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The application of life cycle assessment for the optimization of pipe materials of building water supply and drainage system

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ABSTRACT

The selection of pipe of the building water supply and drainage system in buildings is important for energy conservation. In the past, the building designer mainly considered the use performance and one-time cost of pipes in building water supply and drainage system but ignored the differences in resources, energy consumption and pollutant emissions in the whole life cycle of different pipes. This paper combines the life cycle assessment with the analytic hierarchy process to analyze the energy consumption, resource consumption and its impact on the environment of different pipes in the building water supply and drainage system. The results showed that the energy consumption of PVC-U pipe in the building water supply system could be reduced by 86 % and 91 % compared with that of galvanized steel pipe and copper pipe, and the reduction value in the drainage system was about 86 %.Galvanized steel pipes, copper pipes, and cast iron pipes are approximately 7.3 to 11.3 times larger than PVC-U pipes in a single indicator for comprehensive environmental impact assessment. This study shows that replacing other metal pipes with PVC-U can significantly reduce the environmental impact, which also implies the importance of life cycle assessment in the design of building pipes.

1. Introduction

1.1. Background

With rapid social and economic development, the relationships between man and nature, between man and society and between people have become unbalanced. Many environmental problems such as resource depletion, energy crisis, ozone depletion, global warming, acid rain, eutrophication and haze, etc. have garnered widespread attention in many countries worldwide (Bilgen & Sarikaya, 2015). The construction industry has caused environmental pollution, although it has created a huge economic value and solved the housing problem. From 1996 to 2012, China's construction industry consumed 61.6737 million tons of standard coal and emitted 47.56684 million tons of CO_2 (Hu & Zhu, 2015), this share of energy consumption accounting for 25–30 % of China's national energy consumption (Chang, Ries, & Wang, 2011). Therefore, the impact of greenhouse gases emitted by fossil energy consumption on global warming cannot be ignored. (Scheuer, Keoleian, & Reppe, 2003). The main source of energy in China is fossil fuels (Department of Industry & Transport Statistics of the National Bureau of Statistics, 2004). Therefore, it is very important to choose materials with less energy consumption and use low-carbon energy instead of fossil fuels to reduce environmental impact and achieve sustainable development (Xu, Schwarz, & Yang, 2020). Because building water supply and drainage system (BWSDS) is an indispensable component in the building, it is necessary to optimize the system design to achieve energy conservation (Chang et al., 2011; Lavric, Iancu, & Pleşu, 2007) and improve its management to reduce the environmental impact and save the cost (Piratla & Ariaratnam, 2012). In addition, different types of pipes have different energy consumption due to different production processes and material sources (Matias et al., 2020). Hence, it is helpful to choose the pipeline with lower resource and energy consumption and lower environmental impact to realize the sustainable development of the city. Also, in the selection process of pipes of the BWSDS, the performance and one-time cost of pipes are mainly considered, analyses and comparisons of the whole life cycle of the selected system are lacking. The choice of pipes of the BWSDS should not only consider the sustainability and economic viability of raw material supplies and the impact on the life and health of the client during long-term use but also, pay attention to the impact on the environment as well as the ability to meet requirements of reduced resource use and energy conservation (Liu, Sun, & Wang, 2005).

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1.2. Life cycle perspective

Life Cycle Assessment (LCA) is a useful potential environmental impact assessment theoretical tool that provides a wide range of product information in energy consumption, resource consumption and environmental emissions throughout the life cycle of a product and can provide recommendations and measures for improving the environment. It is a significant tool to realize sustainable development. LCA generally consists of four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation phase (ISO 14040, 2006). AHP considers the complex multi-objective decision-making problem as a system, and decomposes the objective into multiple objectives, then obtains the indicators of multiple levels through further decomposition. Finally, through the fuzzy quantitative method of qualitative indicators, it can be used as the systematic method of multi-objective and multi-scheme decision-making optimization (Abdel Azim, Ibrahim, & Aboul-Zahab, 2017; Singh & Nachtnebel, 2016; Wang, Xu, & Solangi, 2020; Shafique, Azam, Rafiq, Ateeq, & Luo, 2020)

As a mature evaluation tool, The LCA is increasingly used in a water environment, especially in urban water supply and drainage. The use of LCA can complete the inventory analysis of water systems, optimize resource allocation and management, and reduce resource and energy consumption to achieve sustainable development of water systems. Wang et al. evaluated the water environment of Baoji city through LCA and found that the global warming impact of sewage collection stage was relatively large (Wang, Wang, & Xiong, 2006). The emission of greenhouse gases increased with the increase of pipe diameter (Kyung, Kim, Yi, Choi, & Lee, 2017), and the impact of different types of pipes on the environment also varies greatly (Hajibabaei, Nazif, & Sereshgi, 2018; Jin, 2019), which may be due to the difference in the energy flow of different materials in the pipe network system (Venkatesh & Brattebo, 2011). Also, the recycling of different pipes after the end of the life cycle is often neglected, which may affect the accuracy of the evaluation, and recycling will reduce resource consumption and reduce the impact on the environment (Lundin, Olofsson, Pettersson, & Zetterlund, 2003). On the other hand, economic factors often play an important role in urban construction. Hence, for urban construction, Lavric et al. (2007) employed the genetic algorithm to optimize the choice of pipe diameter, Petit-Boix et al. (2016) used channels instead of drainage pipeline under conditions allowing, Venkatesh, Hammervold, and Brattebo (2011) used a systematic research method and a triple bottom line strategy to analyze the inventory in the life cycle of a sewage pipe network to improve the level of construction and management to reduce capital investment is feasible. However, in actual production construction, this may cause people to pay less attention to the environmental impact of construction. Therefore, for a city's sustainable constructiveness, economic and environmental factors should be considered comprehensively. Byrne, Grabowski, Benitez, Schmidt, and Guest (2017) took advantage of a comprehensive model to evaluate the LCA of the road drainage system and found that the green infrastructure at the end had an offsetting effect on the environmental impact of the storm water pipeline system, which shows that the various components of the water and drainage system of the town are closely related. However, The BWSDS as the end of the urban water supply system and the beginning of the urban drainage system is rarely involved, and the loss of some non-renewable resources is seldom considered, which is unreasonable for the sustainable development of the city. For urban buildings, most existing papers on the LCA have studied new materials used in buildings (Li, Froese, & Cavka, 2018) or new construction plans (Mithraratne & Vale, 2004). There are few papers on the LCA of the BWSDS. Some studies have shown that it is necessary to evaluate the life cycle of the BWSDS. Somayeh Asadi, Foster, and Broun (2016) found that the use of PEX pipe can reduce CO2 emission by 42 % and cost expenditure by 62 % compared with the use of copper pipe in the building water supply system, although the latter has better performance in pipeline disinfection than the former; Berglund, Kharazmi, Miliutenko, Björk, and Malmqvist (2018) used LCA to study the environmental impact o of pipeline repair in the BWSDS using pipe replacement, cured-in-place pipe (CIPP) lining (also called slip lining) and renovation by coatings and found that the latter two methods had less impact on the environment under the same technical conditions. There is still a lack of research on the life cycle assessment of the BWSDS, which leads to a lack of clear understanding of the resource consumption, energy consumption and pollutant sources in BWSDS.

