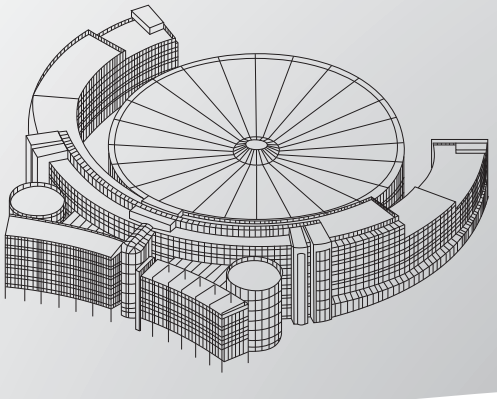
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Chenqing Wang

Contribution to Efficient Water Use and Reducing Environmental Impact of Wastewater in Industry

Fraunhofer IPK
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Foreword of the author

This thesis has been created during my time as a research assistant in the Chair of Assembly Technology and Factory Management in the Institute for Machine Tools and Factory Management (IWF) at the Technische Universität Berlin (TUB).

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Berlin, October 2013 Chenqing Wang

Abstract in English and German

Efficient water use and reduction of environmental impact of wastewater in industry play a role in increasing resource productivity and thus are essential criteria for global sustainable development. Great potential can be identified for a consideration of water efficiency measures in a manufacturing plant and its business chain.

The objective of this thesis is the development of an improvement system for the reduction of water consumption in industrial production and the environmental impact by wastewater discharge. A concept is constructed, by which the critical water use from processes through cells to the factory level will be identified and thus the improvement measures can be undertaken based on that water analysis.

The methodology is based on the integration of value stream mapping method in lean manufacturing, the water consumption analysis through the production flow, and zero emissions methods. Water value stream analysis provides a platform, upon which all water consumers can be identified within a production related organizational connection to each other. The entire water requirement of a factory will be shown with the production flow in a transparent way. Water consumption will be allocated to its consumer. Water losses and water intensity analysis is then undertaken to look for critical water use processes in a factory. Based on this, a map of current water use along the process flow in an industrial factory is presented, which provides a clearly visual representation of water use and wastewater generation within the whole factory.

The improvement guidelines of efficient water withdrawal, reducing loss in distribution, storage and set-up time, operation according to takt time, efficient use technology, raising awareness, recycling and reuse, are offered to increase water availability, increase water efficiency in operation and raise water utilization. With a reduction of water intake to minimum level, methods to achieve maximum wastewater reuse in a business dimension are introduced. An economic and ecological way to achieve zero wastewater can be undertaken based on the idea of industry clusters. The valuable constituents in wastewater can be profit for other production use, especially some agriculture-based production. With a layer model for the description of the condition of wastewater, the methodology of organizational reuse is presented.

The operability of the developed concept is validated with two case studies. The first example shows how the water value stream mapping method is applied in a paint shop of an automotive factory. In the example of treating wastewater from train maintenance, the method of planning a zero wastewater discharge system within the business strategy is exemplarily applied.

Effizienter Wasserverbrauch und die Reduzierung der Umweltbelastung durch Abwasser in der Industrie spielen eine große Rolle in der Ressourcenproduktivität und sind wesentliche Kriterien für eine globale nachhaltige Entwicklung. Die Berücksichtigung von Maßnahmen zur Steigerung der Wassereffizienz in einer Fabrik und entsprechende Geschäftsmodelle bergen ein großes Potential.

Ziel dieser Arbeit ist die Entwicklung eines Systems zur Reduktion des Wasserverbrauchs in der Industrieproduktion und der Umweltbelastung durch die Abwasserentsorgung. Es wird ein Konzept erstellt, mit dem der kritische Wasserverbrauch von Prozessen, Produktionszellen und auf Fabrikebene identifiziert wird, so dass auf diese Wasseranalyse gestützte Verbesserungsmaßnahmen gezielt durchgeführt werden können.

Die Methodik basiert auf der Integration der Wertstrommethode aus dem Feld der sogenannten lean production, dem Wasserverbrauch im Produktionsablauf sowie Nullemissionsmethoden. Die Wasserwertstromanalyse stellt eine Plattform zur Verfügung, auf deren Grundlage alle Wasserverbraucher innerhalb eines Produktionsnetzwerks identifiziert werden können. Der komplette Wasserbedarf einer Fabrik wird im Produktionsablauf auf eine transparente Art gezeigt. Damit wird der Wasserverbrauch den Verbrauchern verursachungsgerecht zugewiesen. Darauf aufbauend wird eine Wasserverlust- und Wasserintensitätsanalyse durchgeführt, um die Prozesse mit kritischem Wasserverbrauch in einer Fabrik zu identifizieren. Auf dieser Grundlage wird eine Darstellung des aktuellen Wasserverbrauches entlang des Prozessverlaufs in einer industriellen Fabrik präsentiert, die eine visuelle Illustration des Wasserverbrauches und der Abwassergenerierung innerhalb der Fabrik darstellt.

Es werden die Verbesserungsmaßnahmen effiziente Wasseraufnahme, Reduzierung der Verluste in Verteilung, Lagerung und Rüstbetrieb, Betrieb nach Taktzeit, effiziente Nutzungstechnologien, Bewusstseinsbildung über Ressourcenverbrauch, Recycling und Reuse abgeleitet, um die Wasserverfügbarkeit zu erhöhen, die Wassereffizienz im Betrieb zu steigern und die Wassernutzung zu verbessern. Zusammen mit der Senkung des Wasserverbrauchs auf das niedrigstmögliche Niveau werden Methoden vorgestellt, um eine maximale Abwasserwiederverwendung in einem Geschäftsmodell zu erreichen. Ein wirtschaftlicher und ökologischer Lösungsansatz für eine abwasserfreie Produktion wird branchenbezogen erarbeitet. Die wertvollen Bestandteile im Abwasser können für andere Produktionssysteme von Nutzen sein z.B. für die landwirtschaftliche Produktion. Mit einem Modell für die Beschreibung des Abwasserzustands wird die organisatorische Wiederverwendungsmethodik präsentiert.

Das entwickelte Konzept wird in zwei Fallstudien validiert. Das erste Beispiel zeigt, wie die Wasserwertstrommethode bei der Lackierung einer Automobilfabrik angewandt wird. Im Beispiel der Abwasseraufbereitung bei der Wartung von Eisenbahnzügen wird die Methode zur Planung eines Nullabwassersystems als mögliches Geschäftsmodell exemplarisch vorgestellt.

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List of abbreviations

AFED	Arab Forum for Environment and Development
BAT	Best Available Techniques
BATAELs	BAT associated emission levels
bn	billion
BOD	Biochemical oxygen demand
BREFs	BAT reference documents
CAGR	Compounded Annual Growth Rate
CCGT	Combined cycle gas turbine
CDC	Cathodic dichromate
CDP	Cataphoretic dip painting
CL	Closed loop cooling
CO	Change over time
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CT	Cycle time
CWA	Clean Water Act
DIN	Deutsches Institut für Normung
DO	Dissolved Oxygen
ELVs	Emissions Limit Values
EN	English
FAO	Food and Agriculture Organization of the United Nations
FD	Factory day
GW	Groundwater
IA	Water input amount
ICGT	Integrated gasification combined-cycle
I/O	Input-Output
ISO	International Organization for Standardization
IWMI	International Water Management Institute

K	Potassium
L	Litre
LCA	Life Cycle Assessment
MDGs	Millennium Development Goals
MED	Multiple Effect Distillation
MSF	Multistage Flash Distillation
N	Nitrogen
NAICS	North American Industry Classification System
NGOs	Non-governmental organizations
OECD	Organisation for Economic Co-operation and Development
ORP	Oxidation-reduction potential
P	Phosphorus
pcs	Pieces
pH	Hydrogen ion activity
PL	Pollutant load
PT	Process time
PV	Photovoltaic
ReW	Recycled water
RO	Reverse osmosis
RW	Rainwater
S	Sulphur
SFA	Substance Flow Analysis
SS	Suspended solids
SW	Surface water
TOC	Total organic carbon
TSS	Total suspended solids
TT	Takt time
TW	Tap water
WSI	Water stress indicator
UF	Ultrafiltration
UN	United Nations

UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNIDO	United Nations Industrial Development Organization
UNU	United Nations University
UV	Ultraviolet
VDI	Verein Deutscher Ingenieure
WELL	Water Efficiency Label
WI	Water intensity
WQ	Water quality
WT	Working time
WUP	Purpose of water use
WW	Amount of wastewater
WWD	Destination of wastewater flow
ZERI	Zero Emissions Research Initiative
ZLD	Zero Liquid Discharge

List of formula

c_{max}	Maximum acceptable concentration
c_{nat}	Natural concentration in the receiving water body
CT	Cycle time
D	Depth of the water tank
EI	Effluent intensity
F_w	Flow rate per unit time
i	Input product
$l_u[i]$	Annual volume of input product i into business unit u
L	Length of the water tank
p	Output product
$P_u[p]$	Annual volume of output product p from business unit u
$P_u'[p]$	The part of $P_u[p]$ that goes to another business unit within the factory
Pcs	Customer demand rate per shift
PL	Pollutant load
R	Radius of the water tank
T	Time per event
TT	Takt time
W	Width of the water tank
WD	Working day
WF_{bus}	Operational water footprint of a business
$WF_{bus,inputs}$	Water footprint of the input product of the business unit
$WF_{bus,overhead}$	Overhead water footprint of a business
$WF_{proc,blue}$	Blue water footprint of a process
$WF_{proc,green}$	Green water footprint of a process
$WF_{proc,grey}$	Grey water footprint of a process
WI	Water intensity
WT	Working time

1 Introduction

1.1 Motivation

According to the “World Population Prospects” report, the population of the world is expected to increase from 6.9 billion in middle 2011 to 9.3 billion in 2050 and to reach 10.1 billion by 2100. If the birth rate remains at the level it had in 2005-2010, the world population would reach nearly 27 billion by 2100 [UNDESA-11].

With such a significant growth rate, meeting the people’s demands will consume much more resources. Thus the ecosystem of the globe will come under increasing pressures and stresses. The present consumption of natural resources exceeds the current regeneration capacity of the earth by more than 25%. If this development persists a second earth would be needed to meet the resource demands in 2050 [Wor-08].

In view of the rising pressure on natural resources and ecosystems caused by human activities, the World Commission on Environment and Development defined sustainable development in the so called Brundtland-Report “Our Common Future” of the United Nations in 1987 as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [UN-87].

The concept of sustainable engineering can be seen as a fundamental requirement for long term survival and prosperity of manufacturing business. The challenge of sustainable engineering lies in how to design processes and products with improved usefulness and less environmental harm [Sel-12]. Energy consumption and greenhouse gas emissions (Carbon dioxide, CO_2) are important in today’s engineering research on sustainability. However, there has started to be an awareness of other environmental impacts, such as water use.

Water is an essential element of daily life for all people. Whether concerning issues of health, sanitation, environment, food, industry and energy production, water should be one of the overriding factors of human economic and social activities. Although 71% of the Earth’s surface is covered by water, only 0.3% of this can be used as fresh water for human beings [Gle-93]. Water-related natural disasters pose a great limitation to human security and sustainable socio-economic development. Water shortage will lead to social and economic stagnation and can even cause conflicts between various regions [UNW-12]. Almost one-fifth of the world's population live in areas of physical scarcity, and about another one quarter face economic water shortage (where countries lack the necessary infrastructure to take water from rivers and aquifers). Therefore, water scarcity issues will impact on the successful achievement of most of the Millennium Development Goals (MDGs) [UNDESA-13].

Most water research concentrates on agricultural use. This is because from a global use point of view, fresh water is consumed mostly in the agriculture sector (70%), while industry uses only 22%. However, water availability is not a global problem, the situation changes dramatically when the local perspective and water quality is taken into account. The water

use in high income countries is quite different from the global consumption situation. Here, most of the water is used in industrial production (59%) [UNW-03].

In Germany the thermoelectric power consumed 64% of the total water consumption in 2006, while industry consumed 23% [Uni-06]. However, it should be noticed that industry also consumes much electricity. In Germany, for example, industry consumed 42% of total electricity in 2010, 43.6% of which was generated by thermoelectric power [AGEB-12]. Taking electricity into consideration, the freshwater withdrawal to support industrial activities in Germany should be more than 30%.

Previous attempts to produce sustainable water use options in industry provide a useful snapshot for directing short-term responses, but are limited only to known technologies developed under current physical conditions. In order to reduce water usage and environmental impact by industrial production, a generic system including water inventory, improvement and management, should be developed to realize the sustainable industrial water use from economic, ecological and social aspects. The ideal situation would be to have zero impact on the environment, by achieving maximum water utilization in the factory and potential methods for zero wastewater discharge in the business strategy.

1.2 Objectives and structure of this thesis

This research aims to provide a rational basis for future potential developments in improving water efficiency and reducing the environmental impact in industry. With the focus on industrial production, technical water research to improve efficiency is represented from the viewpoint of present water use situation in industrial factories, water evaluation and assessment methodologies, and decreasing environmental impacts by reducing wastewater discharge to zero. Based on the state of the art research, a concept is presented, involving increasing water use availability, decreasing water loss, raising water utility together with water management for zero wastewater discharge research and case studies. The result of this work is a consistent basis for the sustainable use of water in industry, which could enable future technical research and water policy to be directed towards the actions. The work is structured as following Figure 1-1.

In chapter 2, the global availability of water resources is researched. From the viewpoint of global water distribution, the water use situation in agriculture, domestic and industrial sectors is presented, but with a focus on industrial use. The environmental impact caused by water is introduced, together with some water problems.

	Activities	Results
Chapter 2: Water Resources		
	• Global water distribution • Water use in agricultural, industrial and domestic sectors • Global problems about water	• Global demands for efficient water use
Chapter 3: State of the Art		
	• Water use activities in industrial factories • Industrial wastewater treatment • Cost spent on water by industries • Water efficiency and improvement methods • Industrial water evaluation and assessment methodologies • Zero wastewater discharge researches	• Systematic methods to improve industrial water use and zero wastewater discharge are missing
Chapter 4: Need to Action		
	• Analysis of the requirement of water efficient improvement system in industrial factory • Objectives of the introduced concept	• Requirements of an industrial factory • Existing methodologies don't meet the reqirements
Chapter 5: Concept		
	• Developing water value stream mapping method • Analysis of current water use data • Improvement guidelines to reduce water intake • Water management to achieve zero wastewater discharge	• Current map of water value stream • Improvement steps • Workflow of zero wastewater
Chapter 6: Implementation		
	• Implementation of the concept in two practical studies • Analysis of the implementation	• Decreasing water use in a painting shop • A systematic treatment plan to achieve zero wastewater

Figure 1-1: Structure of the thesis

In chapter 3, water use situation in industrial production and existing research regarding water assessment and technologies to achieve zero wastewater are described as state of the

art. Some terms and definitions regarding water use in industry are further defined. The water use in a single factory is analysed in industry with water use amount, quality, water treatment and the cost which has to be paid on water. Definitions of water efficiency and methods to increase its efficiency are discussed further. Methodologies for industrial water evaluation and assessment, such as factory water footprint, reducing water consumption, using value stream mapping to assess water use are described. Furthermore, existing technologies to achieve zero wastewater discharge are researched. This chapter closes with a summary of researches and studies which give the background and comparison to the concept.

In chapter 4 the gap to be filled by the work is specified. The requirements of a generic water efficiency improvement system for an industrial factory are analysed. Existing research and projects in this area are evaluated generally. None of them can provide a systematic approach with all these aspects together - current water inventories, future improvement and potential zero wastewater discharge.

In chapter 5 the approach of integrated sustainable water use and discharge with industry is presented. Based on the value stream mapping in lean manufacturing, a current map combining a value stream map and water use in an industrial factory is presented. Water related data are collected from metering, estimation and literature. Water losses and water intensity analysis is done to look for the critical water use point in a factory. Improvement guidelines are defined from the aspects of increasing water availability, increasing water efficiency in operation and raising water utilization. With a reduction of water intake to a minimum level, methods to maximize wastewater reuse in business dimension are introduced. With a layer model of wastewater condition description, potential external reuse methodology is presented.

In chapter 6 the operability of the developed concept is validated with two exemplary case studies, with firstly an example of water value stream mapping method application, and secondly a wastewater treatment example to achieve zero discharge. These two applications of the introduced systematic approach are analysed critically and evaluated from the principle of exemplary implementation.

2 Global availability of water resources

2.1 Water resource distribution on Earth

Water is regarded as one of the most important natural resources. According to the definition from United Nations Educational, Scientific and Cultural Organization (UNESCO), water resources are sources of water that are useful or potentially useful. Water resources on Earth can be divided into three categories:

- Atmospheric water: water exists in the air or cloud. It accounts for about 0.001% of the total Earth's water volume [Gle-96];
- Surface water: water collecting on the ground or in a stream, river, lake, wetland, or ocean;
- Ground water: water located beneath the earth's surface in soil pore spaces and in the fractures of rock formations. It takes 1.7% of the total Earth's water amount [Gle-93].

On the watershed scale, *water availability* is defined as the sum of annual river runoff and groundwater recharge of all the grid cells in the watershed [Alc-97].

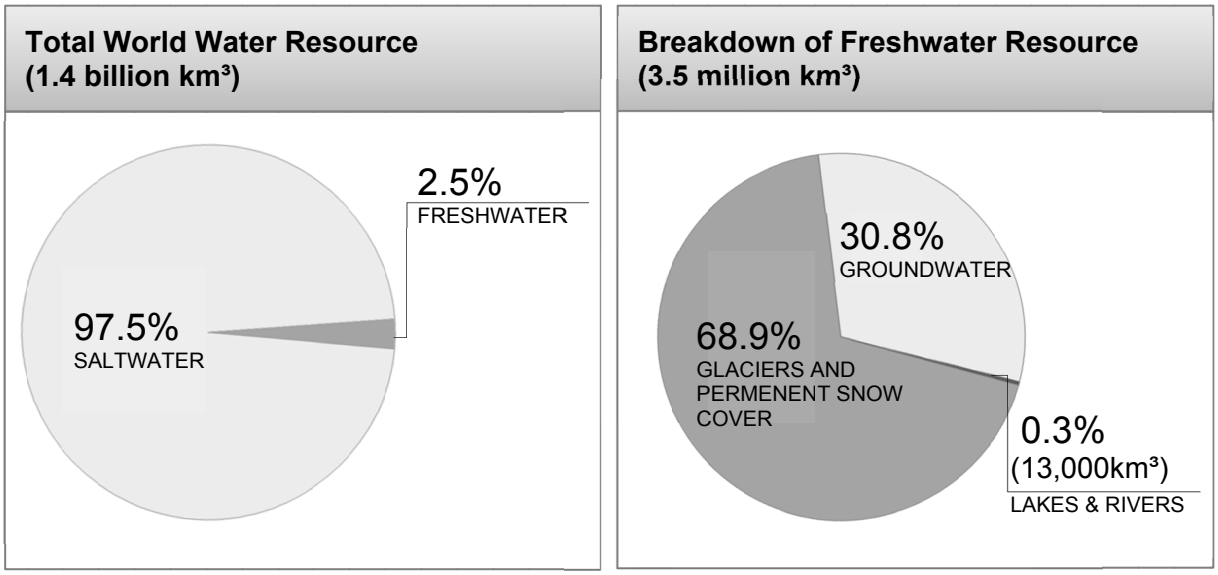


Figure 2-1: Distribution of Earth's water resource (according to [UNW-13])

Figure 2-1 shows the distribution of water resources on earth. The total volume of water resource on Earth is about 1.4 billion km^3. The volume of freshwater resources is around 35 million km^3, which accounts for about 2.5% of the total volume. Of these freshwater resources, about 24 million km^3 (68.9%) is in the form of ice and permanent snow cover in mountainous regions, the Antarctic and Arctic regions. Around 30.8% of the freshwater

resource is stored underground in the form of groundwater (shallow and deep groundwater basins up to 2,000 meters, soil moisture, swamp water and permafrost). This constitutes about 97% of all the freshwater that is potentially available for human use. Freshwater lakes and rivers contain an estimated 105,000 km^3 or around 0.3% of the world's freshwater. The Earth's atmosphere contains approximately 13,000 km^3 of water. The total available freshwater supply for ecosystems and humans is about 10.6 million km^3 of water – about 0.7% of all freshwater resources [Gle-93, UNW-13].

