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A life-cycle assessment of household refrigerators in China

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A R T I C L E I N F O

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A B S T R A C T

China is an important refrigerator producer and consumer in the world. The refrigerator industry is an important contributor to China's economy; however, it also impacts the environment negatively. To improve the sustainability of Chinese refrigerators, it is necessary to evaluate their environmental impacts throughout their life cycles and identify improvement opportunities. This study provides a cradle-to-grave life-cycle assessment of a direct-cooling double-door household refrigerator. Inventory data are obtained from onsite investigations of refrigerator producers and disposal enterprises. Environmental impacts are evaluated using the CML 2001 method built into GaBi (version 6.0). The results show that the environmental impacts of 11 categories are relatively high in the usage phase, and four types of environmental impacts (ODP, TETP, ADP-elements, and ADP-fossil) are also high during the production phase. The hotspots in the life cycle of a refrigerator have been identified as electricity consumption in the usage phase and the consumption of material resources (such as steel) and natural gas in the assembly phase. This quantitative life cycle assessment helps decision-makers to understand the life-cycle environmental impacts of Chinese refrigerators and improve its sustainability.

1. Introduction

As a common modern industrial product, a refrigerator is an essential part of daily human life. Because China is a globally important refrigerator producer and consumer, the refrigerator industry has been an important contributor to China's economy, especially after China's accession to the World Trade Organization (WTO) in 2001. Despite the global economic crisis, China exported 36.31 million refrigerators in 2013 (National Bureau of Statistics of China, 2014). However, the refrigerator industry has a negative impact on the environment, just as other electronic industries do. Typically, the phosphating process discharges wastewater with phosphorus, which can eutrophicate local surface waters (Erol and Thöming, 2005; Zhang, 2010). The foaming process emits cyclopentane gas at a rate of 0.03 kg/h, which is harmful to human health (Liu, 2011). A running refrigerator consumes electricity, which can indirectly cause greenhouse gas emissions (Yuki et al., 2013). At the end of a refrigerator's life, the heavy metals contained in its components can pollute the air, soil, and water if the refrigerator is arbitrarily discarded or landfilled directly as garbage (Liu and Chi, 2013).

To mitigate the negative environmental impact of refrigerators, most countries have environmental protection practices in place. For example, China has enacted a series of policies and regulations to replace the environmentally harmful components of refrigerators with environmentally friendly ones (Nan, 1995; International Organization for Standardization, 2006; Lu, 2006; The Central People's Government of People's Republic of China, 2009). In recent years, to control serious pollution due to electronic waste, the European Union has passed and implemented the Waste Electrical and Electronic Equipment (WEEE) Directive and the Restriction on the Use of Certain Hazardous Substances (RoHS) in Electrical and Electronic Equipment (Koh et al., 2012). These documents have undoubtedly become new technical barriers to the international trade of Chinese refrigerators, which requires that a life-cycle inventory of China's refrigerators be completed (Zhou and Gao, 2007). Previous researchers have compared the environmental impacts of the materials used in refrigerators, including the energy consumption and greenhouse gas emissions of refrigerators with two different foamers, HFC-245fa (pentafluoropropane) and pentane (Johnson, 2004), conducted a life-cycle inventory analysis of the production of HFC-134a from mine to refrigerator (McCulloch and Lindley, 2003), studied the life-cycle climate performance (LCCP) of different refrigerating fluids based on measured data (Yunho et al., 2007), and measured the greenhouse gas emissions of refrigerants in their usage and disposal stages

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(Campbell and McCulloch, 1998). These studies consider the environmental impact of two or more types of materials used in refrigerators in isolation.

Aging refrigerator components also waste energy, sometimes causing the refrigerator to consume 40–60% more energy than the labeled value; this consumption can be partially reduced by simply repairing old refrigerators (Meier, 1995; Akbari et al., 1997). Some studies use the idea of life-cycle assessment (LCA) to calculate the optimum service life of a refrigerator (Horie, 2004; Kim et al., 2006). The concept of LCA also is also used to design more environmentally friendly refrigerators (Gehin et al., 2009; Vendrusculo et al., 2009). These designs include extended product lifetimes and lower energy consumption. In recent years, the disposal and recycling of refrigerators has drawn increasing amounts of attention (Laner and Rechberger, 2007; Altekin et al., 2008). However, most of the published articles emphasize the development of disassembly technologies for recovering materials from waste refrigerators rather than the refrigerators' environmental impact (Lambert and Stoop, 2001; Nicol and Thompson, 2007). A refrigerator's life-cycle environmental impact was evaluated, and the secondary life cycle inventory (LCI) databases greatly increase the uncertainties of these studies (Zhang, 2010).

The study is a cradle-to-grave life-cycle assessment for a typical made-in-China refrigerator based on the data from on-site investigations. The outcome of this study will help to understand the life-cycle environmental impacts of Chinese refrigerators and create a scientific basis for decision-makers to achieve environmental sustainability.

2. Methods

This study was conducted in accordance with the principles of the International Organization for Standardization's (ISO) 14040 series of standards for LCA. LCA is usually carried out in four steps: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA) and (4) life cycle improvement analysis and interpretation. These steps are described in detail below.

2.1. Goal and scope definition

The objective of this study is to quantify resource and energy consumption and environmental emissions during the complete life cycle of a typical refrigerator in China. This study also identifies environmental hotspots and explores improvement opportunities. We selected the direct-cooling double-door refrigerator as our research object because the double-door refrigerator is the most popular type and accounts for nearly half of market share, in which the direct-cooling refrigerator occupied 90.3% market share (Internet Consumer Research Center 2014). The reasons for the popularity of this type of refrigerator are probably the following: (1) A Chinese family most often consists of three people and a refrigerator with a volume of approximately 200 L is appropriate to meet such a family's daily needs; (2) Chinese people prefer to use double-door refrigerators weighing approximately 50–70 kg; (3) Chinese people prefer energy-saving refrigerators with reasonable prices. Technical details of the chosen refrigerator are given in Table SI1.