1.3. Objectives

This paper used the LCA as a tool to study the construction of the BWSDS. In this paper, representative PVC-U, galvanized steel and copper pipes were used for water supply pipes, and PVC-U and cast iron pipes were used for drainage pipes. LCA and AHP were used to evaluate the performance of the BWSDS with different pipes in terms of resource consumption, energy consumption and environmental impact to achieve the following objectives.

- Identify the major environmental factors.
- Find more energy-efficient pipes in the BWSDS.
- Some Suggestions are given for the current research on LCA of the BWSDS in China.

2. System description

We selected a typical 8-story residential building measuring 2.8 m in height as a case study in China. There are two units in the building, and two households share a layout in each unit composed of three rooms, two halls and two bathrooms. There is a bathtub (with a shower), countertop washbasin and toilet in the master bathroom, and there is a shower, washbasin, toilet and washing machine in the second bathroom. There is a double sink in the kitchen and an air conditioner on the balcony. Hot water is supplied for the family by boilers. During the design process of the building water supply system, the same capacity of supply and drainage water in different pipes must be ensured. This study intends to use PVC-U (unplasticized polyvinyl chloride) pipes, hot-dip galvanized steel pipes and copper pipes for calculations on the water supply system and use LCA to analyze the three kinds of pipes in the energy consumption of the entire life cycle. On the other hand, we use PVC-U pipes and cast-iron pipes for calculations on the drainage systems, and we use the LCA to analyze the consumption by the two kinds of pipes throughout the life cycle. The life of ordinary building construction is 30–40 years, 50–80 years or 150 years. Some buildings may require a certain degree of transformation and renewal in the process of use, so the life cycle in this study is 50 years (Chang, Ries, & Wang, 2010). The water supply system diagram is shown in Fig. 1.

The building adopted a water supply mode with a pump-tank combination. Two inlet pipes are set up in the system and introduced into two units. One inlet pipe connects to four water supply riser pipes that are responsible for supplying the users' bathroom and kitchen in the two units. The building adopted a single riser system for the drainage system after a preliminary evaluation of the building. The wastewater from the toilets and kitchens in the two housing units is discharged through four drainage risers in each housing unit, and an outlet pipe is set up in each housing unit. The operating requirements of the building are used to determine the number of equivalents of each pipe segment and obtain the design flow of each pipe segment. After the pipe section of the designed secondary flow is calculated, we determined the pipe diameter of each segment according to the flow equation between the flow and velocity. The comparison data of pipes of the BWSDS are shown in Table 1.

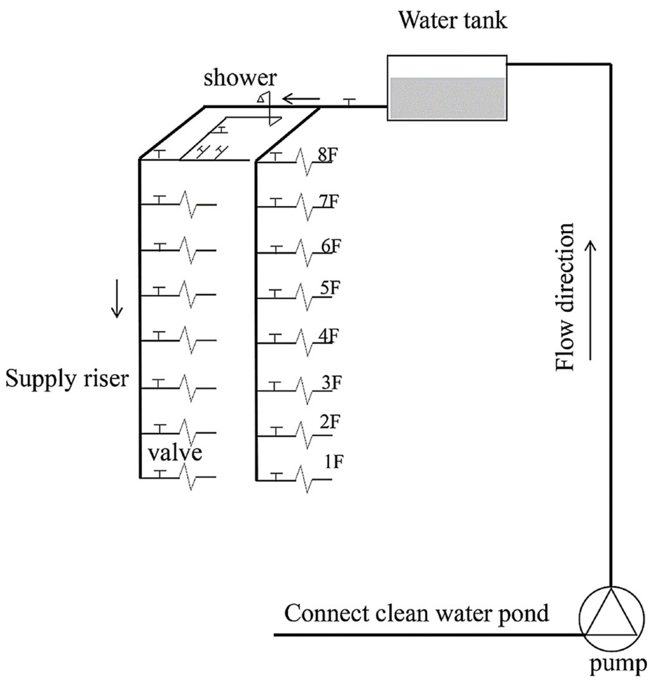

Fig. 1. Schematic diagram of the unit water supply system. 1F represents the first floor.

