Water Footprint and Water Pinch Analysis Techniques for Sustainable Water Management in the Brick-Manufacturing Industry

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Highlights

- Water footprint and pinch analysis are effective tools to manage water consumption.
- Current water consumption footprint for the production of a brick is 2.02 L.
- Direct re-use/recycle reduced the water consumption footprint by 15.6%.
- Water regeneration reduced the water consumption footprint by 80.4%.

Abstract

Brick-manufacturing is an intensive water-consuming industry that requires a sustainable and integrated water management strategy to reduce reliance on freshwater consumption. This study aims to develop a rigorous analytical tool based on water footprint principles and water pinch analysis techniques that can be used to manage and optimise water consumption. By performing thorough water audits, the water consumption footprint (the sum of blue and green water footprints) and the theoretical water pollution footprint (grey water footprint) were quantified. The total water consumption footprint of a brick is determined as 2.02 L, of which blue water is identified as 1.71 L (84.8%) and green water as 0.31 L (15.2%). The theoretical grey water footprint of a brick was found

to be 1.3 L, a value that would have been higher if in-situ wastewater treatment had not been operated before effluent discharge. In order to reduce the water footprint of a brick, water pinch analysis techniques were applied for the brick-manufacturing processes. Two water recovery schemes were explored, *i.e.* direct re-use/recycle and water regeneration. For the former, water targeting was first carried out using the material recovery pinch diagram. Next, an algebraic technique was utilised for the targeting of water regeneration, where an interception unit is used to partially purify the water sources for further re-use/recycle. The network that fulfils the water flow rate targets was then designed using the nearest neighbour algorithm. The calculation indicates that direct re-use/recycle scheme reduces with the standard water consumption footprint reduced only by 15.6%. Water regeneration scheme, on the other hand improved the current value (which relies on an unsystematic water regeneration scheme) by 56.4%. The analysis clearly shows that the water consumption footprint of a brick is improved when the brick-manufacturing industry operates sustainable water management strategies. This study, a first of its kind, demonstrates that integration of water pinch analysis coupled with water footprint concepts, provide a robust and effective tool for the manufacturing industries that aim for sustainable water consumption.

Key Words: Water Consumption; Water Reduction; Direct Re-use/Recycle; Water Regeneration; Optimization.

Abbreviations

COD	Chemical Oxygen Demand
F	Flow Rate
FWR	Freshwater Region
RWR	Regeneration Water Region
SK	Sink
SR	Source
TSS	Total Suspended Solids

1. Introduction

Bricks are one of the oldest building materials. They are an economical product made of cheap abundant materials, (*e.g.* clay, shale), and produced through simple manufacturing processes, (*e.g.* drying, firing), with interesting physical, mechanical and thermal properties, in particular with respect to their strength, durability and compactness (Zhang, 2013; Bories *et al.*, 2014). In the UK, the clay brick sector produced around 1,554 million bricks in 2012 from 60 brick yards across the country (Bricks Development Association (BDA), 2013). However, brick-making is a water-intense industry requiring large volumes of freshwater to be used as water has to be mixed with clay to form it into the desired shape (Smith, 2013). In addition, water is also required for several other water-using processes, mainly, cleaning purposes, *e.g.* continued cleaning of the moulds for moulded processes, or consumed by staff working on a brick yard, *e.g.* use of kitchens and toilets. Under these circumstances, it is important that the water footprint of a brick be calculated, and potential to reduce freshwater consumption be investigated and identified.

The *water footprint*, as a concept, was introduced to quantify and map water use. It is a multi-dimensional indicator that looks both at direct and indirect water use (or virtual (embodied) water content) of a consumer or a producer showing both water consumption volumes, by source, and required volumes of water to assimilate anthropogenic loads of chemicals into freshwater bodies (Wang *et al.*, 2013; Gu *et al.*, 2015). The water footprint of a product, *i.e.* a commodity, a good or a service, is the total volume of freshwater consumed/polluted to produce this product summed over the various steps of the production chain and it indicates how much pressure the product puts on freshwater resources. In a simple production system, it is equal to the sum of the water footprints of the process steps taken to produce the product (Hoekstra *et al.*, 2011; Ercein *et al.*, 2012; Hoekstra, 2016). To quantify the water footprint of a product, three water volumes are required to be known, that is to say the water footprint has three independent components: blue, green, and grey water footprint (Hoekstra *et al.*, 2011; Zhang *et al.*, 2013; Lovarelli *et al.*, 2016). Blue and green water

79 footprints refer to water consumption volumes, so their sum is known as the *water consumption*
80 *footprint* as reported by Gu *et al.*, 2014. . The *blue water footprint* refers to surface and groundwater
81 (water abstracted from rivers, lakes and aquifers) that is consumed (through evaporation or
82 incorporation into the product) so that the product is made. It also includes water abstracted from
83 surface or groundwater in a catchment and returned to another catchment or the sea. On the other
84 hand, the *green water footprint* refers to the volume of rainwater stored in the soil as soil moisture that
85 is consumed during the production process (Jeswani and Azapagic 2011; Morera *et al.*, 2016). The
86 *grey water footprint* is an indicator of water pollution (*water pollution footprint*) and in particular it is
87 an indicator of freshwater pollution that can be associated with the production of a product over its
88 full supply chain. The concept refers to the theoretical volume of water required to dilute the
89 pollutants in wastewater to a concentration that meets the designated water quality standards for the
90 receiving water body. Hence, application of wastewater treatment can reduce significantly the amount
91 of water needed to meet the above-mentioned water quality objectives (Gu *et al.*, 2015; Zhi *et al.*,
92 2015; Wu *et al.*, 2016).

