

Article

Allocation Methodology of Process-Level Carbon Footprint Calculation in Textile and Apparel Products

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Abstract: Textile and apparel industrial processes generate a huge amount of greenhouse gas emissions, which is a severe environmental issue for China. Aiming at greenhouse reduction, a carbon footprint calculation method is presented. In carbon footprint calculations, allocation methodology is among the most significant and controversial issues; it can be a major reason for the LCA uncertainty and robustness caused. What is more, allocation methodology impacts directly on the preparation of data collection and system boundary. Different outcomes can be achieved even for apparently similar systems by using a different allocation approach. Textile production has a large range of production process. During textile production process, it may be a single product production with co-products. The current CF calculation only evaluates GHGs emissions at product or plant level, so the difference of the technology on different processes cannot be deduced. Hence, the choice of proper allocation methodology is a crucial issue to be considered in textile and apparel industry. In this paper, based on characteristics of textile and apparel industry, process-level allocation methodology in textile and apparel industry was put forward. The application of allocation methodology was investigated and analyzed with a case study on cotton T-shirts. Firstly, case study results show that greenhouse gases of the ironing and sewing process are the two largest emissions (ironing, 40.82%, and sewing, 34.85%, respectively). Energy-saving refrigeration equipment needs to be chosen to reduce the greenhouse gases significantly. Secondly, for most processes, CF of S2 (auxiliary CF) accounts for the highest proportion of total CF. Preferred to S1, more attention should be paid to reduce the S2 emissions. Thirdly, GHGs emissions of the polo shirt in the sewing process are significantly higher than that of the T-shirt in the sewing stage (T-shirt, 0.167 kg CO₂ eq/piece, and polo shirt, 0.371 kg CO₂ eq/piece, respectively). This is the consequence that polo shirt's style and structure determine the complexity of its sewing process. Finally, based on the pearson correlation coefficient, T-shirt production (kg) has a significant negative linear correlation (correlation coefficient: -0.868) with the CF (kg CO₂ eq/kg T-shirts), the similar with that (correlation coefficient: -0.963) of all production. Improving the textile and garment production efficiency is significant to reduce the CF of products (per mass) by technological innovation and management optimization. In this study, we demonstrate that the process-level allocation is a feasible method, and can serve as the basis for a textile-specific allocation approach in LCA. Process-level allocation may help to address textile allocation problems and might lead to more detailed LCA results for products. We recommend broad applications and testing of this new allocation approach.

Keywords: textile and apparel products; carbon footprint calculation; process-level allocation methodology; cotton T-shirts; LCA

1. Introduction

As the demand for energy increases, the projected global energy consumption is expected to reach 226 billion MWh by 2035 compared to the current value of 148 billion MWh [1,2]. The continuous growth of energy consumption is directly related to the amount of carbon dioxide (CO₂) released to the atmosphere. As the demand for energy increases, together with the rise of greenhouse gases (GHGs) emissions in the atmosphere, industry is seeking ways to utilize energy efficiently. Therefore, aiming at gathering knowledge about GHGs emissions, a carbon footprint (CF) calculation is presented, and has been grown rapidly, in addition to full LCA [3–6].

The textile and apparel industry, as a fundamental industry of China, has not yet get rid of high energy consumption and a huge amount of water pollution. Textile and apparel sector involves a broad-range and complicated supply chain, which is responsible for the significant amount of GHGs emissions. It is thought to be one of the chief sources of emissions of GHGs [7]. According to a rough estimate out of every 19.8 tons of the total CO₂ one ton is release from textile industry [8]. Therefore, for textile enterprises, accounting CF, and then put forward the corresponding measures for emission reduction are important strategies for the green production of textile enterprises.

In CF calculation, allocation methodology is among the most significant and controversial issues; it partitions multiple inputs or outputs of between co-products. An adequate allocation approach is crucial for the credibility of the LCA results of this sector [9], and it can be the main reason for the LCA uncertainty and robustness caused [10]. What is more, allocation methodology impacts directly on the preparation of data collection and system boundary [11]. The results of CF are influenced by allocation procedure, so that different outcomes can be achieved even for apparently similar systems [12,13]. Hence, the choice of proper allocation methodology is a crucial issue to be considered. By now, allocation methodology mostly has been discussed in LCA standards [14–16]. Two major allocation approaches focused on the co-product level [17,18] and system level [19,20]. Also, foreign researchers applied them to CF or LCI calculation. For allocation method, according to the standards, allocation should be avoided by subdivision or system expansion method. If avoiding allocation is impossible, the ISO series recommends using relevant variables to allocate, such as mass and energy content or use other relevant variables to allocate, such as economic value of products, which is similar with the cost allocation methods in managerial accounting. However, process-level allocation for GHGs emissions have not been devoted enough attention.

Textile production has a large range of production process. Even simple T-shirt production involves at least ten processes. During textile production process, it may be a single product production with co-products. It also may be a management process dealing with more multifunction process. The current CF calculation only evaluates the GHGs emissions on product or plant level, so the difference of the technology on different processes can't be figured out. By analyzing the process-level data, the result can help apparel manufacturers get knowledge of each process CF. Then most promising energy-saving process can be found, and measures can be taken to eliminate the GHGs emissions and optimize the energy consumption control.

Process-level CF calculation needs adequate primary production data. However, for many textile factories, data unavailability is a central issue, especially the process energy data for factories. In the case of the apparel pipeline, different products are produced that are bound to involve the public use of energy (including electricity for lighting and heating, water supply, ventilation and apportionment factory, warehouse, office lighting, electricity, etc.). It is difficult to obtain accurate individual product's energy consumption data. Furthermore, the energy data of process can be accurately measured by using expensive professional meters such as multifunction power analyzers. However, this method is time-consuming and inconvenient for the factories because of the need to stop production. Also, great amounts are needed, which is costly. Those are the reason why it is hard to avoid allocation for textile and apparel products. It needs to consider the actual production and the data collection to determine the allocation index and the basis.