3. Methodology

3.1. Building the LCA model

The purpose of this study is to study the resource consumption, energy consumption and pollutant discharge of construction pipes in the life cycle. To better guide future pipeline design, the weight of pipes in this study is calculated on the premise of meeting the designed water quantity. Then we analysis the inventory, which mainly includes material in the production, transportation, installation running stage, stage of renewable energy consumption, resource consumption and pollutant discharge, through it, we can obtain the total energy consumption (excluding the quality of recycled materials) and each pipe emissions of pollutants in the life cycle. We established an LCA model which based on the life cycle analysis of a BWSDS, as shown in Fig. 2.

3.2. Goal and scope definition

The process of the LCA evaluation of BWSDS includes mining raw materials, manufacturing raw materials, pipe production, product transportation, pipe installation, operation, maintenance, demolition and recycling. Each stage of the life cycle demands the consumption of resources and energy. The goal of this evaluation was to compare the resource consumption, energy consumption and environmental impact of different pipes of the BWSDS during their life cycle to obtain the most suitable pipe type for the building and guide the pipeline design in future.

The definition of the scope of a life cycle is determined by the purpose of the study, the future applications, the study depth and breadth, etc. The scope of the life cycle of the pipe can be defined as starting from the use of raw materials to the removal and recycling steps. The system output and scope definition are shown in Fig. 2. According to the manufacturing process and the application of pipes, the author used LCA to analyze resources and energy consumption as well as environmental effects when using different pipes by choosing representative PVC-U pipes; hot-dip galvanized steel pipes and copper pipes as the water supply pipes while choosing PVC-U pipes and cast-iron pipes as drainage pipes. Inventory analysis is the main part of a building LCA, including inventory analysis of material and energy consumption, which consists of production, site operation, transportation, operation, demolition, total energy consumption, etc. We have simplified the analysis, only consider the main factors, and the secondary factors are ignored. The impact analysis and conclusion are mainly based on production, transportation and operation energy consumption.

In Fig. 3, resource consumption is calculated according to the current widely used processes in China, and the main energy source is fossil fuels, which may not apply to some pipelines that do not rely on fossil fuels for energy production. In addition, the object of this study is general civil residential buildings, which may not apply to buildings with special requirements.

3.3. Functional unit

In LCA, a functional unit refers to the quantified performance of a product system which is used as a reference unit in lifecycle assessment. Functional units must be measurable to ensure comparability of the LCA results (Ding, 2014). The functional unit is set based on the premise of the same or similar factors or parameters associated with the provisions. We consider that different pipes are different in the capacity

Table 1
Specifications and amounts of different pipes.

System	Material	Diameter/mm	Tube length/m	Units approximation mass/ (kg/m)	Quality/kg	Total mass/ kg
Water supply system	PVC-U pipe	20	182.4	0.17	31.008	85.71
		25	67.2	0.27	18.144	
		32	89.6	0.35	31.36	
		40	10	0.52	5.2	
	Hot dip galvanized steel pipe	20	164.8	1.63	268.624	824.49
		25	62.4	2.42	151.008	
		32	89.6	3.13	280.448	
		40	32.4	3.84	124.416	
	Copper pipe	20	164.8	0.86	141.73	494.65
		32	62.4	1.845	115.13	
		32	89.6	1.845	165.312	
		40	32.4	2.237	72.48	
Drainage system	PVC-U pipe	50	64	0.58	37.12	543.62
		75	90	0.91	81.9	
		110	220	1.93	424.6	
	Cast-iron pipe	50	64	7.4	473.6	4959.6
		80	90	12.2	1098	
		100	220	15.4	3388	

Note: Pipeline quality is provided by local suppliers.

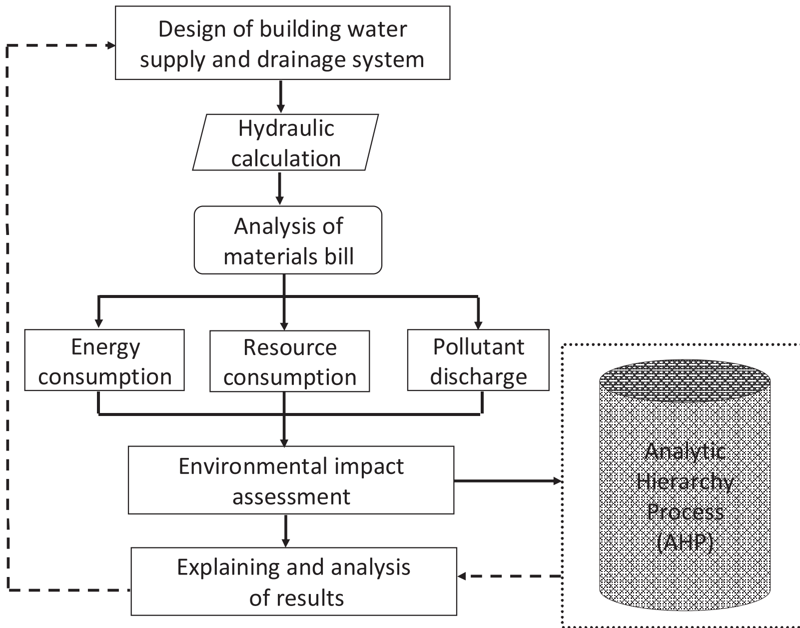

Fig. 2. LCA model of a BWSDS.

of water supply. Therefore, considering the LCA evaluation on the premise that the pipeline has the same water supply is instructive for future pipeline design. We chose the unit pipe quality with the same water supply capacity as the base unit. To compare the consistency, we converted different energy units into standard coal for calculation. Finally, we take kgec/t and tec/t (a ton of product needs a ton/kg of standard coal equivalent) as the functional unit.