93
94 However, water is an important resource in the industry, including the brick-manufacturing sector.
95 The increasingly strict environmental regulations, the increase in water tariffs and wastewater
96 treatment costs coupled with the significant shortage of freshwater resources have made efficient
97 water management imperative. Hence, opportunities for reduction in freshwater usage and wastewater
98 generation in the industry need to be investigated and addressed. With in-plant water recovery, both
99 freshwater and wastewater flow rates can be reduced simultaneously, which lead to improved water
100 footprint values. In the past two decades, various *process integration* and *pinch* analysis tools have
101 been developed to design the water recovery network systematically, and has gained wide acceptance
102 among academic and industrial practitioners. The technique consists of two-stages. In the first stage,
103 the minimum fresh water and wastewater flow rates needed for a process are determined based on
104 first principle, *i.e.* mass balances ahead of detailed engineering design, termed as *targeting*. This is
105 followed by the *network design* stage to achieve the minimum flow rate targets (Foo, 2012). In the
106 context of process integration, *re-use* refers to the scheme where spent water is re-utilised in another

water-using process, but not in the process that it has been previously utilised. On the other hand, *recycle* refers to scheme where spent water is re-utilised in the same process as before (Wang and Smith, 1994). When the potential for direct reuse/recycle is being exhausted, *water regeneration* scheme may be employed, where water sources are partially treated to upgrade its quality before they are sent for re-use/recycle (Wang and Smith, 1994). To date, various water pinch analysis techniques have been developed, these include graphical (e.g. *material recovery pinch diagram*, independently developed by El-Halwagi *et al.* (2003) and Prakash and Shenoy, 2005), algebraic (e.g. Manan *et al.*, (2004) for reuse/recycle; and Ng *et al.*, (2007; 2008) for regeneration system). These techniques are reported both in review papers (Foo, 2009), textbooks (El-Halwagi, 2011; Foo, 2012) and in encyclopaedia chapters (El-Halwagi and Foo, 2014). Various industrial applications have also been reported (e.g. see El-Halwagi, 2011 or Foo, 2012). Finally, some discussion on water footprint and water pinch analysis has also been reported (Klemeš *et al.*, 2011).

This paper is structured as follows. First, the brick-manufacturing case study is described. All water consumed in the brick manufacturing process was quantified. This is followed by the water consumption footprint calculation with existing operating conditions. The data was collected without taking into account the kind of brick that was being produced during the experiments. This was complemented by the theoretical calculation of the grey water footprint of a brick. After initial water footprint calculation, water pinch analysis was carried out to investigate the potential to reduce the water footprint *systematically*. The concentration of total suspended solids (TSS) is taken as the leading water quality parameter in the water streams. Both direct reuse/recycle and regeneration schemes were investigated. The optimum water consumption footprint was calculated for both schemes in order to identify the best scenario.

2. Brick Manufacturing Case Study

A brick-manufacturing site located in the south-east of England has been chosen as a site for investigation. The selected plant, which targets at producing on average 200,000 bricks a day, fulfils its water requirements by using freshwater (either potable mains water or surface water occasionally).

It usually consumes mains water only, which is used by staff, *e.g.* for the use of toilets, the workshop and the kitchen, mixed with clay for the production of the bricks, or for cleaning the moulds or any other in-situ water-consuming process, *e.g.* water required for the operation a dust extractor (dust collection system) in the brick-production area. However, at times, mains water consumed for the cleaning of the moulds is replaced with surface water abstracted from a storage lagoon located on site. This replacement is always restricted to the available quantity and quality of stored water. However, in the brick-manufacturing industry, the use of mains water ought to be restricted to operations where water quality cannot be supported by that of surface water or when available surface water volumes are not adequate. The use of mains water should, in general, be avoided as not only does it increase the running cost of the plant but also treatment to achieve high drinking water quality standards requires high energy consumption and, hence significantly affecting the broader life cycle-based water footprint of a brick (Gu *et al.*, 2015). In this study, average volumetric flow rates of all water-consuming processes within the plant were quantified by installing and using water meters and with the development of a water-auditing tool. During the water audits, the freshwater used for moulds cleaning was abstracted from the storage lagoon. The flow chart showing all water-using processes is displayed in Figure 1. Details about the different water-using processes as depicted in Fig. 1 are provided in Table 1.

NOTE: X: Water meter, ----: Brick production zone.

Fig. 1: Flow chart depicting all water-using processes

Table 1: Details about the water-using processes of the plant

Water-using Process	Description
F ₁	First mains water inlet
F ₂	First inlet of Tank 2: mains water stored in Tank 2 (from first mains water inlet)
F ₃	Water used by staff
F ₄	Wastewater produced by staff
F ₅	Second mains water inlet
F ₆	Water used for the hydrolysis of the polyacrylamide required for in-situ treatment of polluted process water
F ₇	Second inlet of Tank 2: mains water stored in Tank 2 (from second mains water inlet)
F ₈	Inlet of Tank 1 (surface water inlet)
F ₉	Outlet of Tank 1: water used for moulds cleaning
F ₁₀	Outlet of Tank 2: water used for the production of bricks
F ₁₁	Water consumed by the wet pan
F ₁₂	Water consumed by Mixer 1 (double shaft mixer)

F_{13}	Water consumed by Mixer 2 (single shaft mixer)
F_{14}	Inlet of dust extractor
F_{15}	Initial moisture content of clay mixture
F_{16}	Outlet of dust extractor
F_{17}	Total amount of evaporated water (during drying/firing)
F_{18}	Amount of polluted process water after cleaning both the moulds and the gully located underneath the moulding machine
F_{19}	Total amount of polluted process water produced both by the moulding machine (moulds + gully) and the dust extractor
F_{20}	Discharged treated water
F_{21}	Recycled treated water used for the cleaning of the gully located underneath the moulding machine

In this study, flow rates for majority of the streams were continuously monitored using flow meters, with a few being calculated using mass balances and reasonable educated guesses. The meter readings were recorded manually and electronically. Manual readings of totalising water volumes were taken once a day at the same time every day (at 10:00 *a.m.*). The readings were taken in increments of 0.5 m³ with their accuracy being subject to human random error. At the same time, measurements were taken electronically using pulse input data loggers. Once activated, these data loggers could sense and record pulses with each pulse representing a certain volume of water, which was pre-selected. In this case, the increment selected was equal to 0.1 m³ for all water-using processes, except for F_8 and F_{21} , where it was equal to 1 m³. This happened due to the large volumes of water circulated and the limited internal capacity of the data loggers to store data. Three measurements were performed with each one lasting twelve days. Average flow rates based on both manual and electronic readings (<5% recording error) were calculated and a final average flow rate was determined for each measurement. Finally, out of the three measurements, an average flow rate was calculated for each water-using process.