2.2. System boundary

Based on the ISO 14040 standard and the research objective, we divided the life cycle of a refrigerator into a production stage (including raw material extraction, parts production and assembly), a transportation stage, a usage stage, and a disposal stage. Based on on-site investigations of three refrigerator producers and one recycling company, we defined the service life as 10 years rather than the 10–15 years used by other researchers (Zhang, 2010). The geographic boundaries of the refrigerator's transportation were within the territory of China. The system's boundary is shown in Fig. 1.

2.3. Functional unit

The functional unit was defined as “the complete life cycle of a 61 kg direct-cooling double-door refrigerator made in China, used for 10 years (24 h/day), and disposed of in China through a state-of-the-art recycling system.”

2.4. Data collection

First-hand data from representative Chinese enterprises were collected for this study. The GaBi (version 6.0) databases (Weidema and Hischier, 2006; PE International, 2012), literature and statistical yearbooks were used as secondary data sources to guarantee the consistency of our data set. Details of the data sources and a description of the data collections can be found in Table SI2. The data's quality was qualitatively evaluated with the assumption that primary data were of higher quality than secondary data.

2.5. LCIA methods

We used GaBi (version 6.0) to organize the inventory data and perform the impact assessment, as shown in Fig. SI3. The mid-point CML 2001 method (updated in Nov. 2010) was used to determine hotspots in the life cycle of a refrigerator. The impact categories considered in this analysis are: abiotic depletion (ADP elements and ADP fossil), acidification potential (AP), global warming potential (GWP), photochemical ozone creation potential (POCP),

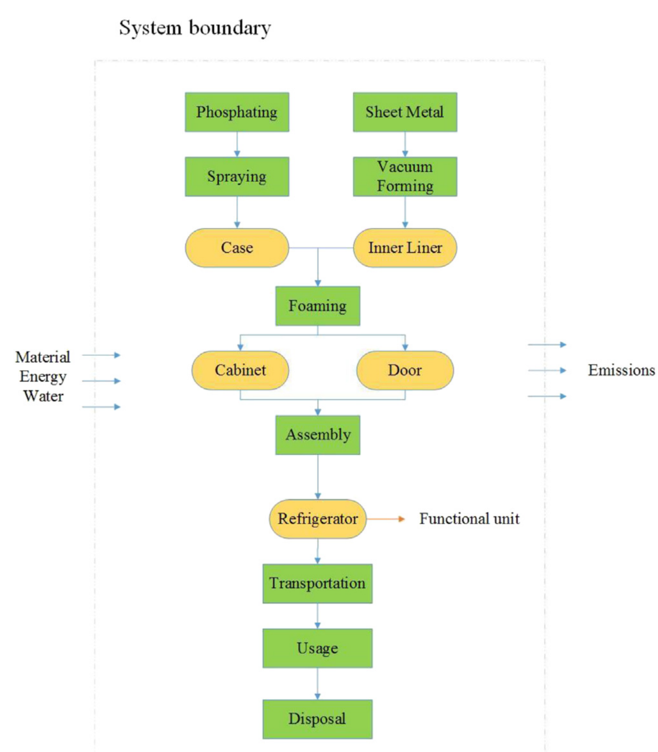

Fig. 1. System boundary for the complete life cycle of a refrigerator.

ozone layer depletion potential (ODP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), and terrestrial ecotoxicity potential (TETP). These categories were chosen because of their relevance to the life cycle of a refrigerator.

3. Results

3.1. LCI results

Inventory data of refrigerators in the production and disposal phases are provided in Tables 1 and 2. Based on the statistical database (Tables SI4 and SI5), the average transportation distance for a refrigerator is 1348 km. The LCI data on refrigerator transportation is based on the Ecoinvent database v2.2: Transport, "transport, lorry 16–32 t, EURO3" (RER = Region Europe).

The service life of one refrigerator was assumed to be 10 years for this study. The rated power use of the refrigerator is 0.35 kWh/day, and it is assumed to run for 365 days per year during its service period. Therefore, the electricity consumption in the use stage can be calculated as: 0.35 kWh/day × 365 days/year × 10 years = 1277.5 kWh.

In addition, due to the depletion of refrigerant during a refrigerator's service life, each refrigerator is provided with additional refrigerant once (Xu, 2010; Zhang, 2010).

3.2. LCIA results

Table 3 shows the life cycle impact assessment (LCIA) results for one refrigerator in all of the selected categories. Fig. 2 presents the relative contribution of each different life-cycle stage to each impact category for one refrigerator.

The usage stage is found to be the dominant contributor to most impact categories, excepting ODP, ADP-elements, and ADP-fossil. Contributions to these three categories are primarily attributable to the production stage. In the entire life cycle of a refrigerator, the environmental impact of waste discharge is not as obvious as that of energy consumption. In addition, MAETP has the maximum value of the four categories pertaining to ecological toxicity. Recycling waste refrigerators can greatly mitigate their environmental impact.

The environmental impact is concentrated in the usage and production stages of the refrigerator's life cycle. The transport stage causes little environmental impact and the usage stage produces indirect effects which can be mitigated by improving technologies. Therefore, we analyzed the environmental impact of the production phase, and then sought improvement opportunities.

