycle of a wool carpet consists of five stages – wool production, wool yarn production, wool carpet production, wool carpet use, and wool carpet recycling. The wool production stage considers on-farm sheep and crop production activities related to sheep breeding, sheep shearing, and sheep food production. The wool yarn production stage includes the associated activities of scouring and dyeing to produce wool yarn from greasy wool.

In addition, the wool carpet production is the manufacturing process of a wool carpet including tufting, drying, and finishing. In this stage, the tufting process includes all cutting and assembly of a wool carpet. Next, the wool carpet use stage includes all activities related to installation, maintenance, and cleaning during the service time of a wool carpet. In the end-of-life stage, the recycling case of a wool carpet is only considered, while including shredding and separation activities of a wool carpet to reuse the post-costumer wool carpet as fertilizer. Transportation activities occur between each production stage from greasy wool to post-costumer wool carpet.

3.1.2. Wool carpet raw material production

In order to estimate the energy consumption and carbon emissions in the raw material acquisition of a wool carpet, this study references the farming data on greasy wool from the life cycle assessment of the Australia Merino industry, including on-farm sheep production and crop production (Wiedemann et al., 2016). Among the energy consumption and carbon emissions of three types of Merino wool, this study uses the energy consumption (12.50 MJ/kg) and the carbon emissions (19.50 kg CO_2-e/kg) for the medium Merino wool, which is suitable for a wool carpet. Based on Building for Environmental and Economic Sustainability (BEES) by Lippiatt (2007), this study assumes that wool carpet production requires five types of raw materials – water (30 L/kg), greasy wool (1.25 kg/kg), latex (0.95 kg/m^2), PVC (0.13 kg/m^2), and lubricant (0.05 kg/kg). The energy and carbon emission densities of the raw materials for wool and nylon carpets are tabulated in Table 1.

Since the carbon emission density values of other raw materials besides wool are not available, this study estimates them by multiplying the energy density of a raw material by the carbon emission density of electricity, 0.19528 kg CO_2-e/MJ (EPA, 2017). For instance, the carbon emission density of the fiberglass, 5.47 kg CO_2-e, is estimated by multiplying the energy density of fiberglass, 28 MJ/kg, by the carbon emission density of electricity, 0.19528 kg CO_2-e /MJ.

In the raw material production stage, the total energy requirement is calculated by multiplying the energy density of a product by the manufactured amount of that product using Equation (1). In addition, the energy consumption of any associated transportation activity is calculated by multiplying energy density of a transport

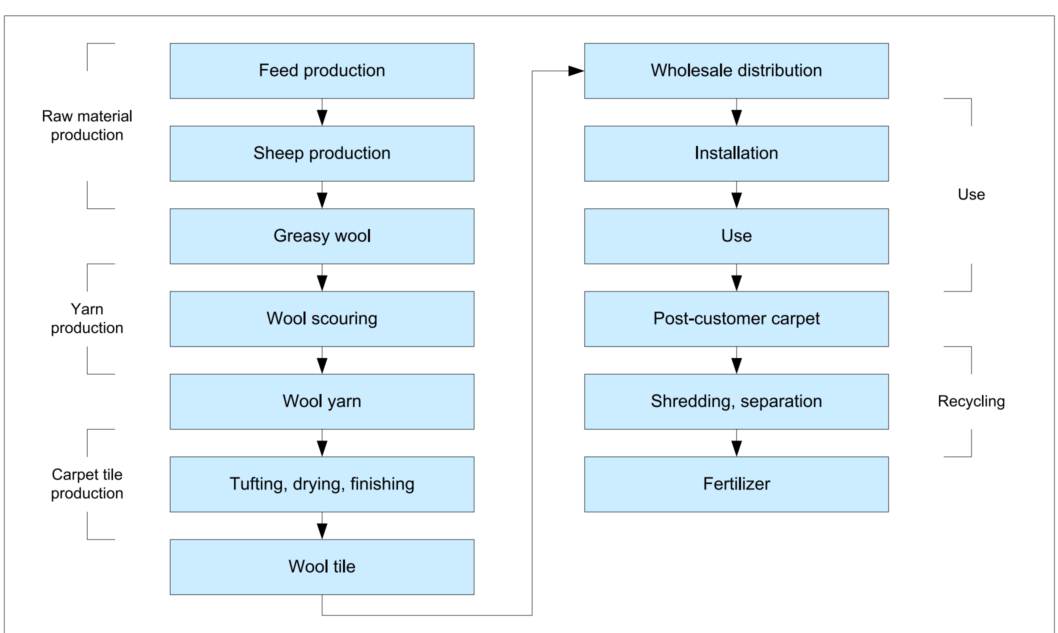

Fig. 1. The system boundary of a wool carpet's life cycle.

Table 1
The energy density and carbon emission density of raw materials.

Material Type	Energy	Carbon Emission	Source
Caprolactam	117.40 (MJ/kg)	22.93 (kg CO_2-e/kg)	Textile Exchange, 2016
Fiberglass.	28 (MJ/kg)	5.47 (kg CO_2-e/kg)	Hammond and Jones, 2006
Latex	16.57 (MJ/kg)	3.24 (kg CO_2-e/kg)	Albers et al., 2008
Lubricant	3.6 (MJ/kg)	0.70301 (kg CO_2-e/kg)	Gresham and Totten, 2008
Polyethylene	22.77 (MJ/kg)	4.45 (kg CO_2-e/kg)	Albers et al., 2008
PVC	25.88 (MJ/kg)	5.05 (kg CO_2-e/kg)	Recio et al., 2005
Water	0.00745 (MJ/L)	0.00145 (kg CO_2-e/L)	Plappally and Lienhard, 2012
Wool	12.50 (MJ/kg)	19.50 (kg CO_2-e/kg)	Wiedemann et al., 2016

mode by the freight weight of a transport mode over the traveled distance.

$$\begin{aligned}\text{Energy} = {} & \sum \text{energy density of a product (MJ/unit)} \\ & \times \text{the manufactured number of products (unit)} \\ & + \sum \text{energy density of a transport mode (l/ton}\cdot\text{km)} \\ & \times \text{the freight weight of a transport mode(ton)} \times \text{distance (km)}\end{aligned} \tag{1}$$

As shown in Equation (2), the total carbon emission production and carbon emission generated from the associated transportation activity are calculated in the same way as in Equation (1), substituting carbon emission density for energy density.

$$\begin{aligned}\text{Carbon} = {} & \sum \text{carbon density of a product (kg carbon emission/unit)} \\ & \times \text{the manufactured number of products (unit)} \\ & + \sum \text{carbon emission density of a transport mode(kg carbon emission/ton}\cdot\text{km)} \\ & \times \text{the freight weight of a transport mode(ton)} \times \text{distance (km)}\end{aligned} \tag{2}$$

3.1.3. *Wool carpet production*

Wool carpet manufacturing consists of three production processes – greasy wool production, wool fiber production, and wool carpet production. The main inflows and outflows for the production of a wool carpet, from raw wool through wool yarn, are shown in Fig. 2, based on the technical manual and user guide from BEES by Lippiatt (2007). In the process of wool yarn production, the original mass of raw wool is decreased by 20% after the grease and dirt are removed in the scouring process (Lippiatt, 2007).

According to BEES (Lippiatt, 2007), in the production of 0.09 m^2 of wool carpet with wool fiber (1.4 kg/m^2), 0.1575 kg of raw wool and 0.126 kg of wool yarn are required. As shown in Fig. 2, the production of 0.126 kg of wool yarn requires 0.07056 MJ of electricity, 0.5418 MJ of natural gas, 0.0063 kg of lubricant, and 3.78 L of water, while generating 0.01645 kg CO_2-e of carbon emissions as a byproduct of the energy consumption. In addition, as shown in Fig. 2, the production of 0.09 m^2 of wool carpet requires 0.162 MJ of electricity, 0.738 MJ of natural gas, 0.0855 kg of latex, and 0.0117 kg of PVC, while producing 0.39193 kg CO_2-e of carbon emissions from the energy consumption.