This paper aims to put forward a process-level allocation methodology for CF calculation in textile and apparel products. The approach is less compelling theoretically but overcomes the problem of data availability and can account for the energy use and emission differences associated with producing individual product. In addition, the approach pays attention to the fact that different products go through different processes. Consequently, the results based on allocation are sensitive to any changes in the individual processes. The goal of the paper is to further investigate the carbon emission reduction opportunities and support strategic decision-making. Section 2 reviews the literature related to the allocation methodology on CF. Section 3 introduces the construction of the process-level allocation method in CF calculation for textile and apparel products. The applicability of the method for typical cotton T-shirts are demonstrated in Section 4 and conclusions are drawn in Section 5.

2. Literature Review

The standards ISO 14040 and ISO 14044 offer a reference for the whole industry's allocation procedure, and instead of a specific industry, they offer a hierarchy of choices rather than a particular method [9]. The method provided by LCA standards are similar. According to the method, trying to avoid the use of allocation should be considered firstly. If avoiding allocation cannot be achieved, physical indicators (outputs, mass, volume, and energy value) between products is preferred to economic indicators [21,22].

2.1. Avoiding Allocation

In the calculation of product CF, the first consideration should be given to avoiding the use of allocation methods. There are two ways to avoid allocation.

- a. The Subdivision Method. Multiple products are divided into multiple subprocesses that belong to each product, and then the input and output data for each subprocess are collected. The subdivision method has higher requirements on the quality of data. It generally requires companies to install energy consumption meters in order to obtain real-time data, which is difficult to achieve in textile industry.
- b. The System Expansion Method. Finding alternative production processes that are equivalent to target production process. The alternative production process here is a production process with the same kind and quantity of products as target product. Maarten et al. [17] used this method in the case of power generation and used natural gas power generation as an alternative process for coke oven gas power generation. However, this method has limitations. On the one hand, the alternative production process is more difficult to find. On the other hand, the alternative production process has a different CF compared to the aiming production process. Thus, the accuracy of the accounting results will be affected.

It is difficult to find an alternative production system because of the profound differences in the production process in textile products. Besides, most enterprises do not install the energy real-time meters and the energy data records of a product is poor in textile production enterprises. Therefore, none of avoid allocation is are completely satisfactory.

2.2. Allocation Method

If "avoiding" is not possible, the ISO series recommends using the physical relationship [18,23–27] or economic value [28] of products, which is similar to the cost allocation methods in managerial accounting. ISO series recommendation offers a reference for allocation method in textile and apparel industry. The allocation method is to find a certain relationship between multiproduction process in order to allocate the overall CF to a certain product.

- a. Physical relationship between products: allocation according to the physical relationship between products. The most common physical parameter is mass.

- Mass or volume of the product: the overall CF should be allocated according to the mass or volume. In the production system, the larger quantity product has generally larger CF. But this method is based on the premise that the CF in unit quantity of different products is equal. In fact, due to the difference in product properties, the energy consumption and material consumption of different products are different. This method is not suitable for large carbon emissions where there is only energy output without mass output, for example, the allocation of electricity and heat.
 - Energy value: This method is applicable to the accounting of CF generated by fossil fuels and steam consumed in production. However, to the best of our knowledge, this method has not been used for apparel industry. This method is used in the example of Maarten et al. (2013) for waste generation, and the carbon emission of two processes of raw iron production and electricity production is allocated by the energy proportion of C converted into CO and CO converted to CO₂ in the energy of C converted into CO₂. This method also has its limitations. In this case, it is assumed that in the production of raw iron, C is converted only into CO. But, most of the C during real production is converted into CO₂ directly.
- b. The other allocation method is used when the physical relationships between the products cannot be clarified. The economic relationship between the products is often used as the indicator [29]. However, this allocation method has its limitations. The method is a hypothesis that the higher price value of the product, more energy will be consumed. The economic value is a comprehensive indicator that reflects the combination of production cost, brand value, market value. Besides, economic allocation method is in some ways more problematic due to the temporal and geographical variability [30]. Therefore, an economic relationship cannot directly reflect the environmental burdens relationship between the products.

The above is the general principle and method proposed by literature. In the literature the applications of the LCA method are at home and abroad [31], and there is a comparative analysis of various allocation methods for a certain production process [22]. Most of it is for a relatively simple product system or co-product level, which cannot be applied to process-level allocation. Two allocation problems arise in process level: what share of total GHGs emissions should be firstly allocated to an individual product and then to an individual process. However, the current allocation shows that physical and economic allocation can avoid the need for huge amounts of the data and make the allocation procedure feasible and simple. Additionally, ISO 14040 suggests physical relationship be preferred to economic relationship. Hence, for complex and process-level product systems, it needs to find the appropriate and practical allocation basis based on the physical relationship with the characteristics of textile industry.

3. Allocation methodology

For the plants, monthly or annual data contained used energy and materials consumption data is easy to obtain. Accordingly, a solution combining the highly informative value of CF with a reasonable process-level allocation methodology is thought to be appropriate.