3. Water Footprint Analysis

3.1. Development of Water Audits

A water auditing tool aimed at quantifying all average water flow rates of the plant was developed. As seen in Figure 1, there are three main incoming water flow rates, namely F_1 , F_5 , F_8 , which feed the brickworks with freshwater (mains or surface water). F_1 and F_5 feed the system with mains water only. All this mains water, except for a small amount shown as F_6 in Figure 1, is stored in Tank 2 and is entirely used for the production of bricks and evaporates during the drying and firing processes. F_8 can feed the system with either mains or surface water. This water is stored in Tank 1 and used for mould cleaning purposes and is returned as wastewater (polluted process water) to be treated on site. It is mainly treated by coagulation/flocculation using neutral/slightly anionic polyacrylamide followed by sedimentation to reduce turbidity resulting from clay suspensions.

For additional rigour, water flow rate sub-metering for each individual process was also monitored in order to quantify the volume of freshwater that was used both for activities that are directly related to bricks production and the volume of water that was used indirectly for overhead activities. The overhead water footprint of a product, *e.g.* a brick, refers to freshwater use that is not fully associated with its production but refers to freshwater use associated with supporting activities and materials used in the business (Jefferies *et al.*, 2012). In this study, all water used is related to activities that are directly associated with the product, except for freshwater used by staff in the toilets, the workshop and the kitchen (F_3), used for the hydrolysis of the polyacrylamide (F_6), and used for the operation of a dust extractor (F_{14}) operated to improve breathable air quality in the brick-making area. It also helped calculate the initial water (moisture) content of the clay mixture (F_{15} in Figure 1), an entity required for the calculation of the green water footprint of a brick. To estimate moisture content, all water added to the clay mixture had to be quantified, so F_{11} (freshwater added to the wet pan), F_{12} (freshwater added to the double-shaft mixer) and F_{13} (freshwater added to the single-shaft mixer) had to be monitored. Details about the quantification of the initial moisture content will be discussed in Section 3.2.2 where the green footprint of a brick is calculated. Finally, it helped confirm (using mass balances) that mains water was negligibly wasted (0.25% recording error) due to plant operation - mains water increases significantly the running cost, so it has to be used as efficiently as possible.

As all polluted process water used for cleaning purposes is safely collected in sedimentation tanks prior to treatment, we can assume that negligible losses take place during its collection. Table 2 illustrates the measured and calculated average flow rates per run.

3.2. Evaluation of the Water Footprint

In this particular case study, it is important to calculate the current water consumption footprint of a brick, which is the sum of the blue and green water footprints. The current water consumption footprint will be further improved with the application of water pinch analysis to further reduce the blue water footprint of the product. Quantification of the grey water footprint, which indicates the theoretical extent of ambient water pollution, has also been undertaken. In general, the brick-making industry deals mainly with clay and sand and it is a nearly chemical-free industry. In this study, all wastewater produced on-site, namely sewage and polluted process water, is treated before being discharged, a step that significantly reduces the grey water footprint. Although the water footprint assessment of a product is usually expressed as the sum of the blue, green and grey water footprints, the combination of a hypothetical “water pollution volume” (grey water footprint) with real “water consumption volumes” (blue and green water footprints) for total water footprint is considered to have no environmental meaning (Gu et al., 2015) and therefore in this work they will be quantified and presented separately.

Table 2: Measured and calculated flow rates

Flow Rate (m ³ d ⁻¹)	Run 1	Run 2	Run 3	Average Flow Rate (m ³ d ⁻¹)
	Measured Flow Rate (m ³ d ⁻¹)			
F ₁	42.7	43.0	38.9	41.5
F ₂	35.7	34.1	33.7	34.5
F ₅	79.6	87.9	82.5	83.3
F ₆	4.1	4.3	3.7	4.0
F ₈	189.3	234.7	206.9	210.3
F ₁₁	14.4	19.5	17.6	17.2
F ₁₂	16.9	16.9	14.9	16.2
F ₁₃	39.8	37.0	38.2	38.3
F ₁₄	41.4	42.3	41.6	41.8
F ₁₅	58.1	61.2	60.7	60.0

F_{17}	129.2	134.6	131.4	131.7
F_{21}	503.8	389.6	557.0	483.4
Calculated Flow Rate ($\text{m}^3 \text{d}^{-1}$)				
$F_3 = (F_1 - F_2)$	7.0	8.9	5.2	7.0
$F_4^A = (F_3)$	7.0	8.9	5.2	7.0
$F_7 = (F_5 - F_6)$	75.5	83.6	78.8	79.3
$F_9^B = (F_8)$	189.3	234.7	206.9	210.3
$F_{10}^C = (F_2 + F_7)$	111.2	117.7	116.2	115.0
$F_{16}^D = (F_{14})$	41.4	42.3	41.6	41.8
$F_{18} = (F_9 + F_{21})$	693.1	624.3	763.9	693.8
$F_{19}^E = (F_{16} + F_{18})$	734.5	666.5	805.5	735.5
$F_{20} = (F_6 + F_{19} - F_{21})$	234.8	281.2	252.2	256.1

^AWater used in toilets, the workshop and the kitchen turns into sewage.

^BWater volume entering Tank 1 is equal to water volume leaving the tank.

^CWater volume entering Tank 2 is equal to water volume leaving the tank.

^DWater volume entering the dust extractor is equal to water volume leaving it.

^EAll polluted water is safely collected, so no freshwater is wasted.

3.2.1 Evaluation of Blue Water Footprint

The blue water footprint is the volume of all freshwater (both mains and surface water) that is required to be consumed to make a brick. It is the sum of the amount of mains water ($F_1 + F_5$) and the top-up lagoon water (F_8) consumed divided by the daily brick production. Under the current operating conditions, its value would remain the same even if only mains water supply was used. The recycle F_{25} will not contribute to this calculation as it is not water consumed and/or evaporated during the brick-making process, nor is it abstracted from a catchment ending in another catchment or the sea.