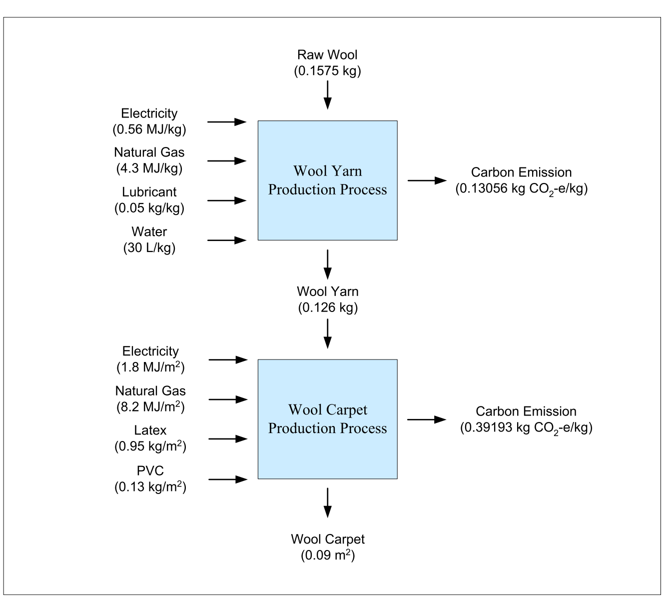

Fig. 2. The main inflows and outflows for wool carpet production.

Fig. 3 illustrates the general manufacturing process for a tufted wool carpet, consisting of four major processes – preparing the yarn, dyeing the yarn, tufting the carpet, and finishing the carpet. After the collected greasy wool is transported to a yarn production facility, the raw wool is scoured, bleached, dried, carded, and spun to prepare wool yarn (Lippiatt, 2007). After being transported to the carpet manufacturing facility, the wool yarn is tufted, woven into the backing with specific densities, patterns, and styles of carpet, and then the tufted carpet is adhered to the backing. In the finishing process, a coating of latex is applied to the underside of the carpet. Finally, after the drying process, the wool carpet is complete.

According to BEES (Lippiatt, 2007), the energy requirement and carbon emission production for the production of one FU of wool carpet (0.09 m^2) is tabulated in Table 2. The scouring and tufting processes require most of the energy in a wool yarn production and a wool carpet production, respectively. Since no data on carbon emission density at each process in the wool carpet production is available, the carbon emission density of each process is estimated as in the raw material production stage.

In a similar way, the total energy consumption for the other stages of the carpet's life cycle is estimated by multiplying the energy density of a process by the amount of energy required in the process, using Equation (3). Similarly, the energy consumption of related transportation activities is calculated by multiplying the energy density of a transport mode by the freight weight of a transport mode over the traveled distance.

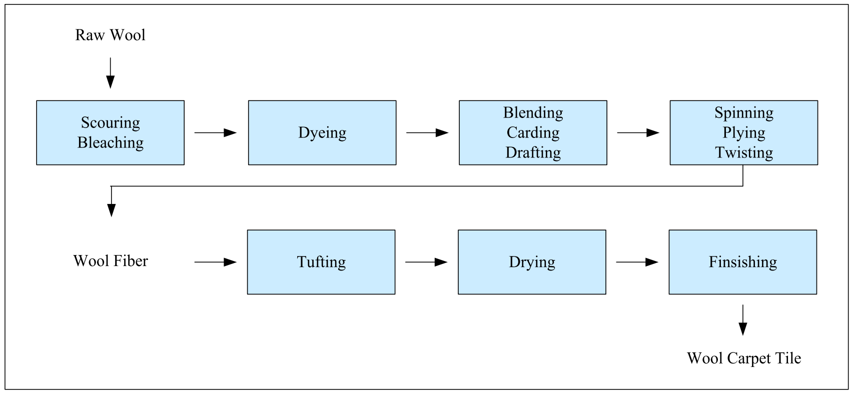

Fig. 3. Wool carpet manufacturing process.

Table 2
Wool carpet production processes (Lippiatt, 2007).

Process (Unit)	Energy (MJ/Unit)	Carbon (kg CO_2-e/Unit)	Process (Unit)	Energy (MJ/Unit)	Carbon (kg CO_2-e/Unit)
Scouring (kg)	3.86	0.75378	Spinning (kg)	Negligible	Negligible
Bleaching (kg).	Negligible	Negligible	Plying (kg)	Negligible	Negligible
Dyeing (kg)	1	0.19528	Twisting (kg)	Negligible	Negligible
Blending (kg)	Negligible	Negligible	Tufting (m^2)	8.34	1.63
Carding (kg)	Negligible	Negligible	Drying (m^2)	1.44	0.28120
Drafting (kg)	Negligible	Negligible	Finishing (m^2)	0.22	0.04296

$$\begin{aligned}\text{Energy} = &\sum \text{energy density of a process (MJ/unit)}\\ &\times \text{the energy requirement of a process(unit)}\\ &+\sum \text{energy density of a transport mode(l/ton}\cdot\text{km)}\\ &\times \text{the freight weight of a transport mode(ton)} \times \text{distance (km)}\end{aligned} \tag{3}$$

In addition, as shown in Equation (4), the total carbon emissions are calculated by multiplying the carbon emission density of a process by the energy consumption of a process, while the carbon emission from the associated transportation activity is calculated by multiplying the carbon emission density of a transport mode by the freight weight of that transport mode over the traveled distance.

$$\begin{aligned}\text{Carbon} = &\sum \text{carbon density of a process (kg carbon emission/unit)}\\ &\times \text{the energy requirement of a process (unit)}\\ &+\sum \text{carbon emission density of a transport mode(kg carbon emission/ton}\cdot\text{km)}\\ &\times \text{the freight weight of a transport mode(ton)} \times \text{distance(km)}\end{aligned} \tag{4}$$

3.1.4. Wool carpet installation and use

This study assumes that the finished wool carpets are delivered to the distribution facility for customer purchase. In order for a customer to use the carpet, the carpet needs to be delivered and installed, requiring energy consumption and emitting carbon to the atmosphere. Since there is no available data on energy consumption and carbon emissions of different types of carpet in the installation stage, this study follows the study of Crowley et al. (2010) and assumes that the wool carpet and the nylon carpet require the same amount of energy and generate the same amount of carbon emissions in the carpet installation stage and the carpet use stage. Thus, for one FU of a wool carpet (0.09 m^2), this study assumes the carpet installation phase requires 2.74 MJ/m^2 (0.2466 MJ/FU) of energy requirement and 0.5693 kg CO_2-e /m^2 (0.04816 kg CO_2-e/FU) production, while the use phase has 6.28 MJ/m^2 (0.5652 MJ/FU) of energy consumption and 1.32 kg CO_2-e /m^2 (0.11037 kg CO_2-e/FU) emissions (Crowley et al., 2010).

3.1.5. Wool carpet recycling and transportation

Although the disposed post-consumer product could follow several end-of-life routes or destinations – reuse, repair, remanufacturing, material recycling, incineration, and/or landfill (Huisman, 2003), this study assumes that the face fiber of disposed wool carpet is remanufactured as a fertilizer and the rest becomes landfill. As shown in Fig. 4, recycling of the wool carpet comprises two processes: shredding and air separation. In order to be remanufactured, the collected wool carpet is first shredded into little pieces. Next, the heavier backing is separated through a centrifugal air separation. The separated wool pieces are collected and used as fertilizer. The waste backings are transported to a landfill site.

In the recycling process to recover the wool fiber from the post-consumer wool carpet, 0.0582 MJ/kg of energy is consumed and 0.01137 kg CO_2-e/kg of emissions are generated in the shredding process, while 0.0001 MJ/kg of energy is consumed and 0.00002 kg CO_2-e /kg of emissions are generated in the air separation process (Subbiah, 2008). The carbon emission density value of each process is estimated by multiplying the energy density value of each process by the carbon emission density of electricity, 0.19528 kg CO_2-e/

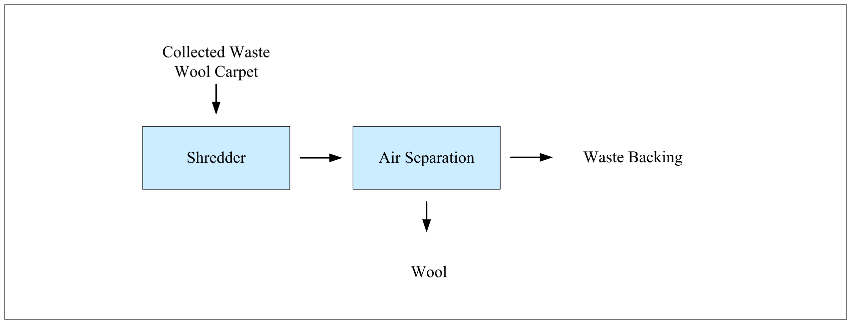

Fig. 4. Wool carpet recycling process.