3.2.1. Production

The main parts of the refrigerator production process are cabinet manufacturing (CAM), door manufacturing (DM), compressor manufacturing (COM), accessory manufacturing (AM), and assembly (AS). Their contributions to each impact category are shown in Fig. 3. Compressor manufacturing is the dominant contributor to the ADP elements category and to the four toxicity indicators (HTP, FAETP, MAETP, and TETP). Cabinet manufacturing is the most significant contributor to the other environmental impact categories.

We also analyzed the contributions of each part of the compressor manufacturing process to each impact category. The largest portion of the compressor's contribution to ADP (elements) is due to its use of copper, steel, and aluminum. The consumption of steel is responsible for the largest portion of the compressor's contributions to the four toxicity indicators (HTP, FAETP, MAETP, and TETP). Upstream coal and electricity use contribute heavy metals (especially copper II, chromium, cobalt and nickel II), selenium, and vanadium to the process of manufacturing the steel.

Due to the consumption of large amounts of natural resources, including copper and iron ores, the largest portion of ADP (elements) is due to the consumption of copper (75.52%), followed by the consumption of steel (22.10%). It should be noted that the upstream production processes of copper and steel also consume coal, steam, water, and other resources. The FAETP is dominated by the consumption of steel (55.38%) and copper (41.38%). The MAETP is dominated by the consumption of copper (32.20%), steel (29.55%), and aluminum (34.32%). The upstream production stages of these materials generate heavy metals (especially copper II, beryllium, cobalt and nickel II). The possible loss of these substances into water can contribute to the FAETP and the MAETP. Similarly, the primary contributors to the HTP are copper (48.21%), steel (35.70%), and aluminum (14.55%) production. The main reason for these large contributions is the emission of heavy metals into the air and of selenium and vanadium into freshwater as a result of upstream coal and electricity production processes. The dominant contributors to the TETP are the consumption of steel (81.25%) and copper (12.23%). Heavy metal (especially chromium) emissions into the air and industrial soil resulting from the production of steel are the major reason for these contributions. Another important reason is the possible volatilization of mercury II, which is related to amalgamation in ore smelting process.

We also examined the contributions of specific parts of the major contributors to each impact category involved in the cabinet's life cycle. The dominant contributor to the ADP fossil category is the spraying stage, which accounts for over 70% of the total impact. Its contribution is related to the use of electricity, compressed air, and natural gas, the upstream production of which consumes fossil resources. In addition, the production of epoxy resins consumes natural gas, crude oil, and hard coal. The foaming stage is the second largest contributor to the ADP fossil category because it involves direct consumption of electricity and compressed air. The hotspots are concentrated in the foaming, vacuum shaping, and spraying processes. The largest contributors to the AP are SO_2 and NO_x, which are emitted directly during coal burning in the foaming stage and indirectly due to the consumption of electricity in the foamer's upstream production stage. Although the foaming machine is sealed, the blowing agents in the interlayers still leak from the injection port during the vacuum-shaping process, when the heating temperature is lower than the decomposition temperature of high impact polystyrene (HIPS). During the vacuum-shaping process, heating generates a small amount of organic waste, including non-methane hydrocarbons (NMHC). The workpiece solidifies after electrostatic spraying, generating a small amount of organic volatile organic compound (VOC) waste. The foaming phase accounts for nearly half of the total EP of a refrigerator and is followed by the sheet metal phase, which accounts for 22.20% of the total EP. The upstream production of steel and the use of diisocyanate for foaming makes the production stage a significant contributor to the eutrophication potential, which results in the high load of phosphorus, nitrate and chemical oxygen demand (COD) in wastewater. The dominant contributors to the GWP are the spraying (33.42%), foaming (31.38%) and vacuum shaping (25.46%) phases, which together account for over 90% of the total GWP of creating the refrigerator's cabinet. The largest portion of the GWP is due to the use of HFC-245fa because the 100-year GWP of 1 g of HFC-245fa is 858 times as high as that of CO_2 (Stocker et al., 2013). More than 80% of the blowing agent's contribution to the GWP is from indirect emissions due to energy consumption during its production. Less than 1% is due to leakage during the production stage (Johnson, 2004). The second largest contributor to the GWP is

Table 1
Main inventory data for a refrigerator in the production stage.