In addition to calculating the total blue water footprint, its two parts, namely the direct and the overhead water footprint are calculated. Table 3 summarises the blue water footprint accounting with an average blue water footprint being equal to $1.71 \text{ L brick}^{-1}$. The results clearly demonstrate that most of blue water consumption (84.2%) was directly related to the production of the brick.

Table 3: Evaluation of the blue water footprint of an average brick

Blue Water Footprint (L brick^{-1})	Measurement 1 ($N = 191,520$) ^A	Measurement 2 ($N = 199,584$) ^A	Measurement 3 ($N = 194,779$) ^A	Average
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Direct Blue Water Footprint (BWF_D) BWF_D = (F₁ + F₅ + F₈ - F₃ - F₆ - F₁₄)/N	1.47	1.41	1.45	1.44
Overhead Blue Water Footprint (BWF_O) BWF_O = (F₃ + F₆ + F₁₄)/N	0.28	0.27	0.27	0.27
Blue Water Footprint (BWF) BWF = (F₁ + F₅ + F₈)/N	1.75	1.68	1.72	1.71

^A Average daily production of bricks (bricks d⁻¹).

3.2.2. Evaluation of the Green Water Footprint

The initial amount of water stored as moisture in the clay mixture is regarded as green water. This amount of water is calculated on the basis that the average weight of a green brick, *i.e.* a brick just before drying and firing, is 3 kg (0.003 ton) and the final average water (moisture) content of a brick on a wet basis is 22.5%. The following formula (Equation 1) is used and results are shown in Table 4:

$$F_{15} = \left(N \times W \times \left(\frac{22.5}{100} \right) \right) - F_{11} - F_{12} - F_{13} \quad \text{Equation 1}$$

1

where:

F₁₅: weight of water in the clay mixture (ton d⁻¹)

N: daily production of bricks (bricks d⁻¹)

W: weight of a green brick (ton)

F₁₁: water added to the wet pan (ton d⁻¹)

F₁₂: water added to the double shaft mixer (ton d⁻¹)

F₁₃: water added to the single shaft mixer (ton d⁻¹)

Table 4: Estimation of the initial moisture of the clay mixture

Parameters	Measurement 1 (N = 191,520) ^A	Measurement 2 (N = 199,584) ^A	Measurement 3 (N = 194,779) ^A
Final Moisture Content (on a Wet Basis) (%)^B	22.5	22.5	22.5
Water in Initial Clay Mixture F₁₅ (m³ d⁻¹)^C	58.2	61.3	59.8

^A Average daily production of bricks (bricks d⁻¹).

^B Accepted that final moisture content is 22.5% (on a wet basis).

^C Assumed that each average green brick weighs 3 kg.

Using the results of Table 4, the green water footprint of a brick is calculated (Table 5).

Table 5: Calculation of the green water footprint of an average brick

Green Water Footprint (L brick ⁻¹)	Measurement 1 (191,520) ^A	Measurement 2 (199,584) ^A	Measurement 3 (194,779) ^A	Average
Green Water Footprint (GWF) GWF = F ₁₅ /N	0.30	0.31	0.31	0.31

^A Average daily production of bricks (bricks d⁻¹).

3.2.3. Evaluation of Water Consumption Footprint

The current water consumption footprint of a brick is the sum of the blue and green water footprint and is on average equal to 2.02 L, and it corresponds to the consumption of 395.1 m³ d⁻¹ of freshwater (F₁ + F₅ + F₈ + F₁₅). This value needs to be further reduced for optimum freshwater consumption and wastewater generation reduction. Figures 2 and 3 provide a detailed schematic of the current water consumption footprint.

Fig. 2: Water consumption footprint of a brick

Fig. 3: Water consumption footprint of a brick per process

However, in order to be able to evaluate the direct re-use/recycle scheme that will follow (within the framework of water pinch analysis), the water consumption footprint, before any treatment and/or re-use/recycle takes place on the site, needs to be calculated. Results are given in Table 6 below:

Table 6: Water footprint of a brick prior without water regeneration/treatment

Initial Water Consumption Footprint	Measurement 1 (N = 191,520) ^A	Measurement 2 (N = 199,584) ^A	Measurement 3 (N = 194,779) ^A	Average
Initial Water Consumption Footprint ($WCF_{Initial}$) $IWF = (F_1 + F_5 + F_8 + F_{15} + F_{21} - F_6)/N$	4.54	4.09	4.83	4.49

^A Average daily production of bricks (bricks d⁻¹).

3.2.4. Theoretical Grey Water Footprint

In this study, there are two independent effluent streams that should be taken into account when calculating the grey water footprint of a brick, namely sewage that is treated aerobically before being discharged (F_4) and spent process water that is treated by coagulation/flocculation followed by

sedimentation before its discharge (F_{20}). Chemical Oxygen Demand (COD) concentration has been selected as the water quality parameters to identify pollution levels in the treated sewage; while TSS concentration was selected for process water. Reduction in their levels is indicative of the efficiency of the selected wastewater treatment methods. The following formula is used to estimate the grey water footprint (Franke *et al.*, 2013).

$$\text{GrWF} = \frac{\text{Effl} \times C_{\text{eff}} - \text{Abstr} \times C_{\text{act}}}{C_{\text{max}} - C_{\text{nat}}} \quad \text{Equation 2}$$

where:

GrWF: grey water footprint (volume time⁻¹)

Effl: effluent volume (mass time⁻¹)

C_{eff} : pollutant concentration in the effluent (mass volume⁻¹)

Abstr: water volume of the abstraction (volume time⁻¹)

C_{act} : actual concentration of the intake water (mass volume⁻¹)

C_{max} : maximum acceptable concentration (mass volume⁻¹)

C_{nat} : natural concentration of a receiving body (mass volume⁻¹)