Water withdrawal, however, has a strong correlation with the economic growth of a country or region [Kat-08]. Three commonly used definitions – water abstraction, water extraction and water withdrawal, are defined as following in a global scale:

- Water abstraction: freshwater taken from ground or surface water sources, either permanently or temporarily, and conveyed to the place of use [OECD-05];
- Water extraction: the same meaning as water abstraction;
- Water withdrawal: The removal of water from some type of source, such as groundwater, for some use by humans. The water that is not consumed is subsequently returned to the environment after use, but the quality of the returned water may not be the same as when it was removed. Withdrawn water can be used (e.g. for cooling) without being consumed [UNW-12].

Unlike energy, water is not a global but a regional problem. The distribution of water withdrawal by sector and continent can be seen in Table 2-1. Asia took the first place with both total water withdrawal and total freshwater withdrawal with about 2500 km^3/year. Agriculture in Asia consumed the largest part of water with 81.4%, while in Europe the situation is totally different. Industry used most of the water, with a proportion of more than 50%. It should also be noticed that, in Asia people use more desalinated water than any other continent [FAO-13].

The two major characteristics of water resources are their renewability and variability [UNW-03, p.10]. Most of the water resources are renewable within clear limits, except for some groundwater. The renewability of water resource has the potential to decrease the amount of fresh water extracted. In some parts of the world, like India, China, Sao Paulo state and South Africa, water demand will greatly exceed the supply in 2030 (Figure 2-2) [Wat-09]. So it is very urgent to increase the water efficiency to fill the significant gap between water supply and increasing water demands. Water resources are also variable, over both space and time. There are huge differences of water availability in different places of the world and over the seasons in some regions.

Table 2-1: Water withdrawal by sector and freshwater withdrawal by continent in 2005 [FAO-13]

Continent	Total withdrawal by sector						Total water withdrawal*	Total freshwater withdrawal
	Municipal		Industrial		Agriculture			
	km³/year	%	km³/year	%	km³/year	%	km³/year	km³/year
Africa	28	12.5	11	5.1	184	82.4	224	224
Americas	135	16.9	285	35.5	381	47.6	801	801
Asia	227	9.0	242	9.6	2057	81.4	2526	2521
Europe	72	19.8	191	52.5	101	27.7	364	364
Oceania	5	16.7	3	9.5	20	73.8	27	27
World	**467**	**11.8**	**732**	**18.6**	**2743**	**69.9**	**3942**	**3936**
* Includes use of desalinated water								

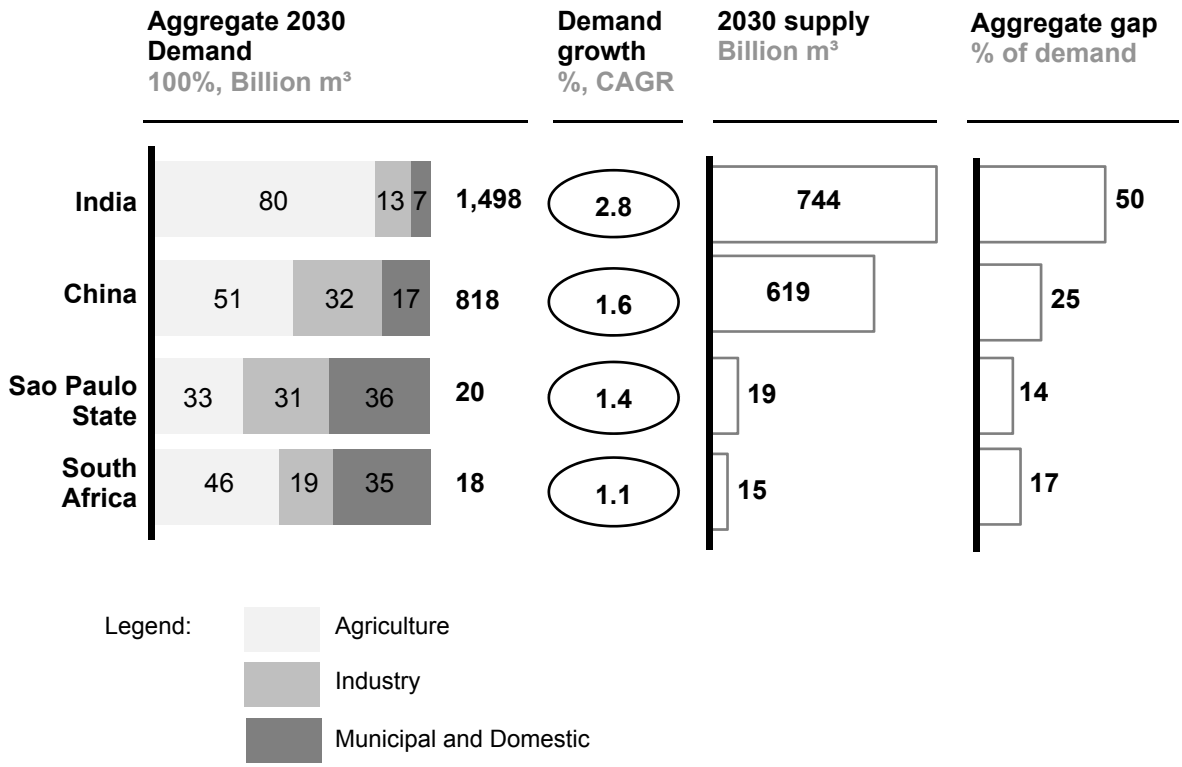


Figure 2-2: Base-case demand, supply, corresponding and gaps for the regional case studies [Wat-09]

2.2 Water usage worldwide

Water supply from surface water, e.g. rivers, streams, plays the most important role in people's access to water. Besides that, advanced technologies to increase access to water can be defined in four ways: wastewater reuse and recycling, groundwater abstraction, saltwater desalination, and atmospheric water generation.

Freshwater usage data in the World Water Development Report [UNW-03] show that water use for industry worldwide represents approximately 22% of total global freshwater use, while 70% of the water is used in agriculture and only 8% in domestic use. However, in high income countries, especially in OECD countries, the situation changes totally with almost 60% of the total freshwater used in the industrial sector, see Figure 2-3. In general, industrial use of water increases with the income of a country.

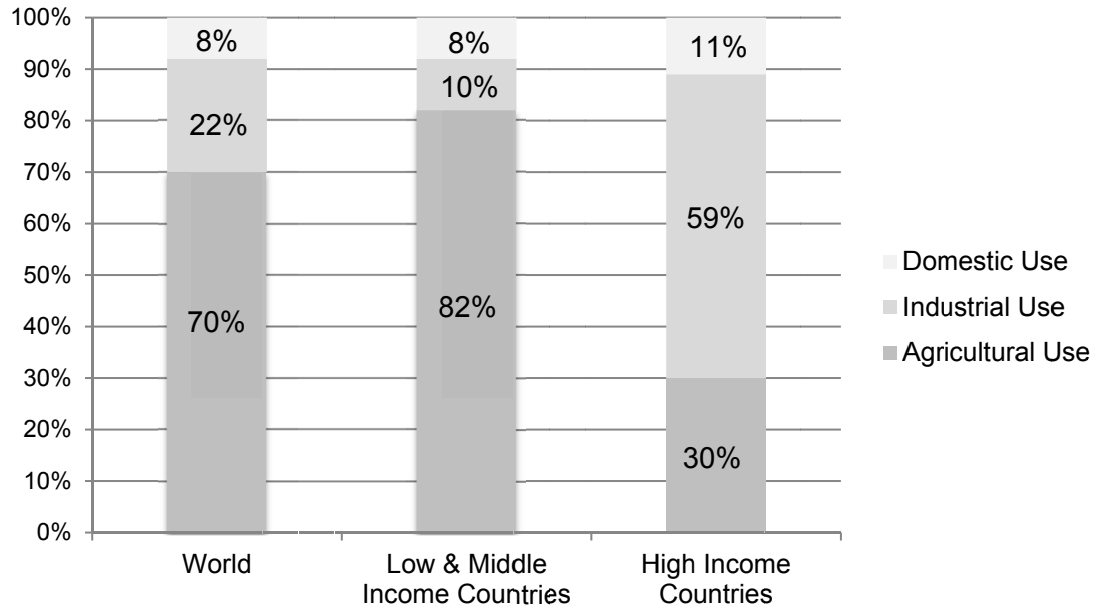


Figure 2-3: Competing freshwater uses for main income groups of countries [UNW-03, p. 228]

2.3 Global water problems

2.3.1 Water scarcity

Scarcity is the problem of humans who have unlimited wants and needs in a world of limited resources. Water scarcity can be broadly understood where human and environmental water demand exceeds the water availability in a country or region.

WINPENNY defined water scarcity as an imbalance of supply and demand under prevailing institutional arrangements and/or prices; an excess of demand over available supply; a high rate of utilization compared with available supply, especially if the remaining supply potential is difficult or costly to tap [Win-97]. The United Nations World Water Development Report

defined water scarcity as “the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully” [UNW-06b]. Based on that, Food and Agriculture Organization of the United Nations (FAO) defined water scarcity as “a gap between available supply and expressed demand of freshwater in a specified domain, under prevailing institutional arrangements (including both resource ‘pricing’ and retail charging arrangements) and infrastructural conditions” [FAO-08]. Those definitions are all consistent in that, water scarcity is a relative difference between the demand and its availability. Differences in emphasis depend upon the natural water availability potential and the infrastructure for water supply.

The other two terms related to water scarcity are:

- Water shortage: a shortage of water supply of an acceptable quality; low levels of water supply at a given place and a given time relative to design supply levels as a result of insufficient water resources, lack of infrastructure or poorly maintained infrastructure; or low levels of water resources as a result of annual or seasonal differences in climate or a range of hydrological or hydro-geological factors;

- Water stress: the symptoms of water scarcity or shortage, e.g. growing conflict between users, and competition for water, harvest failures and food insecurity. This term is used to describe a variety of circumstances and causes [FAO-08].

The World Water Development Reports summarize the reasons of water scarcity into population dynamics and associated changes in the natural landscape, economic and financial turbulence, international trade, human attitudes and lifestyle, see Table 2-2.

Table 2-2: Causes of water scarcity [UNW-09]

Demographic Drivers	- Population growth - Age distribution - Urbanization and the growth of informal human settlements - Migration
Economic Drivers	- Globalization - The global food crises and the rising cost of fuel and energy - Water trade: virtual water and growing awareness of water footprints
Social Drivers	- Poverty - Education - Culture and values - Lifestyles and consumption patterns

Of these reasons, population growth is one of the most important. Water use has been growing at more than twice the rate of population increase in the last century. By 2025, 1,800 million people will be living in countries or regions with a severe water scarcity, and two-thirds of the world population could be under stress conditions [UNW-06b].

From the definition and causes discussed before, it is noticeable that there are various reasons for and types of water scarcity in a country/region. Four aspects of water scarcity are described by FAO:

- Scarcity in availability of water of acceptable quality with respect to aggregated demand, e.g. Mauritania;
- Scarcity due to the lack of adequate infrastructure, irrespective of the level of water resources, because of financial , technical or other constraints;
- Scarcity in access to water services, because of the failure of institutions (including legal rights) to ensure reliable, secure and equitable supply of water to users;
- Scarcity due to human pollution, e.g. Yellow River basin in China [FAO-08].

2.3.2 Water pollution

Human activities leave most waste inadequately treated, thereby causing pollution. This will ultimately affect precipitation, surface water and groundwater. The EU Water Framework Directive, defines water pollution as “the direct or indirect introduction, as a result of human activity, of substances or heat into the water or land which may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, which result in damage to material property, or which impair or interfere with amenities and other legitimate uses of the environment” [WFD-00].

In general, water pollution is caused by urban wastewater, industrial emissions and agriculture. The most important water contaminants created by human activities with their potential sources are listed in Table 2-3.

Since most water pollution comes from industrial wastewater discharge, the effects on both environment and human beings call for an efficient use of water and adequate treatment before discharging into the water bodies.

Table 2-3: Freshwater pollution types and sources [UNW-06a]

Pollution type	Primary sources	Effects
Organic matter	- Industrial wastewater - Domestic sewage	- Depleting oxygen; - Affecting aquatic life.
Pathogens and microbial contaminates	- Domestic sewage - Cattle and other livestock - Natural sources	- Spreading infectious diseases through drinking water
Nutrients	- Agricultural lands - Urban areas - Some industrial discharge	- Over-stimulating growth of algae; - Human illness through drinking water.
Salinization	- Leached from alkaline soils by over irrigation - Over-pumping coastal aquifers resulting in saltwater intrusion	- Killing crops and reducing yields; - Undrinkable freshwater
Acidification (precipitation or runoff)	- Electric power generation, industrial stack and auto/truck emissions (wet and dry deposition) - Acid mine drainage from tailings as well as mines.	- Negatively impacting on aquatic organisms
Heavy metals	- Industries and mining sites	- Toxic to aquatic organisms and humans
Toxic organic compounds and micro-organic pollutants	- Industrial sites and automobiles - Farmers - Home gardeners and municipal wastewaters	- Toxic effects in aquatic fauna and human
Thermal	- Dams and reservoirs slowing water and allowing it to warm - Industry from cooling towers and other end-of-pipe above-ambient temperature discharges	- Changing oxygen levels and decomposition rate of organic matter in water
Silt and suspended particles	- Natural soil erosion - Agriculture - Road building - Deforestation, construction and other land use changes	- Reducing water quality for drinking and recreation; - Degrading aquatic habitats.

2.3.3 Increasing water price

Excessive water use and wastewater discharges can have negative impacts on the water environment. Therefore, the price of water consists of the cost of supplying drinking water and disposing of sewage. As water price is one of the measures to control or reduce water demand by different users, most countries are changing to water pricing systems that encourage economic efficiency and more sustainable use of water resources [Lal-03]. There are some countries, which have introduced water taxes as part of their water charges to reflect the environmental cost of abstraction and use, e.g. Germany. However, no comparable approach defines the charges required to recover the costs of water protection and the improvement of aquatic systems [Lal-03].

According to Berliner Wasserbetriebe, with an increase price of drinking water up to 2.0 €/m³ in Berlin in 2011, people tend to use water less and less. Figure 2-4 shows a trend of water consumption per person per day in Germany in the last few years. In the year with stable water price, people used more water, e.g. between 2001 and 2003. In the meanwhile, water consumption showed a sharp decrease when the water price increased sharply, e.g. in 2004.

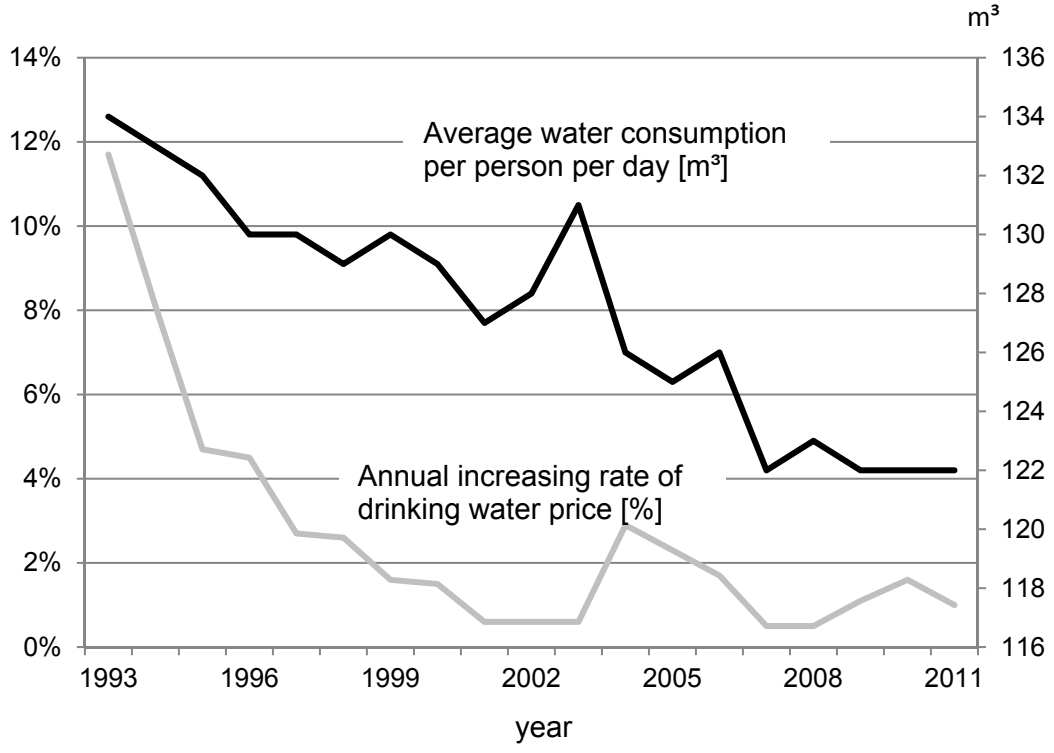


Figure 2-4: Trend of water consumption with the rising water price in Germany [Koc-12]

Another example comes from Beijing, where is considered as one of the most water shortage cities in China, see Figure 2-5. The water price kept increasing in the last years, especially in summer, water prices have been tripled in an attempt to reduce consumption [UNW-03]. In

2008, a new water channel was built to convey the water from neighbouring province to ease the several years of drought in Beijing, which leads to a small decrease of water price in this year. In the meanwhile, Beijing's water consumption has barely changed in the past decade even though prices more than doubled between 2001 and 2004.

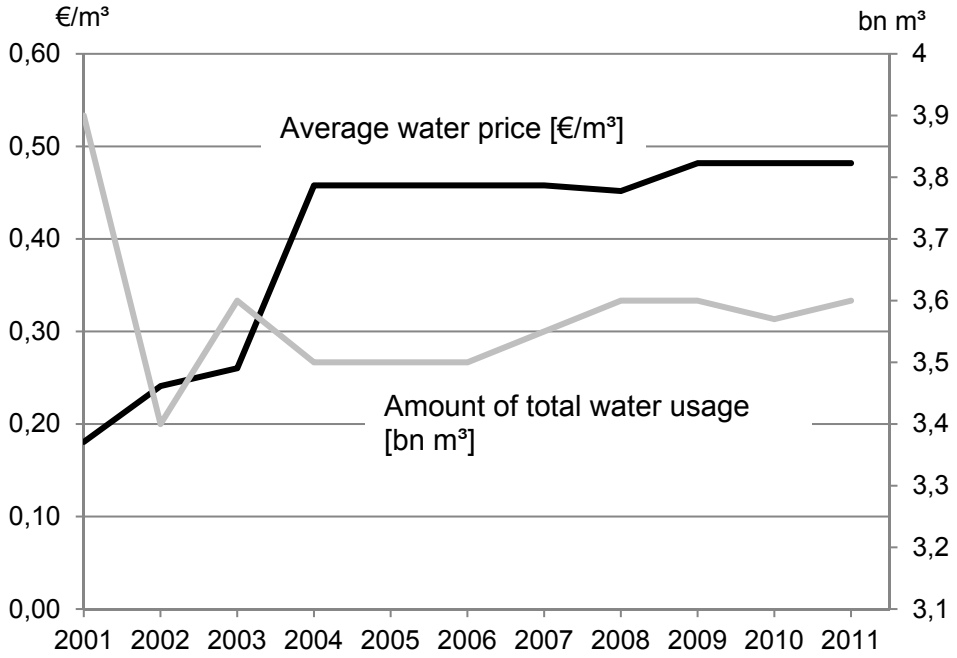


Figure 2-5: The average water price and amount of total water usage in Beijing [Source: Beijing Municipal Statistics Bureau]

A survey from NUS Consulting Group shows that, water prices in all the surveyed countries, e.g. Denmark, Germany, United Kingdom, United States, indicate a continuous increase in the last few years. Although there are different reasons for this increase in those countries, sustainable use of water resources is the biggest consideration for water price increase [NUS-06]. Besides, the growing demand for fresh water, high maintenance costs, recent increasing trends in labour cost, state support, climate condition, laws and environmental standard, demographic development and continuous rising energy price, all contribute to the increasing trend of water price.