Category	Subcategory	Sheet metal		Phosphating		Spraying		Vacuum shaping		Foaming		Injection molding	Refrigerating system		Final assembly
		Cabinet	Door	Cabinet	Door	Cabinet	Door	Cabinet	Door	Cabinet	Door	Shelves drawers	Compressor	Accessory	
Energy	Electricity (kWh)	0.348	0.051	0	0	0.334	0.087	2.517	0.944	1.969	0.511	0.534	2.519	0	1.134
	Natural gas (m^3)	0	0	0	0	0.176	0.046	0	0	0	0	0	0.048	0	0
	Steam (kg)	0	0	6.176	1.601	0	0	0	0	0	0	0	0	0	0
	Compressed air (m^3)	0.784	0.115	0	0	0.752	0.195	5.664	2.124	4.432	1.149	1.203	0.048	0	2.552
Material(g)	Water (m^3)	0	0	0.005	0.001	0	0	0.012	0.004	0	0	0	0.033	0	0
	Steel	13,076.923	1923.076	0	0	0	0	0	0	0	0	0	14,926	2166.667	0
	Copper	0	0	0	0	0	0	0	0	0	0	0	1258	50	0
	Aluminum	0	0	0	0	0	0	0	0	0	0	0	1581	608.323	0
	Sodium silicate	0	0	3.529	0.915	0	0	0	0	0	0	0	0	0	0
	Sodium carbonate	0	0	2.646	0.686	0	0	0	0	0	0	0	0	0	0
	Sodium hydroxide	0	0	0.882	0.228	0	0	0	0	0	0	0	0	0	0
	Silane coupling agent	0	0	2.646	0.686	0	0	0	0		0	0	0	0	0
	Fluorozirconate	0	0	2.646	0.686	0	0	0	0	0	0	0	0	0	0
	Epoxy resin	0	0	0	0	88.229	22.881	0	0	0	0	0	0	0	0
	High impact polystyrene (HIPS)	0	0	0	0	0	0	7272.727	2727.272	0	0	222.222	0	0	0
	Isocyanate	0	0	0	0	0	0	0	0	5145.542	1334.457	0	0	0	0
	Cyclopentane	0	0	0	0	0	0	0	0	381.151	98.848	0	0	0	0
	Polyether polyol	0	0	0	0	0	0	0	0	3811.513	988.486	0	0	0	0
	Pentafluoropropane (HFC-245fa)	0	0	0	0	0	0	0	0	190.575	49.424	0	0	0	0
	Polyvinyl chloride (PVC)	0	0	0	0	0	0	0	0	0	0	466.666	0	0	0
	Color master batch	0	0	0	0	0	0	0	0	0	0	500	0	0	350.832
	Rubber	0	0	0	0	0	0	0	0	0	0	0	0	0	287.403
	Magnetic powder	0	0	0	0	0	0	0	0	0	0	0	0	0	479.002
	Corrugated paper	0	0	0	0	0	0	0	0	0	0	0	0	0	3917.630
	Expandable polystyrene (EPS)	0	0	0	0	0	0	0	0	0	0	0	0	0	1697.168
	R600a (Isobutane)	0	0	0	0	0	0	0	0	0	0	0	0	0	50
Emissions to air (g)	Fly ash	0	0	0	0	0.086	0.022	0	0	0	0	0	2.094	0	0.054
	Sulfur dioxide	0	0	0	0	0.035	0.009	0	0	0	0	0	0	0	0
	Nitrogen dioxide	0	0	0	0	0.311	0.080	0	0	0	0	0	0.022	0	0
	Non-methane hydrocarbon (NMHC)	0	0	0	0	0.749	0.194	0.162	0.061	2.859	0.741	0	1.205	0	1.000
Emissions to water (g)	Chemical oxygen demand (COD)	0	0	2.751	0.713	0	0	3.146	1.179	0	0	0	5.528	0	0
	Suspended solid (SS)	0	0	1.334	0.345	0	0	1.525	0.572	0	0	0	2.211	0	0
	Oil waste	0	0	0.043	0.011	0	0	0.049	0.018	0	0	0	0.176	0	0
	Ammonia nitrogen	0	0	0.175	0.045	0	0	0.201	0.075	0	0	0	0.221	0	0
Solid waste (g)	Waste steel	145.299	21.367	0	0	0	0	0	0	18.968	2.789	0	7.407	0	0
	Waste epoxy resin	0	0	0	0	2.646	0.686	0	0	0	0	0	0	0	0
	Waste high impact polystyrene (HIPS)	0	0	0	0	0	0	8.081	3.030	0	0	7.168	0	0	0
	Waste polyurethane	0	0	0	0	0	0	0	0	10.600	5.419	0	0	0	0

Table 2
Main inventory data for a refrigerator in the disposal stage.

Processing	Recovered (kg)				Remainder (kg)	Electricity (kWh)	Solid waste (kg)			Waste gas (kg)
Artificial disassembly	Compressor 17.779	R600a 0.005	Rubber 0.287403846	Magnetic powder 0.4790025		0.082				R600a 0.045
Crushing	Cabinet 29.800	Door 7.113	Shelves drawers 1.181	Accessory 2.833	40.929	6.876				CFC11 0.002
Magnetic separation	Steel 16.823				23.762	0.264	Steel 0.343			
Winnowing	PUR 10.682				13.078	0.460	PUR 0.001			
Eddy current separator	Aluminum 0.596	Plastic 10.162	Copper 0.049			0.169	Aluminum 0.012	Plastic 0.534	Copper 0.001	

Table 3
LCIA results for one refrigerator based on the CML 2001 method.

Impact category	Value	Unit
Abiotic depletion elements (ADP elements)	6.89E−04	kg Sb-equiv.
Abiotic depletion fossil (ADP fossil)	1.87E+04	MJ
Acidification potential (AP)	1.57E+01	kg SO_2-equiv.
Eutrophication potential (EP)	1.47E+00	kg P-equiv.
Global warming potential (GWP)	1.67E+03	kg CO_2-equiv.
Ozone layer depletion potential (ODP)	5.41E−05	kg R11-equiv.
Photochemical ozone creation potential (POCP)	8.37E−01	kg Ethene-equiv.
Freshwater aquatic ecotoxicity potential (FAETP)	2.65E+02	kg DCB-equiv.
Marine aquatic ecotoxicity potential (MAETP)	1.80E+06	kg DCB-equiv.
Human toxicity potential (HTP)	5.08E+02	kg DCB-equiv.
Terrestrial ecotoxicity potential (TETP)	4.02E+00	kg DCB-equiv.

direct CO_2 emission from hard coal burned on-site to produce steam and indirect CO_2 emission from on-site electricity consumption. The contribution to the ODP is primarily from the spraying stage, in which the production of epoxy resin uses bromine, a potent ozone-depleting substance. In addition, the non-methane volatile organic compounds (NMVOCs) used in the spraying phase can lead to ozone layer depletion. The POCP is mainly attributable to the direct NO_x and SO_2 emissions due to heating during the spraying phase and to the indirect NO_x and SO_2 emissions due to electricity consumption during the foaming phase. The POCP was also influenced by NMVOCs from various phases.