For C_{max} , the ambient water quality standard for the receiving freshwater body is used. In this study, the C_{max} for COD is 30 mg L⁻¹ and for TSS is 25 mg L⁻¹ (Franke *et al.*, 2013, Hoekstra, 2015). The natural concentrations (C_{nat}) can be assumed to be negligible. Even though this may lead to an overestimation of the grey water footprint as natural concentrations may not necessarily be zero (Franke *et al.*, 2013, Hoekstra, 2015). The results are illustrated in Table 7. A total of 210.3 m³ (F_8) has been abstracted directly from the lagoon with a C_{act} for TSS equal to 55 mg L⁻¹ (average measured TSS concentration for lagoon water), whereas 52.8 m³ ($F_3 + F_6 + F_{14}$) of tap water has been abstracted indirectly from a catchment with an unknown C_{act} . After use, 7 m³ (F_3) of tap water has returned as sewage and 45.8 m³ ($F_6 + F_{14}$) has returned as polluted process water). Based on the WHO guidelines (1996), the C_{act} for COD is 20 mg L⁻¹. For TSS concentrations, the C_{act} value was assumed to be 30 mg L⁻¹ based on the fact that sewage treatment in the area must produce treated water with TSS

concentrations $\leq 30 \text{ mg L}^{-1}$ prior to discharge into neighbouring water bodies. Table 6 shows that the total grey water footprint of a brick is 1.3 L, a value that would have been higher if no in-situ wastewater treatment had been applied.

Table 7: Grey water footprint of a brick

Water Quality Parameter	Effl ($\text{m}^3 \text{ d}^{-1}$)	C_{eff} (mg L^{-1})	Abstr ($\text{m}^3 \text{ d}^{-1}$)	C_{act} (mg L^{-1})	Grey Water Footprint GrWF ($\text{m}^3 \text{ d}^{-1}$)	Grey Water Footprint GrWF (L brick ⁻¹) ^A
COD (Treated Sewage)	7.0	35	7.0	20	105	0.02
TSS Concentration (Treated Process Water)	256.1	75	210.3 45.8	55 30	6267	1.28
Total GrWF (L brick ⁻¹)						1.30

^A Average daily production is 195,295 bricks (out of three measurements).

4. Application of Water Pinch Analysis for Freshwater Reduction

For the purpose of water pinch analysis, it is accepted that both mains and surface water can be used as freshwater sources within the plant, as described above, and when surface water is required, sufficient quantity is stored in the lagoon. Two water recovery schemes are evaluated, *i.e.* direct re-use/recycle and regeneration, to see their contribution in water footprint reduction for the brick-manufacturing process.

4.1. Direct Re-use/Recycle of Spent Process Water

In order to assess the potential for direct water re-use/recycle, existing water regeneration or treatment units in the plant are excluded from the analysis. Hence, no water is to be used for the hydrolysis of polyacrylamide, *i.e.* $F_6 = 0$, as no flocculation/coagulation is taking place. On top of that, it is also assumed that surface water (abstracted from the lagoon) is used for cleaning the gully, *i.e.* F_{21} .

In order to carry out water pinch analysis, the limiting water data needs to be extracted correctly for all water sinks and sources. *Water sinks* refer to units/processes that consume feed water, (usually the inlet streams for the process units). On the other hand, *water sources* refer to water-containing streams

that leave the operation (outlet streams). For this case study, the TSS concentration is identified as the leading contaminant in considering water recovery system. Their limiting concentrations and flow rates for all water sources and sinks are summarised in Table 8. As shown, there are six sinks and two sources. Note that the total source flow rate is less than that of the total sinks, because part of the added water ($69.4 \text{ m}^3 \text{ d}^{-1}$) has been transformed into steam (F_{17} in Fig 1). Readers may refer to the detailed discussion on the limiting water data identification reported elsewhere (Foo *et al.*, 2006; Foo, 2012). Two sources of freshwater are then available for use in this case. Apart from the pure freshwater source (TSS concentration = 0 mg L^{-1} , *i.e.* mains water), an impure freshwater source (TSS concentration = 55 mg L^{-1}), which is surface water abstracted from the lagoon, is also available for use. The main purpose of carrying out water pinch analysis is to reduce the flow rates of both pure freshwater surface water.

Table 8: Water sinks and water sources summary for the brick-making industry

Sinks	Description	Flow Rate $F_{SKj} (\text{m}^3 \text{ d}^{-1})$	Concentration $C_{SKj} (\text{g m}^{-3})$	Load $m_{SKj} (\text{g d}^{-1})$
SK ₁	Mixer 1 (F_{12})	14.9	0	0
SK ₂	Wet Pan (F_{11})	16.2	0	0
SK ₃	Mixer 2 (F_{13})	38.3	0	0
SK ₄	Dust Collection System (F_{14})	41.8	0	0
SK ₅	Moulds Cleaning (F_8)	210.3	65 ^A	13669.5
SK ₆	Gully Cleaning (F_{21})	483.4	75 ^A	36255
Total		804.9		
Sources	Description	$F_{SRi} (\text{m}^3 \text{ d}^{-1})$	$C_{SRi} (\text{g m}^{-3})$	$m_{SRi} (\text{g d}^{-1})$
SR ₁	Spent Water from Dust Extractor (F_{16})	41.8	90 ^A	3762
SR ₂	Spent Water used for Cleaning (F_{18})	693.7	180 ^B	124866
Total		735.5		

^A Estimated based on the company's guidelines.

^B Based on measurements.