3.1. CF Data Construction and Allocation Technical Framework

With the purpose and CF methodology, the conception of Carbon Footprint Unit (CFU) conception is raised. CFU is the unit that CF data are clustered into in accordance with process flow unit. According to the energy consumption generation and data collection mode, the CF data are divided into three individual sections: production equipment CF, auxiliary CF, and operation CF. All specific contents are included in sections as shown in Figure 1. This step aims at better representing energy and material

data elements constituted of CFU, which is shown by Figure 2. The CF of individual product can be formalized mathematically (Equation (1)), which is shown in Figure 3.

$$\begin{aligned}
 CF_{tex}^{prod}(x) &= CF_{process}(x) + CF_{auxiliary}(x) + CF_{operation}(x) \\
 &= \sum_{i=1}^n CF_{processi}(x) + \sum_{i=1}^n CF_{auxiliaryi}(x) \\
 &\quad + \sum_{i=1}^n CF_{operationi}(x)
 \end{aligned}
 \quad (1)$$

where $CF_{tex}^{prod}(x)$ is the CF of a certain product. $ICF_{process}(x)$ is the production equipment CF (S1). $CF_{auxiliary}(x)$ is the auxiliary CF (S2). $CF_{operation}(x)$ is the operation CF (S3). $CF_{processi}(x)$ is the GHGs caused by the production equipment in a certain CFU. $CF_{auxiliaryi}(x)$ is the GHGs caused by the auxiliary equipment (air conditioning, lighting, ceiling fans, exhaust fans, and other equipment) or materials (raw materials, packaging materials, etc.) in a certain CFU. $CF_{operationi}(x)$ is the GHGs caused by the operation equipment or materials in a certain CFU. i is a certain CFU. n is the number of CFU.

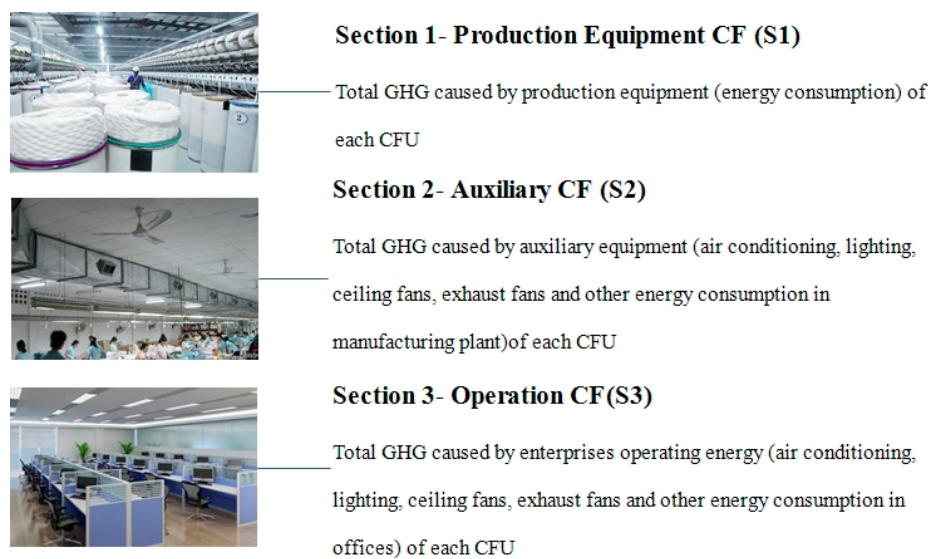


Figure 1. Individual section divisions.

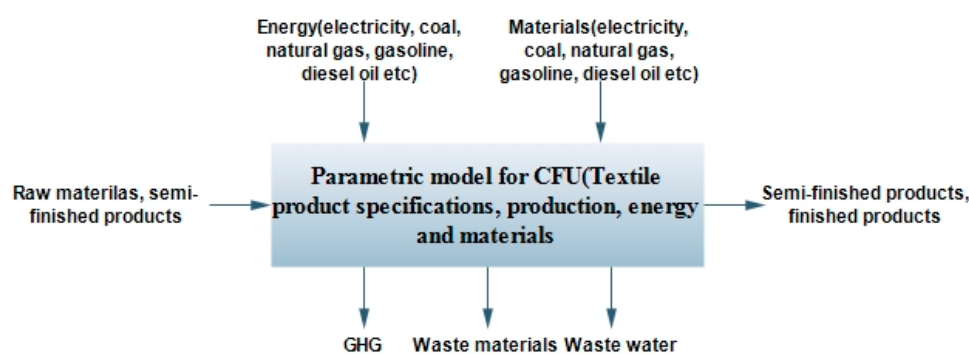


Figure 2. CFU structure.

As discussed in Section 1, the problems that what share of total GHGs emission should be allocated to an individual product and then to an individual process. According complex industry characteristics and obtained data, three allocation methods are presented—products allocation method, sections allocation method, and auxiliary allocation method. The technical framework of allocation method is shown in Figure 4. Following steps must be involved in the CF allocation:

- Developed a process-level flow chart. The chart shows major refining processes that are interconnected by energy and material streams. The study incorporated an appropriate level of

detail, which was prepared as part of a comprehensive energy and materials flow analysis and is available without violating confidentiality of information for a given factory.

- Splitting the total CF data into different products by products allocation method (Equation (2) or (3)).
- Under a certain product, splitting the CF data of individual product into three sections by sections allocation method (Equation (4), Equation (5), Equation (6)).
- Splitting the CF data of S1 into CFU by sections allocation method. Splitting the CF data of S2 into CFU by auxiliary allocation method (Equation (7)). Splitting the CF data of S3 into CFU equally.
- CF of individual product can be formalized mathematically by Equation (1).

