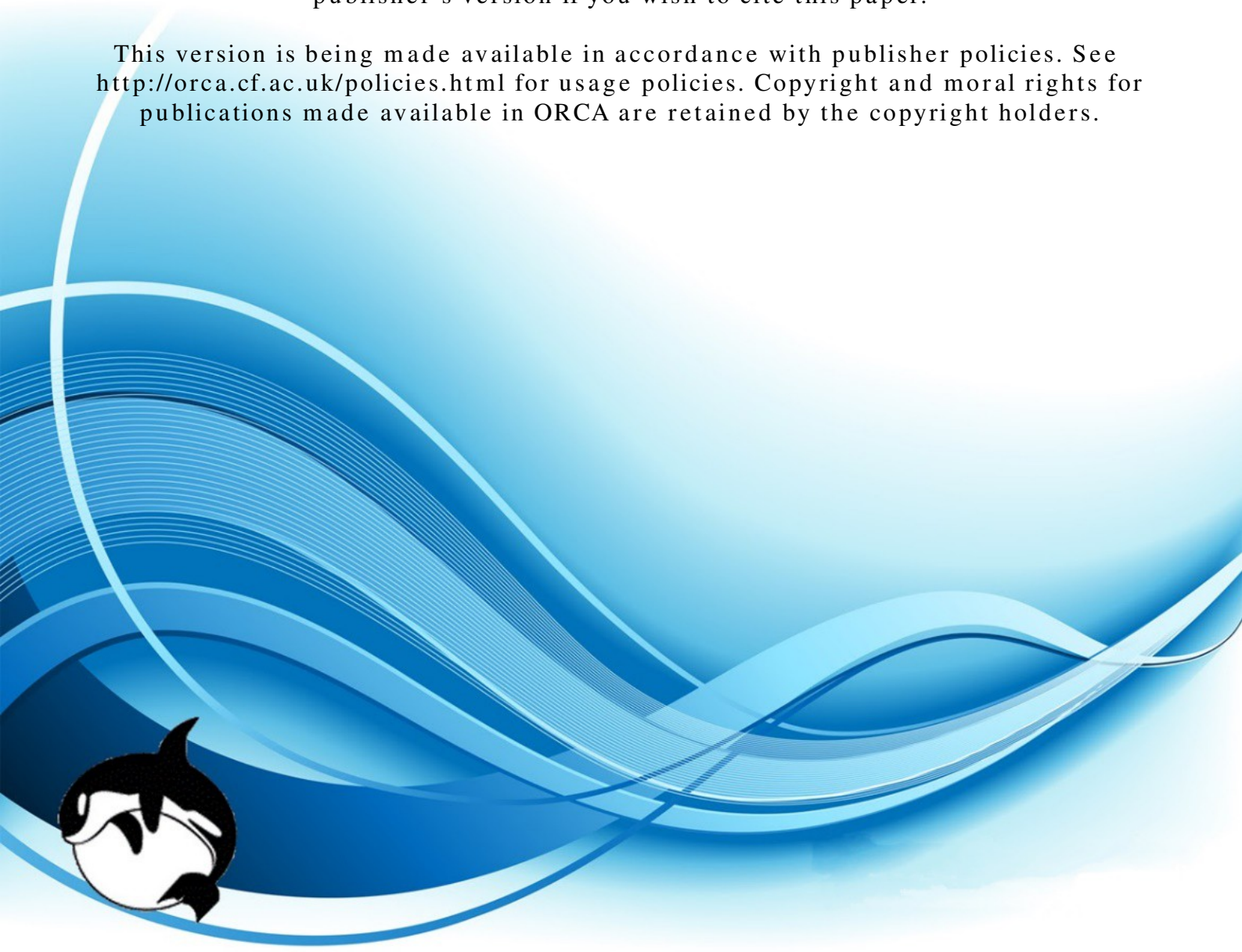

Supporting information

Life cycle assessment and life cycle costing of sanitary ware manufacturing: a case study in China

Jiangxiang LV [a,b], Fu GU [c,d *], Wujie ZHANG [c,d], Jianfeng GUO [e,f],

[a] *Key Laboratory of Road Construction Technology and Equipment, Ministry of Education, Chang'an University, Xi'an 710064, Shaanxi, China.*

[b] *Institute of Energy, School of Engineering, Cardiff University, Cardiff CF24 3AA, United Kingdom.*

[c] *Department of Industrial and System Engineering, Zhejiang University, Hangzhou 310027, China.*

[d] *National Institute of Innovation Management, Zhejiang University, Hangzhou 310027, China.*

[e] *Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China.*

[f] *School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China.*

[*] **Corresponding to**: Dr. Fu GU, Zhejiang University, E-mail address: gufu@zju.edu.cn (Fu GU).