3.4. Inventory analysis

3.4.1. PVC-U pipes' inventory

The raw material for polyvinyl chloride is vinyl chloride. At present, the main production processes of vinyl chloride are direct chlorination, oxychlorination and the production of vinyl chloride carbide and acetylene. Among them, oxychlorination is the most commonly used in the world to produce polyvinyl chloride with ethylene and chlorine (Mulder & Knot, 2001). It needs 0.492t (Energy consumption per unit of production is 1.935 tec/t) ethylene and 0.599 t chlorine (Energy consumption per unit of production is 0.788 tec /t), with the consumption of 0.09 tec, to produce 1 t vinyl chloride (Lan, Ke, & Su, 1996; Li, 2006a). The main production of PVC is the suspension method in China, the production of 1 t of PVC needs 1.01 t of vinyl chloride, consumption of 0.246 tec (Huang, Jiang, & Li, 2001). For the production of PVC-U pipes, besides polyvinyl chloride, it also generally required to add about 5% light calcium carbonate (Cao, Yuan, & Chen, 2003) (Energy consumption per unit of production is 0.3 tec/t) (Wang & Cui, 2000). According to its production process and unit energy consumption, we can calculate that the raw material energy consumption of PVC-U pipe is 1.696 t/tec (E_1). And 0.32 tec (Ej) is required to produce 1 t PVC-U pipe from existing materials. Because the product will be recycled, the average number of cycles, the regeneration rate, the regeneration process energy consumption values and the processing success rate are 3.333(n), 70 % (X_z), 0.16 tec/t (E_2), and 90 %(X_C) (Li, 2006a), respectively. The production of ethylene mainly comes from petroleum, and the production of 1 t PVC-U requires 5 t of mixed ore (Li, 2006a).

According to the Department of Industry and Transport Statistics of the National Bureau of Statistics (2004) 30 % of the plastic products and their raw materials are transported by motor vehicles (fuel consumption per unit transportation is 0.071 L/(t·km), while the rest is transported by rail (energy consumption per unit transportation da is 7.3gec/ (t·kj)), and the transportation distance they experience is 61 Km and 780 Km respectively, the energy consumption of raw material transportation (Ecy) and manufactured goods transportation (Eyy) were calculated to be 6 kgec/t.

3.4.2. Hot dip galvanized steel pipes' inventory

The main raw material of galvanized steel is steel. The steel-making raw materials are mainly molten iron, scrap steel, and slag former.

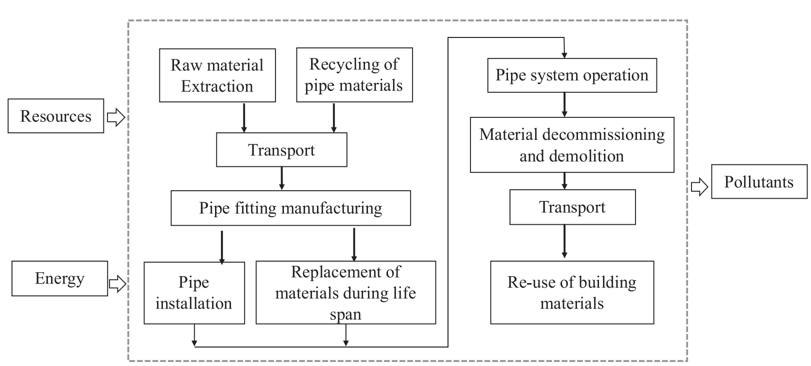

Fig. 3. Overview of the system goal and scope definition for the BWSDS. The dotted box outside said the scope of the study, Pollutants, energy and resources represented the index of the output.

Methods of steel making are mainly the blast furnace process, direct-reduction process and smelting reduction process. The principle is that the ore can produce pig iron by physical and chemical reactions under specific conditions (reducing substances CO, H_2, and C and a suitable temperature). In the blast furnace process, one ton of iron production needs 1.812 t mixed ore, 0.5 t coke and 0.075 t pulverized fuel ash (Na, 2005), in which the energy consumption values of the sintering and iron-making processes are 0.06 tec/t and 0.41 tec/t, respectively (Zhou, 2002). Referring to the research on renewable materials (Li, 2006b), the comprehensive energy consumption of this process is 1.18 tec/t (E_1), the regeneration rate is 80 % (X_z), the average cycle times is 5 (n), the energy consumption of the regeneration process is 0.47 tec/t (E_2), and the processing success rate is 75 % (X_C). Energy consumption of material forming processing is 0.144 tec/t (Ej) (Compilation Commission of Dynamical Engineer Handbook, 2001).

The transportation energy consumption is calculated based on ore transport according to statistical data in China (Department of Industry & Transport Statistics of the National Bureau of Statistics, 2004; National Bureau of Statistics, 2004). Metal and other raw material shipments are calculated as 30 % for motor transport and 70 % for rail transport. The average distances for rail transport of metal ore and finished metal are 574 km and 1083 km, respectively. The average distance for rail transport of coal is 574 km, and the average road freight transport distance between the two sides is calculated as 61 km. Based on the above data, it can calculate that the energy consumption for the comprehensive transportation of raw materials of metal ores is 5kgce/t (E_{cy}) and that for the transportation of metal productions is 7kgce/t (E_{yy}).

3.4.3. Copper pipes' inventory

There are three main copper tube production methods: conductive copper tube production, copper oxide production and the compound method. These three main methods used for the production of copper pipes have not only good performance but also very convenient operation. The method of conductive copper production is the most common method for producing copper material, which has been used for a long time and employs very mature technology. This method is the main copper pipe production method in China. The energy consumption values of raw materials and reproduction processes are 4.61 tec/t (E_1) and 0.65 tec/t (E_2) (Zhou, 2003), respectively; the processing success rate is 70 %(X_C); and the production of 1 t copper pipes requires 5 t of crude oil resources (Lan, 2003).