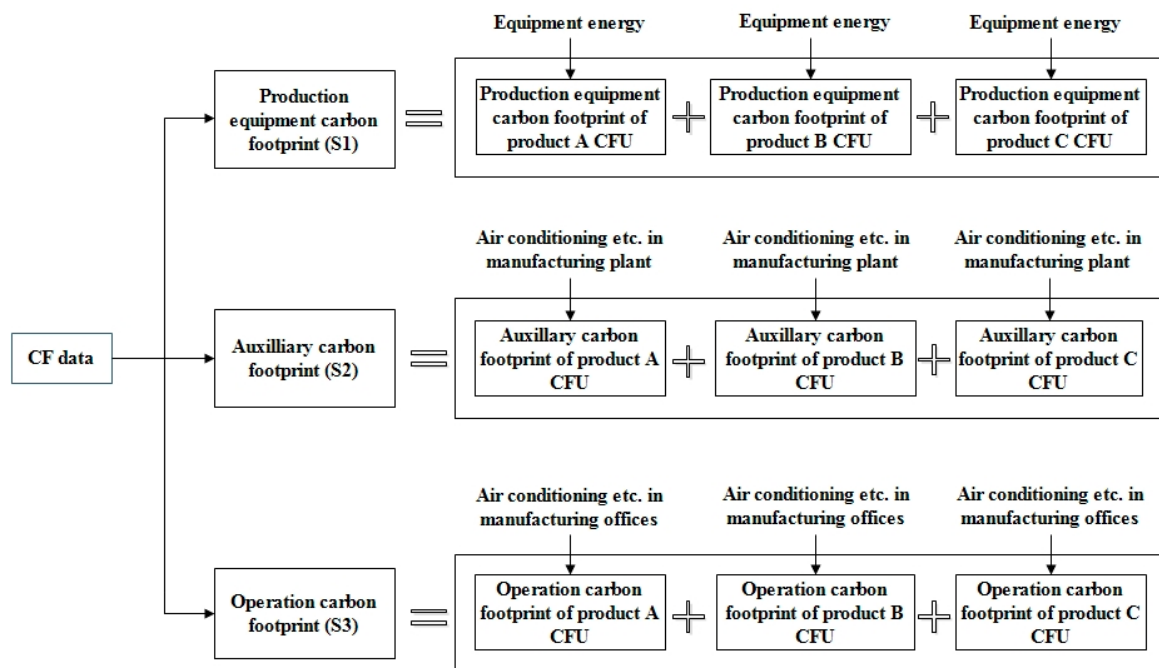


Figure 3. Data construction of CF.

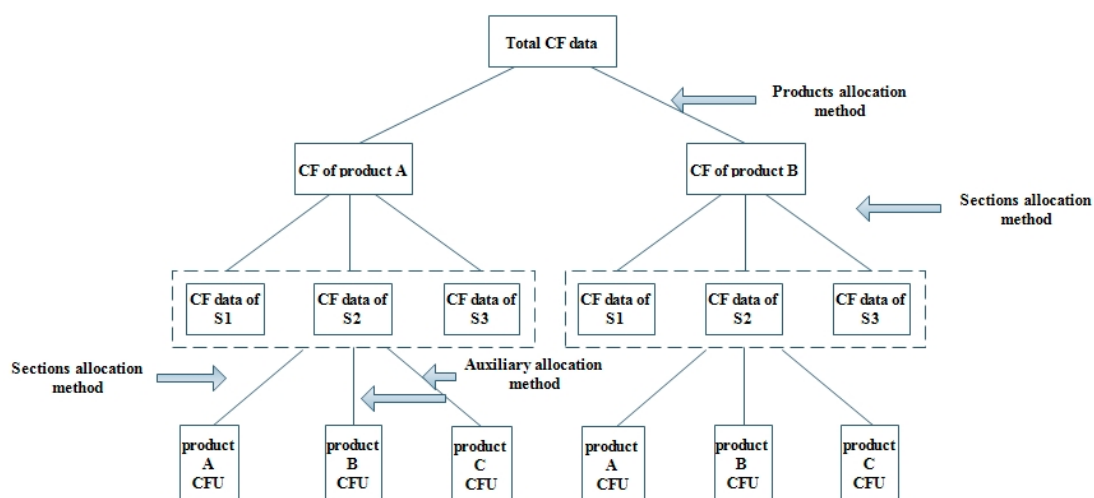


Figure 4. The technical framework of allocation method.

3.2. Products Allocation Method

This step aims to allocate CF data of individual product from co-products. The monthly or annual data are a blend of dozens of different products data. These data should be divided meaningfully. Allocation of different products commonly use mass index which we have discussed in Section 2. If we use a mass-based allocation, mass serves as the weighting factor for allocating energy among different products. This seems to be a rational choice, because in each process, energy use is usually proportional to the mass of products processed. Therefore, the productions allocation method is based on the weight, which contains the ratio of mass and unit yield. The weight indirectly reflects the public resources the product consumes. Data can be allocated by Equation (2). If unit yield data cannot be obtained, the allocation principle is given in Equation (3).

$$CF(x) = W \times \frac{\frac{m_x}{U(x)}}{\sum_{x=1}^n \frac{m_x}{U(x)}} \times C \quad (2)$$

where $CF(x)$ is the amount of individual product GHGs caused by energy consumption (kg CO₂ eq). W is the amount of energy consumption (kW·h or L or m³). $m(x)$ is the production mass (piece, kg, or one-hundred meters) of a certain product. $U(x)$ is the unit yields (piece/h, kg/h, one-hundred meters/h) of a certain product. x is a certain product. n is the number of product categories. C is the emission factor of energy (kg CO₂ eq).