The material pinch recovery diagram (El-Halwagi *et al.*, 2003; Prakash and Shenoy, 2005) is next plotted in Figure 4 to identify the minimum fresh water and wastewater flow rates for the direct re-use/recycle scheme. Since two freshwater sources are available, the targeting procedure shall follow the two-step approach proposed by Wan Alwi and Manan (2007), *i.e.* the higher quality pure freshwater source (0 mg L^{-1}) is targeted prior to the impure source (55 mg L^{-1}). As shown in Figure 4, an impure fresh water locus (with a slope corresponding to 55 mg L^{-1}) is plotted and slid horizontally from the origin, staying entirely below but touching the *sink composite curve*. The distance of the

impure locus from the origin indicates the minimum flow rate of the pure freshwater source (F_{FW1}), *i.e.* $111.2 \text{ m}^3 \text{ d}^{-1}$. Next, the *source composite curve* is plotted and slid along the impure locus staying entirely below but touching the sink composite curve. The horizontal distance of the impure locus where the source composite curve is shifted indicates the minimum flow rate of impure freshwater source (F_{FW2}), *i.e.* $569.4 \text{ m}^3 \text{ d}^{-1}$ (see Figure 4). The distance of the source composite curve extended from the sink composite curve indicates the amount of wastewater generated from the network, *i.e.* $611.2 \text{ m}^3 \text{ d}^{-1}$. As shown in Figure 4, there are two pinch points for this case, *i.e.* 0 and 180 mg L^{-1} . Note that the pinch point of 0 mg L^{-1} controls the pure freshwater flow rate, while that of 180 mg L^{-1} controls the surface water flow rate.

Fig 4: Material recovery pinch diagram for targeting multiple freshwater feed

Fig. 4 shows that application of direct re-use/recycle reduces the volume of blue water from $804.9 \text{ m}^3 \text{ d}^{-1}$ to $680.6 \text{ m}^3 \text{ d}^{-1}$, corresponding to a reduction of 15.4%. On the other hand, the wastewater generation has been reduced by 16.9% to $611.2 \text{ m}^3 \text{ d}^{-1}$, instead of $735.5 \text{ m}^3 \text{ d}^{-1}$ prior to pinch analysis.

This reduction in freshwater consumption reduces equally the water consumption footprint from 4.49 L to 3.79 L, which is derived from the following calculation: $(680.6 \text{ L (Blue Water)} + 60 \text{ L (Green Water: } F_{15})) / 195,295 \text{ (Average Daily Production: N)}$ leading to a reduction of 15.6%.

4.2. Regeneration of Spent Process Water

After the water flow rate reduction potential via direct re-use/recycle is exhausted, water regeneration scheme is next evaluated to optimise the use of water in order to reduce the water footprint of a brick. The plant already treats spent process water using sedimentation followed by coagulation/flocculation with produced water having a final TSS concentration of 75 mg L^{-1} . In this work, it is assumed that the process water will first be sent for sedimentation, which is then regenerated to an improved outlet concentration of 10 mg L^{-1} with a new filtration unit. Surface water is excluded from the analysis in this case, as regenerated water has an improved (*i.e.* lower) TSS concentration.

The targeting procedure is based on an algebraic technique proposed by Ng *et al.* (2007, 2008). For the sake of brevity, only the main targeting steps are described here. Readers may refer to the original work (Ng *et al.*, 2007) for detailed instruction. In principal, the water sinks and sources are allocated into two regions, *i.e.* *freshwater region* (FWR) and *regeneration water region* (RWR), where flowrate targeting is carried out. By doing so, the flow rates of water regeneration is identified in the RWR as $418.7 \text{ m}^3 \text{ d}^{-1}$. In the FWR, the freshwater flow rate is identified as $111.2 \text{ m}^3 \text{ d}^{-1}$, while a total of $41.8 \text{ m}^3 \text{ d}^{-1}$ of wastewater is identified in the same region. The targeting results are shown in Tables A1 and A2 in the Appendix.

Next, the *nearest neighbour algorithm* (Prakash and Shenoy, 2005) was used to design the water network. For the sake of brevity, only the two important equations used representing the material and contaminant balances are shown here (Equations 3 and 4). Readers may refer elsewhere (Prakash and Shenoy, 2005; Foo, 2012) for the complete design procedure with the nearest neighbour algorithm. In essence, a pair of sources (one of just lower (SR_k) and one of just higher concentration (SR_{k+1}) is used to fulfil the flow rate and impurity load constraints of the water sink. Sources (including fresh water)

are allocated in order of increasing contaminant concentration values. Similarly, the allocation was carried out for the sinks are in ascending order of contaminant concentration.

$$F_{SR_k,SK_j} + F_{SR_{k+1},SK_j} = F_{SK_j} \quad \text{Equation 3}$$

$$F_{SR_k,SK_j} C_{SR_k} + F_{SR_{k+1},SK_j} C_{SR_{k+1}} = F_{SK_j} C_{SK_j} \quad \text{Equation 4}$$

with F_{SR_k,SK_j} being the allocated flow rate from source SR_k to sink SK_j . Figure 5 shows the water regeneration network for the brick-manufacturing case study.

Fig. 5: Minimum freshwater network design by nearest neighbour algorithm.

At the current operating conditions where unsystematic regeneration takes place, the plant requires $325.5 \text{ m}^3 \text{ d}^{-1}$ ($F_6 + F_8 + F_{11} + F_{12} + F_{13} + F_{14}$) of freshwater (blue water), and generates $256.1 \text{ m}^3 \text{ d}^{-1}$ (F_{20}) of wastewater. After systematic regeneration, only $111.2 \text{ m}^3 \text{ d}^{-1}$ (65.8% reduction) of fresh water (blue water) was required, while wastewater flow rate was reduced to $41.8 \text{ m}^3 \text{ d}^{-1}$ (83.9% reduction). This reduction in freshwater consumption reduced the water consumption footprint of a brick from

2.02 L to 0.88 L, with the latter being derived from the following calculation: (111.2 L (Blue Water) + 60 L (Green Water: F_{15})/195,295 (Average Daily Production: N) leading 56.4% further reduction.

5. Water Footprint Reduction upon Water Pinch Analysis

Results from water pinch analysis show that both recovery schemes do improve freshwater consumption and the water footprint of a brick as illustrated in Table 9.

Table 9: Water consumption footprint of a brick for direct reuse/recycle and regeneration schemes

Water Reduction Scheme	Water Consumption Footprint (L brick ⁻¹) ^{A,B}	Reduction (%)
No water management strategy	4.49	-
Water pinch analysis: Direct re-use/recycle	3.79	15.6
Unsystematic Regeneration	2.02	55.0
Water Pinch Analysis: Regeneration	0.88	80.4

^A Average daily production is 195,295 bricks (out of three measurements).