Table 3
The energy consumption and carbon emissions of raw materials.

Raw material (Unit)	Energy (M MJ/Unit)	Carbon (M kg CO_2-e/Unit)	Energy (%)	Carbon (%)
Greasy wool (kg)	271.71	423.86	52.65	89.87
Lubricant (kg).	3.13	0.61124	0.61	0.13
Water (l)	3.89	0.75643	0.75	0.16
PVC (kg)	41.79	8.15	8.10	1.73
Latex (kg)	195.52	38.23	37.89	8.11

MJ (EPA, 2017). Due to the limited available empirical data on the traveled distance of raw materials and carpet, this study uses the travel distance data provided by BEES (Lippiatt, 2007). Thus, this study assumes that a vessel transports the greasy wool from Australia to the United States over 15,187 km. In addition, this study assumes a truck transports the carpet from the distribution facility site to the customer site over the average travel distance of 5 km, while assuming other materials are transported by a truck over the average distance of 402 km.

For example, to meet the expected wool carpet demand (138 M FU) of the year 2017, 521.67 M L of water, 21.74 M kg of raw wool, 11.30 M kg of latex, 1.61 M kg of PVC, and 0.87 M kg of lubricant are required. As shown in Table 3, greasy wool consumes the largest amount of the total energy consumption and the largest amount of the total carbon emissions in raw material production of a wool carpet.

According to the expected carpet demand in the United States market for the year 2017, the wool carpet consumes 2.82 B MJ of energy and produces 0.87586 B kg CO_2-e of emissions during the wool carpet's 25 years service life (Bowyer et al., 2009) as shown in Table 4. In the case of a wool carpet, the carpet use stage consumes the largest portion of the total energy consumption, accounting for 69.19%, and the raw material production stage consumes 18.31%, the second largest portion of the total energy consumption. In addition, the raw material production stage produces the largest part of the total carbon emissions, 58.85%, while the carpet use stage generates the second largest part of the total carbon emissions, 43.61%.

Table 4
Energy consumption and carbon emission at each stage of wool carpet.

Process	Energy (M MJ)	Carbon (M kg CO_2-e)	Energy (MJ/FU)	Carbon (kg CO_2-e/FU)
Raw material production	516.03	471.61	3.74	3.42
Yarn production	84.51	2.27	0.61236	0.01645
Carpet tile production	124.21	0.9	4.87	0.03527
Installation	34.03	6.65	0.24660	0.04816
Use	1950.07	381.94	14.13	2.77
Recycling and disposal	1.80	0.37085	0.01301	0.00254
Transportation	107.72	0.78054	8.17	0.0592
Total	2813.37	875.86	20.42	6.35

On the other hand, as an alternative method of recycling, the combustion process consumes 5.63 MJ of energy and generates 1.10 kg CO_2-e of emission per 1 kg of post-consumer carpet (EPA, 2015). In the year 2017, the combustion process of the post-consumer wool carpet uses 97.91 M MJ (0.70946 MJ/FU) and generates 19.13 M kg CO_2-e (0.13862 kg CO_2-e/FU).

3.2. *Life cycle assessment for a nylon carpet*

Due to the strength, resilience, and abrasion resistance characteristics of nylon, a nylon carpet is the most popular commercial carpet, accounting for nearly 65% of all carpets manufactured in the United States (Carpet Buyers Handbook (CBH), 2016). Since nylon carpet has the resilient ability to restore to its original form after being bent and compressed, it is also the most durable (Carpet Buyers Handbook (CBH), 2016). In order to estimate the energy use and the carbon emissions of a FU (0.09 m^2) of nylon carpet tile, composed of a nylon 6 facing, a polymer backing, and a fiberglass filler, this study analyzes the nylon carpet's entire life cycle (Lippiatt, 2007). Based on the expected U.S. carpet demand (1.24 B m^2) in the year 2017 (Freedonia, 2014), the expected demand of nylon carpet is predicted to be 807.35 M m^2 (8970.56 M FU) that year.

3.2.1. *System boundary of nylon carpet*

As shown in Fig. 5, the life cycle of a nylon carpet is composed of five stages – raw material production, nylon yarn production, nylon carpet production, nylon carpet use, and nylon carpet recycling. The raw material production considers only the related activities to produce caprolactam, while the nylon yarn production includes only the associated activities of extrusion to manufacture the nylon yarn from caprolactam. The nylon carpet production consists of twisting, warping, tufting, blending, coating, and finishing. As in the wool carpet case, it is assumed that the tufting process includes all cutting and assembly activities of a nylon carpet. The use stage considers all associated activities of installation, maintenance, and cleaning of a nylon carpet during its entire life cycle. In addition, for the end-of-life stage, this study considers only recycling, where the raw material caprolactam is recovered from the post-costumer nylon carpet. Finally, this study accounts for the energy consumption and carbon emissions occurring from the transportation activities between each stage over the entire life of a nylon carpet.

3.2.2. *Nylon carpet raw material production*

Since the demand of nylon carpet is expected to be 807.35 M m^2 in the year 2017, the nylon carpet production needs 2462.43 M kg of PVC, 750.84 M kg of latex, 650.56 M kg of caprolactam, 104.96 M kg

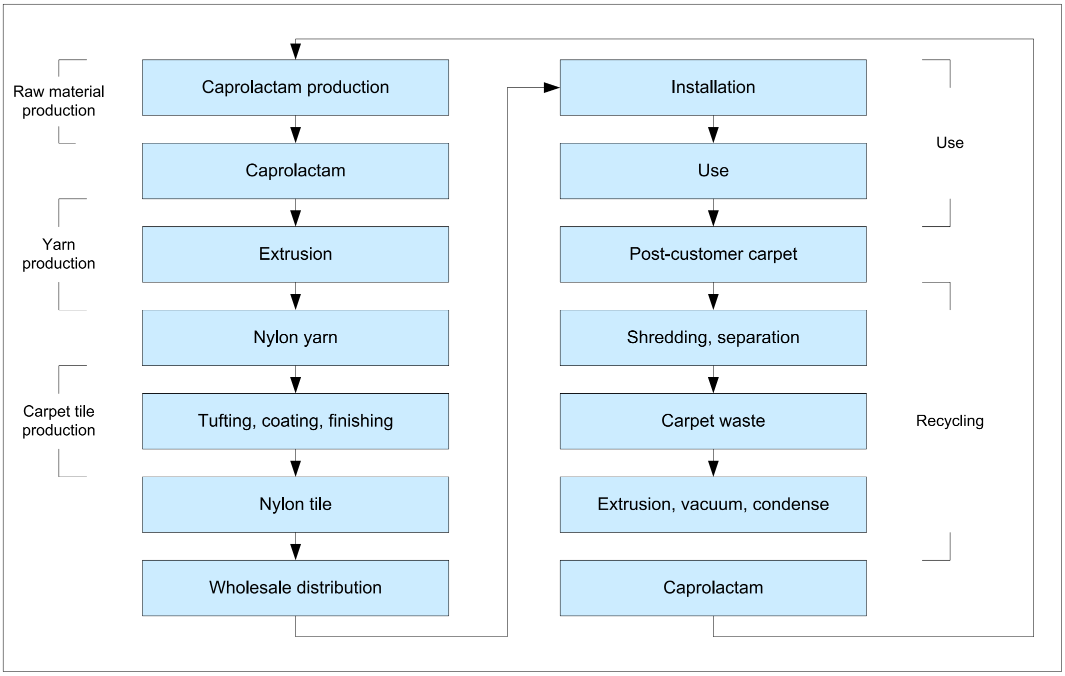

Fig. 5. The system boundary of a nylon carpet's life cycle.

of polypropylene, and 54.90 M kg of fiberglass. Thus, the raw material production of nylon carpet requires 157.65 B MJ (17.57 MJ/FU) of energy, contributing 68.86% of the total energy consumption in the nylon carpet life cycle, and produces 30.78 B kg CO_2-e (3.43 kg CO_2-e/FU) of emissions, contributing 71.49% of the total carbon emissions in the nylon carpet life cycle. In respect to energy requirements and carbon emissions, two materials – caprolactam and PVC – contribute about 90% of the total energy consumption and the total carbon emissions at the raw material production stage of a nylon carpet.