$$CF(x) = W \times \frac{m(x)}{\sum_{x=1}^n m(x)} \times C \quad (3)$$

3.3. Sections Allocation Method

This step aims to divide the CF of individual product into three sections (S1, S2, and S3). Under the process of textile and apparel production, the equipment (air conditioning, etc.) with large electricity consumption use inductive load device, of which a motor works as a variety of electrical or mechanical power source. The power factor is assumed to be the same across the different equipment. Regarding the above assumption, the weight is based on the rated power of three sections. The three sections energy allocation principle is given in Equation (4), which can also be the method of dividing the S1 data into the CFU after simple revision. For S2 and S3 allocation, the Equation (5) and Equation (6) are shown.

$$CF_{process}(x) = Q \times \frac{\sum_{i=1}^n (S_{pi}(x) \times T_{pi}(x) \times N_{pi}(x))}{\sum_{i=1}^n (S_{pi}(x) \times T_{pi}(x) \times N_{pi}(x)) + \sum_{j=1}^m (S_{aj}(x) \times T_{aj}(x) \times N_{aj}(x)) + \sum_{k=1}^p (S_{ok}(x) \times T_{ok}(x) \times N_{ok}(x))} \times C \quad (4)$$

$$CF_{auxiliary}(x) = Q \times \frac{\sum_{j=1}^m (S_{aj}(x) \times T_{aj}(x) \times N_{aj}(x))}{\sum_{i=1}^n (S_{pi}(x) \times T_{pi}(x) \times N_{pi}(x)) + \sum_{j=1}^m (S_{aj}(x) \times T_{aj}(x) \times N_{aj}(x)) + \sum_{k=1}^p (S_{ok}(x) \times T_{ok}(x) \times N_{ok}(x))} \times C \quad (5)$$

$$CF_{operation}(x) = Q \times \frac{\sum_{k=1}^p (S_{ok}(x) \times T_{ok}(x) \times N_{ok}(x))}{\sum_{i=1}^n (S_{pi}(x) \times T_{pi}(x) \times N_{pi}(x)) + \sum_{j=1}^m (S_{aj}(x) \times T_{aj}(x) \times N_{aj}(x)) + \sum_{k=1}^p (S_{ok}(x) \times T_{ok}(x) \times N_{ok}(x))} \times C \quad (6)$$

where $CF_{process}(x)$ is the amount of GHGs caused by production equipment electricity consumption (kW·h). x is a certain product. $CF_{auxiliary}(x)$ is the amount of GHGs caused by auxiliary equipment electricity consumption (kW·h). $CF_{operation}(x)$ is the amount of GHGs caused by operation equipment electricity consumption (kW·h). Q is the amount of total electricity consumption (kW·h). i is a certain production equipment. n is the number of production equipment. j is a certain auxiliary equipment. m is the number of auxiliary equipment. k is a certain operation equipment. p is the number of operation equipment. $S_{pi}(x)$ is the rated power of a certain production equipment (kW). $T_{pi}(x)$ is the actual working hours per day of a certain production equipment. N_{pi} is the number of a certain production equipment. S_{aj} is the rated power of a certain auxiliary equipment (kW). T_{aj} is the actual working hours per day of a certain auxiliary equipment. N_{aj} is the number of a certain auxiliary equipment. S_{ok}

is the rated power of a certain operation equipment (kW). T_{ok} is the actual working hours per day of a certain operation equipment. N_{ok} is the number of a certain operation equipment. C is the emission factor of the energy (kg CO₂ eq). The above data are obtained by spot investigation except C .

3.4. Auxiliary Allocation Method

CFU with the auxiliary energy and materials consumption (including lighting, air conditioning, exhaust fans, ceiling fans, etc.) needs to be divided into different processes. Auxiliary energy (electricity, steam, heavy oil, etc.) consumption is influenced by each process efficiency. Therefore, the allocation is done according to the unit yield. Unit yield indicates the intensity of production output and indirectly reflects the production complexity of certain product. The higher the unit yield is, the faster the production is, and the fewer auxiliary resources the product consumes. Therefore, the data can be allocated by Equation (7).

$$CF_{auxiliaryi}(x) = E_{auxiliary}(x) \times \frac{\frac{1}{U_i(x)}}{\sum_{i=1}^n \frac{1}{U_i(x)}} \times C \quad (7)$$

where $CF_{auxiliaryi}(x)$ is the amount of GHGs by auxiliary energy consumption per CFU (kW·h, L or m³). x is a certain product. $E_{auxiliary}(x)$ is the amount of auxiliary energy consumption (kW·h or L or m³). $U_i(x)$ is the unit yield (piece/h, kg/h, or one-hundred meters/h) in a certain CFU. i is a certain CFU. n is the number of CFU which share the same public consumption. C is the emission factor of the energy (kg CO₂ eq).

There has no significant relation between operation energy consumption with process efficiency. Therefore, operation energy consumption of CFU is the average data of operation energy consumption without considering the unit yield.

4. A Case Study: Cotton T-Shirts

LCA is a tool for the analysis of environmental impacts of a functional unit. To deal with this and render studies better comparable, lots of efforts are undertaken to standardize assumptions and procedures and build up reference databases. This research chooses the manufacture stage of typical cotton T-shirts as a case study. The CF of it were accounted and evaluated by using allocation methodology and the other process were under the LCA standard in order to get better data quality and compatible results.

4.1. Alternatives and Functional Unit

A company mainly engaged in knitting textile and apparel production. The product types can be broadly divided into cotton T-shirts and cotton polo shirts. The white T-shirts were made of pure cotton in size M with plain-printed patterns and a turtleneck. The average weight of a T-shirt is 0.125 kg. The functional unit is defined as one kilogram for the cotton T-shirt.