3 Water management in industry

3.1 Terms and definitions

Some terminologies which relate to water use in industry are described in this chapter.

Terms of water consumption and water use are often confused when regarding industrial use. However, there is an important distinction between these two expressions [Tej-12]:

- *Water use* is defined as all the water flows into the factory and then exits in evaporation, product and waste embedded, and mostly as wastewater;
- *Water consumption* is defined as the freshwater withdrawals which are evaporated or embedded in product and waste. Basically, the water molecule is not available in with liquid form for reuse after it is consumed, at least not immediately. Water consumption is one part of the water use.

A widely used catalogue of water use for the production of a product is green water, blue water and grey water:

- *Blue water* is defined as the amount of water withdrawn from groundwater and surface water that does not return to the system from which it came;
- *Green water* refers to the water evaporated through crop growth that originates from soil moisture (from rainfall);
- *Grey water* refers to the volume of polluted water associated with the production of goods and services. After extraction and use, water is normally discharged with a slightly changed quality (grey water) or more heavily polluted (black water) [Ger-08].

When addressing types of water use in industry, an often used expression is “process water”. According to DIN4046, *process water* is defined as „water with different quality, including drinking water, for commercial, industrial, agricultural or similar purposes” [DIN-4046]. In the industrial sector, process water refers to the water used to produce a product or affect a process.

Wastewater means the water containing waste including grey water, black water or water contaminated by waste contact, including process-generated and contaminated rainfall runoff. Water reuse is an important way to increase water efficiency, Table 3-1 summarizes the terms used to describe water reuse in the industry. Water reuse can be categorized as “direct” or “indirect”, depending on whether the reclaimed water is used directly or mixed with other sources. On an international scale, direct non-potable water reuse is the dominant mode for supplementing public water supplies for irrigation, industrial cooling water, river flow augmentation, and other applications [Asa-98]. Unplanned indirect potable water reuse, through wastewater effluent disposal to streams, rivers, and groundwater basins, has been

an accepted practice around the world for centuries. Planned indirect water reuse involves linking the discharge of treated wastewater with potential downstream water uses [Lev-04].

Table 3-1: Terminology used to describe water reuse in industry [Lev-04]

Term	Definition	Application
Wastewater processing	Application of treatment technology to modify water quality.	
- Water recycling	Recovery of wastewater from a specific use and redirection of the water back to the original use; typically involves only one use or user.	• Steam–electric industry • Manufacturing industry • Minerals industry
- Wastewater reclamation	Treatment or processing of wastewater to make it reusable.	
Product	End result of treatment.	
- Recycled/reclaimed water	The end product of wastewater reclamation that meets water quality requirements and is reused for a specific purpose.	
Water reuse	Beneficial use of treated wastewater.	
- Direct reuse	The direct use of reclaimed water.	• Agricultural and landscape irrigation • Cooling water and other industrial uses • Urban applications • Dual water systems
- Indirect reuse	Mixing, dilution, and dispersion of treated wastewater by discharge into an impoundment, receiving water, or groundwater aquifer prior to reuse.	• Groundwater recharge
Potable water reuse	Use of highly treated reclaimed water to augment drinking water supplies.	
- Direct potable reuse	Incorporation of reclaimed water into a potable water supply system, without relinquishing control over the resource.	
- Indirect potable reuse	Incorporation of reclaimed water into a potable water supply by including an intermediate step in which reclaimed water is mixed with surface or groundwater sources upstream of intakes for drinking water treatment facilities.	
- Non-potable water reuse	Includes all water reuse applications other than direct or indirect use for drinking water supplies.	• Irrigation • Industrial cooling water • River flow augmentation • Other applications

The terms “recycled” and “reclaimed” water are generally interchangeable, although the preferred term may differ regionally. Recently, public perception studies have indicated that the term “recycled” is often preferred over “reclaimed” based on their connotations [Roc-12]. In this dissertation, recycled water will be used.

Industrial wastewater treatment covers the mechanisms and processes used to treat waters that have been contaminated in some way by anthropogenic industrial or commercial activities prior to its release into the environment or its reuse.

3.2 Water use in industrial factories

3.2.1 Overview in industrial sectors

In many cases, only a fraction of the water withdrawal is used consumptively in industry, and the remaining will be discharged to the same or a different water source after or without treatment, becoming available for another withdrawal use. An overview of industrial freshwater withdrawal in different regions in the world is shown in Figure 3-1. In high-income countries, e.g. Europa, North America, the share of industrial water withdrawal kept in a high rate in the past 20 years. In the meanwhile, in emerging countries, water used in industry took a lower proportion than agricultural and domestic use.

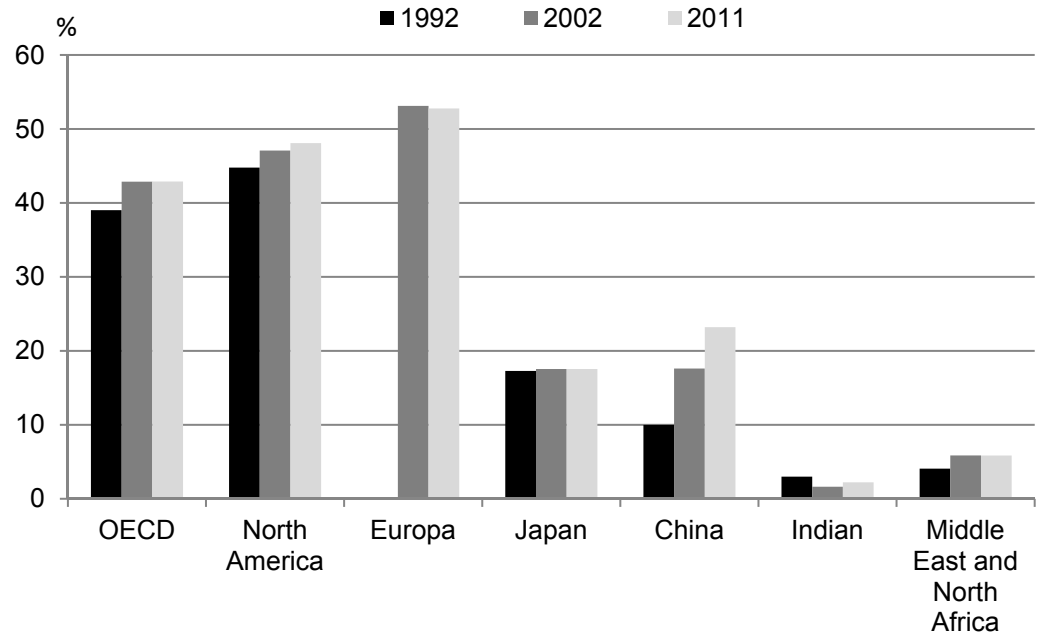


Figure 3-1: Freshwater withdrawals from 1992 to 2011: share of industry in total water withdrawals (Source: World Bank)

A continuous decrease in both freshwater withdrawal and wastewater discharge in industry in Germany from 1995 to 2007 is shown in Figure 3-2. The difference between the amount of freshwater withdrawal and wastewater discharge occurs mainly because of water losses, evaporation, products drying, embodied water (e.g. in food industry) and water in waste sludge [Hil-08]. From 1995 to 2007, the total freshwater withdrawal has decreased by 26%, while the wastewater discharge decreased by 28%. The amount of treated wastewater has also decreased by 47% within these years [Sta-12]. Latest data are only available related to the freshwater withdrawal and wastewater discharge in different states.

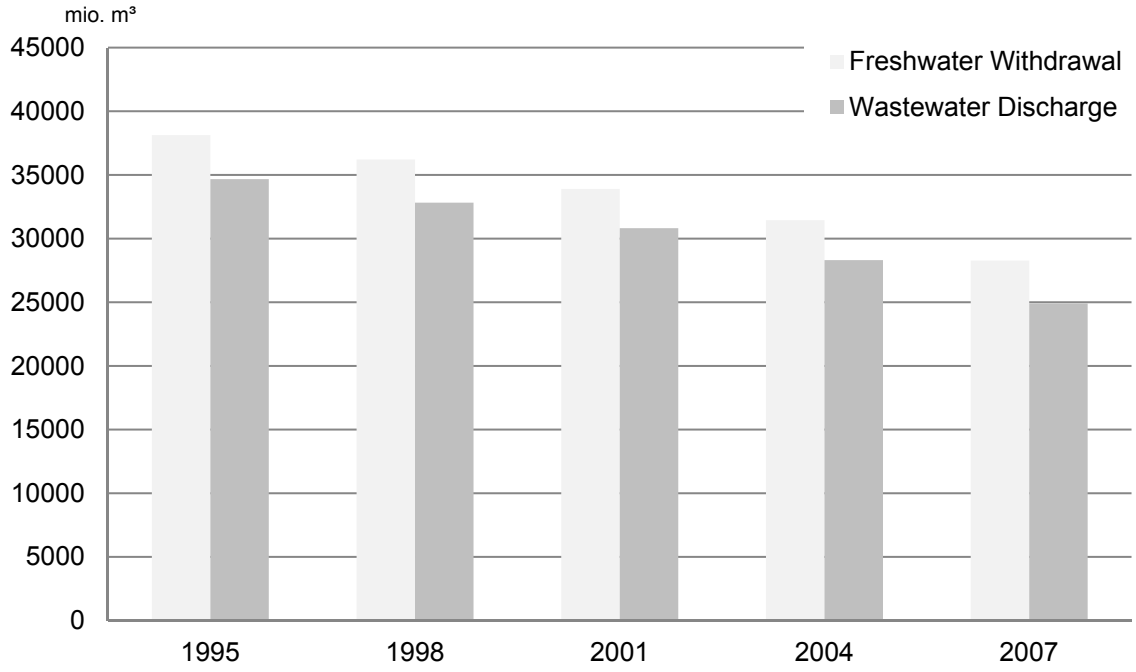


Figure 3-2: Freshwater withdrawal and wastewater discharge in industry in Germany from 1995 [Sta-12]

Looking more deeply into different industrial sectors, Figure 3-3 shows the freshwater use by sectors in Germany in 2007. Freshwater withdrawal represents the total amount of freshwater removed from the source. In total, industry consumed about 26.9 km³ water in Germany [Sta-09]. Energy industry is the leading user of freshwater, accounting for 74.8% of the total freshwater use, i.e. about 20.1 km³. Of this, 19.7 km³ were abstracted independently of the public water supply. Chemical industry usage ranks the second, accounting for 12.7%, followed by mining and quarrying industry with 4.0%. Steel and paper industries contributed respectively 2.8% and 2.0% to the total freshwater withdrawal. The least water usage was in the leather industry consuming only 3 million m³ (0.01%).

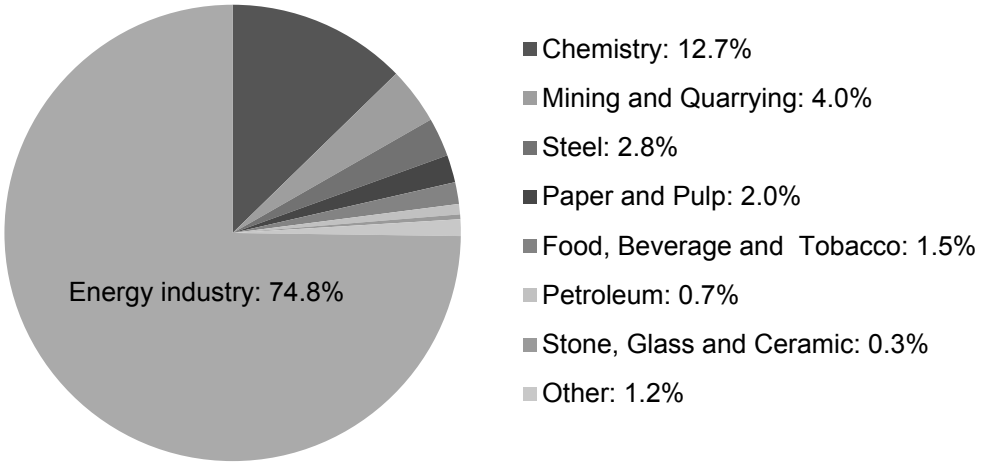


Figure 3-3: Freshwater withdrawal by industrial sectors in Germany in 2007 [Sta-09]

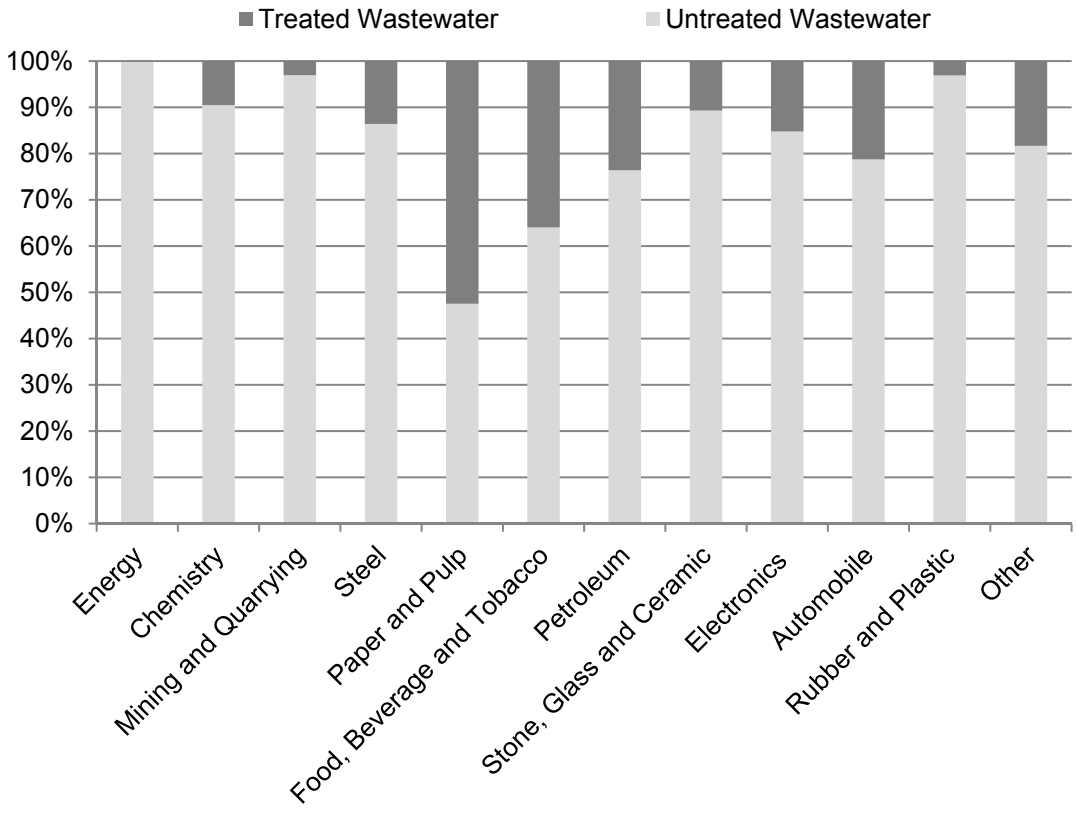


Figure 3-4: Wastewater discharge from industry in Germany in 2007 [Sta-09]

Industrial wastewater of similar quality to ordinary domestic sewage can be treated by municipal facilities. But wastewater with high concentrations of toxic pollutants (e.g. heavy

metals, volatile organic compounds), conventional pollutants (e.g. oil, grease, biochemical oxygen demand (BOD) and total suspended solids (TSS)), or other nonconventional pollutants such as ammonia, need specialized treatment systems [Arm-99, EPA-13a].

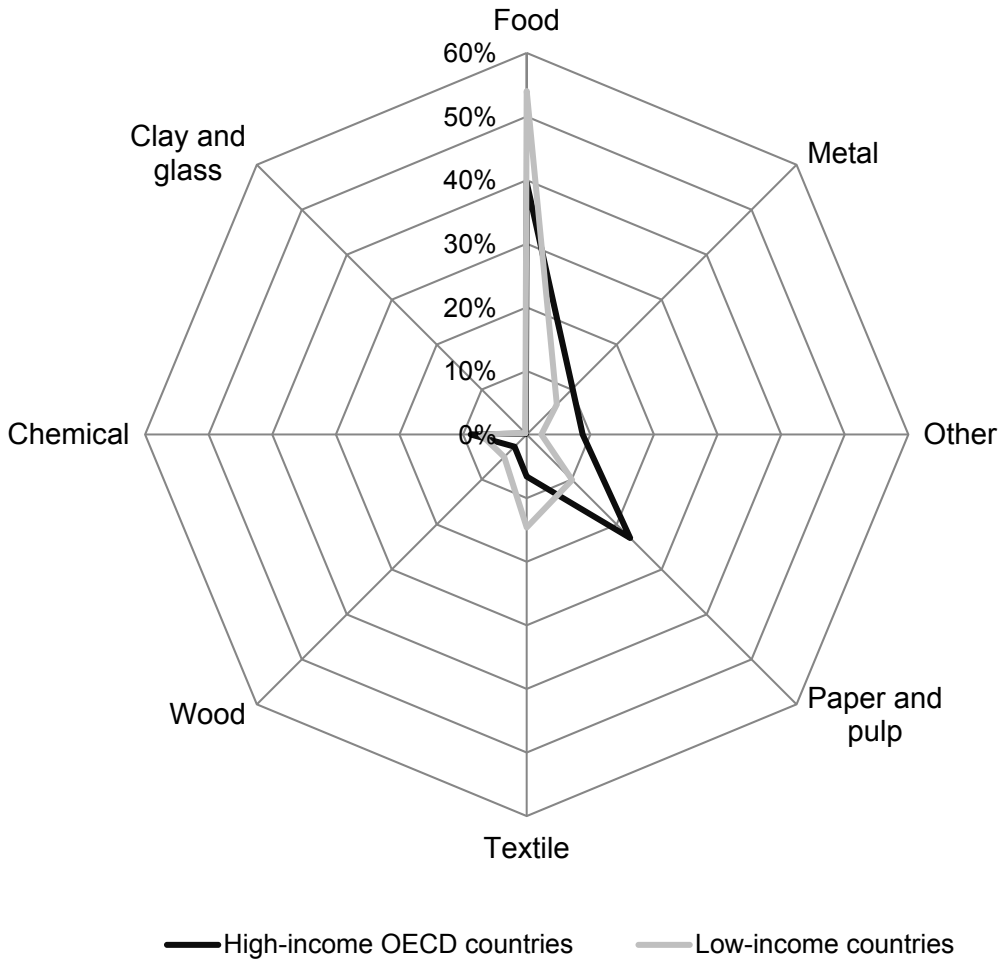


Figure 3-5: Contribution of main industrial sectors to the production of organic water pollutants [UNW-03, p. 229]

Figure 3-4 presents the wastewater discharge situation from industry in Germany in 2007. Compared to the largest wastewater outflow with almost 20 billion m³ from thermoelectric power plants, the chemical industry occupies second place with nearly 3.5 million m³ wastewater discharge [Sta-09]. In general, the quantity of freshwater withdrawal exceeds wastewater by a constant amount in Figure 3-3. Nevertheless, wastewater treatment is different in various sectors. With more than a 50% treatment rate, the paper and pulp industry spends most on wastewater treatment, followed by the food, beverage and tobacco industry sector with 35% treated wastewater discharge. In thermoelectric power plants,

however, only 7.5% wastewater is treated. The large amount of untreated wastewater is mostly from cooling water [Sta-09].