3.2.3. Nylon carpet production

Nylon carpet manufacturing is composed of three production processes – caprolactam production, nylon fiber production, and nylon carpet production. Fig. 6 shows the main inflows and outflows for the nylon carpet production, according to BEES (Lippiatt, 2007), from caprolactam through nylon carpet. In the process of 0.09 m^2 functional unit (FU) of nylon production with nylon fiber (0.81 kg/m^2), 0.07363 kg of caprolactam and 0.0729 kg of nylon yarn are required. In the process of nylon yarn production, the original mass of caprolactam is decreased by 1% through the extrusion process (Li, 2007).

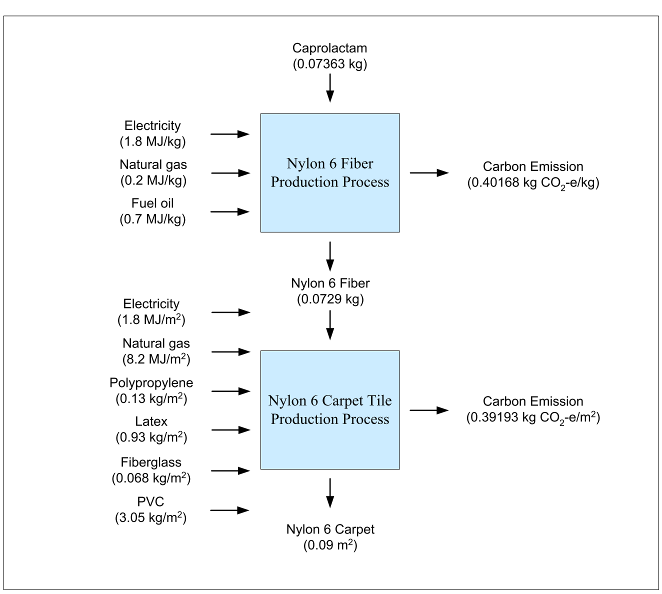

Fig. 6. The main inflows and outflows for nylon carpet production.

Again referring to BEES (Lippiatt, 2007), in order to produce 0.0729 kg of a nylon fiber, the nylon yarn fiber production process requires 0.13122 MJ of electricity, 0.01458 MJ of natural gas, and 0.05103 MJ of fuel oil, while generating 0.02928 kg CO_2–e of carbon emissions from energy use. In addition, as shown in Fig. 6, the nylon carpet production process needs 0.162 MJ of electricity, 0.738 MJ of natural gas, 0.00612 kg of fiberglass, 0.0837 kg of latex, and 0.0117 kg of polypropylene, along producing 0.03527 kg CO_2–e of carbon emissions from energy use in the production process of 0.09 m^2 of nylon carpet.

After being delivered from the raw material manufacturer, the raw material caprolactam is extruded to produce a nylon yarn, Nylon 6 fiber. Next, the nylon yarn is tufted by being woven into the backing with specific densities, patterns, and styles of carpet. After the tufting process, the tufted carpet is adhered to the backing. Then the tufted carpet is steamed, blended, coated, dried, and finished. The carpet goes to the coating stage, where a coating of latex is applied to the underside of the carpet, then is dried in the drying process. Finally, the complete nylon carpet is ready for customer use. The general manufacturing processes for a nylon carpet, according to Li's study on nylon carpet (2007), are described in Fig. 7.

Based on the energy proportion on the life cycle assessment of chemical processes (Li, 2007), the production energy usage and the carbon emissions at each process of nylon carpet manufacturing are tabulated in Table 5. The carbon emission density is calculated by multiplying the energy density of each process by the carbon emission density of an energy source. For example, the extrusion

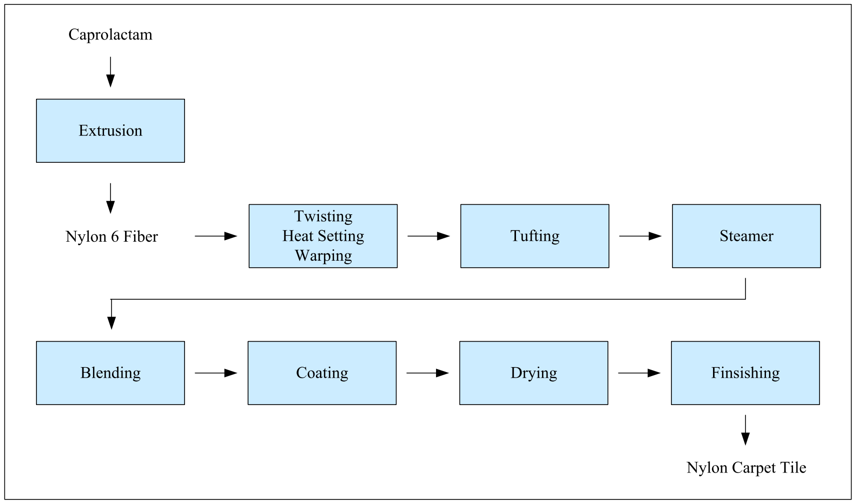

Fig. 7. Nylon carpet manufacturing process.

Table 5
Nylon carpet production processes (Li, 2007).

Process (Unit)	Energy (MJ/Unit)	Carbon (kg CO_2-e/Unit)	Process (Unit)	Energy (MJ/Unit)	Carbon (kg CO_2-e/Unit)
Extrusion (kg)	2.7	0.52726	Steaming (m^2)	2.04	0.39837
Twisting (m^2).	0.107	0.02089	Blending (m^2)	0.295	0.05761
Heat setting (m^2)	1.306	0.25504	Coating (m^2)	2.303	0.44973
Warping (m^2)	0.066	0.01289	Drying (m^2)	2.647	0.51691
Tufting (m^2)	0.862	0.16833	Finishing (m^2)	0.377	0.07362

process requires three types of energy sources – 1.8 MJ of electricity, 0.2 MJ of natural gas, and 0.7 MJ of fuel oil – to process one kg of caprolactam and generates 0.40168 kg CO_2-e, which is obtained by the summation of each carbon emission production generated from the three types of energy sources. In its carbon emission estimation, this study uses the carbon emission density of 0.19528 kg CO_2-e/MJ for electricity, 0.00493 kg CO_2-e/MJ for natural gas, and 0.07027 kg CO_2-e/MJ for fuel oil, respectively (EPA, 2017).

3.2.4. Nylon carpet installation and use

This study assumes that after the finished nylon carpet is distributed to the distribution facility, it is installed and used by the customer. For the carpet installation and use stages of nylon carpet, this study assumes that the same amount of energy is consumed and the same amount of carbon emissions are generated as in the case of the wool carpet in the previous section. In the installation stage, the nylon carpet requires 2.21 B MJ (0.2466 MJ/FU), contributing 0.97% of the total energy consumption of the nylon carpet life cycle, while producing 0.43199 B kg CO_2-e (0.04816 kg CO_2-e/FU), contributing 1.00% of the total carbon emissions of the nylon carpet life cycle. On the other hand, during the 11 years' service life of nylon carpet (Bowyer et al., 2009), the use stage of nylon carpet consumes 55.77 B MJ (6.22 MJ/FU), contributing 24.36% of the total energy consumption in the entire life cycle, while generating 10.92 B kg CO_2-e (1.22 kg CO_2-e/FU), contributing 25.37% of the total carbon emissions in the entire life cycle.

3.2.5. Nylon carpet recycling and transportation

This study assumes that in the recycling and disposal stage, the collected nylon carpets first go through the depolymerization process to reproduce the raw material for the nylon yarn, caprolactam, from the disposed post-customer nylon carpets (Subbiah, 2008). The recycling process of a nylon carpet is illustrated in Fig. 8.