4.2. System Boundary

All relevant processes are included within the boundary of the T-shirts manufacture system, as shown in Figure 5. The energy consumption arising from manufacturing are included. Furthermore, those for manufacture management are included as well. In this paper, the GHGs emissions were excluded as followings: human energy inputs to processes (e.g., the checking process are finished by manual rather than by machine); the energy inputs to printing and washing processes due to lack of data; the wastes associated with the production of which the impact was insignificant (<1% of total impacts). The space boundary is shown in Table 1.

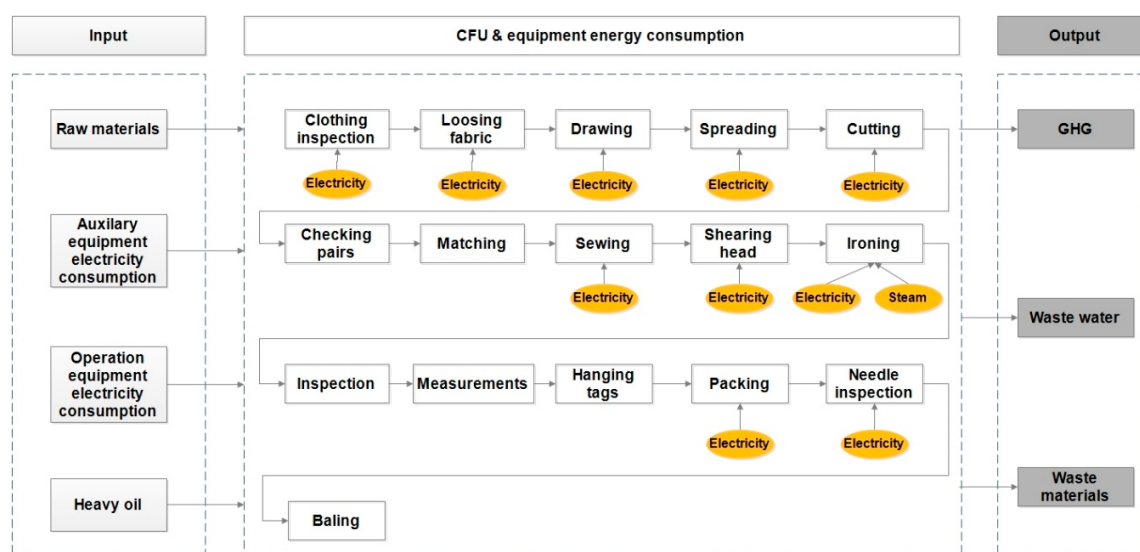


Figure 5. The system boundary of cotton T-shirts.

Table 1. Space boundary of cotton T-shirts.

Production area	Electricity (Purchased)			Heavy Oil	93# Gasoline
	Office Area	Warehouse	Restroom	Production Area	Transportation
1B After treatment section	3A Quality inspection office (Conference office)	1A Production warehouse	1B Restroom	1B After treatment section	Vehicles
2B Sewing section	Management office	2A Material warehouse	2B Restroom		
3A Sewing section			3A Restroom		
3B Cutting section					

4.3. Data Sources

All data used in the CF accounting must obey the data quality requirements, which ensure the CF data of completeness, consistency and reproducibility. For LCA process, primary data are preferred rather than secondary data. Data used in this case study are obtained from primary data and secondary data. The whole plant only has one meter and energy consumptions are recorded by month. Data collection list includes monthly energy, material inputs, equipment rated power, the daily working time, unit yield, and other information according to the allocation methodology. Data on the monthly energy, material inputs, and equipment rated power were collected on site. Data on the daily working time, yields, and other information were the average or general industry data. The data collection results related to this article can be found in Supplementary Materials: The data collection results of the product.

4.4. Results and Discussion

CF of cotton T-shirt was calculated according to above mentioned. The detailed calculation results are shown in Supplementary Materials: The calculation results of the product carbon footprint. During analysis, mathematical analysis methods such as descriptive analysis and partial correlation analysis are employed by using SPSS 18.0 software.

4.4.1. CFU of Cotton T-shirts

Each CFU accounted for the proportion of total CF are shown in Figure 6. The GHGs of Ironing process accounts for the highest proportion of 40.82%, followed by GHGs of the sewing process, 34.85%.

GHGs of other process accounted for the industrial CF are less than 5%. GHGs of ironing and sewing process are relatively large. Ironing process takes a lot of energy for generating steam, which has a high emission factor. While in sewing section, air conditioning are needed from May to September. In the future of the textile and apparel industry, low-carbon energy, the energy-saving refrigeration equipment is chosen to reduce CF significantly.

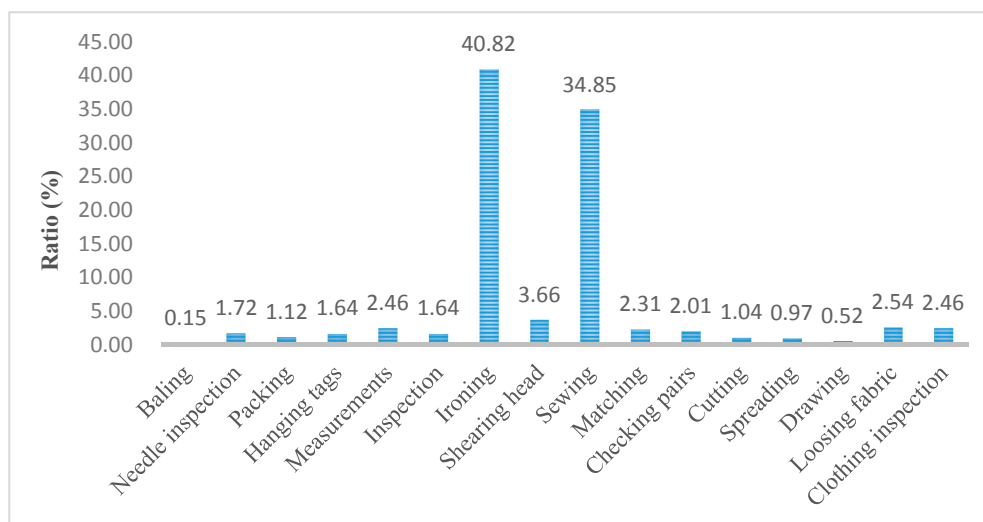


Figure 6. The ratio of each CFU accounted for total CF (%).