Since copper and steel pipes are both metals, they consume the same amount of energy for transport, according to national statistics. So, the E_{cy} is 5kgec/t; the E_{yy} is 7kgec/t. The energy consumption of the moulding process is 0.680 tec/t (Ej) (Li, 2006b). The regeneration rate is 90 %(X_z). The average number of cycles is 10 (n) (Li, 2006b).

3.5. Impact assessment

According to the discharge of pollutants in the life cycle of the pipe, the impact of pollutants on the environment is classified as global warming, atmospheric acidification, biological toxicity, eutrophication of water bodies (Vahidi et al., 2016; Lundin et al., 2003). Then through the potential factor of pollutants to the various pollutants unified quantitative indicators, and then through the hierarchical analysis process of the single indicator to evaluate the impact on the environment. The model of AHP is as follows Fig. 4.

4. Results and discussion

4.1. Energy consumption of different pipes during their life cycle

4.1.1. Production and transport stages of water supply pipes

According to the inventory statistics in section 3.3, the allocation method is used to calculate the internal consumption within the life cycle of each pipe. For the detailed calculation process, please refer to S1 (Appendix: Supplemental Material (SM) S1). The calculation formula is as follows (Li, 2006a):

$$E_z = (E_1 + E_{yy})(1 - X_Z) + E_{Z2}X_Z + E_2\left(\frac{1}{X_C} - 1\right) + \left(\frac{E_j}{X_C}\right) + E_{cy} + E_e;$$

$$E_{Z2} = \frac{E_1 + E_{yy} + (n-1)(E_2 + E_{Cy})}{n}$$

Where the E_1 is the energy consumption of raw materials (tec/t), E_2 is the energy consumption of pipeline material regeneration process (tec/t), Energy consumption per unit of production of pipeline materials over the life cycle (tec/t), E_{yy} is the energy consumption of raw material transportation (tec/t), E_{cy} is the energy consumption of material transportation (tec/t), n is an average number of cycles of material, X_c is the success rate of material processing into pipes, X_c is material regeneration rate, E_j is the energy consumption of materials processed into pipes (tec/t), E_e is the loss in energy production, about 10 %.

PVC -U pipes, Hot-dip galvanized steel pipes, copper pipes for energy consumption per unit production are 1.47tec/t, 1.17tec/t, 2.85tec/t. There are obvious differences in energy consumption of the different pipes, which mainly come from the difference in pipes production technology. The production of PVC pipes to meet the water supply capacity of the study unit requires 255.42 kg of petroleum raw materials, while the production of the galvanized steel pipes and the copper pipes requires 1,494.79 kg and 2,473.75 kg of ore raw materials, respectively. It can be seen that the demand for raw materials in the production of different pipes is greatly different, for metal pipes more resource consumption may lead to higher energy consumption (Vahidi et al., 2016). Also, the introduction of recovery rate will reduce the difference in energy consumption of different pipes.The unit energy consumption of copper pipe with recovery rate is 38 % lower than taht without recovery rate, while the unit energy consumption of PVC and galvanized steel pipe is 13 % and 0.8 %, respectively. Therefore, for pipes, not considering recycling rate will exaggerate its resources, energy consumption and environmental impact.

In terms of total energy consumption, the energy consumption of PVC-U, galvanized steel pipe and copper pipe are 125.99 kgec, 965.18 kgec and 1409.75 kgec respectively. We can confirm that PVC-U has the lowest energy consumption of the three pipes. From the weight of the three kinds of pipe demand, PVC-U demand is the lowest. As a result, PVC-U requires fewer resources and energy consumption, so PVC-U has great advantages in reducing energy consumption. Greater demand not only results in excessive consumption of energy and resources in terms of production but also in the transport phase (Hollaway, 2010). Although the weight of copper pipe is lower compared the galvanized steel pipe, the energy consumption of copper pipe is higher than that of galvanized steel pipe. This is mainly because copper pipe production requires more ore material and the production success rate is lower. Therefore, it is very necessary to improve the recovery rate and choose pipes with less resource consumption for reducing energy consumption.

4.1.2. Production and transport stages of drainage pipes

The direct energy consumption in the life cycle of PVC-U drainage pipes and cast-iron drainage pipes are 799.12kgec, 5802.73kgec, respectively. Their resource consumption is 1619.99 kg of petroleum and 8986.8 kg of ore. The energy consumption of PVC-U pipes is the lowest in the four kinds of pipe. The difference in energy consumption of the drainage pipeline is a larger than that of the water supply pipeline. The main reason is that the pipe diameter of the pipeline is larger, leading to the consumption of the pipe material. Therefore, when choosing the pipe with larger pipe diameter, the influence of energy consumption should not be ignored in the selection of the pipe material.

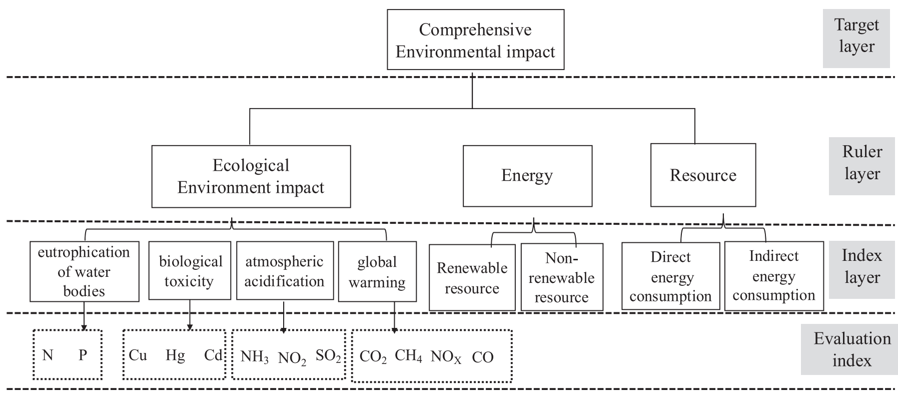

Fig. 4. Hierarchy analysis model. N represents Nitrogen. P represents phosphorus. The gas emission mainly bases on the main components of energy raw materials used in the life cycle of pipe materials. For example, CO_2 and SO_2, due to the C and nitrogen elements contained in coal and oil, eutrophication and aquatic toxicity are mainly considered as the wastewater generated in the production process enters the water body.