3.2.2. Disposal

The relative contribution of each phase to each impact category in the disposal stage is shown in Fig. 4. Steel recycling brings major benefits to all of the environmental impact categories. HIPS recycling primarily benefits the GWP, AP, ADP fossil and POCP

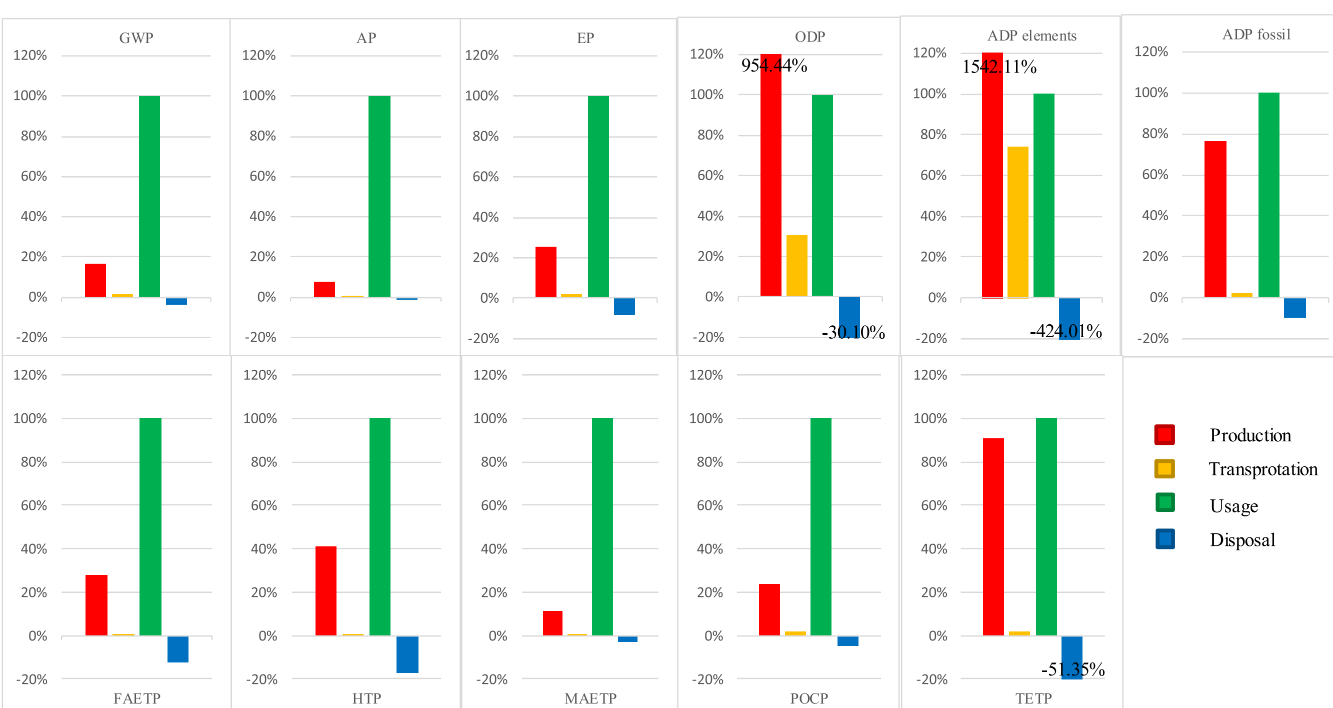

Fig. 2. Relative contributions of a refrigerator to each impact category.

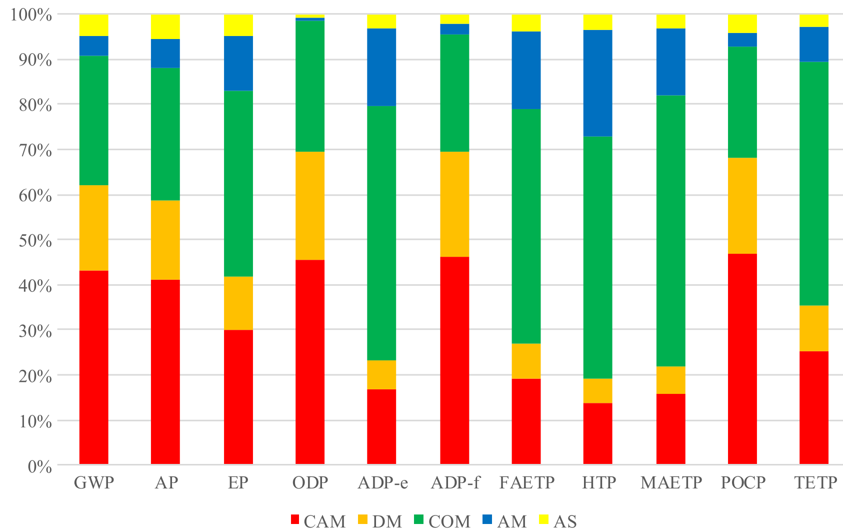

Fig. 3. Relative contributions of the production process to each impact category. CAM, DM, COM, AM, AS represents Cabinet manufacturing, Door manufacturing, Compressor manufacturing, Accessory manufacturing, and Assembly, respectively.

categories; its contributions to other categories are much less significant. Copper recycling benefits the ADP elements and HTP categories. The environmental impacts of PUR incineration and landfill use are low. But the recycling process consumes electricity, causing an environmental impact during the disposal stage.