^B Mains water stored in the bricks, has also been taken into account during the calculations above.

^C Non-re-usable/recyclable treated water manages to cover sufficiently the amount of abstracted water.

The results confirm that water recovery must be performed in a systematic manner rather than being an ad-hoc decision. This also shows the application of water pinch analysis is an important water footprint reduction strategy whose implementation is imperative. It is worth mentioning that the grey water footprint is also expected to be significantly reduced for both schemes with water regeneration being the optimal scenario. This is due to the fact that the wastewater produced and discharged is less in terms of quantity but also in quality. However, quantification of any grey water footprint improvement was beyond the scope of this work.

6. Conclusions

This work concentrated on quantifying the water footprint of a brick as well as investigating the potential of its systematic improvement using water pinch analysis. Following detailed water audits, the current water consumption footprint, which is subject to unsystematic water regeneration is 2.02 L brick⁻¹. A theoretical and indicative grey water footprint was calculated and was found to be equal to 1.3 L brick⁻¹, a value that would have been higher if no wastewater treatment had taken place. To reduce the water footprint of a brick systematically, water pinch analysis techniques were implemented. Improved new water consumption footprints were finally calculated. In this case, the standard water consumption footprint (a footprint value without any water management strategy taking place) needs to be calculated and it was found to be equal to 4.49 L. Direct re-use/recycle reduced it only by 15.6%. However, systematic water regeneration reduced it by 80.4% as well as it reduced the current water consumption footprint, which is equal to 2.02 L and has relied its calculation on an unsystematic water regeneration scheme that has not been optimized, by 56.5%. In addition, systematic water regeneration shows that surface water is not used as regenerated spent water can cover the water needs of the plant. This unique case study has been able to demonstrate that the combined use of water footprint with pinch analysis can provide water intensive manufacturing industries with a sound and robust water management tool that can significantly improve their water consumption and consequently their long term sustainability.

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References

- Allan JA. Virtual water: a long term solution for water short Middle Eastern economies? Occasional Paper 3, School of Oriental and African studies, University of London; 1997.
- BDA, 2013. Brick Leads the Way in Sustainability Stakes, London: Brick Development Association, United Kingdom

474 Bories, C. Borredon, M.E. Vedrenne, E. Vilarem, G. 2014. Development of eco-friendly porous fired
 475 clay bricks using pore-forming agents: a review. *J. Environ. Manag.* 143,186-196.

476 Ercin, A.E. Aldaya, M.M. Hoekstra, A.Y. 2012. The water footprint of soy milk and soy burger and
 477 equivalent animal products. *Ecol. Indic.* 18, 392-402.

478 El-Halwagi, M.M. Foo, D.C.Y. 2014. Process Synthesis and Integration, in Seidel, A. and Bickford,
 479 M. (Ed.). *Kirk-Othmer Encyclopaedia of Chemical Technology*. John Wiley and Sons.

480 El-Halwagi, M.M. Gabriel, F. Harell, D. 2003. Rigorous graphical targeting for resource conservation
 481 via material recycle/reuse networks. *Ind. Eng. Chem. Res.* 42, 4319-4328.

482

483 El-Halwagi, M.M. 2011. Sustainable design through process integration: fundamentals and
 484 applications to industrial pollution prevention, resource conservation, and profitability
 485 enhancement. Elsevier.

486 Foo, 2012. D.C.Y. Process integration for resource conservation. CRC Press, Boca Raton, Florida,
 487 US.

488 Foo, D.C.Y. 2009. State-of-the-art review of pinch analysis techniques for water network synthesis,
 489 *Ind. Eng. Chem. Res.* 48, 5125-5159.

490 Foo, D.C.Y. Manan, Z.A. El-Halwagi, M.M. 2006. Correct identification of limiting water data for
 491 water network synthesis. *Clean Technol. Envir.* 8, 96-104.

492 Franke, N.A. Boyacioglu, H. Hoekstra, A.Y. 2013. Grey water footprint accounting: tier 1 supporting
 493 guidelines. *Value of Water Research Report. Series No. 65*.

494 Gu, Y. Xu, J. Keller, A.A. Yuan, D. Li, Y. Zhang, B. Weng, Q. Zhang, X. Deng, P. Wang, H. Li, F.
 495 2015. Calculation of water footprint of the iron and steel industry: a case study in Eastern China. *J.*
 496 *Clean. Prod.* 92, 274-281.

497 Gu, Y. Xu, J. Wang, H. Li, F. 2014. Industrial water footprint assessment: methodologies in need of
 498 improvement (Viewpoint). *Environ. Sci. Technol.* 48, 6531-6532.

499 Hoekstra, A.Y. Chapagain, A.K. Aldaya, M.M. Mekonnen, M.M. 2011. The water footprint
 500 assessment manual (setting the global standard). EarthScan.

501 Hoekstra, A.Y. 2016. A critique on the water-scarcity weighted water footprint in LCA. *Ecol. Indic.*
502 66, 564-573.

503 Hoekstra, A.Y. 2015. Assessing and measuring environmental impact and sustainability. Chapter 7:
504 the water footprint of industry, Elsevier Inc.

505 Jefferies, D. Muñoz, I. Hodges, J. King, V.J. Aldaya, M. Ercin, A.E. Canals, L. M. I. Hoekstra, A.Y.
506 2012. Water footprint and life cycle assessment as approaches to assess potential impacts of
507 products on water consumption. Key learning points from pilot studies on tea and margarine, J.
508 *Clean. Prod.* 33, 155-166.

509 Jeswani, H.K. Azapagic, A. 2011. Water footprint: methodologies and a case study for assessing the
510 impacts of water use. *J. Clean. Prod.* 19, 288-1299.

511 Jia, X., Li, Z., Wang, F., Foo, D. C. Y., and Tan, R. R., (2015). A new graphical representation of
512 water footprint pinch analysis for chemical processes. *Clean Technologies and Environmental*
513 *Policy.* 17(7): 1987-1995.