4.1.3. Operation stage of pipes

Due to the power consumption of the pump in the operation stage is the same, the energy consumption of the phase is the same for the three different pipes, all 56919.60kgec.

Since the energy resource consumption during the operation is the same (same power supply), and the energy consumption in the operation phase is high, this difference may be covered up when analyzing the difference in the environmental impact of different pipes. Therefore, the following environmental impact assessment does not include the operational phase.

Some unavoidable accidents occur in the process of using pipes, so repair and maintenance are needed. As this part of the energy consumption is small, its influence on the entire life cycle assessment is negligible and is ignored here.

4.2. Environmental impact assessment of the life cycle of building water supply and drainage system

Through the classification of environmental impact, the different influencing factors under the same influencing types can be aggregated by the method of using the environmental load index to obtain the integrated environmental load of each influencing type. Environmental impact (EB) represents the potential degree of a certain impact that a group of emissions of substances exert on the specific environmental categories, the bigger the number, the bigger the impact:

$$EB = (W_a \times PF_a) + (W_b \times PF_b) + (W_c \times PF_c) + \ldots$$

Where a, b, c represents various chemical substances contained in the emissions; W represents the weight of various substances; PF represents the potential factors of various substances that impact certain types in the environmental category

The potential factor researched and used by British Imperial Chemical Industries (ICI) is used in this paper, as shown in Table 2.

Currently, regarding the proportion of China's energy production and consumption, raw coal account for 66 %, oil accounts for 66 %, and water electricity accounts for 10 % (Department of Industry & Transport Statistics of the National Bureau of Statistics, 2004). According to the proportional distribution of the total energy consumption above composed of the electricity consumption and pollutant emissions per unit of energy substance, namely, coal and oil (Department of Industry & Transport Statistics of the National Bureau of Statistics, 2004; Mao, Bai, & Li, 1992), as shown in Table 3 and Table 4, we obtained more realistic results after aggregating the emissions of different pollutants. For the detailed calculation process, please refer to S2 (Appendix: Supplemental Material (SM) S2**)**, the final results are shown in Figs. 5–7.

By providing a scaling value for global warming, air acidification, eutrophication and aquatic toxicity, a judgment matrix can be built, as shown in Table 5.

We use analytic hierarchy process to calculate the eigenvector $W = [0.466\ \ 0.277\ \ 0.161\ \ 0.096]^T$, and the maximum eigenvalue $\lambda_{max} = 4.031$ of the matrix.

$$EI = (\lambda_{max} - N)/(N-1) = 0.01,\ RI = 0.90$$

$ER = EI/RI = 0.01/0.9 < 0.10$ means the evaluation matrix above has satisfactory consistency so that we can use the weight value W.

Hence, single indicator B is obtained as $B = A \times W = [117.70\ 4.13\ 1.31E\text{-}3\ 1.68E\text{-}5] \times [0.466\ 0.277\ 0.161\ 0.096]^T = 55.99$. The values in vector A are the EB values of each pipeline in global warming, atmospheric acidification, aquatic toxicity and eutrophication, respectively. The single index of the PVC-U, hot-dip galvanized steel and copper water pipes can be calculated as 55.99, 428.90 and 626.43, respectively, while the values for the PVC-U and cast-iron drainage pipes are 355.11 and 2595.88, respectively.

Figs. 5 and 6 show the discharge of pollutants from various pipes in the BWSDS. As can be seen from Figs. 5 and 6, a large amount of CO_2 is discharged into the atmosphere during the production and transportation stage. This is because energy comes mainly from fossil fuels such as oil and coal in nowadays, and the use of such high-emission fuels is the main cause of the most CO_2 emissions (Luo, Cang, Zhang, Yang, & Liu, 2019). According to Bribian, Capilla, and Uson (2011), due to the metal

Table 2
Potential factors, PFs, in different environmental impact categories.

Impact categories	Impact substance	PF
Global warming	CO_2	1
	NO_X	40
	CH_4	21
	CO	3
Atmospheric acidification	NH_3	1.88
	NO_2	0.7
	SO_2	1.0
Aquatic Toxicity	Hg	16.67
	Cd	2.0
	Cu	1.0
Eutrophication	N	1.0
	P	0.067

Table 3
Emissions of different pollutants in producing (per kWh) electricity.

Name	Name of pollutants	Amount(kg)	Subtotal (kg)
Air Pollutants	Carbon monoxide	0.081	4.034
	Carbon dioxide	0.631	
	Hydrocarbon	0.032	
	Hydroxide	3.18	
	Sulfur dioxide	0.11	
Water Pollutants	Blunt ash water	2.454	2.454
Solid Waste	Waste rock and tailings	0.578	0.742
	Fly-ash	0.147	
	Slag	0.017	
Total			7.23

Table 4
Emission factors of particulate matter and gaseous matter for industrial fuel oil and coal.