4. Discussion

4.1. Potential hotspots

A hotspot is an activity with a potentially significant environmental or social impact as a result of specific mechanisms in a phase of a product's life cycle, which can be geographically based and vary among different impact categories. A potential hotspot can be identified by the following steps: (1) Identify the processes that contribute most to each environmental impact based on the results of the LCIA. (2) For each identified process, analyze the main elementary flows that contribute to its environmental impact based on the LCI and CML 2001. (3) Identify the human activities that are most responsible for the main elementary flows leading to the hotspot.

In this study, we identified possible environmental hotspots in the life cycle of a refrigerator and specified their mechanisms and impacts, as shown in Fig. 5. These hotspots are areas where improvements can be made. It should be noted that contributions made by background cradle-to-gate LCIs are hard to identify as potential hotspots and their mechanisms, such as LCIs for a few refrigerator components because the main elementary flows identified for these LCIs are aggregated consequences of upstream and on-site human activities which cannot be separated.

4.2. Improvement opportunities

An improvement opportunity addresses one or more hotspots by reducing environmental impacts or expanding environmental benefits. These opportunities include improvements in product design, advances in manufacture practices, consumer encouragement, supply chain optimization, etc. The improvement opportunities for each hotspot that emerged from this study are listed in Table 4.

Because the usage stage is responsible for most of the environmental impacts, daily consumer behaviors that reduce energy consumption should be encouraged, such as choosing products that consume less energy, according to their energy efficiency labels, placing refrigerators in locations with good ventilation and out of direct sunlight, not putting hot food in the refrigerator because

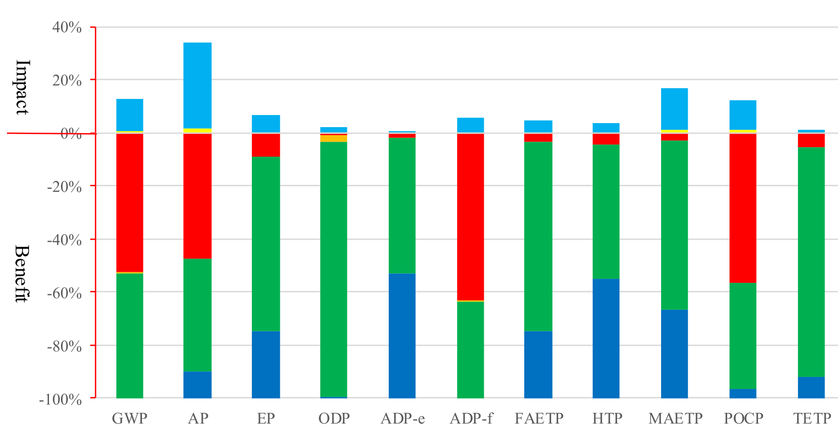

Fig. 4. Relative contributions of the disposal process to each impact category.

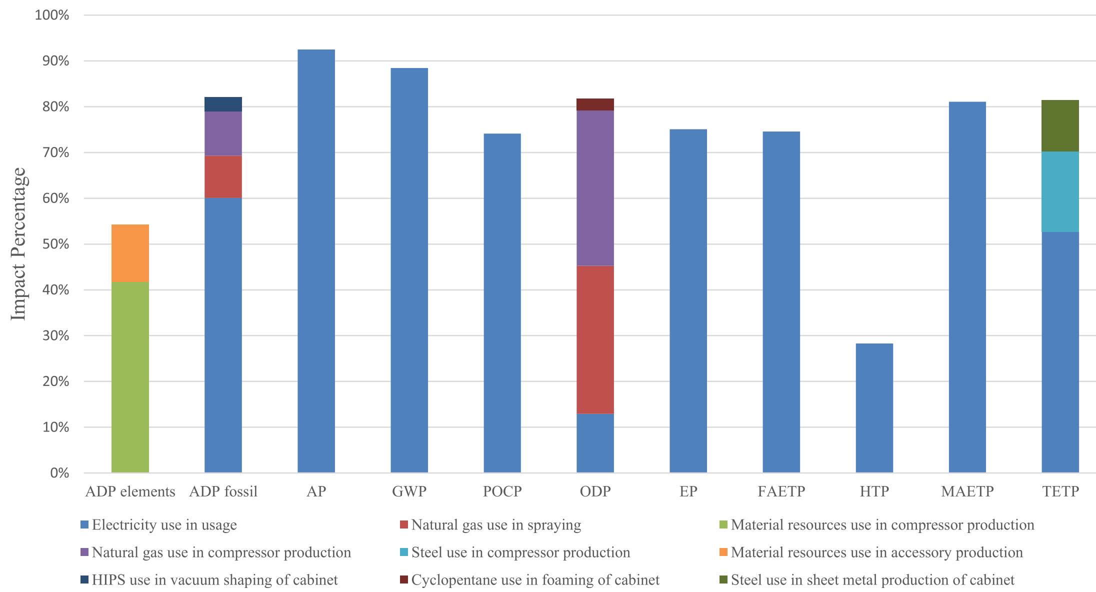

Fig. 5. Potential hotspots during the refrigerator's life cycle.

doing so can cause a sharp increase in the refrigerator's internal temperature, leading to higher electricity consumption (Ye, 2012), and reducing the number of times the door is opened and closed, which can result in a 7% energy reduction (Chen, 2011a,b). It is also recommended that less food be stored in the refrigerator and that storage times be reduced. For families living in the northern part of China, where winter temperatures usually drop below 0 °C, natural outdoor “refrigerators” can substitute for ordinary indoor refrigerators. Finally, because over-use of the components results in higher electricity consumption, old refrigerators should be retired at an appropriate age.