Table S1. Energy, coke oven gas and water consumption to produce one FU of sanitary ware.

Life cycle stage	Electric energy (kWh)	Coke oven gas [m^3]	Groundwater [kg]
1. Raw material extraction	-	-	-
2. Raw material transportation	-	-	-
3. Body preparation	126.8	0	1192.9
4. Glaze preparation	24.5	0	1573.2
5. Mould Preparation	11.5	19.6	184.6
6. Casting	168.9	0	7123.0
7. Drying	1.96	272.6	0
8. Glazing	40.6	0	773.4
9. Firing	41.4	474.7	0
10. Packing	8.24	1.33	0
11. Waste treatment	9.19	0	0
12. Delivery	-	-	-

"-" denotes the information cannot be directly acquired.

Table S2. Types and amounts of the raw materials that are consumed during the production of one FU of the sanitary ware products, and the locations of the respective suppliers and the distances between the suppliers and the studied factory.

Raw materials	Amount (kg)	Location of supplier	Distance [km]
Feldspar	246.5	Lulong, Hebei province	68
Ball clays	267.8	Jiangmen, Guangdong province	2,292
Quartz	334.8	Jiangmen, Guangdong province	2,292
Kaolin	338.7	Qinyang, Henan province	854
Dolomite	5.9	Shanxi Province	642
Calcite	9.8	Dandong, Liaoning province	699
Talc	2.0	Tangshan, Hebei province	25
Zinc oxide	1.5	Tangshan, Hebei province	25

Table S3. Data for the modelling of the primary materials and energy.

	Product	Dataset	Source
Raw materials	Feldspar	"*Ecoinvent 3.5 GLO market for feldspar*"	Ecoinvent
	Ball clay	"*Ecoinvent 3.5 RoW market for clay*"	Ecoinvent
	Quartz	"*EU-28 Expanded clay (EN15804 A1-A3)*"	Gabi
	Kaolin	"*GABI DE Kaolin*"	Gabi
	Dolomite	"*Ecoinvent 3.5 GLO market for dolomite*"	Ecoinvent
	Calcite	"*GABI AT Talcum (underground mine Alps)*"	Gabi
	Talc	"*GABI AT Talcum (underground mine Alps)*"	Gabi
	Zinc oxide	"*Ecoinvent 3.5 GLO market for zinc oxide*"	Ecoinvent
	Plaster of Paris	"*CN Gypsum plaster (CaSO4 beta hemihydrate)*"	Gabi
Water	Groundwater	"*EU-28 Tap water*"	Gabi
Energy	Electricity	"*CN Electricity grid mix 3.6MJ*"	Gabi
	Coke oven gas	"*Ecoinvent for coking*"	Ecoinvent
	Natural gas	"*GABI EU-28 Natural gas*"	Gabi

Table S4. Data and assumptions for the modelling of the raw material transportation process.

Process	Remarks, data and assumptions
Raw material transportation	The raw materials are mined in different sites in China. Based on the acquired geographical information about the distance between the raw material extraction sites and manufacturing site, the distances of transport each type of materials are obtained, as shown in Table S4. The distances are obtained using Baidu Map. Based on Table S4, with the information of weight and transportation distances of each type of raw materials, the average transportation distances from raw materials extraction sites to the sanitary ware manufacturing site is calculated to be 1406.8 km. The means of transportation are assumed to be big trucks, described by using the Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*".

Table S5. Raw materials used to fabricate the bodies and glazes that are used in the production of one FU of the sanitary ware products.