According the study of Subbiah (2008), after the collected nylon carpet is shred into little pieces of nylon carpet, the heavier backing is separated through centrifugal air separation. The separate nylon pieces react with a catalyst in the extruder and turn back into caprolactam. Next, the vapor caprolactam is condensed and collected through a vacuum pump process. The collected caprolactam is used as new raw material for nylon yarn production. The energy requirements (Subbiah, 2008) and the carbon emissions for the recycling of a nylon carpet are tabulated in Table 6. In this stage, the carbon emission density of each process is estimated by multiplying the energy density of each process by the carbon emission density of electricity, 0.19528 kg CO_2-e/MJ (EPA, 2017).

In responding to the expected carpet demand in the United States market for the year 2017, the nylon carpet requires 228.95 B MJ of energy and generates 43.06 B kg CO_2-e of emissions during its entire life cycle time. As shown in Table 7, in the case of a nylon carpet, the raw material production stage consumes the most energy (68.86%), and the carpet use stage consumes the second largest portion (24.36%), while the raw material production stage generates the most total carbon emissions (71.49%), and the carpet use stage produces the second largest (25.37%).

According to the study of Subbiah (2008), 0.09571 kg of caprolactam is recovered from one kg of post-costumer nylon carpet (0.00698 kg/FU). Thus, the recycling of a FU of nylon carpet saves 0.81945 MJ of energy and 0.16005 kg CO_2-e in the raw material production stage. In line with the demand of the year of 2017, it is possible to reduce 7348.08 M MJ of energy consumption and 1435.19 M kg of carbon emission equivalent production by using recycled caprolactam from nylon carpet recycling. In other words, the use of recycled raw material has the potential of reducing 3.21% of the total energy consumption and 3.33% of carbon emissions in 2017. On the other hand, as an alternative of a recycling stage, to the combustion process uses 3.68 B MJ (0.41043 MJ/FU) and produces 0.71936 B kg CO_2-e (0.08019 kg CO_2-e/FU).

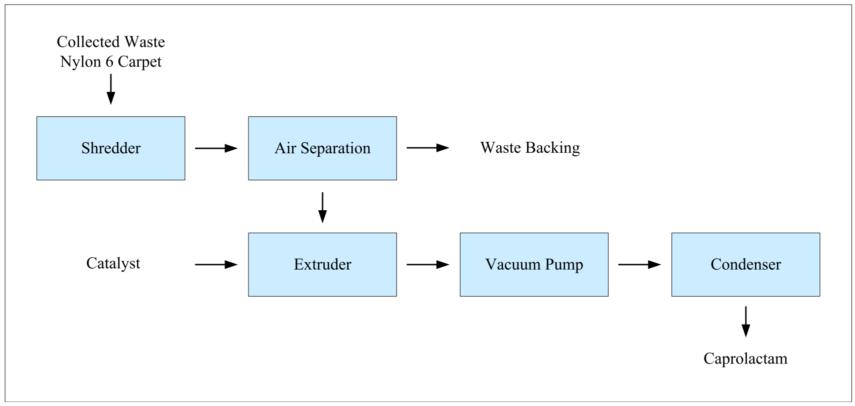

Fig. 8. Nylon carpet recycling process.

Table 6
The nylon recycling process.

Process (Unit)	Energy (MJ/Unit)	Carbon (kg CO_2/Unit)	Process (Unit)	Energy (MJ/Unit)	Carbon (kg CO_2/Unit)
Shredding (kg)	0.0582	0.01137	Condenser (kg)	0.1176	0.02296
Separation (kg).	0.107	Negligible	Vacuum (kg)	0.058	0.01133
Extrusion (kg)	0.0884	0.01726			

Table 7
Energy consumption and carbon emissions at each stage of nylon carpet.

Process	Energy (B MJ)	Carbon (B kg CO_2-e)	Energy (MJ/FU)	Carbon (kg CO_2-e/FU)
Raw material production	157.65	30.78	17.57	3.43
Yarn production	1.77	0.26268	0.19683	0.02928
Carpet tile production	8.07	0.31642	0.9	0.03527
Installation	2.21	0.43199	0.2466	0.04816
Use	55.77	10.92	6.22	1.22
Recycling and disposal	0.64532	0.12602	0.07194	0.01405
Transportation	2.83	0.21568	0.31593	0.02404
Total	228.95	43.06	25.52	4.80

3.3. System dynamics

By analyzing the interactions among variables and model structure in a complex system over time, system dynamics predicts the dynamic behavior of the system and estimates the impact of uncertain model parameters on the outcomes of the model in the system boundary (Hwang et al., 2013). This study uses the system dynamics approach to analyze the impact of the uncertainty of market share on the total energy consumption and the total carbon emission production in the United States carpet market from the year 2017 to the year 2030 through a parametric sensitivity analysis and a Monte Carlo simulation.

3.3.1. Casual loop diagram

The cause and effect relationships among model parameters in the carpet life cycle system are illustrated in Fig. 9. As the carpet demand increases, the amount of raw material requirements also increases. The increased amount of raw materials causes an increase in the production of carpet yarn, which leads to an increase in carpet production. As carpet production increases, the carpet installation and the carpet use also increase. The increased use of carpet causes an increased amount of recycling and disposal of carpet. The increased amount of recycled carpet makes the production of raw materials for nylon carpet decrease through the recovery of the raw materials of carpet from the post-customer carpet product.

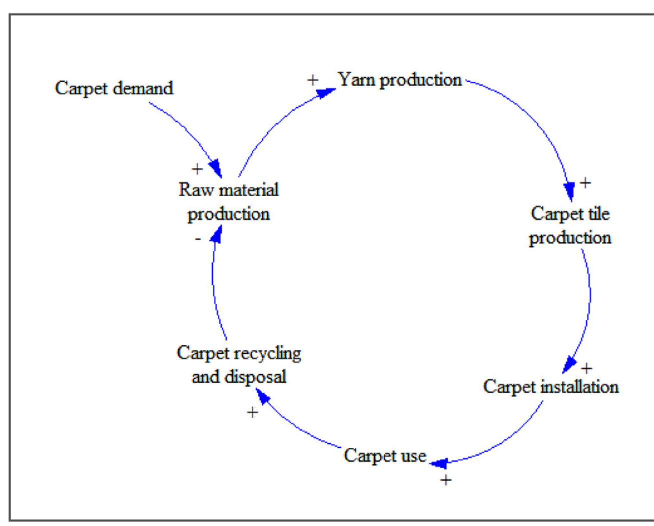

Fig. 9. Casual loop diagram of a carpet life cycle.

3.3.2. Stock and flow diagram

Based on the cause and effect relationships of the parameters in the casual loop diagram, the stock and flow diagram of a carpet life cycle model, shown in Fig. 10, is developed using Vensim, a system dynamics modeling tool. Following the extrapolated carpet