4.4.2. CF Comparison in S1, S2, and S3

S1, S2, and S3 can be obtained based on process-level allocation method. Figure 7 shows the CF ratio of different sections in each process. From Figure 7, for most processes, CF of S2 (Auxiliary CF) accounts for the highest proportion of total CF, especially for the packing, hanging tags, matching, and checking pairs processes. These processes are manually manufactured without production equipment. For using production equipment processes, S2 also constitutes a large proportion (more than 40%) of total CF. S2 CF of baling process is zero due to no auxiliary equipment used in this working area. S2 emissions come from lighting, fans, and air conditioning. We estimate the number of the lighting in each working area. At least 500 lighting are installed in sewing section, cutting section and after treatment section. What is more, in the sewing section, which involves a large number of workers, in order to maintain high levels of productivity, air conditioning were used from May to September. These factors may be the cause of high GHGs emissions in S2. Therefore, preferred to S1, reducing S2 emissions should be paid more attention to. Reducing the emission of S2 can be achieved by increasing the unit yield or improving the work efficiency of employees. In addition, energy-saving lighting system and air conditioning can be used instead of current equipment. Finally, the optimization of plant layout can also reduce the emissions of S2.

4.4.3. T-shirt CF Comparison with Co-product CF

The plant produces polo shirts as well as T-shirts. Our allocation method provides a way to calculate the carbon footprint of co-product. The results are shown in Figure 8 compared with CF of T-shirts.

Figure 8 shows that the GHGs emissions of polo shirt in the sewing process is significantly higher than that of cotton T-shirt in the sewing stage (cotton T-shirt: 0.167 kg CO₂ eq/piece; cotton polo shirt: 0.371 kg CO₂ eq/piece). The T-shirt has the highest carbon emissions in the ironing process, followed by sewing process; on the contrary, the polo shirt has the highest GHGs emissions in the sewing process, followed by ironing process. In addition, the CF of the two types apparel in the ironing stage are similar with cotton T-shirt 0.068 kg CO₂ eq/piece and cotton polo shirts 0.080 kg CO₂ eq/piece. The

sum of carbon emissions of two kinds of garment products in ironing and sewing processes accounts for more than 75% of total CF. This is consequence of polo shirt's style and structure determines the complexity of its sewing process. Therefore, the polo shirt consumes more energy and material inputs in the sewing process. Besides, the production processes of the T-shirt do not include button attaching and buttonhole processes. The CF of the polo shirt in buttoning and buttonhole processes account for a certain proportion of the total CF (3.17% and 4.03%, respectively), which is only lower than the ironing and sewing processes. However, the CF of the polo shirt in the sewing stage is much higher than that of the T shirt in the sewing stage. So, even after excluding the above two processes, the CF of the polo shirt is still higher than that of the T-shirt.

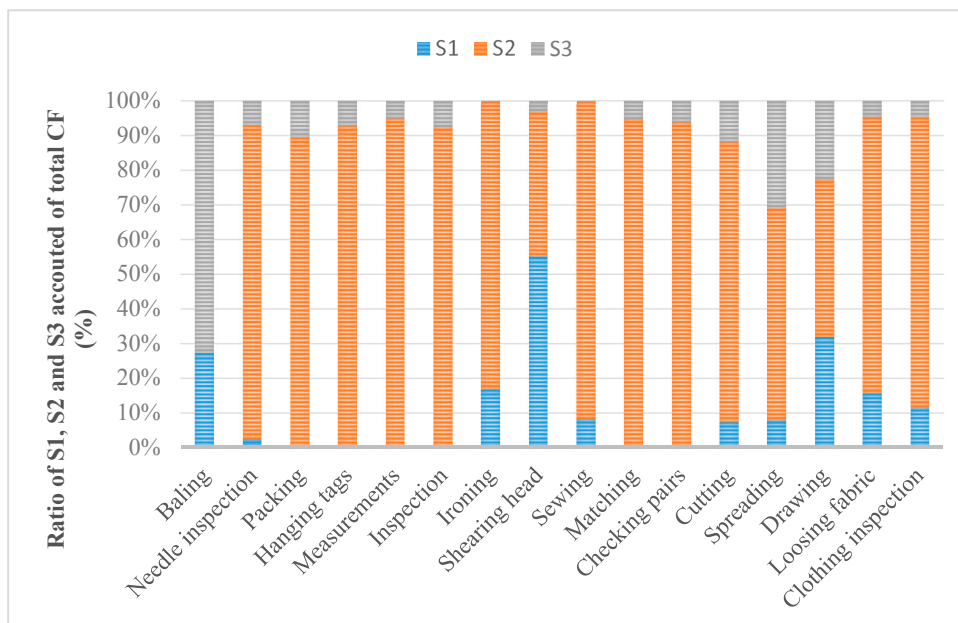


Figure 7. Ratio for S1, S2, and S3 accounted of total CF (%).