Generally, industrial wastewater can be divided into two types: inorganic and organic. Inorganic compounds (heavy-metal) are produced mainly in the coal and steel industry, non-metallic minerals industry and industries for surface processing of metals [Shi-11].

Global estimates of emissions of organic water pollutants by different industry sector are shown in Figure 3-5. Obviously, the food and beverage sector represents the most important polluter in low-income countries with 54% of the total organic water pollutants. Wood based industries, including paper and pulp, and textiles also contribute also significantly to the organic pollutant load. That is the reason why the percentage of treated wastewater in paper and food industry is much higher than in other industrial sectors.

3.2.2 Applications

3.2.2.1 Manufacturing industry

According to *North American Industry Classification System (NAICS)*, the manufacturing sector is defined as comprising establishments engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products. It consists of these subsectors: food manufacturing, beverage and tobacco product manufacturing, textile mills, textile product mills, clothing manufacturing, leather and allied product manufacturing, wood product manufacturing, paper manufacturing, printing and related support activities, petroleum and coal products manufacturing, chemical manufacturing, plastics and rubber products manufacturing, non-metallic mineral product manufacturing, primary metal manufacturing, fabricated metal product manufacturing, machinery manufacturing, computer and electronic product manufacturing, electrical equipment, appliance, and component manufacturing, transportation equipment manufacturing, furniture and related product manufacturing, and miscellaneous manufacturing [NAICS-07].

As described above, a small amount of water used by industry comes from the public water supply system. Within the mining, manufacturing and energy industries, manufacturing industries use the largest amount of public water. In Germany in 2007, 80.6% of the total water withdrawal was self-supplied (water not obtained from public supply), while this figure is 85.5% in the mining industry and 97.9% in the energy industry [Sta-09]. The reason may be that the mining and energy industry use large amounts of water for cooling, which has a low quality requirement. The situation in each industrial factory depends upon the volume and nature of its industrial activity. This affects the amount of water extracted, and whether it is ground or surface water. Hence, because of the diverse manufacturing sectors, the intensity of water use varies.

The manner in which these waters are used by industry varies dramatically from industry to industry. The use of water in manufacturing activities is summarized in Figure 3-6. They can generally be divided into two: water for plant operations and water for production purposes. Water use in plant operations contributes to normal plant activities, namely, steam raising, plant and building cooling and heating, fire fighting services, floor washing and personal use. For production purposes, water is also used to support the process, which varies from different product to be produced. The activities of product washing, conveying, preparation, plant washing, produce processing and water included in the product definitely require water. Normally, water is utilized in a factory for three main reasons: Processing purposes and inclusion in final outputs (e.g. beverages), cooling purposes (e.g. primary metal industry) and miscellaneous purposes such as cleaning and sanitation [Flö-13].

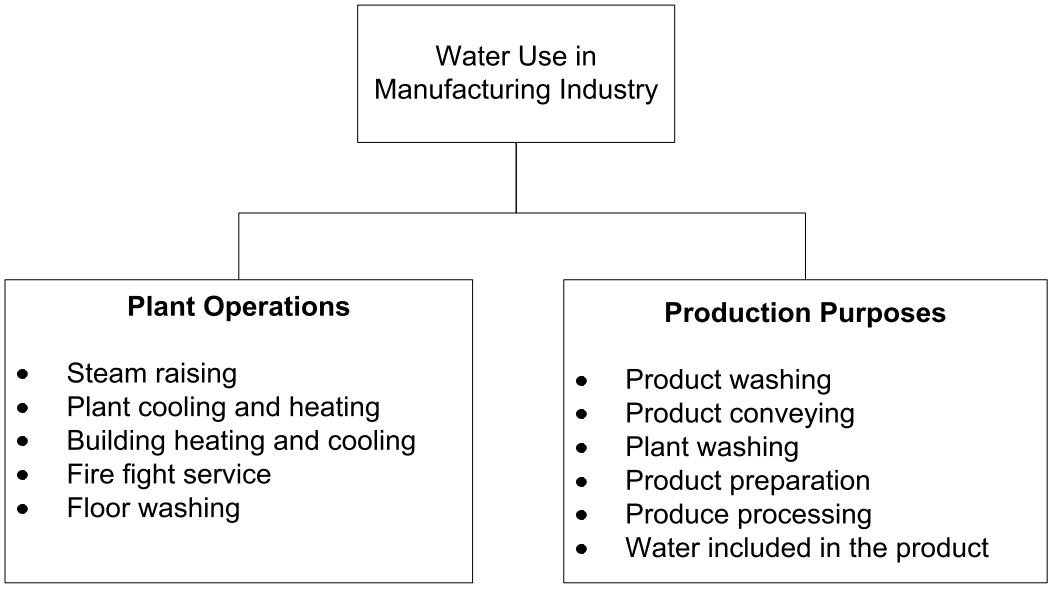


Figure 3-6: Water use activities in manufacturing industry

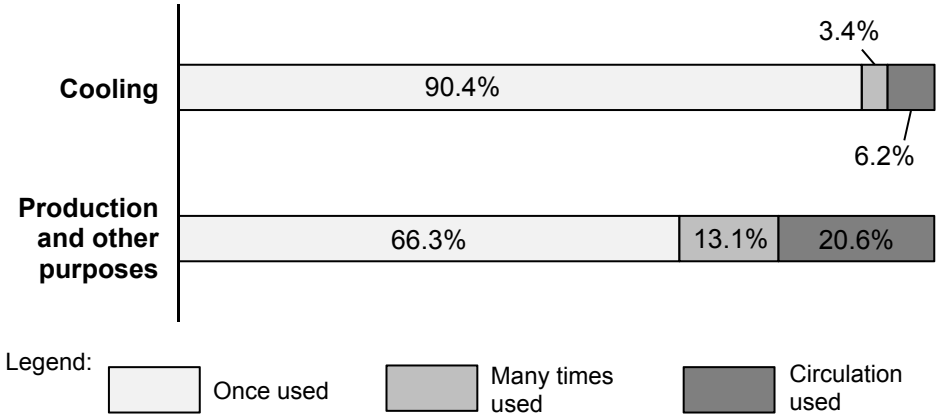


Figure 3-7: Water use situation in manufacturing industry in Germany in 2007 [Sta-09]

Of the nearly 5.7 billion m³ freshwater used in manufacturing industry in Germany in 2007, 76.2% was used for cooling, 20.7% for production, 1.2% for personal use, 0.1% for irrigation and 1.8% for other use [Sta-09].

Different operations can have different frequencies of use for water. Some water is used only once, while other water may be used many times. There are also some cases, where circulated water is used, e.g. water for material conveying. The report shows that in manufacturing industry in Germany in 2007, 76% of the freshwater was only used once, 16% many times and 8% was circulated water. Within industry, the greatest use of water is for cooling (93.2%), of which 90.4% was used only once, 3.4% was used many times and 6.2% was circulated. The other water was used for production and other purposes, which takes 6.8% of the total water use. The water use frequencies are different, respectively 66.3% for once use, 13.1% for many times and 20.6% as circulated water, see Figure 3-7.

The treatment rate of wastewater from different manufacturing industries in Germany in 2007 is as shown above in Figure 3-4. For the total manufacturing sector, more than 82% of the total wastewater was not treated, 85% of which came from cooling processes [Sta-09].

3.2.2.2 Energy industry

According to the classification from DOUGLAS WESTWOOD, the energy industry contains sectors of bio fuels, biomass, geothermal, hydro, hydrogen/fuel cell, microgeneration, nuclear, offshore wind, oil & gas, onshore wind, solar PV, wave & tidal, carbon capture & storage, gas storage [Dou-09]. Although in the energy industry, different sources can be used to generate energy, all require water for various production processes, including cooling in thermal processes, cleaning materials, fuel production (fossil, non-fossil and biofuels), powering turbines and emissions scrubbing.

The most significant character of water use in the energy industry is the large amount of water used for cooling. 40% of the USA's industrial water is used for cooling power plants, and this number is estimated to reach 30% in China in 2030 [UNEP-11]. Much of this water, with final consumption (evaporation) estimated at around 5% of withdrawals, is returned without significant quality impacts at global and regional scales， but with a persistent temperature increment that impacts on local ecosystems [UNW-09].

Water use efficiency in the energy sector differs with the applied power generation technologies, as illustrated by an assessment of 19 power generation systems in the United States (Figure 3-8). This suggests considerable potential for improving efficiency. As shown in the figure, the technology with geothermal steam with a close-loop tower consumes the largest amount of water for one megawatt hour of electricity, with more than 1000 gallons water. Other water intensive power generation technologies are: a solar tower with CL tower, a solar trough with CL tower, nuclear with a CL pond, nuclear with a CL tower, nuclear with

an open loop, fossil stream with a CL pond and fossil stream with a CL tower. The water consumption in coal mining varies greatly in different plants. The least average water consumption takes place in the gas combined cycle and gas turbine sector. Outflows of water used in cooling nuclear power plants demand sufficient river flow to reduce the temperature in order to mitigate adverse ecological impacts. Thus, substantial water flows are required but doesn't add value to the product.

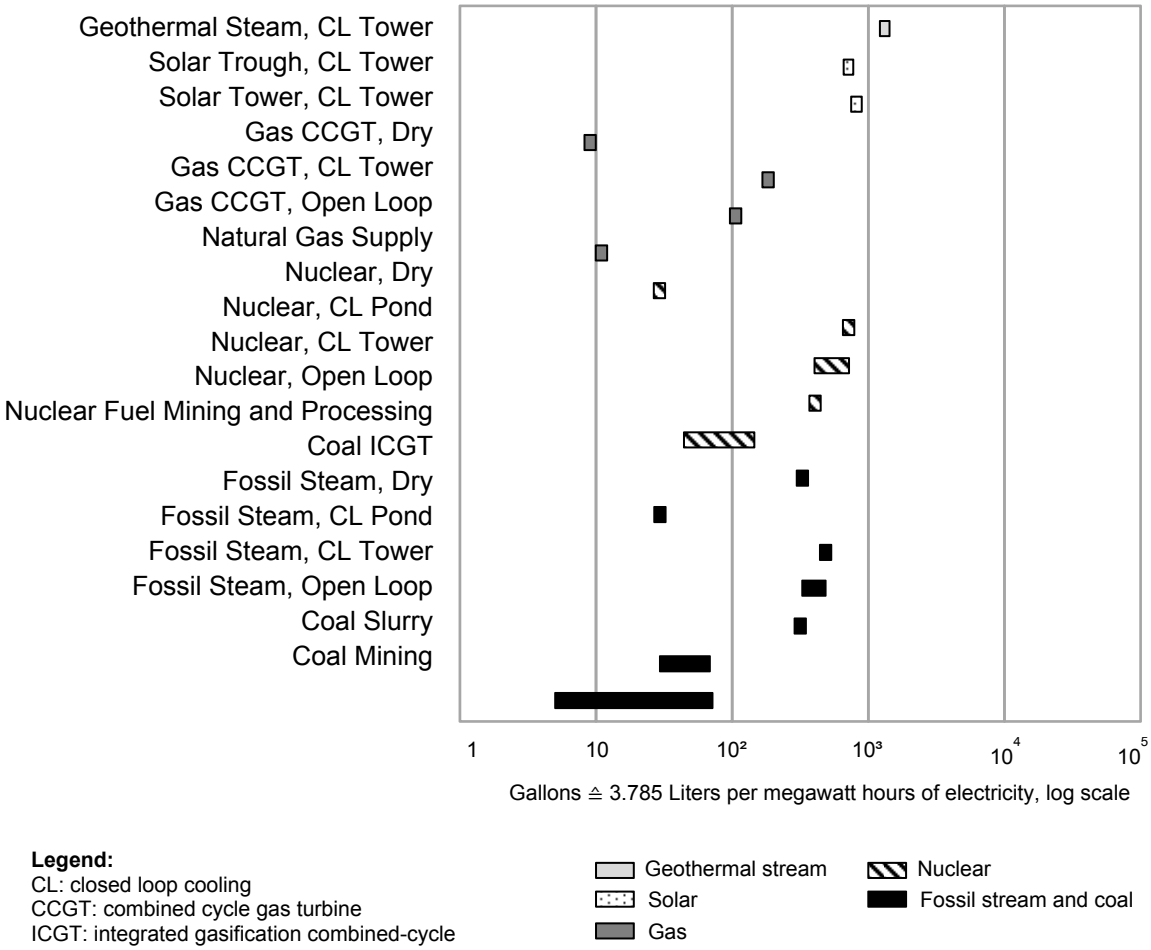


Figure 3-8: Water consumption for power generation technologies in the United States, 2006 [USD-06]

Water withdrawal statistics for thermoelectric power are dominated by power plants that return virtually all the withdrawn water to the source. While this water is returned at a higher temperature and with other changes in quality, it becomes available for further use. In the U.S., thermoelectric power accounted for 41% of the water withdrawal in 2005 [USGS-09]. In Germany, thermoelectric power consumed 64% of industrial water consumption in 2006 and even 74.5% (20.1 billion m³) in 2007, 80% of which was used as cooling water. The rest was used as boiler feed water and personal use water [Uni-06]. About 19 billion m³ wastewater

(94.5% of the total freshwater withdrawal) was discharged directly into the surface water resource from German thermoelectric power plants in 2007 [Sta-09].

Hydropower generation, with the most direct link between energy and water, requires large quantities of water. Just as other energy generation sectors, the nature of water use is non-consumptive. Water is returned to the river after passing through turbines. However, substantial losses also occur through evaporation from reservoirs.

Table 3-2 summarizes the main water use purposes and wastewater influences in several energy sectors. Thermoelectric and hydroelectric power generation can impact upon natural water bodies. Discharge from open-loop cooling systems can affect water temperature and oxygen levels. Air emissions from fuel combustion, such as mercury, sulphur, and nitrogen oxides, can lead to negative impacts on downwind water quality and aquatic ecosystems. The solar PV industry needs very little water for washing. In biofuel and synfuel, water is needed for fuel processing and the wastewater mostly needs to be treated.

Table 3-2: Water use and wastewater in different energy industries [Hut-04]

Energy generation type	Water use	Wastewater
Electric Power Generation		
Thermoelectric (fossil, biomass, nuclear)	Surface water and ground water for cooling* and scrubbing	Thermal and air emissions impact surface waters and ecology
Hydroelectric	Reservoirs lose large quantities to evaporation	Can impact water temperatures, quality, ecology
Solar PV and Wind	None during operation: minimal water use for panel and blade washing	
Refining and Processing		
Biofuels and ethanol	Water for growing and refining	Refinery wastewater treatment
Synfuels and hydrogen	Water for synthesis or steam reforming	Wastewater treatment
* Impaired water may be saline or contain contaminants.		

3.2.3 Industrial water treatment

Industrial water treatment is used to satisfy the water quality requirements of both water-related industrial processes, such as heating, cooling, processing, cleaning and rinsing, and of the local or national regulations regarding disposal of wastewater into community treatment plants or into natural water bodies. The term *water quality* is used to describe the

physical, chemical, biological and aesthetic properties of water that determine its fitness for a variety of uses and for the protection of aquatic ecosystems [DWAF-96].

3.2.3.1 Water constituents

Water quality is mainly decided by the substances dissolved, colloidal or suspended in the water. There are some similar terms with relation to the constituents: water constituents, water contaminants and water pollutants. Water constituents refer to all the constituents existing in the water, which could be good, harmful or neutral to the production. Water contaminants are any potentially undesirable substances which are present in the water. Water pollutants mean specifically the substances introduced into the natural water body that causes undesired effects. In this paper, we use the definition of water constituents to define the quality of water used in the production.

There are many constituents which can adversely affect the fitness for water use. The most commonly present constituents of significant concentrations, which have an effect on industrial equipment, processes and products are listed in Table 3-3. The main negative effect caused by constituents of pH, Fe, Mn, Alk, SO4, SiO2, SS, COD, TDS is corrosion and scaling, which reduces the heat exchange efficiency, restricts water flow and decreases working volume. Some constituents are strictly unacceptable in food and beverage processes, which have the highest quality requirements among the industrial sectors.

Table 3-3: Main industrial water constituents and effects on industrial production (according to [DWAF-96])

Effects / Constituents	Damage to equipment and structures	Interference with processes	Product quality
pH (hydrogen ion activity)	• Corrosion and scaling processes	• Optimum working range around pH 7	• No direct effects
Fe (Iron)	• Foul boilers, heat exchangers and pipelines • Leather clothing	• Dyeing • Pulp production • Ion exchange resin	• Food and beverage • Pulp and paper • Bleaching
Mn (Manganese)	• Foul boilers, heat exchange surfaces and pipelines • Destroy resin exchange structure	• Tanning • Bleaching • Dyeing • Pulp	• Hides • Fabrics • Pulp and paper • Food and beverage

Alk (Alkalinity)	• Water heating system • Heat exchange system • Screens, vacuum pumps, heating bath • Cleaning system	• Textiles • Leather • Food • Beverage	• Beverage • Textile
SO_4 (Sulphate)	• Calcium sulphate scale • Microbial-influenced / induced corrosion	• Dyeing • Fermentation of beer	• Leather colour • Steel products • Beer
Cl (Chloride)	• Stainless steel • Cadmium, copper silver and tin plating tanks	• Dairy	• Finished steel products • Plastic • Beer
SiO_2 (Silica)	• Steam generation system • Cooling • Evaporation	• Pulp and paper • Settling white liquor	• Paper
SS (Suspended Solids)	• Steam generation system • Cooling system • Pump • Pipelines • Ion exchange resins • Paper machine	• Finishing of paper products • Bleached fibres • Bottling of carbonated drinks	• Dyed products • Paper products and textile • Beverages
COD (Chemical Oxygen Demand)	• Heat exchange • Cooling • Steam generation	• Textiles • Leather • Paper • Cooling • Beverages	• Pharmaceuticals • Paper
TDS (Total Dissolved Solids)	• Causing corrosion and scaling	• Heat exchange process	• Patchiness in dyeing • Medical products • Beverages

3.2.3.2 Water quality criteria for production use

Regarding the effects of water constituents on industrial processes, equipment and products, four categories of water related processes have been defined in South Africa according to the degree of water purity or tightness of specification for the required quality as in Table 3-4.

Category 1 represents the highest water quality, with relatively stringent specifications or limits for most or all the relevant water quality constituents. Standard or specialised technology is essential to provide water conforming to the required quality specifications. Consequently, costs of in-house treatment to provide such water are a major consideration in

the economy of the process. Processes with water quality in category 2 require water of a quality between the high quality required for category 1 processes and domestic water quality (category 3 processes). Specifications for some water quality constituents are tighter or more stringent than required for domestic water quality. Standard technology is usually sufficient to reach the required water quality criteria. Cost for such additional water treatment begins to be significant in the economy of the process.

Process for domestic water quality is the baseline minimum standard. Water of category 3 may be used in the process without further treatment or with minimum treatment. Low to standard technology may be necessary to reach the specifications laid down for a desired water quality. Costs of further in-house treatment are not significant in the economy of the process. Water with category 4 can be used in processes that, within certain limitations can use water of more or less any quality for their purposes without creating any problems. No additional treatment is usually required and there is therefore no further cost.

Table 3-4: Industrial water quality categories [DWAF-96]

Application / Categories	Cooling water	Steam generation	Process water	Product water	Wash water
Category 1 (highest quality)	Evaporative cooling (high recycle)	High pressure boiler: demineralisation of feed water	• Phase separation • Petrochemicals	Pharmaceu-ticals	No residual washing (electronic parts)
Category 2	• Evaporative cooling (high recycle) • Solution cooling • Water heating	High pressure boiler: demineralisation of feed water	• Solvent • Heat transfer medium • Humidification • Lubrication • Gas cleaning	• Beverages • Dairy products • Petrochemical	Reaction vessel washing
Category 3 (domestic quality)	• Evaporative cooling (once through) • Bearing cooling • Mould cooling	Low pressure boiler	• Solvent • Dilution agent • Gland seal • Vacuum seal • Lubrication • Descaling (iron and steel) • Gas scrubbing	• Beverages • Food products • Baking • Confectionery • Chemicals • Surface washing (table tops, walls)	• Domestic use • Fire fighting
Category 4 (lowest quality)	Ash quenching	Transport agent		• Dust suppression • Fire fighting • Irrigation	Rough washing (floors, trucks, raw materials)

Automatic water quality analysers are usually used because of the need for continuous measuring and for other similar reasons. Typical analysers are shown in Table 3-5.