	Raw material	Weight (kg)
Bodies	Feldspars	212.0
	Ball clays	267.8
	Quartz	301.3
	Kaolin	334.8
Glazes	Kaolin	3.9
	Feldspar	34.4
	Dolomite	5.9
	Calcite	9.8
	Talc	2.0
	Quartz	33.5
	Zinc oxide	1.5

Table S6. Data and assumptions for the modelling of the manufacturing processes.

Process	Remarks, data and assumptions
Body preparation	Grind the body raw materials mixed with water using ball mills into slurry. Iron in the slurry is removed by the magnetic iron remover. Then the slurry is mixed using slurry mixer. Finally, the slurry is pumped to the slurry tanks using plunger pumps and waiting for use in the casting process. The weights of total raw material used in body preparation are obtained through interview. The types of raw material and associated composition ratios are obtained from interview and a report titled "Sanitaryware production: use of waste glass for saving energy and resources" (https://www.mineraliin dustriali.it/wp-content/uploads/2017/06/MI_report_eng_stampa.pdf). Electricity is consumed by different types of machines, including ball mills, magnetic iron remover, mixer and pumps. The water and electricity consumption are recorded by the water meter and electric meter, respectively. The meters are installed on the production line and the water and electricity consumption data are obtained with the help of technicians in the company.
Glaze preparation	Grind the glaze raw materials mixed with water using ball mills into glaze. Then the glaze is passed through sieves to remove coarse particles and magnets to remove iron particles. In order to give required properties, the glaze is mixed using spiral mixer. The weight of total raw material used in glaze preparation are obtained through interview. The types of raw material and associated composition ratios are obtained from interview and a journal paper: Li, J., Liang, J., Wang, F., Wang, L., 2014. The role of firing process on bubble formation in a glaze layer of sanitary ware. Thermochimica Acta 588, 75-80. Energy and water consumption in the glaze preparation process is recorded by the water and electricity meters installed on the production line. The data is acquired from the energy and water meters with the help of the technicians in the company.
Mould Preparation	The mould is prepared by mixing water with Plaster of Paris in proper ratio. The ratio between plaster and water is assumed to be 4:3. Heat is need to dry the mould to remove extra water from the mould. After the mould has been dried, it becomes hard and can be used for casting. The weight of total mould consumed and Plaster of Paris required is obtained from the statistics of the company. The water, coke oven gas and electricity consumption are obtained from the water meter, gas meter and electricity meter installed on the mould production workshop. The means of transportation for Plaster of Paris are assumed to be big trucks, described by using the Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*". The transportation distance is assured to be 200 km.

Casting	There are both low pressure casting and high-pressure casting for the sanitary ware production in the company. In the low-pressure casting process, the slurry is poured into the mould and until the mould is full of slurry. Then the excess slurry is drained through drain hole. In the high-pressure casting process, the slurry is injected into the mould using compressed air. The high repressure casting process allows a faster production speed. The casted ware, which is called as green ware, is allowed to dried and then released from the mould. The green ware is allowed to dry for several days before being sent to the drying process. In the casting process, large amount of water is used, including keeping required moisture content in the mould, demoulding, flushing and cleaning of pipes and moulds. The electricity is used to drive the machines, including casting machine, lifting machines and spiral mixer. The water and electricity consumption are recorded with water and electricity meter, from which we obtain the water and electricity consumption data. In the casting process, when the mould is used for many times, it could be damaged and out of use. The waste mould will be recycled for use in other industry, such as cement industry. The waste mould transportation distance for recycling is assumed to be 200 km. The transportation means are large truck, the Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*" is used.
Drying	The green ware is moved through drier which has an atmosphere temperature of 110 C to 120 C. The mechanically combined water is removed from ware. The drying process of the green ware with be taken around 10 hours. After the drying process has finished, the moisture content of the ware will be varying from 0.5% to 1.5%. Large amount of heat is needed for drying. Part of the heat is from the waste heat of the kiln. Most of the heat needed is produced by burning coke oven gas in the hot air stove. The amount of coke oven gas and electricity consumed is obtained by the gas meter and electric meter installed in the drying workshop.
Glazing	Before glazing, the ware is inspected and the defected wares will be repaired or recovered to produce slurry. The glazing is done by manual or by robots to control the nozzle to spray the glaze onto the surface of the green ware. In the glazing process, electricity is consumed to drive the glaze machine and robots. Water is used to wash the glaze in the floor. The water and electricity consumption are obtained by the water and electric meter installed in the glazing production line.
Firing	Firing is a key process since it is responsible the qualification of the sanitary wares. The sprayed wares are loaded in kiln car which move through the kiln. There are two types of kiln: tunnel kiln and shuttle kiln. The firing cycle last for 10 to 17 hours. In the firing process, physical and chemical reaction