Ecologically sound design is important for mitigating the environmental impact of the usage stage. At present, the selection of a molding technique is based on past experience in designing refrigerator molds and the traditional mold test. A further study on optimizing the refrigerator vacuum-shaping molding technique to reduce energy and freshwater consumption and improve the level of clean production has been completed (Xu, 2010). In 2008, the Ministry of Commerce of the People's Republic of China established a rule for the maximum allowable energy consumption and a minimum energy efficiency grade for household refrigerators, forcing refrigerator manufacturers to make their designs more ecologically sound. Energy efficiency standards and energy efficiency labeling have been the best ways to reduce energy consumption and provide consumers with a positive return. Recent studies show that the development and effective implementation of new energy efficiency standards, energy labeling, and consumer awareness of energy saving products could save 277.5 TWh of energy by 2020 (Wang et al., 2009).

4.3. Comparison of the present study with other studies

There are few studies that involve an assessment of the complete life cycle of a refrigerator. Most of the previous studies concentrated on a specific process or life-cycle stage or compared the environmental impacts of refrigerators made using different technologies and materials. These studies most often focused on the production phase, and only a few assessed the environmental impact of use and reuse. There has been only one complete LCA of the environmental impact of refrigerators (Zhang, 2010). Because the impact categories selected for the present study are different, we have compared the results for approximate indicators. In Table 5 an overview of the general framework and results of the two studies is given.

Table 4
Improvement opportunities in hotspots.

Improvement opportunities	Hotspot(s) addressed	Description
Change the structure of the electrical grid and provide cleaner energy	Electricity use in usage	Reduce the environmental burden of upstream electricity production (Kim et al., 2006)
Develop new bonderite and surface conditioners that dry faster	Natural gas use in spraying for refrigerator door production Natural gas use in compressor production	Reduce the use of natural gas (Erol and Thöming, 2005, 2006)
Strengthen eco-design and on-site management	Material resource use in compressor production Material resource use in accessory production Compressed air use in cabinet vacuum-shaping	Reduce the consumption of copper (Gehin et al., 2009) Promote energy-saving performance appraisal with education (field research)
Collect steel scrap and steel board for recycling	Steel use in compressor production Steel use in the production of sheet metal for the cabinet	Reduce primary steel consumption (field research)
Collect HIPS scrap for recycling Develop a new foamer that is more environmentally friendly	HIPS use in cabinet vacuum-shaping Cyclopentane use in cabinet foaming	Reduce primary HIPS consumption (field research) Reduce the environmental burden of foamer usage (McCulloch and Lindley, 2003; Johnson, 2004; Yunho et al., 2007)

Table 5
Comparison with the results of another study.

Category		Current study	Zhang Jianpu
Functional unit		61 kg	52 kg
Database		Ecoinvent	IDEMAT 2001, BUWAL 250
Methodology		CML 2001	Ecoindicator-99
System boundary	Transportation	Nationwide	Jiangsu province
	Usage	10 years, 0.35 kWh/day	15 years, 0.58 kWh/day
Result	GWP	1.67E+03 kg CO_2-equiv.	1.11E+02 kg CO_2-equiv.
	ADP fossil	1.87E+04 MJ	1.23E+05 MJ
	AP	1.57E+01 kg SO_2-equiv.	1.23E+01 kg SO_2-equiv.
	ODP	5.41E−05 kg R11-equiv.	3.89E−03 kg R11-equiv.

The two studies agree fairly well on the production phases, but there are discrepancies in the other phases. A possible explanation for the large difference in the transportation phase is that the distribution distances differ due to China's large geographical area. As in our study, his results show that, during the life cycle of a refrigerator, resource consumption is the main factor impacting the environment, particularly the consumption of mineral and fossil resources.

4.4. Limitations

While we have attempted to collect extensive data to quantify the cradle-to-grave life-cycle impacts of refrigerators, there are some limitations in our research.

Uncertainty can be defined in many ways, but one definition that appears to be useful in the present context is: “the discrepancy between a measured or calculated quantity and the true value of that quantity.” Examples include: data uncertainty, model uncertainty, epistemic uncertainty, etc. In this list, we distinguish between sources and types of uncertainties. Sources are the input elements of the LCA that may be uncertain, and types refer to the different things that may be “wrong” with these sources. In the LCA, we distinguished the following sources:

Data, e.g., the amount of electricity used by a process and the GWP of dinitrogen oxide; choices, e.g., system boundaries, allocation principles, and time horizons in the LCIA; relations, e.g., the linear dependence of the distance traveled distance on the fuel required, the linear dependence of acidification on SO_2 emissions, and the discounting formula used to determine long-term impacts.

The types of uncertainty are partly related to these sources, as these examples illustrate: data can show variability, e.g., although the enterprise chosen for study was thought to be representative of the wider industry, the actual data obtained from the enterprise contain uncertainties, due to, for example, fluctuations in electricity consumption during production tasks; data can be outdated, e.g., the electricity consumption in the usage stage, which was modeled on the Ecoinvent database using China-specific data from 2005, was found to be the dominant source of impact for all of the categories. However, the energy mix of the national power grid has changed in recent years, reducing the proportion from fossil fuels and increasing the proportion from clean and renewable energy sources (Chen, 2011a,b), and the emission standards for air pollutants from thermal power plants have been tightened (Ministry of Environmental Protection of the People's Republic of China, 2012); data may be erroneous, e.g., workers gave us an estimate, but we mistakenly thought it was a measured value; data may be incomplete, e.g., information on the emissions of contaminants from electronic components in the manufacture and disposal stages, which would reduce the results in Table 3, especially those for ADP elements, TETP, and HTP; data may be subject to round-off errors, e.g., 0.342 may have been entered as 0.3, which is an error of more than 10%; and the data may be simplified, e.g., the upstream production data for steel plate came directly from the Ecoinvent database.