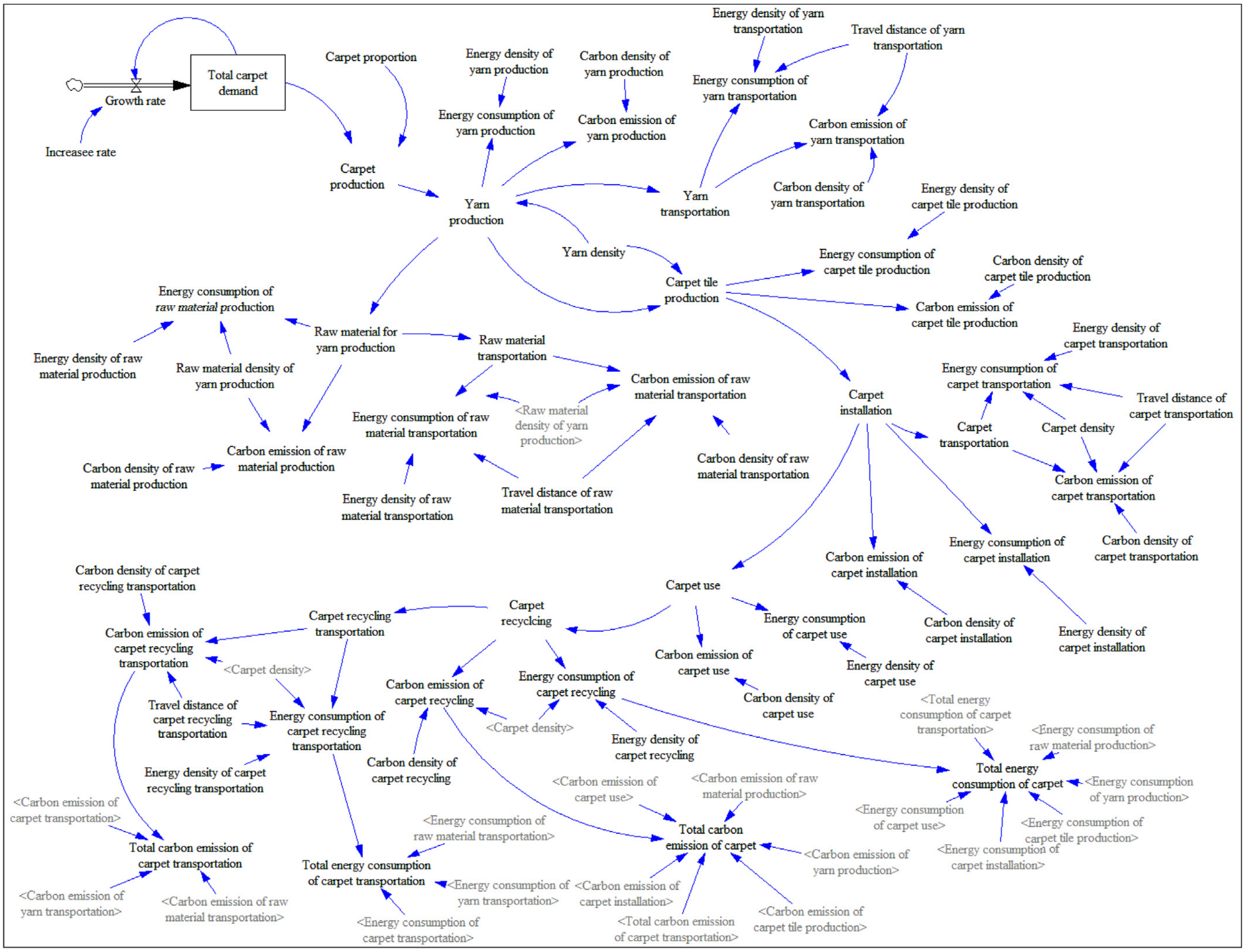

Fig. 10. Stock and flow diagram of a carpet life cycle.

demand in the United States from the year 2017 to the year 2030, the total energy consumption amounts and the total carbon emission production amounts are estimated during the entire life cycle of a carpet from the raw material extraction stage to the carpet recycling and disposal stage. The total energy consumption amounts and the total carbon emission amounts are estimated by the summation of the energy required and the carbon emissions generated at each stage of the carpet's entire life cycle.

Using Equation (3), the energy requirement is calculated at each stage by multiplying the energy density of a process by the processed product amounts. Similarly, using Equation (4), the carbon emission amount is calculated by multiplying the carbon density of a process by the processed product amounts. In the associated transportation activities of each stage, the energy requirement is calculated by multiplying the energy density of a transport mode by the freight weight of a transport mode over the traveled distance. Similarly, the carbon emission production is calculated by multiplying the carbon emission density of a transport mode by the freight weight of a transport mode over the traveled distance.

3.3.3. Sensitivity analysis

Since the carpet demand is expected to annually increase by a 4.5% increase rate from the year 2017 to the year 2019 (Freedonia, 2014), this study extrapolates that the demand of carpet will increase from 1.24 B m^2 (13.78 B FU) in the year 2017 to 2.20 B m^2 (24.44 B FU) in the year 2030 by a 4.5% increase rate. Using the extrapolated data of the carpet demand, this study utilizes the developed model to estimate the energy consumption and the carbon emission of the two types of carpet until the year of 2030. Fore example, Fig. 11 shows that in the year 2017, the wool carpet is expected to consume 2.82 B MJ of energy and produce 0.87586 B kg of carbon emissions equivalent, while the nylon carpet is predicted to use 228.95 B MJ of energy and generate 43.06 B kg of carbon emissions equivalent.

In order to investigate the impact of market share uncertainty on the total energy consumption and carbon emission production, this study utilizes the developed life cycle carpet model to conduct a parametric sensitivity analysis and a Monte Carlo sensitivity analysis. In the parametric sensitivity analysis, this study analyzes the uncertain market share of the two types of carpet on the total energy use and carbon emission amount. In order to increase the practical use of the developed model, this study develops the input and output interface of a carpet model, which provides the energy consumption amount and the carbon emission amount in responding to the variation of market share, as shown in Fig. 12.

As the market share of a wool carpet is increased at the rate of 0.01% from the year 2017 to the year 2030, the total energy consumption of a carpet industry decreases annually on average

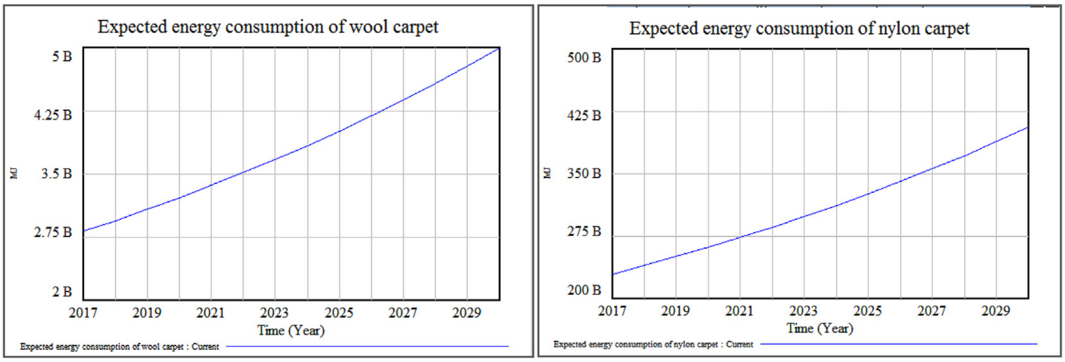

Fig. 11. The energy consumption of two types of carpet.

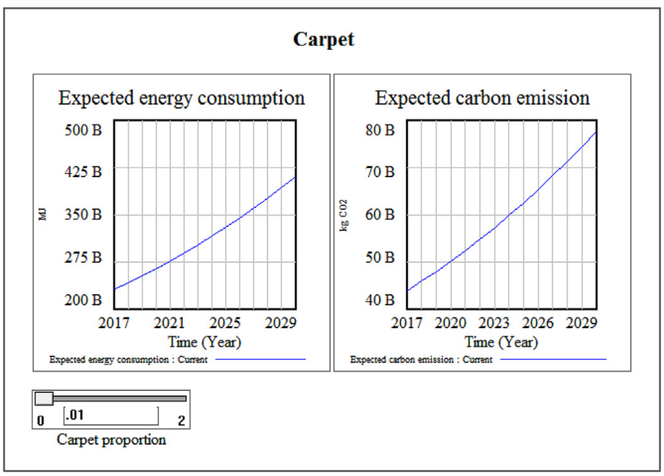

Fig. 12. The input and output object.

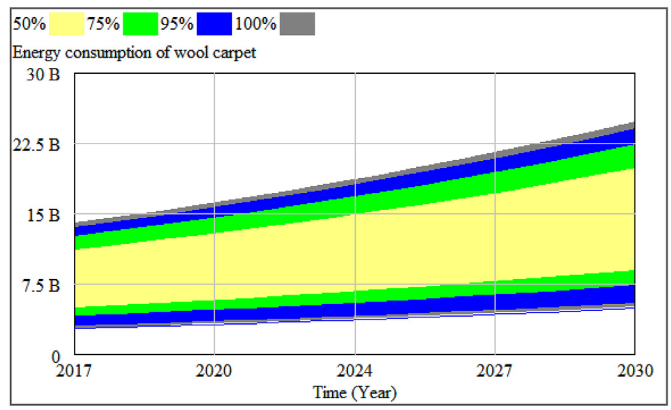

Fig. 13. The sensitivity analysis of the energy consumption.