514 Klemeš, J. Lam, H.L. Foo, D.C.Y. 2011. Water integration for recycling and recovery in process
515 industry, Atimtay, A. T. and Sikdar, S. K. (Eds.): *Security of Industrial Water Supply and*
516 *Management Springer.*

517 Lovarelli, D. Bacenetti, J. Fiala, M. 2016. Water footprint of crop productions: a review. *Sci. Total*
518 *Environ.* 548-549.

519 Manan, Z.A. Tan, Y.L. Foo, D.C.Y. 2004. Targeting the Minimum Water Flow rate Using Water
520 Cascade Analysis Technique. *AIChE Journal.* 50, 3169-3183.

521 Morera, S. Corominas, Ll. Poch, M. Aldaya, M.M. Comas, J. 2016. Water footprint assessment in
522 wastewater treatment plants. *J. Clean. Prod.* 112, 4741-4748.

523 Ng, D. K. S., Foo, D. C. Y. Tan, R. R. and Tan, Y. L. (2007). Ultimate Flowrate Targeting with
524 Regeneration Placement, *Chemical Engineering Research and Design*, 85 (A9) 1253–1267

525 Ng, D.K.S. Foo, D.C.Y. Tan, R.R. Tan, Y.L. 2008. Extension of targeting procedure for “ultimate flow
526 rate targeting with regeneration placement”. *Chem. Eng. Res. Des.* 85, 1253 - 1267.

527 Prakash, R. Shenoy, U.V. 2005. Targeting and design of water networks for fixed flow rate and fixed
528 contaminant load operations. *Chem. Eng. Sci.* 60, 255-268

Smith, D. Clay bricks and clay blocks: a resource efficiency action, Report 018, The Green Construction Board (2013).

Tan, R. R., Foo, D. C. Y., Aviso, K. B. and Ng, D. K. S. (2009). The Use of Graphical Pinch Analysis for Visualizing Water Footprint Constraints in Biofuel Production. *Applied Energy*, 86: 605-609.

Wan Alwi, S.R. Manan, Z.A. 2007. Targeting multiple water utilities using composite curves. *Ind. Eng. Chem. Res.* 46, 5968-5976.

Wang, Z. Huang, K. Yang, S. Yu Y., 2013. An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China. *J. Clean. Prod.* 42, 172-179.

WHO, 1996. Water quality assessments - a guide to use of biota, sediments and water in environmental monitoring. 2nd Edition.

Wang, Y.P. Smith, R.1994. Wastewater Minimisation. *Chem. Eng. Sci.* 49, 981-1006.

Zhang, L. 2013. Production of bricks from waste materials - a review. *Constr. Build. Mater.* 47, 643-655.

Wu, B. Zheng, W. Chen, H. Zhao, Y. 2016. Grey water footprint combined with ecological network analysis for assessing regional water quality metabolism. *J. Clean. Prod.* 112, 3138-3151.

Zhang, G.P. Hoekstra, A.Y. Mathews, R.E. 2013. Water footprint assessment (WFA) for better water governance and sustainable development (Editorial). *Water Resour. Ind.* 1-2, 1-6.

Zhi, Y. Yang, Z. Yin, X. Hamilton, P.B. Zhang, L. 2015. Using grey water footprint to verify economic sectors' consumption of assimilative capacity in a river basin: model and a case study in the Haihe River Basin, China. *J. Clean. Prod.* 92, 267-273.

Appendix

Table A1: Targeting for regenerated water (F_{RW}) flow rate in the RWR

C_k (g m ⁻³)	ΔC_k (g m ⁻³)	$\Sigma_j F_{SKj}$ (m ³ d ⁻¹)	$\Sigma_i F_{SRi}$ (m ³ d ⁻¹)	$\Sigma_i F_{SRi} - \Sigma_j F_{SKj}$ (m ³ d ⁻¹)	$F_{C,k}$ (m ³ d ⁻¹)	Δm_k (g d ⁻¹)	Cum. Δm_k (g d ⁻¹)	$F_{RW,k}$ (m ³ d ⁻¹)	$F_{C,k}$ (m ³ d ⁻¹)	m_k (g d ⁻¹)	Cum. Δm_k (g d ⁻¹)
$F_{RW} = 418.70$											
10				0							
	45				0	0			418.70	18841.63	
55				0			0	0			18841.63
	10				0	0			418.70	4187.03	
65		210.3		-210.3			0	0			23028.66
	10				-210.3	-2103			208.40	2084.03	
75		483.4		-483.4			-2103	-32.35			25112.69
	15				-693.7	-10405.5			-274.00	-4124.96	
90			41.8	41.8			-12508.5	-156.36			20987.74
	90				-651.9	-58671			-233.20	-20987.74	
180			651.9	651.9			-71179.5	-418.70			0
	999820				0	0			$F_{RW} = 418.70$	4186.28x10 ⁵	
1000x10 ³							-71179.5	-0.070			4186.28x10 ⁵

Table A2: Targeting for freshwater (F_{FW}) and wastewater (F_{WW}) flow rates in the FWR

C_k (g m ⁻³)	ΔC_k (g m ⁻³)	$\Sigma_j F_{SKj}$ (m ³ d ⁻¹)	$\Sigma_i F_{SRi}$ (m ³ d ⁻¹)	$\Sigma_i F_{SRi} - \Sigma_j F_{SKj}$ (m ³ d ⁻¹)	$F_{C,k}$ (m ³ d ⁻¹)	Δm_k (g d ⁻¹)	Cum. Δm_k (g d ⁻¹)	$F_{FW,k}$ (m ³ d ⁻¹)	$F_{C,k}$ (m ³ d ⁻¹)
$F_{FW} = 111.2$									
0		111.2		-111.2					
	55				-111.2	-6116			0
55				0			-6116	-111.2	
	10				-111.2	-1112			0
65				0			-7228	-111.2	
	10				-111.2	-1112			0
75				0			-8340	-111.2	
	15				-111.2	-1668			0
90				0			-10008	-111.2	
	90				-111.2	-10008			0
180			41.8	41.8			-20016	-111.2	
	999820				-69.4	-69387508			$F_{WW} = 41.8$
1000000							-69407524	-69.4075	