In addition, choices may have been made inconsistently across alternatives, e.g., different allocation methods may have been selected for different product chains (steel consumption was allocated in accordance with the mass ratio in the sheet metal bending process, but dusting powder was allocated in accordance with the area ratio in the spraying process); choices may have been made inconsistently across the LCIA, e.g., the method chosen for the LCIA, the mid-point CML 2001 method, has some uncertainties. For human toxicity, the CML 2001 score is dominated by contributions from metals, whereas the EDIP 97 score is due to a solvent and nitrogen oxides. Metals are the main contributors to aquatic toxicity in both methods, vanadium for CML 2001 and strontium for EDIP 97. Because GaBi 6.0 has been updated to include CML 2010 and the most accurate database, we decided to use this evaluation method (Dreyer et al., 2003). It was difficult to directly assess the human toxicity and ecotoxicity of bonderite and surface conditioners due to the lack of characterization factors in the Ecoinvent database. Therefore, we assumed that the pollution due to bonderite and surface conditioners is the same as it is in the production stage. We calculated the pollution value by modeling the production process in GaBi, with parameters in accordance with chemical handbooks.

4.5. Sensitivity analysis

A sensitivity analysis of the primary energy demand and environmental impacts was conducted with the assumption that the

Table 6
A sensitivity analysis of some important parameters.

Process	Sheet metal for cabinet	Phosphiding for cabinet	Vacuum shaping for cabinet		Foaming for cabinet		Transportation	Usage	Disposal
Parameter	Steel consumption	Steam 2consumption	Compressed air consumption	HIPS consumption	Diisocyanate consumption	Cyclopentane consumption	Distance	Electricity consumption	Steel recycling
Variation	±10%	±10%	±10%	±10%	±10%	±10%	±10%	±10%	±10%
ADP elements	±0.90%	±0.00%	±0.39%	±0.08%	±0.42%	±0.17%	±0.54%	±0.73%	±1.57%
ADP fossil	±0.15%	±0.01%	±0.02%	±0.57%	±0.21%	±0.09%	±0.13%	±6.80%	±0.26%
AP	±0.04%	±0.00%	±0.01%	±0.10%	±0.08%	±0.01%	±0.05%	±9.44%	±0.07%
EP	±0.28%	±0.00%	±0.06%	±0.08%	±0.12%	±0.09%	±0.16%	±8.29%	±0.48%
FAETP	±0.43%	±0.00%	±0.07%	±0.05%	±0.02%	±0.02%	±0.05%	±8.36%	±0.76%
GWP	±0.11%	±0.01%	±0.01%	±0.27%	±0.15%	±0.02%	±0.1%	±8.74%	±0.19%
HTP	±0.4%	±0.00%	±0.10%	±0.08%	±0.02%	±0.03%	±0.04%	±7.82%	±0.70%
MAETP	±0.12%	±0.00%	±0.03%	±0.01%	±0.01%	±0.01%	±0.02%	±9.23%	±0.21%
ODP	±0.26%	±0.03%	±0.02%	±0.00%	±0.00%	±0.27%	±0.48%	±1.54%	±0.46%
POCP	±0.11%	±0.00%	±0.01%	±0.33%	±0.17%	±0.10%	±0.14%	±8.48%	±0.19%
TETP	±1.66%	±0.01%	±0.20%	±0.23%	±0.05%	±0.06%	±0.11%	±6.44%	±2.90%

processing technology was unchanged. The analysis is based on the characteristics of refrigerators listed in Table SI1.

We selected steel consumption, steam consumption, compressed air consumption, HIPS consumption, diisocyanate consumption, cyclopentane consumption, transportation distance, electricity consumption, and the amount of steel recycling and their contributions to the inventory as the operating parameters for the sensitivity analysis. Each of these operating parameters changed by 90–110% when compared with the baseline operating conditions. The findings of the sensitivity analysis are shown in Table 6.

The results of the sensitivity analysis show that all of the impact categories except ADP elements are sensitive to electricity consumption in the usage stage, which indicates that clean energy could improve this type of environmental impact. The behavior of customers using the refrigerator indirectly affects its environmental performance. Steel recycling in the disposal stage is the factor to which the ADP elements category is the most sensitive; its measurement varied approximately ±1.57% from the baseline. Transportation distance has a secondary influence on the ODP, followed by steel recycling in the disposal stage. HIPS consumption in the vacuum-shaping part of cabinet production has a secondary influence on the ADP fossil, GWP and POCP categories, with changes of approximately ±0.57%, ±0.27% and ±0.33%, respectively. A variation of ±10% in steel recycling in the disposal stage results in changes of ±0.76% and ±2.90% in the FAETP and TETP, respectively. The next largest changes are in steel consumption, which provides the sheet metal for the cabinet.

5. Conclusions

In this paper, we presented a cradle-to-grave LCA of a refrigerator based primarily on first-hand survey data. It was found that the environmental impacts, represented by 11 categories, were relatively high in the usage phase; however, the environmental impact categories of ODP, TETP, ADP-elements, and ADP-fossil were also very high in the production phase. In the production stage, compressor manufacturing was the dominant contributor to the ADP elements category and the four indicators of toxicity (HTP, FAETP, MAETP, and TETP), and cabinet manufacturing contributed the most to the other environmental impact categories. Thanks to a reasonable approach to recycling waste refrigerators, the impact of raw material consumption in a refrigerator's complete life-cycle has been greatly reduced. Hotspots were identified in the usage and production stages of a refrigerator. Most of the impact categories evaluated were contributed to by direct or indirect energy consumption.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.02.031.

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