Material discharge coefficient	Particulates Kg/t	SO_2 Kg/t	CO Kg/t	CH_4 Kg/t	NO_2 Kg/t	Aldehydes Kg/t	Remarks
When using industrial fuel	2.6	18S	0.0025	0.33	4.5 − 9	0.11	S represents the percentage of sulfur in the fuel
When using industrial coal	6.5A	19S	1	0.5	7.5	0.0025	A represents the percentage of coal ash % S represents the percentage of sulfur in coal

Note: The contents of ash and sulfur account for 40 % and 1.8 %, respectively.

pipes with high contents of embodied energy, its greenhouse gas emissions in the production and transportation stage are much higher than the PVC pipes. Fig. 7 shows the single index evaluation of the environmental impact of each pipe in the BWSDS, from which we can see that global warming is an important factor affecting the index. Compared with Shi, Cai, Weng, Wang, and Sun (2019), we assign a higher proportion of global warming in the comprehensive evaluation, which is determined by the urgency of global warming and the high greenhouse gas emissions of each pipes. Of course, the fundamental reason that leads to the dominance of global warming in environmental impact assessment is still the use of a large number of fossil fuels. The choice of PVC pipes with less energy and resource consumption is conducive to reducing the impact of building piping systems on the environment in the life cycle.In addition, it is important to note that NO_X contributes over 57 % of the global warming impact score, making it a significant contributor to global warming over the lifetime of the BWSDS.

As can be seen from Fig. 7, the contribution of other impacts other than global warming to the single assessment of environmental impact assessment is not high, because we have invested more energy to control the emission of this part of pollutants in the production stage. According to the comprehensive comparison of various pipe materials, it can be concluded that the use of the PVC-U pipes to replace the galvanized steel pipes and the copper pipes in the building water supply system can reduce the environmental impact of 86 % and 91 %.The environmental impact of using PVC-U pips in the drainage systems was 86 % lower than that of using the cast-iron pipes. Combined with the consumption of resources and energy, the low resource and energy consumption of the PVC-U pipes is the main reason for this result. In contrast, the galvanized steel pipes, the copper pipes and the cast-iron pipes not only have a higher environmental impact on the piping system of the building system, but also have a higher environmental impact in the sewage system (Vahidi, Jin, Das, Singh, & Zhao, 2016). On the other hand, Hajibabaei et al. (2018), found that the environmental impact of the same type of pipes also increased as the pipe diameter increased. However, we often ignore that the water carrying capacity will also increase with the increase of pipe diameter. Therefore, it is recommended to consider the impact of various pipe materials on the environment from the perspective of the water conveyance capacity in the BWSDS. In a certain capacity of water transport, choose a smaller diameter to reduce the impact on the environment.

5. Conclusions

1 According to the results of environmental assessment, PVC-U pipes have the minimum value in the resource consumption, energy consumption and the single assessment index of environmental impact. Therefore, we suggest promoting the use of PVC-U pipes in similar residential buildings, and metal pipes are not recommended.
2 From a single impact assessment index, global warming is the main problem. But, the current energy resources in the world determine that the majority of countries with petrochemical feedstock as the main energy structure is difficult to change in a short time. We should pay more attention to the selection of pipe materials,

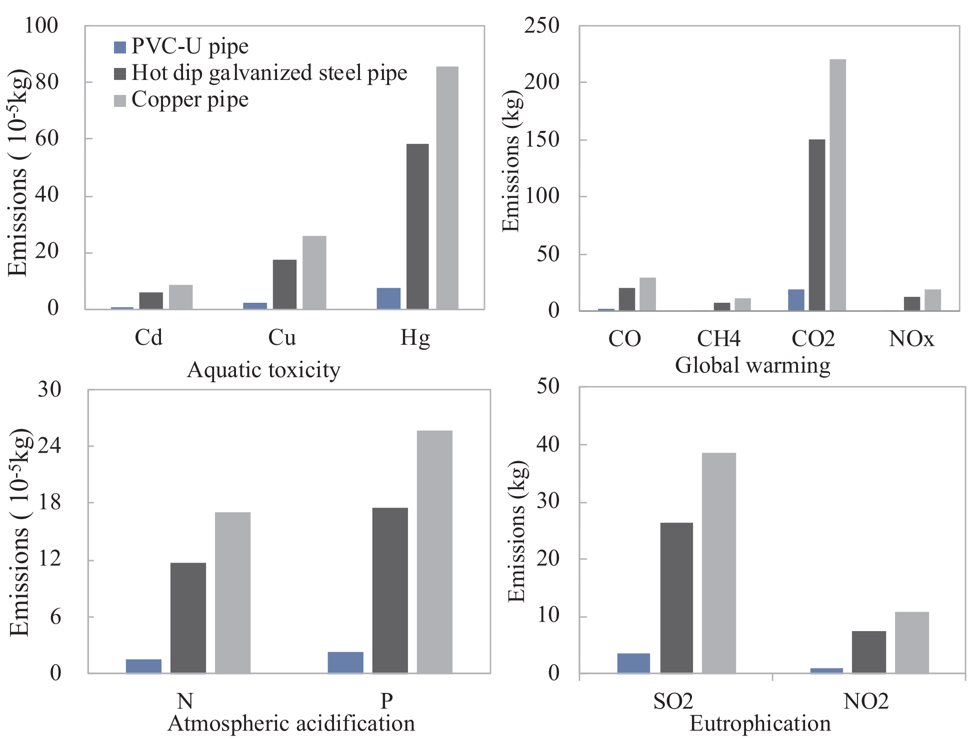

Fig. 5. Discharge of pollutants from the water supply system. NH_3 data is not obtained, so it is not shown.