Table 3-5: Typical water analyser for water quality monitoring or test [Sug-03]

Name	Measuring method (examples)	Principle of measuring
Water thermometer	Thermoelectric thermometry	Measuring temperature of liquid by thermoelectromotive force of thermocouple
pH-meter	Glass electrode method	Measuring potential difference generated between relative electrodes in solution
Turbidity meter	Ration of transmitted/scattered light method	Measuring ratio of transmitted/scattered light through solution
DO meter	Membrane electrode method	Measuring oxygen in solution by membrane electrode of galvanic cell / polarography
Electric conductivity meter	Electric conductometry	Measuring resistance of solution by electrode
ORP (Oxidation-reduction potential) meter	Metal electrode method	Measuring oxidation-reduction of solution by metal electrode
COD meter	Potassium permanganate titration Potentiometric titration method	Measuring consumed potassium permanganate in solution
Total nitrogen analyser	Ultra violet oxidation method	Measuring ultra violet absorption after oxidized solution by alkaline potassium peroxodisulfate/ultra violet
Total phosphorus analyser	Ultra violet oxidation method	Measuring molybdenum blue absorption of solution after oxidized solution by alkaline potassium peroxdisulfate/ultra violet

3.2.3.3 Wastewater contaminants

There are many types of industrial wastewater with different contaminants generated from different industries. Each sector produces its own particular combination. Table 3-6 gives an overview of the main water contaminants by different industrial sectors. Industrial wastewater treatment goals are firstly, the reuse in cooling system makeup water, process waters, boiler feed water, construction activities and wash-down waters, and secondly, the satisfying of requirements of local or national wastewater discharge regulations.

Table 3-6: Water pollutants by the industrial sector [Shi-11]

Sector	Main Pollutant
Iron and steel	BOD, COD, oil, metals, acids, phenols, and cyanide
Textiles and leather	BOD, solids, sulphates and chromium
Pulp and paper	BOD, COD, solids, Chlorinated organic compounds
Petrochemicals and refineries	BOD, COD, mineral oils, phenols, and chromium
Chemicals	COD, organic chemicals, heavy metals, SS, and cyanide
Non-ferrous metals	Fluorine and SS
Microelectronics	COD and organic chemicals
Mining	SS, metals, acids and salts

3.2.3.4 Treatment technologies

The harmful constituents in the water and pollutants in wastewater should be removed by appropriate treatment technologies. Generally, technologies for industrial water treatment can be divided into four categories: chemical methods, physical methods, physical chemical methods and biological methods. The typical processes of each technology category and its removal mechanisms are shown in Table 3-7.

Six chemical processes can be used to remove substances from water [Woo-01]:

- Reaction to produce an insoluble solid: Procedures for removing metals from wastewater are alkaline precipitation, precipitation of the metal as the sulphide, precipitation as the phosphate, precipitation as the carbonate, or co-precipitation with another metal hydroxide, sulphide, phosphate, or carbonate.
- Reaction to produce an insoluble gas:
- Reduction of surface charge to produce coagulation of a colloidal suspension:
- Reaction to produce a biologically degradable substance from a non-biodegradable substance:
- Reaction to destroy or otherwise deactivate a chelating agent:

- Oxidation or reduction to produce a non-objectionable substance or a substance that can be removed more easily by one of the previous methods.

Table 3-7: Typical water treatment processes and removal mechanisms [Sug-03, Woo-01]

Categories of Wastewater treatment technology	Typical processes	Removal mechanisms
Physical methods	Screen	Screening
	Filtration	Filtering
	Settling	Difference of gravity
	Evaporation, drying	Thermo-energy
	Electrolysis	Electric energy
	Reverse osmosis membrane	Reverse osmosis
Chemical methods	Oxidation	Oxidation reaction
	Reduction	Reduction reaction
	Neutralization, coagulation	Double decomposition
Physical chemical methods	Flotation	Difference of gravity
	Activated carbon adsorption	Adsorption
	Ion exchange resin and membrane	Ion exchange
	Electric Dialysis, Electrolysis	Electrochemical reaction
	Super critical water oxidation	Super critical phase
Biological methods	Activated sludge process, Denitrification, Phosphorus removal	Aerobic decomposition, suspended biomass
	Anaerobic digestion process	Anaerobic decomposition
	Biofilm treatment system	Fixed biomass on floating media or contactors
	Biomembrane	Selective barrier

Biological treatment processes can be classified into aerobic and anaerobic categories. Within each of these two major classes, there are two principal types of systems: suspended growth and attached growth, according to the existing status of microbes. Microbes of the former are suspended in a mixture of liquid, while they are attached to a medium in the latter.

3.2.3.5 Treatment processes

The planning of water treatment processes is based on water laboratory tests and continuous treatability tests on site. When a water treatment process has been used in many installations and sufficient data are available, the treatment processes can be decided based on the water quality analysis. When a new process is adopted in a newly built factory and no test sample is available, water quality from similar production systems will be taken as references, or it will be estimated from the raw materials, production processes, and yield rate. When a new treatment process is to be built or the amount and/or quality of wastewater fluctuate largely, on-site continuous tests to verify the performance is indispensable in order to avoid risks and evaluate the efficiency.

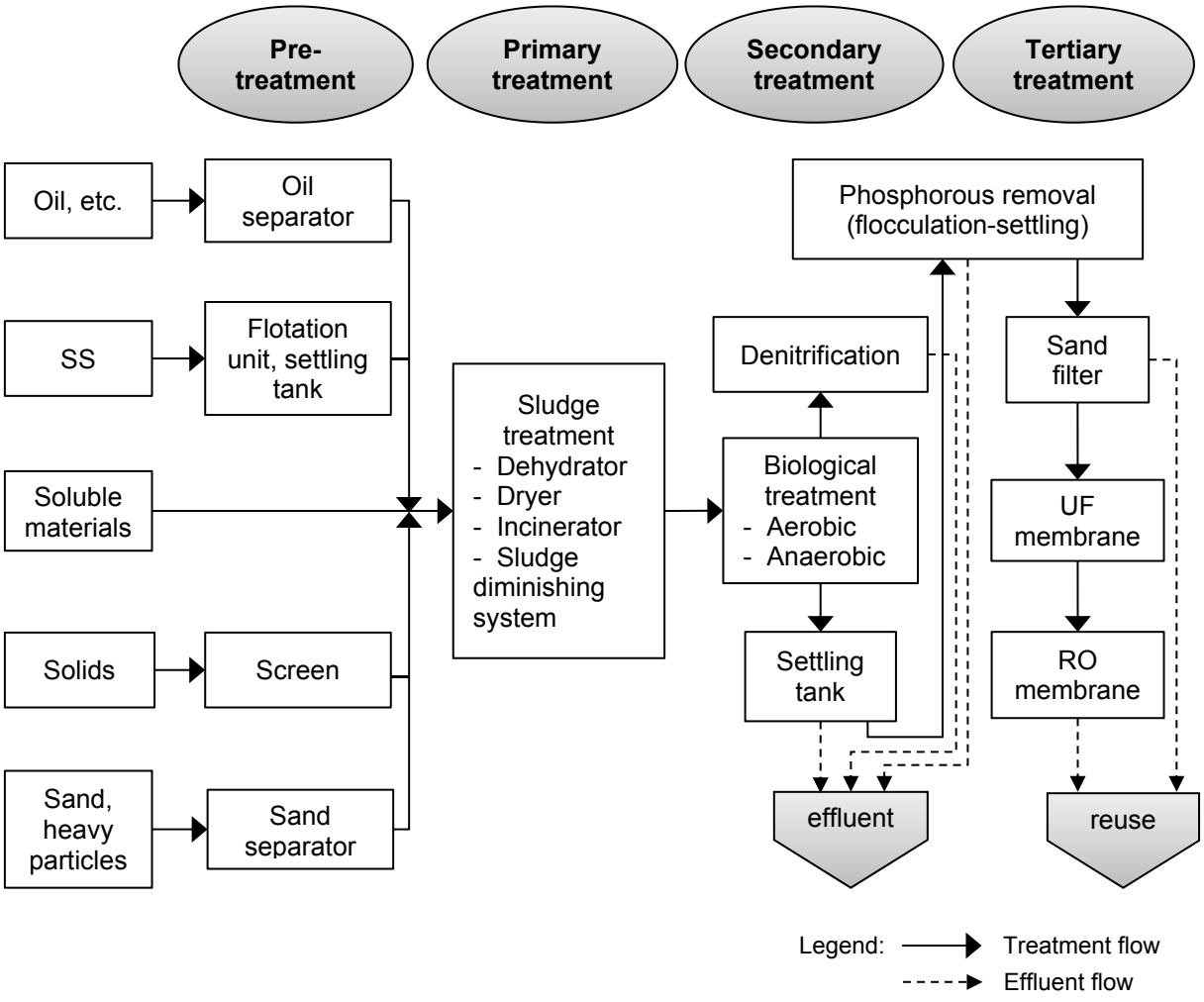


Figure 3-9: Example of an industrial wastewater treatment system with its processing units [Sie-13a, Woo-01]

An example of schematic wastewater treatment system consisting of several units for different types/qualities of wastewater is shown in Figure 3-9. In general, four treatment steps will be undertaken, verifying wastewater quality: pre-treatment, primary treatment, secondary

treatment and tertiary treatment. Pre-treatment removes the pollutants that can be easily collected before they damage the pumps and other equipment in following treatment steps. After that is the primary wastewater treatment, which involves the physical separation of suspended solids from the wastewater flow. Secondary treatment consists of removing or reducing contaminants or growths that are left in the wastewater from the primary treatment process. Biological treatment is usually used to treat wastewater in this step, because it is the most effective type of treatment on bacteria, or contaminant growth. With a removal rate of organic matter up to 90%, two common conventional methods are attached growth processes and suspended growth processes. In tertiary wastewater treatment, stubborn contaminants will be finally cleaned up. The effluent will become even cleaner and can therefore be used again in various processes. It may involve physical-chemical separation techniques such as membranes for advanced filtration, ion exchange, carbon adsorption. The practical treatment processes should be changed according to the quality of the wastewater. Some treatment phases, e.g. pre-treatment, may not be needed.

3.2.4 Costs of water for industry

In industry, water from different sources will lead to different water prices. A decision-making is drawn between the “economic” source (i.e. whether water comes from the public water supply system or from direct abstractions) and the “environmental” sources (i.e. whether water comes from groundwater, surface water or rainwater) [OECD-99]. The price of industrial water is primarily influenced by the “economic” source of water. According to the local charge system, industrial water users can either “accept” the price charged by public water suppliers, or they can “create” their own price, by investing in water abstraction and treatment facilities.

The influence factors of “economic” water sources are:

- Price of water provided from public water supply system;
- Cost of direct abstraction licenses (Taking Berlin for example, a permit is needed before a well is drilled to extract groundwater. The depth of the well and the yearly abstraction water volume should be stated in the proposal of a permit [BWG-08].);
- Charges for direct abstraction;
- Water treatment cost to get the required quality of water from both public water supplier and direct abstraction.

Influence factors of “environmental” sources are:

- Relative investment costs;
- Operation and maintenance costs;

- Treatment cost to reach the required quality for factory use from direct abstraction.

Because of the policies in different countries, industry may pay different fees for water use. For example, in France, the revenues for direct abstraction are significant. However, in Germany, abstraction fees exist only for groundwater and only in some states. Industrial users tend to access the cheapest water, taking into account the water resource situation, public and environmental regulators in their countries or regions. A study shows that ¾ of the water used in industry in Europe is not drawn from the public water supply system [Rot-01]. In Germany, about 95% of the water used in industry is drawn using the industry's own equipment and only 0.4% comes from the public supply. Consequently, 90% of the water used by industries in Germany is extracted from surface water [Irm-10].

Sewage charges are calculated through a volumetric or a fixed price structure. In Germany, if the industrial water users discharge a much smaller amount of sewage than their water intake, then they can obtain a rebate of the sewage charge [OECD-99]. The costs of sewage discharges spent by industrial water users are:

- Water treatment fees to satisfy the wastewater discharge policies;
- Charges of sewage discharge.

Germany, for example, has implemented a policy mix for some years, encompassing market-based instruments (discharge permits and effluent taxes) and regulatory measures (discharge limits). It has led to the adoption of advanced abatement measures by wastewater treatment plants and industrial direct dischargers (e.g. the chemicals industry), as well as changes in production processes (e.g. in the paper industry), which has decreased the volume of effluents generated.

3.3 Water efficiency

3.3.1 Definition

The term *efficiency* in general describes the extent to which time, effort or cost is well used for the intended task or purpose. It is defined as the ratio of use and cost.

$$efficiency = \frac{output\ (work)}{input\ (cost)}$$

Water efficiency in general is reducing water wastage by measuring the amount of water required for a particular purpose and the amount of water used or delivered. It is a long-term ethic of conserving water resources, which includes aspects such as innovative technologies, but also changes in water usage patterns, using products and behaviours that could reduce water consumption [Ben-09]. VICKERS indicates the purpose of water efficiency is to obtain

the desired result or level of service with the least necessary water, and he suggests the following definitions of water efficiency:

- Accomplishment of a function, task, process, or result with the minimal amount of water feasible;
- An indicator of the relationship between the amount of water needed for a particular purpose and the quantity of water used or diverted [Vic-02].

The water efficiency of one facility or one system can be evaluated by comparing some existing research, e.g. Best Available Techniques (BAT), and the efficiency ranking system, e.g. WELL (Water Efficiency Label) classification in Europa, WaterSense in the United States and Waterwise in the United Kingdom [Ben-09; EC-08; WELL-13]. To calculate the water efficiency of single facility, WELL uses different criteria, such as volume (flow rate), temperature, time and hygiene for sanitation facility to indicate the classification of water efficiency [WELL-13].

The terms of water efficiency and water conservation are often distinguished. *Water conservation* is defined as activities designed to reduce the demand for water, improve efficiency in use and reduce losses and waste of water, and improve land management practices to conserve water [AWE-13]. The difference lies with the focus on water efficiency, i.e. the key is reducing waste but not restricting use.

3.3.2 Methods to increase water efficiency

As mentioned in chapter 3.3.1, the key to increase water efficiency lies on how to reduce waste. Therefore, methods should be undertaken from the aspect of reducing or avoiding unnecessary water loss.

AFED (Arab Forum for Environment and Development) indicates the common approaches to increase water efficiency in industry, namely, improved production planning and sequencing, good housekeeping, process/equipment modifications, product/material changes, and replacing equipment/technology [AFED-11, p.41]. Generally, water efficiency can be improved through three areas of technologies:

- Increase the available water resource: Rainwater harvesting is one of the best;
- Increase the reuse rate of water in the factory;
- Increase the potential of wastewater usage in other area: wastewater discharged from this factory can benefit other industries in an industry cluster or even be used in agricultural production.

Improvements can be made by identifying and eliminating wastage (such as leaks), and inefficient processes (such as continual spray devices on stop-start production lines). This may be most cost-effective for water savings, as it involves minimal capital outlay. Other saving measures can be made through implementing water-reducing changes:

- Updating processes and plant machinery. A renewal of key plant equipment may increase efficiency. Alternatively, upgrades to more efficient models can be factored in to planned maintenance and replacement schedules.
- Reusing wastewater. As well as saving on mains water, this option may improve the reliability of supply, whilst reducing trade waste charges and associated environmental risks.

3.4 Industrial water evaluation and assessment

A factory consumes water throughout various processes during the production. The methodologies reviewed in the following sections evaluate water usage from production, process and factory viewpoints.

3.4.1 Best Available Techniques (BAT)

Best Available Techniques (BAT) is a term applied with regulations on limiting pollutant discharges with regard to the abatement strategy. It is defined as the “most effective and advance stage in the development of an activity and its methods of operation, which indicate the practical suitability of particular techniques for providing, in principle, the basis for emission limit values designed to prevent or eliminate or, where that is not practicable, generally to reduce an emission and its impact on the environment as a whole” [EPAA-92]. Principally, “techniques” include both the techniques used and the methods in which the installation is designed, built, maintained, operated and decommissioned; “available” techniques means those developed techniques allows implementation in the relevant industrial sector under economically and technically viable conditions, taking into consideration the costs and advantages, and being reasonably accessible to the operator; “best” mean the most effective in achieving a high general level of protection of the environment as a whole [EPA-13b]. With a Europe-wide knowledge of pollution control, the BAT offers a reference of waste treatment technologies and management strategy to prevent the emission pollution, one of which is the wastewater treatment.

The Commission’s guidance on the practical arrangements for the exchange of information under the Industrial Emissions Directive, includes the collection of data, the drawing up of BAT reference documents (BREFs) and their quality assurance [EC-08]. Regarding water use, the BREFs provide references of technologies and emission levels in different industrial

sectors, such as ceramic manufacturing industry, chemist, metals processing, food, drink and milk, iron and steel, large combustion plants, glass, pulp and paper, mineral oil and glass, textiles. In BREFs, general water use information such as water application, wastewater source, quantity and composition is described. The considered methodologies to minimize water consumption and wastewater generation and increase water reuse in the processes in the determination of BAT are presented by sectors.

Besides, the BAT associated emission levels (BATAELs) are addressed with the meaning of "representing the environmental performance that could be anticipated as a result of the application, in this sector, of the techniques described". Distinguished from emission or consumption limit values, the BATAELs are understood as the technical possibility to achieve better emission or consumption levels but due to the costs involved consideration. They are presented as a range [EC-03]. The existing or new techniques could be designed to perform at or even better than the BAT levels.

However, the BREFs have also some weak points. They are written only based on the information provided by the participated industries, member states and NGOs (Non-governmental organizations), that is to say, they don't include all the existing technologies, rather the commonly be used. Furthermore, the local considerations cannot be taken into account, so that they do not contain ELVs (Emissions Limit Values) [Sca-08].

3.4.2 Factory water footprint

3.4.2.1 Definitions

Water use impact assessment for inclusion in Life Cycle Assessment (LCA) offers methods in different scope including use on industrial production [Lév-11]. As one of the methods in the area of LCA, water footprint is used for assessing the water impacts caused by human activities. It comes from the concept of *virtual water*, which was developed by ALLAN in the early 1960s. The virtual water accumulates all quantities of water that have been consumed along the production chain of a product [All-98]. Hence, it comprises water used in the actual manufacturing processes, as well as water used in background processes, such as material or energy production. In contrast to the water inventory, virtual water is divided into three categories: green, blue and grey water:

- *Green water*: The agricultural use of water mainly concerns water which precipitates. It can only be considered for products that use harvested rainwater in their manufacturing processes.
- *Blue water*: Water used in industry comes primarily from water bodies such as rivers, sub-terrain aquifers, or dams. This is called blue water.

- *Grey water*: After extraction and use by industry or households, water is normally discharged with a slightly degraded quality (grey water) or more heavily polluted (black water) [Ger-08].

The *water footprint* according to HOEKSTRA was introduced in 2002 and relies on the virtual water concept, but additionally includes spatial and temporal information. Accordingly, the water footprint is an indicator of freshwater use that looks at not only direct but also indirect water use of a consumer or producer. It can be regarded as a comprehensive indicator of freshwater resources appropriation, in addition to the traditional and restricted measure of water withdrawal [Hoe-02]. The quantitative water footprint of a product has the same value as its virtual water content. Furthermore, water footprints are calculated for individuals, organizations, or nations by multiplying all products and materials consumed with their respective virtual water content and by adding the direct water consumption of the person, organization, or nation.