	happens and the body raw material glaze are fused together. The fuel consumed was coke oven gas due to its low cost, which is produced using coal and has a calorific value of 17.0 MJ/m3. After firing, some wares have minor defects like pin holes and then they will be repaired or sent to refire section. If there is a crack, the defective wares will be rejected and recycled for producing raw materials of ceramic tiles. Due to high amount of heat required, the firing process consumes much coke oven gas. Electricity is consumed by the blowers and control unit in the kiln line. The coke oven gas and electricity are recorded and obtained by the gas and electric meter installed in the glazing production line.

Table S7. Domestic sales data in 2016 and associated delivery distances from the sanitary ware manufacturing site to customers in China.

Region	Sales (10^4 Yuan) [1]	Regional center city	Transportation distance [km] [2]
North China	48,621.81	Beijing	178.00
East China	43,445.44	Shanghai	1,196.00
Central China	17,334.49	Wuhan	1,245.00
South China	10,714.90	Guangzhou	2,209.00
Northeast China	13,071.82	Changchun	841.00
Northwest China	12,601.92	Xi'an	1,240.00
Southwest China	10,677.73	Chengdu	1,933.00

1. Data obtained from the annual report of Huida Group Co. Ltd.
2. Data obtained from Baidu Maps.

Table S8. Overseas sales data in 2016 and associated distances from the sanitary ware manufacturing site to customers overseas.

Country	Sales (10^4 Yuan) [1]	Port	Distance [km] [2]
United States	17971.09	Seattle	9788
Korea	11367.9	Hungnam	1835
Pakistan	8723.42	Juna Bunder	10466
Canada	9433.59	Vancouver	9817
United Kingdom	3248.04	London	20392
Australia	2268.72	Sydney	9440
Sri Lanka	1610.36	China Bay	7814
Ukraine	796.44	Azovstal	16898
Italy	930.29	Naples	16457
Libya	1375.47	Benghazi	15631
Germany	883.21	Hamburg	20937
United Arab Emirates	486.05	Ajman	11456
Others	10811.75	Sete	17314

1. Data obtained from the annual report of Huida Group Co. Ltd.
2. Data obtained from the website of “https://sea-distances.org/”.

Table S9. Data and assumptions for the modelling of the pre-sales processes.

Process	Remarks, data and assumptions
Packing	After the sanitary ware has been produced, it is moved to the packing area, where all the wares are inspected and the qualified wares are packed with cardboard boxes which is tied using straps. The packing process is labour intensive. Lights and heating are used and consumes electricity and coke oven gas. The cardboards are produced in the sanitary ware company. The weights of cardboard boxes are obtained from the cardboard production factory. The coke oven gas and electricity are recorded and obtained by the gas and electric meter installed in the packing factory.
Delivery (Transport sanitary ware to customers in China)	Based on the annual report of Huida Group Co. Ltd., the amount of sales in each sale area in China can be obtained. With the information of the amount of sales and the associated distance between the sales area and the manufacturing site (see Table S5), the average delivery distances from sanitary ware manufacturing site to customers in China is calculated to be 978.6 km. The transportation means are large truck, the Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*" is used.
Delivery (Ship sanitary ware to customers overseas)	Based on the annual report of Huida Group Co. Ltd., the amount of sales in each country in the world can be obtained. With the information of the amount of sales and the associated distance between the country and the manufacturing site obtained using the website of "https://sea-distances.org/" (see Table S6), the average distances from sanitary ware manufacturing site to customers overseas is calculated to be 10622 km. The transportation means are large ship, the Gabi dataset "*EU28: Bulk carrier ocean incl. fuel, 100,000-200,000 dwt, ocean going*" is employed for the oversea transportation.