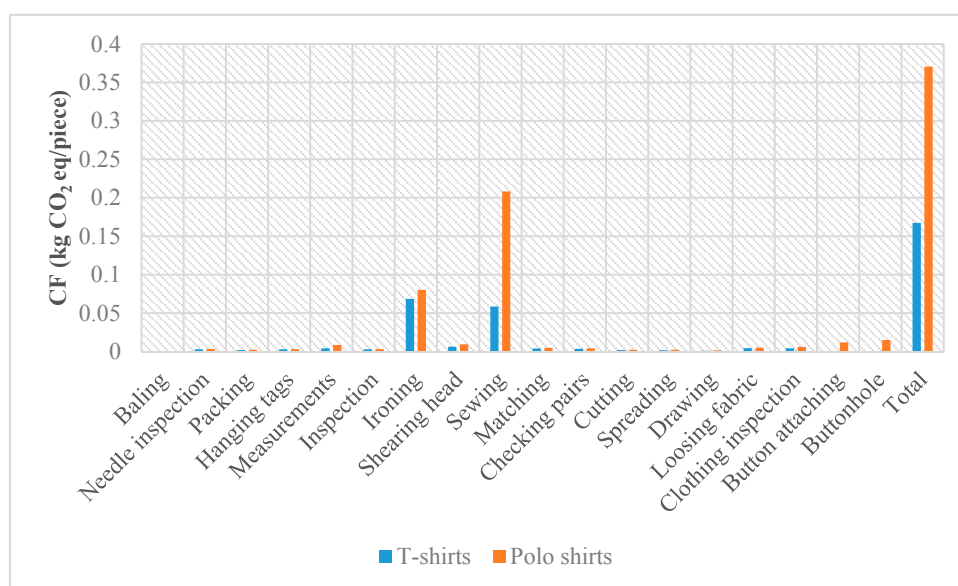


Figure 8. CF of T-shirts and polo shirts.

4.4.4. The Relationship between Production and CF of Cotton T-shirts

Further issues are discussed on the relationship between production and CF of cotton T-shirts in this paper. Relevant data shows that air conditioning used in several months consume more energy dramatically. Therefore, partial correlations between T-shirts production (kg) and all production (kg) with CF (kg CO₂ eq/kg T-shirts) are analyzed, respectively, where the control variable is whether air conditioning (expressed as month type) was used. The results are expressed in Table 2. From Table 2, T-shirt production (kg) has a significant negative linear correlation (correlation coefficient: -0.868) with CF (kg CO₂ eq/kg T-shirts), also similar with that (correlation coefficient: -0.963) of all production. It shows that improving the textile and garment production efficiency is significant to reduce the CF of products (per mass) by technological innovation and management optimization.

Table 2. Correlations between T-shirts production (kg), all production (kg) with CF (kg CO₂ eq/kg T-shirts).

Types		Pearson Correlation Coefficient
T shirts/kg	Pearson Correlation	-0.868
	Sig.	0.000
All types of production/kg	Pearson Correlation	-0.963
	Sig.	0.000

5. Conclusions

This study describes process-level allocation methodology that is reasonable and practical in CF calculation regarding the textile and apparel industry characteristics. From a theoretical point of view, and supported by the results, the allocation method offers vast potential. The results can demonstrate the CFU of each process, different Section CF and co-product CF. In order to test the approach, cotton T-shirts are selected as a case study and the major conclusions are as follows.

- Comparison in each process. GHGs emissions of the ironing and sewing process are relatively large (40.82% and 34.87%, respectively). In the future of the textile and garment industry production, low-carbon energy and energy-saving refrigeration equipment are chosen to reduce industrial CF significantly.
- Comparison in each section. For most processes, CF of S2 (Auxiliary CF) accounts for the highest proportion of total CF. Preferred to S1, reducing S2 emissions should be paid more attention to. Reducing the emission of S2 can be achieved by increasing the unit yield, energy-saving auxiliary equipment and optimization of plant layout.
- Comparison in selected product and co-products. GHGs emissions of polo shirt in the sewing process is significantly higher than that of cotton T-shirt in the sewing stage (cotton T-shirt: 0.167 kg CO₂ eq/piece; cotton Polo shirt: 0.371 kg CO₂ eq/piece). This is consequence of polo shirt's style and structure determines the complexity of its sewing process. Therefore, the product consumes more energy and material inputs in the sewing process.
- Relationship between production and CF. When other factors remain consistent, T-shirt production (kg) has a significant negative linear correlation (correlation coefficient: -0.868) with CF (kg CO₂ eq/kg T-shirts), the similar as that (correlation coefficient: -0.963) of all production. Improving the textile and garment production efficiency is significant to reduce the CF of products (per mass) by technological innovation and management optimization.

By analyzing the data, the most promising energy-saving opportunities can be found, and measures can be taken to eliminate the GHGs emissions and optimize energy consumption control. The approach has shown good practicability and convenience during spot investigation. This procedure has several potential applications: conservation of an in-depth understanding of the system, flexibility of the method, or variability assessment. Although the allocation methodology has been tested in forty

products in China, its applicability still needs broad application. To test the approach and confirm its feasible in textile industry, more researchers need to participate in using the allocation method and public their results. In fact, the allocation method was derived for the China conditions as well as specific processes. The approach serves well for apparel production process in China. But other regions of the world and textile process with significant difference needs to be further discussed. Process-level allocation methodology is useful for the various applications outlined in this paper. However, it still needs more real-time data to test whether the method is consistent with reality. It is likely that growing public interest in the environmental impact of products will increase the demand for GHGs emissions information. Investment should be rewarded by an enhanced amount of better-quality data recorded by textile and apparel factories.

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