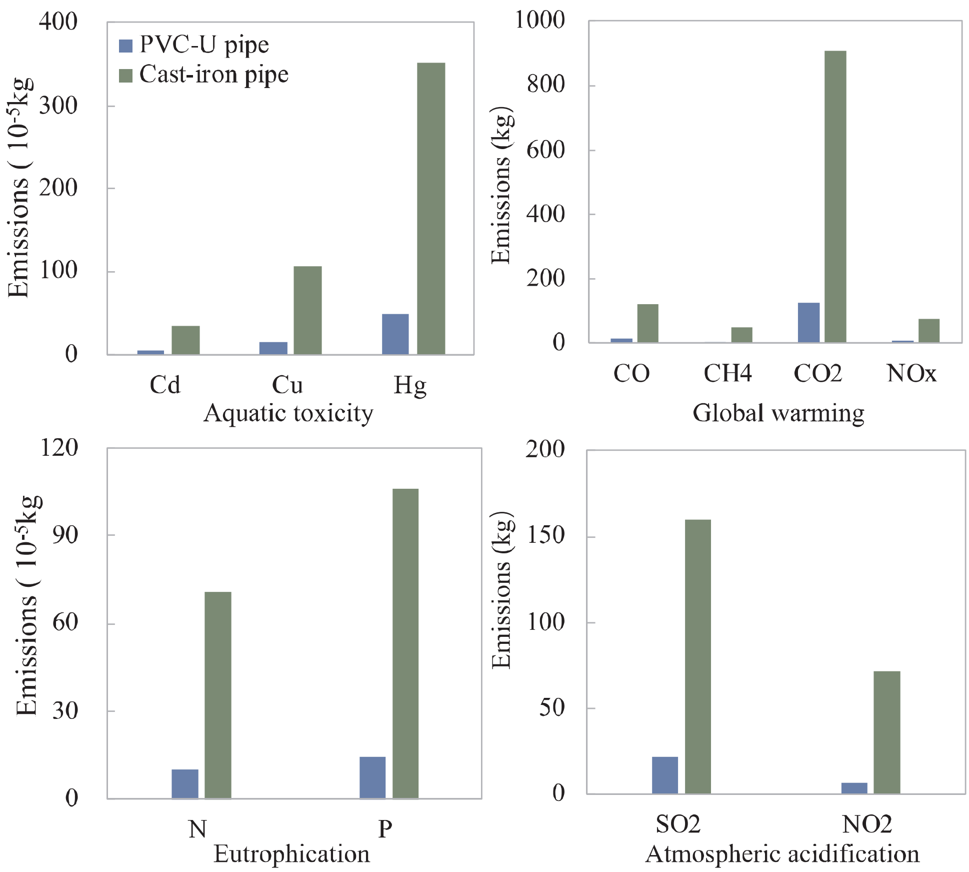

Fig. 6. Discharge of pollutants from the water drainage system. NH_3 data is not obtained, so it is not shown.

promote more environmentally friendly PVC-U pipes, reduce the use of fossil fuels to promote the adjustment of energy structure.

3 Nonetheless, the choice of pipes in the BWSDS is still subject to several other factors, such as architectural requirements, requirements of the building service life, usage occasions, water temperature and quality. As for us, we should build a more balanced and harmonious society by taking all these factors into consideration.

With the restriction of actual conditions, the conclusion of this study may have some temporal and territorial limits, so the conclusion obtained from the application of the life cycle assessment is not fixed,

Table 5
Construction of the judgment matrix.

Impact categories	Global warming	Atmospheric acidification	Eutrophication	Aquatic toxicity
Global warming	1	2	3	4
Atmospheric acidification	1/2	1	2	3
Eutrophication	1/3	1/2	1	2
Aquatic toxicity	1/4	1/3	1/2	1

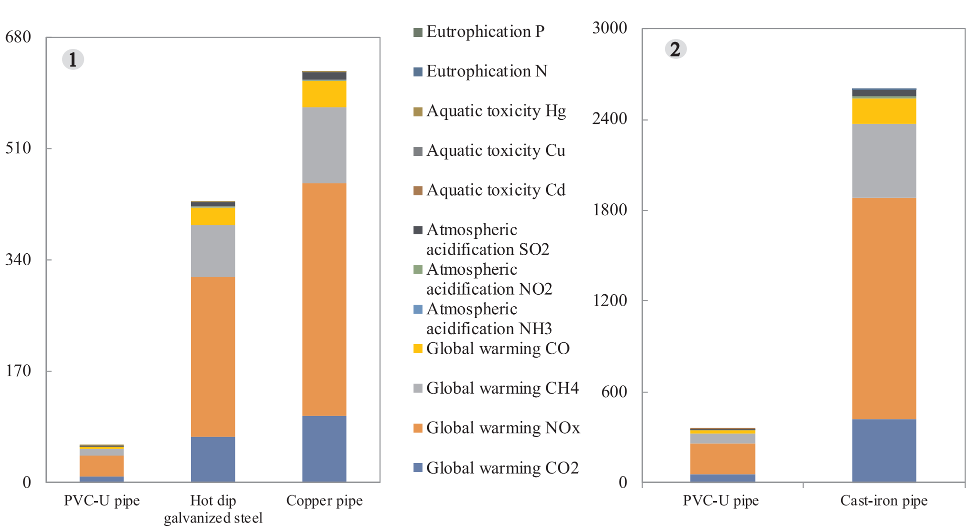

Fig. 7. The single index evaluation of the environmental impact. 1 represents the environmental impact value of the water supply system. 2 represents the environmental impact value of the drainage system. Global warning CO represents the environmental impact value of CO on global warming. Global CH4 represents the environmental impact value of CH_4 on global warming. Global Nox represents the environmental impact value of Nox on global warming. Global CO2 represents the environmental impact value of CO_2 on global warming. The same goes for all the other Atmospheric acidification is, Aquatic toxicity is, Eutrophication is. NH_3 data is not obtained, so it is not shown.

which reflects the complexity of life cycle assessment methods.

For the problems encountered in the course of the study, relevant tasks are proposed to establish and improve the process of production and the database of pollutant emissions and develop database software with more universal significance under the existing framework.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2020.102267.

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