Table S10. Data and assumptions for the modelling of the waste treatment process.

Process	Remarks, data and assumptions
Wastewater treatment	Large amounts of wastewater are generated in the manufacturing processes of sanitary wares. The company has its own wastewater treatment plant. The wastewater treatment process reduces the solid materials from the wastewater to produce reclaimed water which can be recycled and reused for sanitary ware manufacturing. The sludge produced in the waste water treatment process is recycled for producing raw materials of ceramic tile. Electricity is consumed for waste water treatment. The electricity consumption is recorded by the electric meter installed in the waste water treatment plant.

Table S11. Purchasing cost for producing one tonne of sanitary ware (Unit: CNY)

Process	Material cost	Energy cost	Combined cost
3. Body preparation	381.43	69.74	451.17
4. Glaze preparation	40.21	13.45	53.66
5. Mould Preparation	78.17	13.19	91.36
6. Casting	10.54	92.92	103.46
7. Drying	0.00	96.48	96.48
8. Glazing	1.14	22.32	23.46
9. Firing	0.00	188.90	188.90
10. Packing	111.82	5.00	116.82
11. Wastewater treatment	0.00	5.05	5.05

The factory studied in this paper is located in Hebei Province, China. The cost of equipment used for each process of sanitary ware production is analysed based on two production line with an annual output of 47,008 tonnes (2,800,000 pieces) of sanitary wares, as shown in Table S12.

Table S12. Cost of equipment used to produce sanitary ware (Unit: 10,000 CNY)

Process	Equipment	Type	Quantity	Price	Cost	Depreciation cost
2. Raw material transportation	Transportation equipment	Truck	8	30	240	52.36
3. Body preparation	Material feeder machine	60T	2	20	40	4.69
3. Body preparation	Ball mills	QMP-20T	12	20	240	28.11
3. Body preparation	Magnetic Iron Remover	-	8	5.4	43.2	5.06
3. Body preparation	Air compressor	LU90-890Kw	2	20	40	4.69
3. Body preparation	Raw material delivery system	DK800	150	0.1	15	1.76
3. Body preparation	Sieves for slips	XMZ-1200	16	1.5	24	2.81
3. Body preparation	Plunger pumps	NB200-10	8	3.5	28	3.28
3. Body preparation	Pneumatic diaphragm pump	S15B	180	0.38	68.4	8.01
3. Body preparation	Diaphragm pump	DBY-65	10	1.17	11.7	1.37
3. Body preparation	Transformer	2000KVA	2	16	32	3.75
3. Body preparation	Spiral mixer	Φ750	12	0.8	9.6	1.12
3. Body preparation	Lights	-	0.5	180	90	10.54
4. Glaze preparation	Ball mills	QMP-2.5T	6	4	24	2.81
4. Glaze preparation	Glaze mixer	-	8	1.17	9.36	1.10
4. Glaze preparation	Lights	-	0.5	180	90	10.54
5. Mould preparation	Automatic feeding machine	SG-ZG	1	38	38	4.45
5. Mould preparation	Vacuum mixer	ZKJ-1	20	2.6	52	6.09
5. Mould preparation	Electric Hoist	20 meters	10	0.7	7	0.82
5. Mould preparation	Model drying room	-	3	120	360	42.17
6. Casting	Low pressure casting machine	20 meters	180	3.4	1224	143.38
6. Casting	Lifting Machines	20 meters	150	2.8	840	98.40
6. Casting	High pressure casting machine	GY-SX12	4	140	560	65.60
6. Casting	High pressure casting machine for flush toilet	GY-ZB8	4	420	1680	196.80
6. Casting	High pressure casting machine for wash basin	GY-MJJ8	4	120	480	56.23
6. Casting	Air compressor	LU90-890Kw	12	20	240	28.11
6. Casting	Hydraulic lift	3t/2.5×3×2	2	16.5	33	3.87