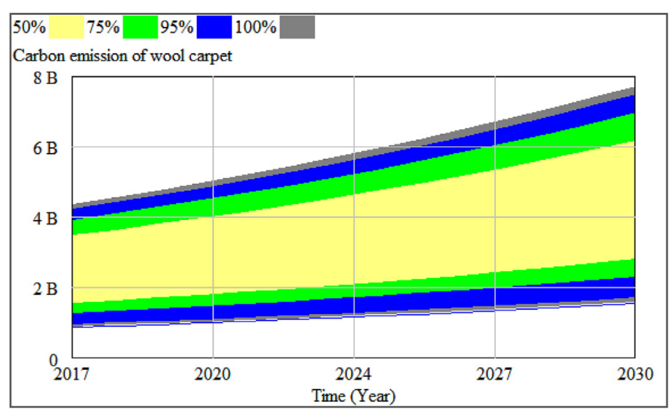

Fig. 14. The sensitivity analysis of the carbon emission.

3.87 B MJ, and the total carbon emissions of a carpet industry decreases annually on average 0.42 B kg CO_2-e until the year 2030. Since the largest amount of carbon emissions are generated from the on-farm sheep production and crop production activities in the raw material production stage of a wool carpet, the increase of market share of a wool carpet leads to an increase of carbon emissions.

In the Monte Carlo simulation, market share is assumed to follow a uniform distribution, with the current market share as the minimum value and five times amount of the market share as the maximum value. From the results of Vensim's Monte Carlo simulation analysis, the energy consumption and carbon emissions of a wool carpet are illustrated in Figs. 13 and 14 in terms of the 50%, 75%, 95%, and 100% confidence bound, respectively.

When the market share of wool is assumed to be increased by five times the current market share, the results indicate that there is a 50% possibility that the expected total energy consumption of wool carpet will be in the range of about 5.5 B MJ and 20.5 B MJ from the year 2017 to the year 2030, while the expected total energy consumption of nylon carpet will be between about 230 B MJ and 395.5 B MJ in the same period. In addition, with the 95% possibility, the total energy consumption of wool carpet is expected to be between approximately 3.5 B MJ and 24.5 B MJ from the year 2017 to the year 2030, while the total energy consumption of nylon carpet is predicted to be in the range of about 225 B MJ and 410.5 B MJ in that period. In response to the expected carpet market share, the uncertainty in the total energy consumption grows gradually from the year 2017 to the year 2030, while the total energy consumption grows larger after year 2024 because of the increasing uncertainty in market share.

On the other hand, with the assumption of a five time increase of the current nylon carpet market share, the results of the sensitivity analysis indicate that the expected total carbon emissions of wool carpet have a 50% possibility of being between about 1.5 B kg CO_2-e and 6.5 B kg CO_2-e from the year 2017 to the year 2030, while the expected total carbon emissions of nylon carpet will be between about 42 B kg CO_2-e and 73 B kg CO_2-e in the same time frame. In addition, with a 95% possibility, the expected total carbon emissions of wool carpet are expected be between about 1 B kg CO_2-e and 7.3 B kg CO_2-e from the year 2017 to the year 2030, while the expected total carbon emission of nylon carpet will be in the range of approximately 40 B kg CO_2-e and 75 B kg CO_2-e in the same time period. According to the predicted market share, the uncertainty in the total carbon emissions increases gradually from the year 2017 to the year 2030, while the increasing uncertainty of market share leads to an increase in the total carbon emission amount after the year 2024.

4. Conclusion

Since the U.S. flooring market is expected to gradually increase, it is important to assess the energy consumption and carbon emissions of the carpet market, an important sector of the flooring market, to mitigate the environmental impacts of the flooring market as a whole. Due to the increasing emphasis on life cycle assessment, this study focuses on the life cycle assessment of two types of carpet, a wool carpet and a nylon carpet, in terms of energy use and carbon emissions, from raw material acquisition to recycled and post-use carpet, along with the related transportation activities. In responding to the expected carpet demand, during its entire life cycle, the wool carpet requires 2.81 B MJ of energy and generates 0.87589 B kg CO_2-e, while the nylon carpet consumes 228.95 B MJ of energy and produces 43.06 B kg CO_2-e. In response to the 1% increase of the current market share, the carpet industry will have on average 3.87 B MJ of energy decrease and generate on average 0.42 B kg of carbon emission increase from the year 2017 to the year 2030.

In the case of a wool carpet, the results of this study indicate that the carpet use stage consumes a large amount, 1950.07 M MJ of energy, contributing 69.19% of the total energy consumption, and generates a large amount, 381.94 M kg CO_2-e, contributing 43.61% of the total carbon emissions, while the raw material production stage also requires 516.08 M MJ of energy, making up 18.31% of the total energy consumption, and produces 471.61 M kg CO_2-e, making up 58.85% of the total carbon emissions. On the other hand, in the case of a nylon carpet, the raw material production phase requires the largest amount of energy, 157.65 B MJ, accounting for 68.86% of the total energy consumption, while generating the largest amount of carbon emissions, 30.78 B kg CO_2-e, accounting for 71.49% of the total carbon emission. In addition, the carpet use phase requires 55.77 B MJ, making up 24.36% of the total energy consumption, as well as produces 10.42 B kg of carbon emissions to the atmosphere, making up 25.37% of the total carbon emissions.

The results of the life cycle assessment of carpet indicate the raw material production stage and the use stage of a wool carpet and a nylon carpet contribute the largest amount of energy and carbon emissions among the other life cycle stages. Thus, to mitigate the environmental impacts of carpet, it is necessary to make concerted efforts to use more environmentally friendly raw materials and environmentally friendly renewable energy, while increasing the recycling of post-use carpet for raw material recovery. In addition, in the case of a wool carpet, the wool carpet would be more environmental-friendly if the raw material of wool were obtained from geographically closer sources than Australia to decrease the environmental impacts of carpet in the transportation activities.

Considering the importance of the U.S. carpet industry, few studies have been conducted on the life cycle assessment of carpet in terms of energy and carbon emissions, and have not assessed the entire life cycle of carpet from the raw material production stage to the carpet recycling and disposal stage, along with transportation activities. In order to mitigate the environmental impact of the carpet industry, estimating the energy consumption and the carbon emissions at each stage of the entire life cycle of carpet is a prerequisite. To contribute to the literature gap on this issue, this study analyzes the entire life cycle of two types of carpet – wool and nylon – in terms of energy consumption and carbon emissions, including the transportation activities.

On the other hand, from a practical standpoint, this study provides the input-output object which estimates the total energy consumption and the total carbon emissions of two types of carpets from raw material acquisition to carpet recycling, while reflecting the portion of market share. In addition, based on the results of this study, the carpet industry can determine on which stages of the carpet's life cycle to focus its efforts to mitigate the environmental impacts of carpet. Based on the proposed methodology approach in this study, further study is planned to analyze total energy consumption and carbon emissions generated from the U.S. floor covering sector of the textile industry.