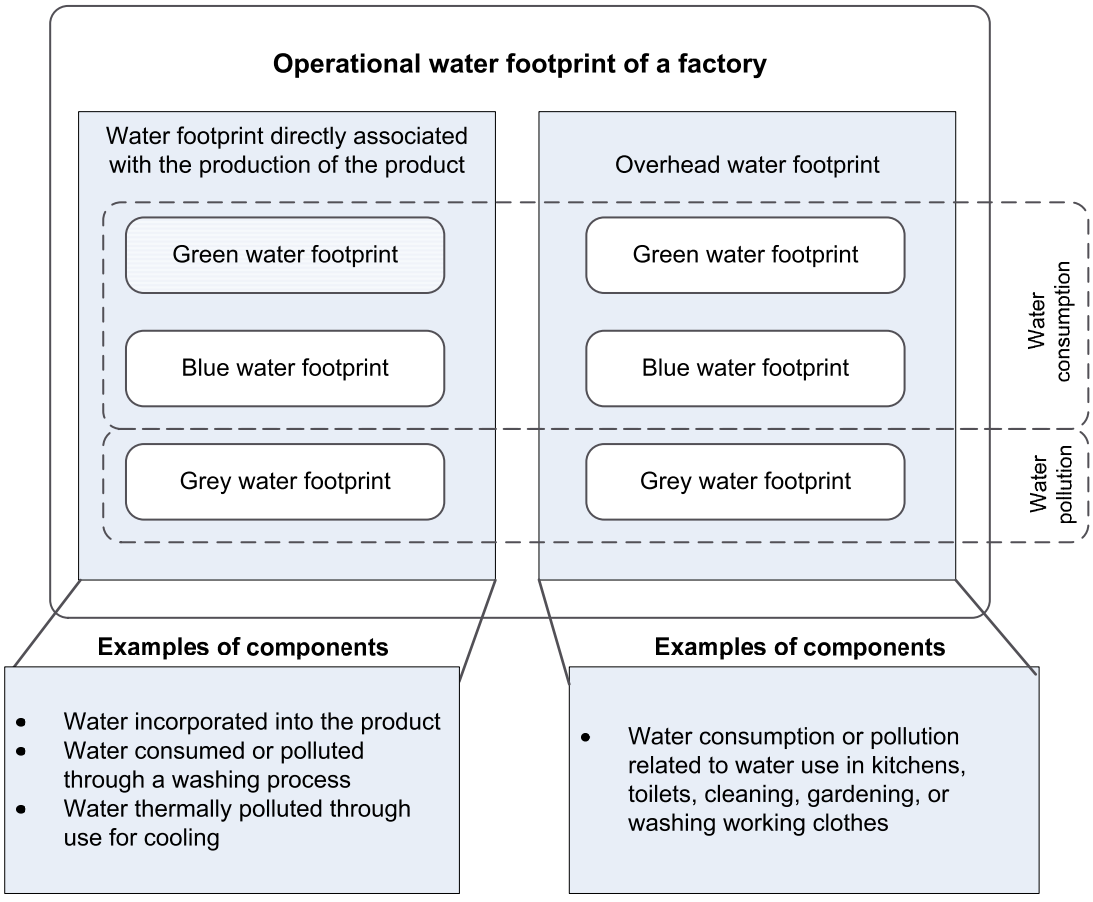


Figure 3-10: Composition and examples of components of an operational water footprint of a factory (according to [Hoe-11])

The water footprint of a business is defined as being the total volume of freshwater that is used directly or indirectly to run and support the business. It consists of two main

components. The operational (or direct) water footprint of a business is the volume of freshwater consumed or polluted because of the operation of the business. The supply chain (or indirect) water footprint of a business is the volume of freshwater consumed or polluted to produce all the goods and services that form the inputs of production of the business.

When referring to a factory, the operational water footprint includes the total volume of freshwater consumed (blue and green water footprint) or polluted (grey water footprint) due to the operation of the factory. The *operational water footprint of a factory* can be horizontally divided into water footprint directly associated with product production and overhead water footprint, and vertically divided into a green, blue and grey water footprint as shown in Figure 3-10. The *water footprint directly associated with the product produced* means the influences on the water resource during product production, e.g. water used by being incorporated into the product, water consumed or polluted through the washing process, water thermally polluted through the use for cooling. The *overhead water footprint* refers to the water footprint pertaining to the general activities for running a factory and to the general goods and services consumed by the factory, e.g. water consumption or pollution related to water use in kitchens, toilets, cleaning, gardening, or washing working clothes. It is used to identify water consumption that is necessary for the continued functioning of the business, but does not directly relate to the production of one product.

From such definitions, the sum of the ‘operational water footprint of a factory’ and the ‘supply chain water footprint’ is equal to the sum of the ‘water footprints of the factory output products’. However, when calculating a product water footprint, the distinction between the direct (operational) and indirect (supply chain) water footprint will be ignored. The process water footprints for all relevant processes within the production system can be simply added together.

3.4.2.2 Organizational boundaries

A factory where the water footprint is calculated is conceived as a coherent entity at one particular location, producing goods and/or services that are supplied to consumers or other business. The factory will be defined by describing the factory units that will be distinguished and specifying the annual inputs and outputs per factory unit. A *factory unit* refers to a part of the total factory that produces one particular product.

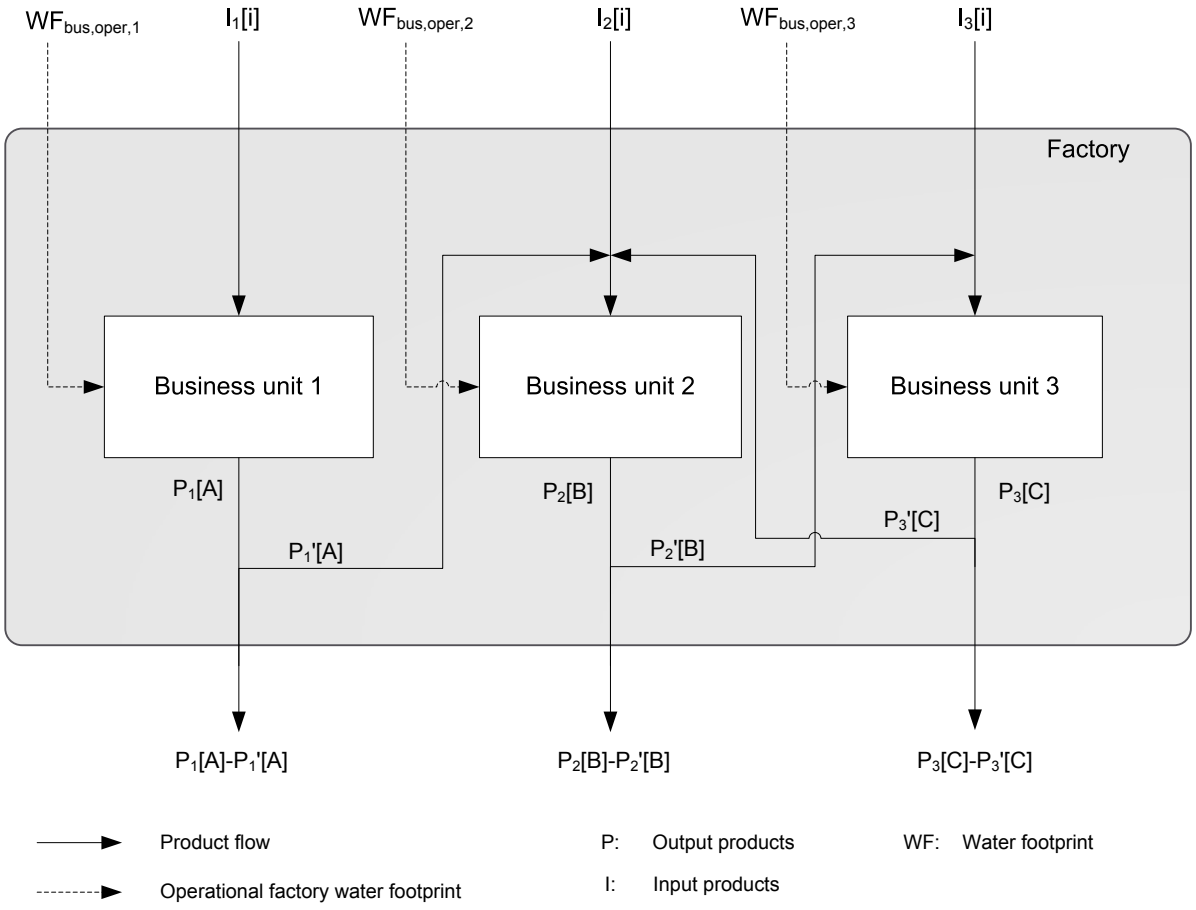


Figure 3-11: Example of a factory consisting of three business units producing products A, B, C

For example, Figure 3-11 shows an example of a factory with three business units, which produce products A, B and C. Part of product A (P_1'[A]) is delivered to business unit 2 in the factory and the other part is sold to another business. The product B which is produced by unit 2 is partly (P_2'[B]) delivered to unit 3 and partly dispatched from the factory. It is the same situation in unit 3, where part of the product is sold externally and part (P_3'[C]) is delivered to unit 2. Each unit has an intake of a number of input products (I_u[i]) purchased from other factories and a direct freshwater input. Product inflow I_u[i] refers to the annual volume of input product I into business unit u. Product outflow P_u[p] refers to the annual volume of output product p from business unit u. Product flow P_u'[p] refers to the part of P_u[p] that goes to another business unit within the factory. This schema can form the basis for calculating a factory operational water footprint, which will be explained in the chapter 3.4.2.3.

When a factory is large and produces different products, it can be useful to divide the business into major business units, and each major unit into a number of minor units. In this

way the factory can be described as a system with subsystems on several levels. Then the water footprint at the lowest level can be added to the water footprint at the second-lowest level, and so on. This total will be the level for the whole factory

3.4.2.3 Calculation

3.4.2.3.1 Water footprint of a single process

The calculation of a factory operational water footprint starts with each single process. As illustrated in chapter 3.4.2.2, it consists of a blue water footprint, a green water footprint and a grey water footprint, expressed as a water volume per unit of time.

Blue water footprint

The blue water footprint of a process refers to the consumptive use of blue water in the process, i.e. blue water evaporation, blue water incorporated into the product, blue water that either does not return to the same withdrawal area or in the same period (LostReturnFlow). All production-related evaporation includes the water that evaporates during water storage, transport, processing, collection and disposal. It is calculated as:

$$WF_{proc,blue} = Blue\ WaterEvaporation + BlueWaterIncorporation + LostReturnflow \quad [volume/time]$$

The volume of water consumption incorporated into industrial processes can be measured. The non-measureable volume of water evaporation during storage, transport, processing and disposal can be deduced from the difference in volume between abstraction and disposal. The databases, which contain typical data for consumptive water use for some manufacturing processes, can also be used as a standard water footprint [Gle-93] [Van-90].

Because the blue water footprint accounts for only the consumptive water use in a process, water reuse and recycling will be an influential factor only when it effectively reduces consumptive water use.

Green water footprint

The green water footprint is the volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (products based on crops or wood), where it refers to the total rainwater evaporation (from fields and plantations) plus the water incorporated into the harvested crop or wood. The green water footprint in a process step is equal to:

$$WF_{proc,green} = GreenWaterEvaporation + GreenWaterIncorporation \quad [volume/time]$$

Only when there is rainwater harvesting in the factory, will the industrial process have a green water footprint. The volume can be easily calculated from the rainwater collector.

Grey water footprint

The grey water footprint of a process step is an indicator of the degree of freshwater pollution as a result of the production process. It is defined as the volume of freshwater that is required to assimilate all pollutants, based on natural background concentrations and existing ambient water quality standards [Hoe-11]. The calculation formula is:

$$WF_{proc,grey} = \frac{PL}{c_{max} - c_{nat}} \qquad [volume/time]$$

PL (in mass/time) means the pollutant load, c_{max} (in mass/volume) refers to the maximum acceptable concentration and c_{nat} (in mass/volume) is the natural concentration in the receiving water body, i.e. the concentration in the water body that would occur if there were no human disturbances in the catchment.

3.4.2.3.2 Operational water footprint of a factory

The operational water footprint of a business unit (WF_{bus}, volume/time) consists of a water footprint which can be directly associated with the production of the product in the business unit and an overhead water footprint:

$$WF_{bus} = WF_{bus,inputs} + WF_{bus,overhead} \qquad [volume/time]$$

The operational water footprint is equal to the consumptive water use, and the water pollution that can be associated with the operations of the factory. Following the calculation of a single process in chapter 3.4.2.3.1, the evaporative flow from the processes, the volume of water incorporated into products and the return flows of water to other catchments where water is withdrawn, will be clearly apparent. In addition, effluent volumes and concentrations of chemicals in them also have to be considered.

The operational overhead water footprint – water consumption and pollution related to general water-using activities in the business unit – can be identified and quantified in the same way as the operational water footprint directly associated with the production process. The overhead water footprint, however, requires more attention when there is more than one product to be produced in the factory. The percentage share of the overhead water footprint should be considered in the definition of business units. The percentage of each product can be determined according to its production value.

Water footprint calculation is reliant on the water-use databases that facilitate its core calculations, such as GABI developed by PE-International in Germany, and many agriculture-based products use datasets from a climate database, e.g. CLIMWAT developed

by Food and Agriculture Organization of the United Nations. However, due to the lack of specific data for water consumption and wastewater generation for various manufacturing processes, databases such as Eco-invent often provide data on water abstraction rather than the consumptive use of water. These databases are often used together with a company's own water database.

3.4.2.4 Sustainability assessment

The factory water footprint is an indicator of freshwater use (in m^3/y) by a factory. A method to determine the sustainability of the factory water footprint is the assessment of the sustainability of all the processes.

Whether the water footprint of a specific process is sustainable or not depends on two criteria [Hoe-11]:

- Geographical context: the sustainability of water footprint of a process is closely related to the sustainability of the water withdrawal area. It is unsustainable when the process is situated in a certain area in a certain period of the year, in which the total water footprint is unsustainable from environmental, social or economic point of view.
- Characteristics of the process: the water footprint of a process is unsustainable in itself – independent of the geographical context – when the water footprint of the process can be reduced or avoided altogether (at an acceptable social cost).

These two criteria definitely need to be evaluated separately for the green, blue and grey water footprint. In industry, the ideal situation is when freshwater that needs to be incorporated into a product is consumed in the process, and there is no water pollution. For the second criterion, the blue and green water footprint that refers to water evaporation in industrial processes can generally be avoided by recapturing the water. Therefore, a process with a small grey water footprint is unsustainable, and the green and blue water footprint which is greater than the ideal water footprint would also be unsustainable.

The sustainability assessment of the factory water footprint can be deduced by considering all the processes within the factory. Generally, a factory with any process that is unsustainable cannot be treated as a sustainable factory. With the help of a calculation of factory operational water footprint, the percentage of the water footprint which is unsustainable can be identified.

3.4.3 Reducing water consumption

3.4.3.1 Water pinch analysis

WANG AND SMITH [Wan-94] developed the Water Pinch Analysis to minimise the freshwater requirements in a continuous process industry, being analogous to pinch design method for heat integration.

The goal of this methodology is to identify a target of minimum requirement of freshwater (the pinch point) for the entire system, through design of a maximum water recovery network by considering the flow rates and concentration levels of different water streams. However, the method overlooks the character of all water-using operations. For example, the water using operation with non-mass exchange, e.g. cooling, the water flow rate is more important than the amount of contaminant. Thus, this methodology fails to address the water conservation opportunities for different water using operations. Based on this methodology, many researchers have developed further approaches to improve it, e.g. from one contaminant to multi-contaminants, and more detailed classification of water-using operations. Some well-known research includes Water Cascade Analysis by Manan et al., cost-effective minimum water utilization network by Alwi et al. and graphical targeting method for water minimization by Hallale [Hal-02, Man-04, Waa-08].

However, related technologies in this area concentrate more on how to find the target point of maximum water recovery, but there is little attention paid to methods of improving the system based on water targeting [Wan-94, Man-04]. Besides, since Water Pinch Analysis was developed for continuous process industry, further research is limited to such an industrial sector.

3.4.3.2 Water minimization framework

A water minimization framework is proposed by Sachidananda and Rahimifard, assessing both direct and indirect usages of water for each process within a production system [Sac-12]. By targeting the water use for production and non-production in the whole plant, a static and dynamic water flow model is developed, based on a tool for a water flow simulation engine. After analysis of developed water flow ratios, critical water processes are determined. Then scenarios for reducing water consumption within manufacturing applications are planned. This concept is introduced with a case study of food manufacturing.

This paper provides an approach for inventory and planning water use within the entire factory. It concentrates on the amount of water used and discharged, but not analysis of water quality. Furthermore, how to identify the water critical processes with the introduced water flow ratios is not specified. Thus it is only a framework for a potential research area to improve the water efficiency, without a technical feasibility investigation.

3.4.4 Using value stream mapping to assess water use

3.4.4.1 Original theory in lean manufacturing

During production, the process of value creation provides the source material with additional value. Thus, the finished products are appropriately referred to as ‘goods’. The *value* of such goods results from their evaluation, which uses production costs as a basis in a producing company. The term *flow* has been widely established for the description of a factory’s production [Erl-13]. Thus, v*alue stream* is defined as all the actions (both value and non-value added) that are currently required to bring a product from inception to completion, through the production flow from raw material to the customer, and the design flow from concept to launch [BSI-08, Rhe-99].

A *value stream map* can be understood in three ways: 1) A qualitative tool that describes how a facility should operate to maximize flow by minimizing waste which add no value to the process; 2) It depicts both material and information flow and linkages between the two; 3) Key measures and metrics are depicted on the map allowing ‘hotspots’ and issues to be easily recognized [BSI-08].

As a lean manufacturing technique, value stream mapping is used to analyse and design the flow of materials and information required to bring a product or service to a consumer. A value stream perspective means working on the big picture and improving the whole, not just a part [Rhe-99]. Although many of the tools and techniques of lean manufacturing have been widely used in discrete manufacturing, ABDULMALEK and RAJGOPAL pointed out value stream mapping can also be used in continuous process manufacturing [Abd-07].

Value stream mapping is a process-mapping method that contributes to the construction of a lean manufacturing factory. Since it focuses on how to avoid waste in production from a system improvement viewpoint, it can be valuable in addressing sustainable manufacturing by reducing resource use. With a predefined set of standardized icons/symbols (see appendix A), the value stream map visualizes the flow of material and information during the passage of the product through the value stream. Sources of waste are clearly represented in the map. The basis of an implementation plan will be formed, helping planners to design how the flow should operate, and thus improve the whole flow to avoid waste. Steps of value stream mapping are shown in Figure 3-12.

A value stream mapping starts with *target identification*. Target here means the product family which the customer needs. This should be clearly understood before starting. A *family* is a group of products that pass through similar processing steps and over common equipment in the downstream processes [Rot-99]. Focusing on the target product family helps to simplify and clarify the value stream map. The *Value Stream Managers (VSM)* in the single process functionality, and the whole product family’s value stream, help to cross the organizational boundaries while collecting information in the factory.