6. Casting	Hydraulic lift	Four floors 5t/3.5×3×2.5 Three floors	4	13.5	54	6.33
6. Casting	Lights	-	0.5	180	90	10.54
7. Drying	Hot air oven	100Kcal	16	54	864	101.21
7. Drying	Suspended conveyor	GY-SX12	0.075	2000	150	17.57
7. Drying	Drying room	-	2	120	240	28.11
7. Drying	Vehicle	2*1.2	1400	0.12	168	19.68
8. Glazing	Glazing Robot	YR-HP20-A20	10	28.5	570	66.77
8. Glazing	Glazing robot supporting system	-	20	20	400	46.86
8. Glazing	Glazing cabinets	Doulbe work stations	50	5.5	275	32.21
8. Glazing	Air compressor	LU90-890Kw	4	20	80	9.37
8. Glazing	Dust removal system	-	50	4.8	240	28.11
8. Glazing	Hydraulic lift	-	8	3.75	30	3.51
8. Glazing	Lights	-	0.5	180	90	10.54
9. Firing	Tunnel Kiln with car conveyance	3.96 m×128 m	2	900	1800	210.86
9. Firing	Top car, trailer and stepper	YZDC	2	17	34	3.98
9. Firing	Shuttle Kiln	100 m^3	2	350	700	82.00
9. Firing	Air compressor	LU90-890Kw	2	20	40	4.69
10. Packing	Roller conveyor	-	2	120	240	28.11
10. Packing	Water leak test machine	ZLSJ	16	2.39	38.2	4.47
10. Packing	Surface grinding	PY400/1200	6	3.8	22.8	2.67
10. Packing	Lights	-	1	180	180	21.09
11. Wastewater treatment	Wastewater treatment station	-	2	191.02	382.04	44.75
11. Wastewater treatment	Wastewater treatment equipment	-	2	29.91	59.82	7.01
12. Delivery	Transportation equipment	-	10	30	300	65.45
Auxiliary equipment	Steam boilers	SZL15-1.25-A II	3	80	240	28.11
Auxiliary equipment	Boiler dust removal system	-	3	50	150	17.57
Auxiliary equipment	Flue gas and waste heat recovery system	-	3	10	30	3.51
Auxiliary equipment	Piping system	-	3	160	480	56.23

From Table S12, the annual depreciation cost of auxiliary equipment is 1054,000 Yuan. It is evenly allocated to the nine processes (except for raw material extraction and transportation and delivery), with each process accounting for 117,100 Yuan of auxiliary equipment cost. Then the cost of equipment for each process is aggregated and shown in Table S13.

Table S13. Cost of equipment of each process to produce sanitary ware (Unit: CNY)

Process	Cost	Cost per tonne
2. Raw material transportation	523599	11.14
3. Body preparation	869086	18.49
4. Glaze preparation	261651	5.57
5. Mould Preparation	652488	13.88
6. Casting	6209765	132.10
7. Drying	1782921	37.93
8. Glazing	2091007	44.48
9. Firing	3132411	66.64
10. Packing	680602	14.48
11. Wastewater treatment	634753	13.50
12. Delivery	654499	13.92

Table S14. Life cycle cost to produce 1 tonne of sanitary ware products.

Categories	**Price [CNY /kg^{-1}]**	**Amount [kg]**	**Cost [CNY]**	**Percentage [%]**
Feldspar	0.417	246.5	102.91	2.69
Ball clays	0.294	267.8	78.63	2.06
Quartz	0.428	334.8	143.29	3.75
Kaolin	0.250	338.7	84.51	2.21
Dolomite	0.264	5.9	1.56	0.04
Calcite	0.362	9.8	3.54	0.09
Talc	1.154	2.0	2.31	0.06
Zinc oxide	0.523	1.5	0.78	0.02
Plaster of Paris	0.505	154.2	77.88	2.04
Cardboard boxes	2.262	49.4	111.73	2.92
Groundwater	0.00148	10,847.1	16.05	0.42
Electricity	0.550	433.1	238.20	6.23
Coke oven gas	0.350	768.2	268.88	7.03
Construction	-	-	151.90	3.97
Equipment	-	-	372.12	9.73
Managing cost	-	-	809.95	21.18
Labour	-	-	260.14	6.80
Maintenance	-	-	12.51	0.33
Transportation	-	-	175.64	4.59
Sales cost	-	-	785.45	20.54
Tax	-	-	125.41	3.28
Total	-	-	3823.40	100.00