References

Abdel-Dayem, M., Mohamad, A., 2001. Potential of solar energy utilization in the textile industry – a case study. Renew. Energy 23, 685–694.
Albers, K., Canepa, P., Miller, J., 2008. Analyzing the Environmental Impacts of Simple Shoes: a Life Cycle Assessment of the Supply Chain and Evaluation of End-of-life Management Options. University of Santa Barbara, Santa Barbara, CA.
Allwood, J.M., Laursen, E.L., de Rodríguez, C.M., Bocken, N.M.P., 2006. Well Dressed? the Present and Future Sustainability of Clothing and Textiles in the United Kingdom. University of Cambridge Institute for Manufacturing, Cambridge, United Kingdom.
Atlas Carpet Mills, 2016. Environmental Product Declaration – Atlas Carpet Mills: Perma-tile Modular Carpet Family.
Barber, A., Pellow, G., 2006. Life Cycle Assessment: New Zealand Merino Wool Total Energy Use. The Agribusiness Group, Auckland, New Zealand.
Baydar, G., Ciliz, N., Mammadov, A., 2015. Life cycle assessment of cotton textile products in Turkey. Resour. Conserv. Recycl. 104, 213–223.
Bowyer, J., Bratkovich, S., Fernholz, K., Lindburg, A., 2009. Life Cycle Assessment of Flooring Materials. Dovetail Partners Inc, Minneapolis, MN.
Brander, M., Tipper, R., Hutchison, C., Davis, G., 2008. Consequential and Attributional Approaches to LCA: a Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels. Ecometrica Press, London, United Kingdom.
Carpet Buyers Handbook (CBH), 2016. http://www.carpetbuyershandbook.com.
Collins, M., Aumônier, S., 2002. Streamlined Life Cycle Assessment of Two Marks & Spencer Plc Apparel Products. Environmental Resources Management, Oxford, United Kingdom.
Crowley, K., Hurley, P., Schneider, M., Singer, J., 2010. Life Cycle of Interface's Bentley Prince Street Carpet vs Traditional Carpets. University of Vermont, Burlington, VT.
Dahllöf, L., 2004. Methodological Issues in the LCA Procedure for the Textile Sector – a Case Study Concerning Fabric for Sofa. Environmental Systems Analysis. Chalmers University of Technology, Göteborg, Sweden.
Forbo Flooring, B.V., 2013. Environmental Product Declaration – Westbond N9000 Carpet Tile.
Freedonia, 2014. http://www.freedoniagroup.com/industry-study/carpet-rugs-3266.htm.
Gresham, R.M., Totten, G.E., 2008. Lubrication and Maintenance of Industrial Machinery: Best Practice and Reliability. CRC Press, Boca Raton, FL.
Hammond, G., Jones, C., 2006. Embodied Energy and Carbon Footprint Database. Bath. University of Bath, United Kingdom.
Hasanbeigi, A., Hasanabadi, A., Abdorrazaghi, M., 2012a. Comparison analysis of energy intensity for five major sub-sectors of the textile industry in Iran. J. Clean. Prod. 23, 186–194.
Hasanbeigi, A., Price, L., 2012b. A review of energy use and energy efficiency technologies for the textile industry. Renew. Sustain. Energy Rev. 16, 3648–3665.
Hong, G., Su, T., Lee, J., Hsu, T., Chen, H., 2010. Energy conservation potential in Taiwanese textile industry. Energy Policy 38, 7048–7053.
Huisman, J., 2003. The QWERTY/EE Concept, Quantifying Recyclability and Eco-efficiency for End-of-life Treatment of Consumer Electronic Products. Delft University of Technology, Delft, Netherlands.
Hwang, S., Park, M., Lee, H., 2013. Dynamic analysis of the effects of mortgage-lending policies in a real estate market. Math. Comput. Model. 57, 2106–2120.
Interface, 2009. Environmental Product Declaration – Modular Carpet Tile Made with Post-consumer Content Type 6,6 Nylon and Post-consumer Content Non-virgin PVC Backing.
Interface, 2011. Environmental Product Declaration – Carpet Tile: GlasBac, Type 6,6 Nylon.
Kalliala, E.M., Nousianen, P., 1999. Life cycle assessment environmental profile of cotton and polyester-cotton fabrics. AUTEX Res. J. 1, 8–20.
Kandilli, C., Koclu, A., 2011. Assessment of the optimum operation conditions of a plate heat exchanger for waste heat recovery in textile industry. Renew. Sustain. Energy Rev. 15, 4424–4431.
Kemal, H., 2004. Energy usage and cost in textile industry: a case study for Turkey. Energy 30, 2424–2446.
Koç, E., Çinçik, E., 2010. Analysis of energy consumption in woven fabric production.

Fibres Text. East. Eur. 18, 14–20.
Koç, E., Kaplan, E., 2007. An investigation on energy consumption in yarn production with special reference to ring spinning. Fibres Text. East. Eur. 15, 18–25.
Li, Y., 2007. Life Cycle Assessment of Chemical Processes and Products. North Carolina State University, Raleigh, NC.
Lippiatt, P., 2007. BEES 4.0: Building for Environmental and Economic Sustainability, Technical Manual and User Guide. National Institute of Standards and Technology.
Martínez, C.I.P., 2009. Energy efficiency developments in the manufacturing industries of Germany and Colombia, 1998-2005. Energy Sustain. Dev. 13, 189–201.
Mihut, C., Captain, K., Gadala-Maria, F., Amiridis, D., 2001. Review: recycling of nylon from carpet waste. Polym. Eng. Sci. 4, 1457–1470.
Morley, M., Heraty, N., Collings, D. (Eds.), 2006. International HRM and International Assignments. Palgrave Macmillan, London, United Kingdom.
Munner, T., Maubleu, S., Asif, M., 2006. Prospects of solar water heating for textile industry in Pakistan. Renew. Sustain. Energy Rev. 10, 1–23.
Ozturk, H.K., 2005. Energy usage and cost in textile industry: a case study for Turkey. Energy 30, 2424–2446.
Palanichamy, C., Sunda Babu, N., 2005. Second stage energy conservation experience with a textile industry. Energy Policy 33, 603–609.
Peng, L., Zhang, Y., Wang, Y., Zeng, X., Peng, N., Yu, A., 2015. Energy efficiency and influencing factor analysis in the overall Chinese textile industry. Energy 93, 1222–1229.
Plappally, A.K., Lienhard, J.H., 2012. Energy requirements for water production, treatment, end use, reclamation, and disposal. Renew. Sustain. Energy Rev. 16, 4818–4848.
Recio, J., Narváez, R., Guerrero, P., 2005. Estimate of Energy Consumption and CO_2 Emission Associated with the Production, Use, and Final Disposal of PVC, Aluminum and Wooden Windows. Environmental Modelling Laboratory, Barcelona, Spain.
Shaw Industry Group Inc, 2012. Environmental Product Declaration – EcoWorx Carpet Tile with EcoSolution Q Face Fiber.
Steinberger, J.K., Friot, D., Jolliet, O., Erkman, S., 2009. A spatially explicit life cycle inventory of the global textile chain. Int. J. Life Cycle Assess. 14, 443–455.
Sterman, J.D., 2000. Business Dynamics: System Thinking and Modeling for a Complex World. Irwin McGraw-Hill, New York, NY.
Subbiah, V., 2008. Sustainability Studies in Recycling Post Consumer Carpet. Georgia Institute of Technology, Atlanta, GA.
Textile Exchange, 2016. Material Snapshot: Nylon 6. Textile Exchange.
The Carpet and Rug Institute (CRI), 2016. http://www.carpet-rug.org.
Tobler-Rohr, M.I., 2011. Handbook of Sustainable Textile Production, Woodhead Publishing Series in Textiles. Woodhead Publishing Limited, Cambridge, United Kingdom.
Transparency Market Research (TMR), 2015. Flooring (Carpets & Rugs, Tile, Vinyl & Rubber Flooring, Wood Flooring, and Others) Market for Residential, Commercial, and Other Applications – Global Industry Analysis, Size, Share, Growth Trends and Forecast 2015 – 2023. Albany, NY.
United States Environmental Protection Agency (EPA), 2015. Carpet, United States.
United States Environmental Protection Agency (EPA), 2017. Greenhouse Gases Equivalences Calculator – Calculation and References, United States.
Vaidyanathan, R., Singh, R., Ley, T., 2013. Recycled Carpet Materials for Infrastructure Applications. Oklahoma Transportation Center.
van der Velden, N.M., Patel, M.K., Vogtländer, J.G., 2014. LCA benchmarking study on textiles made of cotton polyester, nylon, acryl, or elastane. Int. J. Life Cycle Assess. 19, 331–356.
Walser, T., Demou, E., Lang, D.J., Hellweg, S., 2011. Prospective environmental life cycle assessment of nanosilver T-shirts. Environ. Sci. Technol. 45, 4570–4578.
Wang, Y. (Ed.), 2006. Recycling in Textiles. Woodhead Publishing, Cambridge, United Kingdom, pp. 58–70.
Wiedemann, G., Yan, M., Henry, B., Murphy, M., 2016. Resource use and greenhouse gas emissions from three wool production regions in Australia. J. Clean. Prod. 122, 121–132.
Woolridge, A.C., Ward, G.D., Phillips, P.S., Collins, M., Gandy, S., 2006. Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective. Resour. Conserv. Recycl. 46, 94–103.
Zabaniotou, A., Andreou, K., 2010. Development of alternative energy sources for GHG emissions reduction in the textile industry by energy recovery from cotton ginning waste. J. Clean. Prod. 18, 784–790.