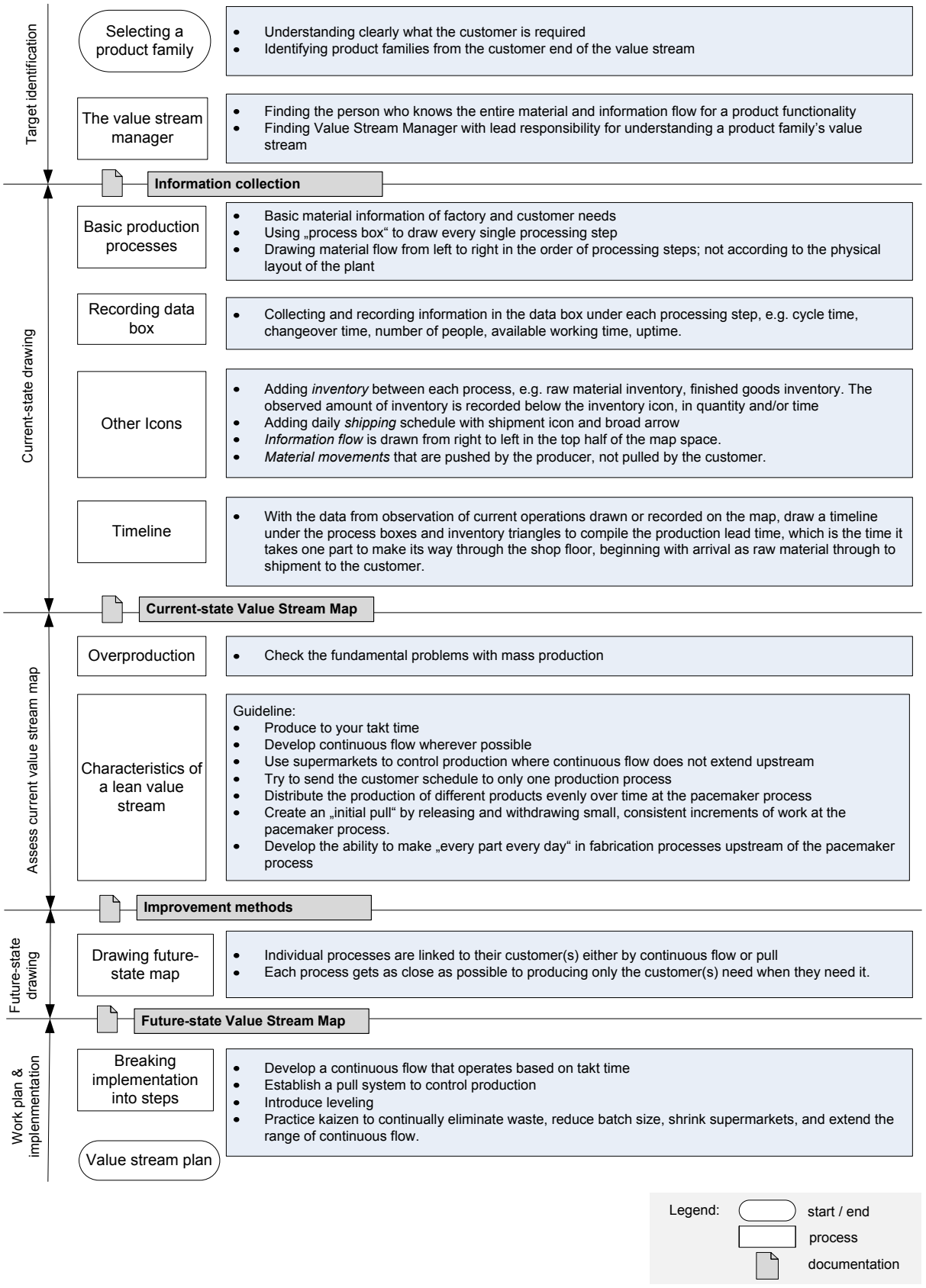


Figure 3-12: Steps of value stream mapping (according to [Rhe-99])

Based on the preparation and information collection, value stream mapping begins with an analysis of *current-state production situation*. A current-state value stream map on the shop floor shows the current steps, delays, and information flows required to deliver the target product or service. This may be a production flow (raw materials to consumer) or a design flow (concept to launch). Standard symbols are used to represent supply chain entities. Current-state drawing starts with the record of the beginning and end of the material flow, i.e. the factory and the customer needs. Basic production processes in the order of processing steps, and the information of each processing step, are then drawn in the map, e.g. cycle time, changeover time, number of people, available working time, and uptime. Other icons like inventory, shipment, information flow and material flow will be added according to the situation in the factory. Finally, the timeline, showing the time which a product takes through each process and inventory, beginning with arrival of raw material through to shipment to the customer, is drawn under the whole material flow [Rhe-99].

Assessment of the current-state value stream map will make it lean and eliminate waste. O*verproduction* is considered the worst of the seven wastes (transportation, inventory, motion, waiting, over-processing, overproduction, defects) of lean manufacturing, which means producing more, sooner or faster than is required by the next process [Ohn-88]. The process should make only what the next process needs, when it needs it. A guideline for a lean value stream is: 1) Produce according to the takt time; 2) Develop continuous flow wherever possible; 3) Use supermarkets to control production where continuous flow does not extend upstream; 4) Try to send the customer schedule to only one production process; 5) Distribute the production of different products evenly over time at the pacemaker process; 6) Create an “initial pull” by releasing and withdrawing small, consistent increments of work at the pacemaker process; 7) Develop the ability to make “every part every day“ in fabrication processes upstream of the pacemaker process [Rhe-99].

A *future-state value stream map* should eliminate the waste by its implementation, and can become a reality within a short period of time. Based on the assessment in the last stage, a chain of production can be built where individual processes are linked to their customer either by continuous flow or pull. Each process gets as close as possible to producing only what its customer needs and at the time when they need it.

With the future-state value stream map and detailed process-level maps or necessary layout, a yearly value stream plan should be made, showing exactly the measurable goals and deadlines step by step. Obviously, it is probable that some problems are found during the implementation. Then there is a need to go back to the future-state value stream map drawing or even to the assessment of current-state map.

3.4.4.2 Related researches with water use

Various research has been done on the standard value stream mapping, using this method to assess energy and environmental impact on production, e.g. energy value stream mapping, environmental value stream mapping [Erl-09, Ple-12]. The existing research, combining value stream mapping with water use, all use value stream mapping to assess the environmental impact of a production system. Water use is only one part of the research which may also include energy use, resources, emissions, etc.

PLEHN ET AL. introduced a combination of environmental and economic performance measurement to achieve high eco-efficiency. A novel approach to environmental value stream mapping is introduced as an interface between a multi-dimensional performance measurement system and a manufacturing system, integrating environmentally and economically relevant process flows in one process model. With a corporate strategy from economic, environmental and productivity, this paper added several elements to the standard value stream map, namely energy, materials, water, waste and emissions. Experimenting in a consumer goods industry, with LCA method to assess energy and material flow and the Swiss method of ecological scarcity (ecofactors or UBP 06) to evaluate the environmental damage, this paper identified improvement areas at the operational level [Ple-12]. This paper gives a comprehensive environmental assessment with value stream mapping, but concentrates less on water use.

The GREEN SUPPLIERS NETWORK paper describes a lean and clean value stream mapping. 10 Green Suppliers Network environmental metrics are added to the standard current state value stream map in the formation of inputs and outputs. Calculating the difference between water used and water needed identifies the amount of water wasted. From that, efforts can be targeted to prioritize improvements in the largest sources of waste [GSN-07].

TORRES JR. AND GATI developed a managerial tool – environmental value stream mapping – for aligning economic and environmental aspects in the production process with the case study of an alcohol and sugar manufacturing industry [Tor-09]. The activated, used and aggregated water are defined in each process. Thus the water loss can be calculated. With a classification of four groups of water losses (latent loss, real loss, latent/real functional loss and intrinsic functional loss), the economic cost of water losses can be calculated. This will enable future improvements to be made. This paper shows a good example of how to integrate water loss with its economic impact, but it does not cover the development of improvement measures.

3.5 Zero wastewater discharge

3.5.1 Definitions

The concept of zero wastewater discharge can be regarded as one part of the zero emission. Generally, emission means in general something that is emitted or discharged [Dic-13]. The substance of emission can be gas, fluid or some other substance like energy. The word ‘zero’ in the ‘zero emission’ means ‘none’. Research regarding decreasing industrial emissions to “zero” is varied, but they all relate to the resources used in the factory. In general, there are three types: zero carbon with no CO_2 emission, zero waste with no solid waste, and zero discharge with no wastewater. However, since these three parts have a strong relationship, they are often researched and implemented together.

PIRKER defines zero emission on four levels, namely absolute zero, analytical zero (detection limit), no facilities or permission, and zero influences to the environment (zero impact) [Pir-03]. PLANASCH defines emissions as unused raw materials and he points out in a zero emissions system, the emissions which pass the defined system boundary must “neither interfere with ecological nor social requirements” [Pla-05, Pla-06]. NGOC et al. defines a zero emissions agro-based industrial system as “a system in which industry and agriculture corporate to produce the products serving important social or industrial needs but no longer generate harmful emissions to human and the environment” [Ngo-08].

The concept of zero discharge in the wastewater treatment area has already been widely known. It covers the recovery of usable water/other materials from wastewater and the reduction or elimination of discharge of polluting substances into the environment away from the wastewater treatment facility. The main objectives of a zero discharge treatment system have been summarized as: no additional pollutants, minimized production of wastes, maximized transfer of pollutants to solid phase, sludge storing and recovery of reusable materials, especially water [Esw-09].

3.5.2 Approaches to planning strategy

To manage an existing factory or establish a new factory and to achieve the goal of zero wastewater discharge, several methods have been established from the perspectives of reducing wastewater generation and recycling of wastewater. An overview of potential methods is shown in Figure 3-13.

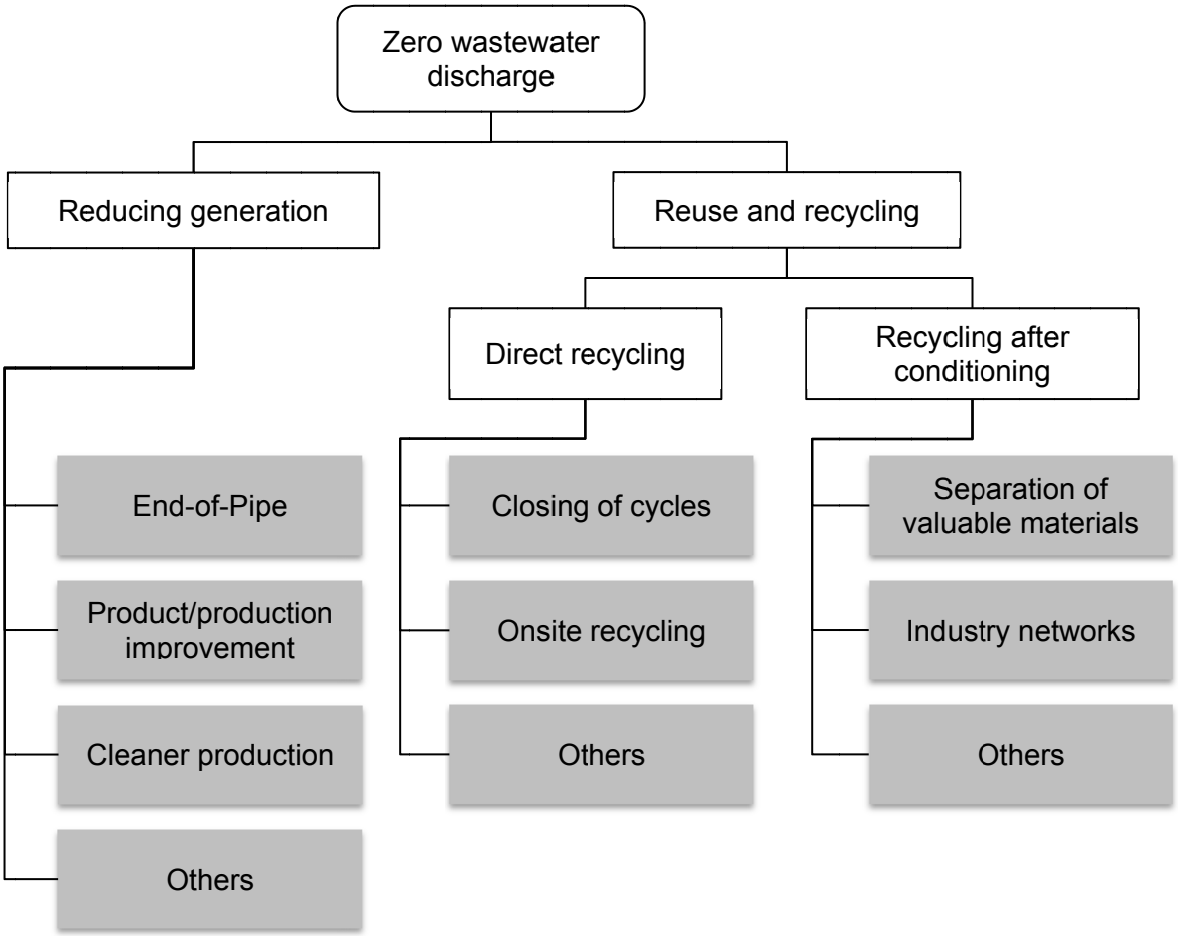


Figure 3-13: Overview of potential methods to achieve a zero wastewater factory (according to [Pir-03])

Direct reducing wastewater generation can lead to a nearly zero discharge. Methods like end-of-pipe, product or production improvement and cleaner production could be applied to reduce the wastewater from the source. Generally, recycling can be divided into direct recycling, which could be recycled by normal wastewater treatment processes, and recycling after conditioning. Methods closing of product cycles and onsite recycling could be applied in a factory. In addition, the wastewater which cannot be reused directly can be reused after appropriate conditioning. Technical measures like the separation of valuable contaminants, and organizational measures like industry network would reduce the wastewater as much as possible.

Some existing research and projects regarding the reduction of industrial wastewater discharge are explained in following sections.

3.5.2.1 End-of-Pipe technique

End-of-Pipe techniques are methods which are used to remove the already formed contaminants from a stream of air, water, waste, product or similar substance. They are normally implemented as a last stage of a process before the stream is disposed of or delivered.

Techniques included in End-of-Pipe for wastewater discharge control are effluent treatment or filtration before the wastewater flows into the environment. It doesn't concentrate on any changes in the production process generating wastewater. According to VDI 3800, End-of-Pipe technologies do not make up an essential part of the production process, but are add-on measures in order to comply with environmental requirements [VDI-3800].

3.5.2.2 Cleaner Production

Cleaner production focuses on the redesign of processes and products by minimizing waste and emissions and maximizing product output. Options to minimize waste and emissions from industrial processes will be identified by analysing the material and energy flow in a company. The concept was developed during the preparation for the Rio Summit as a programme of UNEP (United Nations Environmental Programme) and UNIDO (United Nations Industrial Development Organization) in 1990, defined as "the continuous application of an integrated environmental strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment" [UNEP-13].

Cleaner production doesn't concentrate on how to utilize the wastes, but on how to avoid the waste generation. Three principles can be defined as follows:

- Precaution: The overflow stream from the anthroposphere to the ecosphere should be reduced, especially when the effects to the ecosystem are not known. A substance should therefore only be released when it can be safely utilized in this condition and quantity in the ecosphere.
- Prevention: The prevention or reduction of a substance flow should be carried out at an early stage, and not only at the point where the stream leaves the system of production and consumption.
- Integration: The sole displacement of a substance flow into another medium (air, water, soil) is not a satisfactory solution. All media must be included in the above-mentioned measures. Furthermore, the entire product life cycle must be considered in order to prevent the postponement of emissions. The emission flow must be reduced both in its scope and in its ecological relevance.

In order to apply successfully the concept of cleaner production, following points should be seriously taken into consideration [Pir-03]:

- Paying attention to all the substance and energy flow in the input and output of a factory;
- Analysing the total product life cycle from raw material exaction to the production, supply and use until the recycling and final disposal;
- Accounting for all the media (air, water, soil), which are related to the emissions;
- Analysing the consequences of the economic structural change brought about by this process.

Measures included in cleaner production are closed cycle, “good housekeeping”, separated wastes collection, product improvement, etc.

3.5.2.3 Zero Emissions concept

The concept of “Zero Emissions” was developed in 1994 by the Zero Emissions Research Initiative (ZERI) in United Nations University (UNU). The basic concept is that all industrial inputs can be completely converted into a final product and that waste products can be converted into value added inputs for another chain of production [ZERI-13]. In this context, the manufacturing line can be viewed as a series of production cycles and recycling systems. To reach the goal of Zero Emissions, factories can be placed in a so-called cluster, within which the waste/emission/by-product of one factory can totally be treated as the required material for another factory. In this way, there is no waste and damaging emission from the industry cluster. Thus the concept of Zero Emissions can be regarded as one of the methodology to achieve sustainability.

From the ecological perspective, the prevention of waste and emissions is the ultimate solution to pollution problems, which leads to the full use of natural resources at the same time. With the maximum use of renewable resources, the consumption of natural resources can be brought down to a sustainable level.

From the economic perspective, the concept of zero emissions generates greater competition, because it will inevitably increase efficiency. With the development of society or industry, the concentration has moved from the productivity of labour and capital to the use of materials. In other words, producing more from less. In this sense, Zero Emissions can be understood to be a new standard for resource efficiency [Aac-12].

From the social perspective, Zero Emissions advocates an industrial transformation, whereby businesses emulate the sustainable cycles found in nature, and where society minimizes the load on the environment.

Looking back in history, the development path of measures to control and reduce emissions from industrial pollution sources can be divided into three main phases: end-of-pipe, cleaner production and Zero Emissions, see Figure 3-14.

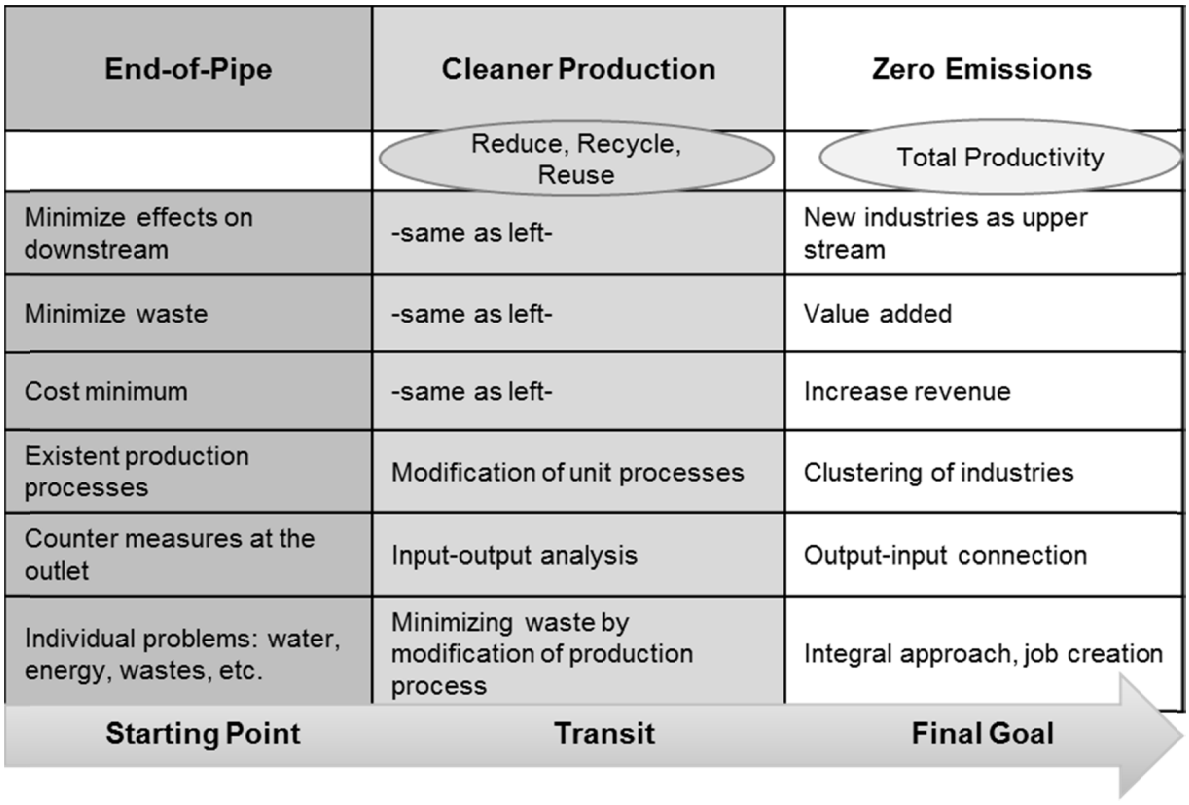


Figure 3-14: Three phases of measures to control and reduce emissions from industrial pollution sources [ZEF-13]

Zero Emissions could easily be understood as no emission from production processes. From a technical viewpoint, and the laws of physics, it is inevitable that chemical reactions do not reach exactly 100% yield and waste heat emissions, it seems that the concept of Zero Emissions is not tenable. The Zero Emissions concept of UNU does not assert that all the emissions of a set of industrial processes can achieve exactly zero. Rather the meaning of Zero Emissions has two aspects:

- Systemic view: Even if emissions are unavoidable from certain processes, they will be considered in the context of industrial and natural processes, so that the use or exploitation of this waste/emission may effectively lead to “zero” emissions, meaning no defective impact to the environment.

- Continuous improvement: The term refers to a process of continuous improvement towards an idealized goal. The principle of this “zero” is exactly the same as “Zero Defects” in quality management, and “Zero Inventory” in cost maintenance. “Zero Defects” helps companies reduce their storage, and introduces the so-called “just-in-

Defects" helps companies reduce their storage, and introduces the so-called "just-in-time" system. The system and the associated concepts have been accepted worldwide, although neither production nor storage errors have disappeared as a result. The developed concept "Zero Emissions" adds the two aforementioned management approaches to a new industrial triad. As well as care for the environment, waste materials from production processes can be seen as a source of significant cost savings and thus maximizing profit [Aac-12, ZEF-13].

Based on the principle of the Zero Emissions concept, PAULI developed the methodology which can be applied to any industry. It is summarized as five main steps [Pau-10]:

Step 1: Total Throughput using Input-Output-Table

A review of the industry identifies opportunities to minimize inputs and maximize outputs. The target is full use of inputs, i.e. total throughput. If this cannot be achieved, the next step of the methodology is applied.

In this step, an Input-Output analysis of each considered process should be established. Such a method is an existing tool in an integrated applied management tools system (e.g. ISO 14001, cleaner production, etc.). A top-down approach is recommended as a first step in creating a rough balance of the entire process. An example of an Input-Output-Table of such total throughput analysis is shown in the following Table 3-8.

Table 3-8: Example of an Input-Output-Table

Output / Input	Production Process 1	Production Process 2	Production Process 3	Production Process 4
Value 1	50 / 20	50 / 10	50 / 0	50 / 20
Value 2	20 / 5	20 / 5	20 / 10	20 / 0
Value 3	30 / 5	30 / 5	30 / 5	30 / 15

Normally, the savings and potential for improvements will be shown in this step, which can be captured and utilized in a detailed sub process balance. Another advantage of the use of I/O balance sheets is that many companies which are ISO certified and have experience of cleaner production have normally already used them. Thus, an effort doesn't need to be made for these surveys [Böc-02]. An example result after the improvement to reduce resource consumption based on Table 3-8 is shown in Table 3-9.

Table 3-9: Improved Input-Output-Table

Output / Input	Production Process 1	Production Process 2	Production Process 3	Production Process 4
Value 1	40 / 20	40 / 5	40 / 0	40 / 15
Value 2	20 / 5	20 / 5	20 / 10	20 / 0
Value 3	25 / 5	25 / 5	25 / 5	25 / 10

After all the potential for saving and improvements of existing processes, within the given technical and economic options, some residual amounts of by-products still remain to be used. The result of this step is a detailed Input-Output balance of the total throughput of the material flow in the system.

Step 2: Output-Input Models

An inventory is made of all “wastes”, i.e. outputs not consumed in the final product or its process of manufacture. An active search is then initiated undertaken to identify industries which could use the outputs, or modified versions of them, as inputs.

The function of Output-Input models is to search for more creative uses of the current waste material. For this purpose, the exact composition of the waste must be analysed (chemical analysis), which is essential for it to be targeted for further use and reuse. As an example, fruit juice production will produce different waste materials, one of which contains considerable amounts of various vitamins or antioxidants, and therefore they could be valuable input materials for the pharmaceutical industry. It is important to identify the creative recycling opportunities with potential value from the waste material. It is also noteworthy that in joint processes the use of waste materials could be applied in a cascade (for example, the valuable materials extracted from juice production could be used as feed for animals, whose manure in turn could be used as a substrate for biogas plants to produce energy, etc.).

Table 3-10 shows, for example, how the waste material can be reused in different ways. In the analysis table, material input and output will be identified, which can be reused appropriately. The total amounts of the waste material are listed in the last column, which represents the total recovery of the waste material. Only when the upper and lower values are identical will the waste material be fully utilized (see waste material 2). The waste material 1 and 2 will then be transported to a different reuse field. During reuse, more waste material will inevitably be produced, which can be seen as a further step in the Output-Input-Table. As long as one waste product can be used as an input of some process, it belongs to the Zero Emissions method.

Table 3-10: Example of an Output-Input-Table for waste product

Input / Output	Reuse method I	Reuse method II	Reuse method III	Sum
Waste Material 1	50 / 20	50 / 10	50 / 0	50 / 30
Waste Material 2	20 / 5	20 / 5	20 / 10	20 / 20
Waste Material from Method I	30 / 5	30 / 5	30 / 5	30 / 15
Waste Material from Method II	… / …	… / …	… / …	… / …
Waste Material from Method III	… / …	… / …	… / …	… / …

After an exhaustive collection of all the possible alternatives, the feasibility of each process and sub process should be evaluated. The technical feasibility (state of the art, existing local capacities) and economic feasibility of the joint use of waste should be tested clearly (with traditional methods of economic calculation) and evaluated (according to the fulfilment degree of the “zero-emission” conditions) [Böc-02]. The difficulty of all the influences on this system is that, the statement effect the entire system is often subject to restrictions. The assessment methodology of the technical and economic feasibility of the reuse process according to ZERI includes: definition and evaluation of a market for the products of extended value creation; setting the required energy expenditure; acquisition of the necessary investments; determining the need for additional work space; possible effects on the labour market (job creation).

Step 3: Industry cluster

The goal of this step is to combine the production processes and industries in into “clusters” in the best way. In this way all “emissions” (waste product, energy) could be reused by transferring them from one factory to other factories, so that the synergy can be most efficiently exploited. One of the key tasks is identifying the optimal size of an industrial operating unit in the given circumstances (environment), in order to ensure the possible highest possible efficiency in the cluster.

Growth does not occur by duplicating the optimized operating unit, but from simply scaling up or down an optimized process. This technology is based on events in the world of nature, and can be applied most easily to the agricultural sector. In this complex field, there is still a great need for research of all industrial sectors. Further components of the Upsizing principle are the identification of new and innovative technologies for the efficient use of raw materials

and the integration of public authorities (“Policy”) in new development concepts. Since many new ideas are to be implemented and integrated with existing systems, they still need a new framework and thus a change in legislation.

Step 4: Breakthrough Technologies

In cases where present engineering know-how, product and process technologies are not yet able to secure effective and economical coupling of outputs and inputs, research into breakthrough technologies or system designs is initiated. Therefore, this step occurs only when the process input and output cannot be acquired. Recently, there has been no unified suitable technology for all industry to reach the goal of Zero Emissions in ZERI system.

Step 5: Industrial Policy

Identification of industries and the isolation of necessary breakthroughs must be accompanied by the design of appropriate government policies. As sectors with no previous tradition of working together are combined, collaborative efforts involving policy makers, industry representatives and academia should be launched. As the last step, the developed process should be documented and tested by consensus with relevant laws. There may be a need to prepare a document to support changes in the law.

3.5.2.4 ZERMEG

The project “Zero Emission Retrofitting Method for Existing Galvanising Plants (ZERMEG)” was done in Austria by a combination of several industries and universities [Fre-06]. In ZERMEG, a methodology was developed for the existing galvanic equipment, so that the use of water and chemicals can be decreased and recycled to maximum effect. A computer program “QUICK” to calculate the optimal consumption of water for washing and a program “ZEPRA” for mathematical modelling of the reaction were established. The developed method was further successfully applied in three case studies. From the practical analysis, results of ZERMEG are a reduction of the specific consumption of water by 80-90%, and clear reduction of specific consumption of chemicals.

The project applied in depth the total recycling and a serious zero-emission-concept to degreasing and pickling in galvanising companies. With such a methodology, the rinsing cascades in several plants were changed. In the case of Pengg, the water consumption in the batch pickling plant was reduced by 50 %. At AT&S, an electrolysis plant to recover copper was implemented with a recovery of 20 kg per day. At the hot dip galvaniser Mosdorfer, the topping of the pickling baths was optimized with a 50% reduction of acid consumption. In the automatic copper plating plants of Rotoform, the spray rinses were improved with a reduction of water consumption by 50%, and acid consumption by 40% [Fre-06].

3.5.2.5 Industrial symbiosis

Industrial ecology is an emerging field of material and energy flows through industrial systems. It operates at three different levels, ranging from the regional or global level through the inter-firm level to the level of individual facility. Applied to manufacturing, the systems-oriented industrial ecology suggests that industrial design and manufacturing processes are not conducted in isolation from their surroundings, but rather are influenced by them and, in turn, influence them [Gra-94].

As one part of industrial ecology, industrial symbiosis occurs at the inter-firm level, including exchange options among several organizations, and is concerned with resource optimization among collocated companies [Jac-06]. Industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantage, involving the physical exchange of materials, energy, water, and by-products. The key to industrial symbiosis is collaboration and the synergistic possibilities offered by geographic proximity. Eco-industrial parks are seen as concrete realizations of the industrial symbiosis concept [Che-00].

Industrial symbiosis consists of place-based exchanges among different entities. By working together, businesses strive for a collective benefit greater than the sum of individual benefits that could be achieved by acting alone. This type of collaboration can advance social relationships among the participants, which can also extend to surrounding neighbourhoods. However, the symbioses need not occur within the strict boundaries of a “park,” despite the popular usage of the term eco-industrial park to describe organizations engaging in exchanges.

In practice, the industrial symbiosis predicts that turning waste output from one facility into valuable material for another facility will lead to environmental benefits because of a reduced intake of virgin material and/or reduced emissions. The environmental effects of water-related industrial symbiosis exchange are analysed in terms of their ability to reduce the intake of high-quality water by means of water substitution and water cascading.

3.5.2.6 Zero Liquid Discharge

Zero Liquid Discharge (ZLD) is a process from which no effluent, or discharge, is left over. ZLD systems employ the most advanced wastewater treatment technologies to purify and recycle virtually all of the wastewater produced. Thus, they have numerous economic and environmental advantages, since water is recycled and reused, saving on cost and treatment of raw water. However, the cost of ZLD systems is too high and has normally been used in areas of water-shortage [Mic-08, Sie-13b].

A case study shows that, in the International Truck and Engine Corporation assembly plant in Mexico, a ZLD system has been installed with the technologies of sanitary collection, biological water treatment, microfiltration membrane softening, reverse-osmosis (RO) water

recycling and evaporation ponds. Satisfying the requirement of pre-treatment and wastewater treatment, this system significantly lessens the demand for fresh water [Sie-13].

Another case has been designed for a power plant in Italy. Through some efficient water treatment technologies like Bio-filtration and RO, the ZLD system can treat sufficient boiler feed water to the required quality of pure water.

3.6 Analysis in summary

In summary, it is noted that, the known approaches have identified the potential to improve water efficiency in their application areas. However, an integrated approach from production processes to factory management along the production flow is still absent.

The overall evaluation of current related approaches is shown in Table 3-11. Criteria are classified according to the research fields in water use level, including production process, production system and factory level, and in wastewater treatment for treatment process, treatment system and factory cluster. The industry sectors to apply these methodologies are also classified in process industry, manufacturing industry and general industry.

Table 3-11: Evaluation of current related approaches

Research groups / project	Descriptions	Application Area: Water use level – Production process	Water use level – Production system	Water use level – Factory	Wastewater treatment – Treatment process	Wastewater treatment – Treatment system	Wastewater treatment – Factory cluster	Industry sector
Best Available Techniques (BAT) on water use	Most effective techniques	●	●	◑	●	●	○	G
Water footprint	Calculation of direct and indirect water use to produce a product	◑	●	◑	○	○	○	G
Water Pinch Analysis	Mathematical optimization technique for reducing water consumption and wastewater generation	●	○	○	○	●	○	P
SACHIDANANDA	Simulation supported framework of reducing factory water consumption	○	◑	●	◑	●	○	M
PLEHN ET AL.	Combining environmental and economic performance measurement to achieve high eco-efficiency	◑	●	○	○	○	○	M
Green suppliers network	Adding environmental aspects into lean manufacturing	◑	●	○	○	○	○	G
TORRES JR. AND GATI	A managerial tool for aligning economic and environmental aspects in production process	◑	●	○	○	○	○	M
End-of-Pipe	Removing the already formed contaminants	○	○	●	●	●	○	G
Cleaner production	Redesign of production processes and products	●	●	●	○	○	○	G
PAULI	Converting waste products into value added inputs for another chain of production	○	○	●	◑	●	●	G
Industrial symbiosis	Resource optimization among collocated companies	○	○	●	◑	●	●	G
Zero liquid discharge	Using the most advanced wastewater treatment technologies to purify and recycle all the wastewater	○	○	●	●	◑	○	G
ZERMEG	Zero emission retrofitting method for existing galvanizing plants	○	●	○	◑	●	●	P

● – Central research field, ○ – No research field, ◑ – Part research field

G – General industry, M – Manufacturing industry, P – Process industry

4 Need for action

Today, industrial companies are facing the challenge of increasing environmental requirements, of global competition and of the cost pressure to pay for it. Conflicts between employees and management, lack of technical knowledge, economic, social and political impacts also act as a barrier for management to take necessary steps to prevent the environmental impacts [Pun-01]. Increasing the water efficiency in industrial factories is one of the possibilities to meet this challenge.

The characteristic of water which differs from other resources as a raw material in industry is the cost of water. It is not just the cost of purchase, but also includes handling, heating, holding, treating and discharging, often multiplying the cost by 20-30 times [Aus-09]. Direct benefits from improving water efficiency measures are reducing the cost of water and reducing wastewater generation by lowering consumption and therefore total water intake. In the meantime, other effects may result, such as declining demands for wastewater discharge rights and enhancing the company image for customer. This could lead to an increase in sales. Generally, benefits from saving water include:

- Lower water costs: Includes water supplied to the site and discharged to the sewer as waste;
- Lower energy costs: Energy and water in industry are often linked, e.g. decreased pumping, heating, cooling and treatment requirements which also save energy;
- Lower capital cost of equipment: As less water is used, the amount of pumping, storage and transport is reduced;
- Wastes: Wastewater treatment often results in the generation of prescribed wastes, which are costly to dispose of;
- Lower environmental impacts from spills, leaks and effluent discharges;
- Carbon tax: When energy use is reduced, this can lead to a saving in carbon tax by reducing CO_2 emissions;
- Better quality products. In some cases, efficiency improvements will increase the performance of production processes and the quality of the product.

Methods of auditing and management of water consumption are commonly found in large manufacturing and energy enterprises. The lack of simple cost-effective methods and tools in a water efficiency improvement system has often been cited as the single biggest obstacle in water minimization efforts, especially within small and medium-sized industrial enterprises [Sch-02, Red-08]. In most applications, water metering systems typically used at factory level

are capably of measuring the input and output flow rate, but are unable to provide a detailed breakdown of water used at cell or process level.

Most industrial water saving projects focus on some special area of water use, in particular within the process industries: They are hardly able to provide a systematic approach to increasing water efficiency along the whole production chain and minimizing the environmental impacts of wastewater.

In summary, there is a high demand for methods and tools to improve water efficiency and minimize environmental impacts by wastewater in industrial factories. Such solutions should meet the following requirements:

- An overall audit or inventory should be made of current water sources and application processes, wastewater generation and reuse, recycling, discharge in the whole factory. The collected water information should always relate to the process. Hence, a detailed analysis of water and related process information is required.
- Knowledge of internal wastewater reuse and recycling can originate from the amount and quality of each water-related process or operation, based on the wastewater treatment technologies. Thus a water quality cascading analysis is required, and an evaluation of treatment technologies should be undertaken to support decision-making.
- External wastewater reuse and recycling, especially for agriculture-based production use, requires a basic knowledge of substances in the wastewater. A substance test or calculation based on literature is needed.
- Improvement of water efficiency should result in increased water availability, reduction of water intake and minimum environmental impacts.
- The large amounts of process water data and the numerous options of water treatment methods call for an easily understood methodology with work flows which are easily manageable.
- The method should not only concentrate on improving existing production industries. It can also be used as a design aid tool for future product production and factory building.

Based on these requirements, a systematic approach should be developed, which can identify critical water use from processes through cells to the factory level, and an improvement potential on both reducing water intake and reducing environmental impact.

Numerous research papers have shown that the value stream mapping method from lean manufacturing can be used as a tool to assess the environmental impact of manufacturing industries [EPA-08, Erl-09, Erl-12, Gov-10, Ple-12, Rei-11]. The biggest advantage or benefit

of a value stream map is that presents an overall picture of the process, and providing a beneficial form of visual communication between everyone involved. It easily identifies where the non-value-added waste is, and how to improve it. Based on this theoretical background, a new method can be developed, combining value stream mapping with water flow analysis to show a visual representation of water-related activities in the whole factory.

The production optimization of the value stream mapping method, from a mainly commercial position as it has been applied to lean manufacturing, has been adopted by manufacturing industry over the years, and described above. This method can be further developed for sustainable manufacturing by increasing awareness and assessment of water use in a factory.

By combining the advantages of production process optimization, and service related factory water consumption, the water value stream method aims at providing precise information on the water footprint generated in production and to systematically develop improvements. Goals of this method can be accomplished as follows:

- Identifying the key processes/steps with the greatest water consumption;
- creating transparency about the waste of water along the value creation chain;
- pointing out potentials/opportunities to reduce water use in the plant;
- defining improvement measures to increase water use efficiency;
- achieving cost savings and compliance with ecological provisions;
- providing the basis for the strategic integration of water issues into manufacturing.

5 Integrated industrial water value stream to achieve zero wastewater discharge

5.1 Approach

The concept of integrated industrial water value stream to achieve zero wastewater discharge, which is introduced in this paper, contributes to an efficient water use in the industrial sector and a low negative impact on the environment. With this concept, the current water intake and usage within a manufacturing plant will be analysed. Based on this, efficient improvement technologies will be highlighted, and the issue of water use awareness will be also raised. In the wastewater reuse phase, the application areas are not only limited to a factory and industry. A broad viewpoint will be taken, including delivering to other factories and production chains, where this could be of benefit.

The method takes into account three aspects to improve water efficiency: Firstly, reducing water use as much as possible in every process/step, including identifying water leaks; secondly, identifying the processes which can use water of relatively low quality, and the wastewater generated from some processes, which can be treated up to improve quality, and thus increase the number of times water can be used in one factory; thirdly, increasing water availability with technical methods, such as rainwater harvesting. These three aspects provide an overview of sustainable water use in the entire value chain.

The basic idea of this approach lies in the combination of value stream mapping method in lean manufacturing, and the analysis of water usage within industrial factories. Since it is a visual representation of all the water related activities involved in production, it gives a quick and easy overview of water demand, water use and wastewater generation for each process along the process chain. The result of this concept is a basis, by which industrial factories can understand the detailed water use, both along the production chain and in the plant building and the comprehensive improvement measures in water efficiency through the factory. It also defines the destination direction of the wastewater output, through which a goal of zero wastewater will be achieved within a factory cluster.

The emphasis of this approach is on improvement guidelines to increase water efficiency and the identification of appropriate technologies for treating wastewater output to zero discharge. Fundamental to achieving this improvement is the accurate data collection and analysis, which identify critical process(es) or/and operation(s). Essentially, it identifies appropriate treatment technologies by contaminant analysis of wastewater. Structure of the methodology is shown in Figure 5-1, which includes water value stream analysis, water value stream design and water management.

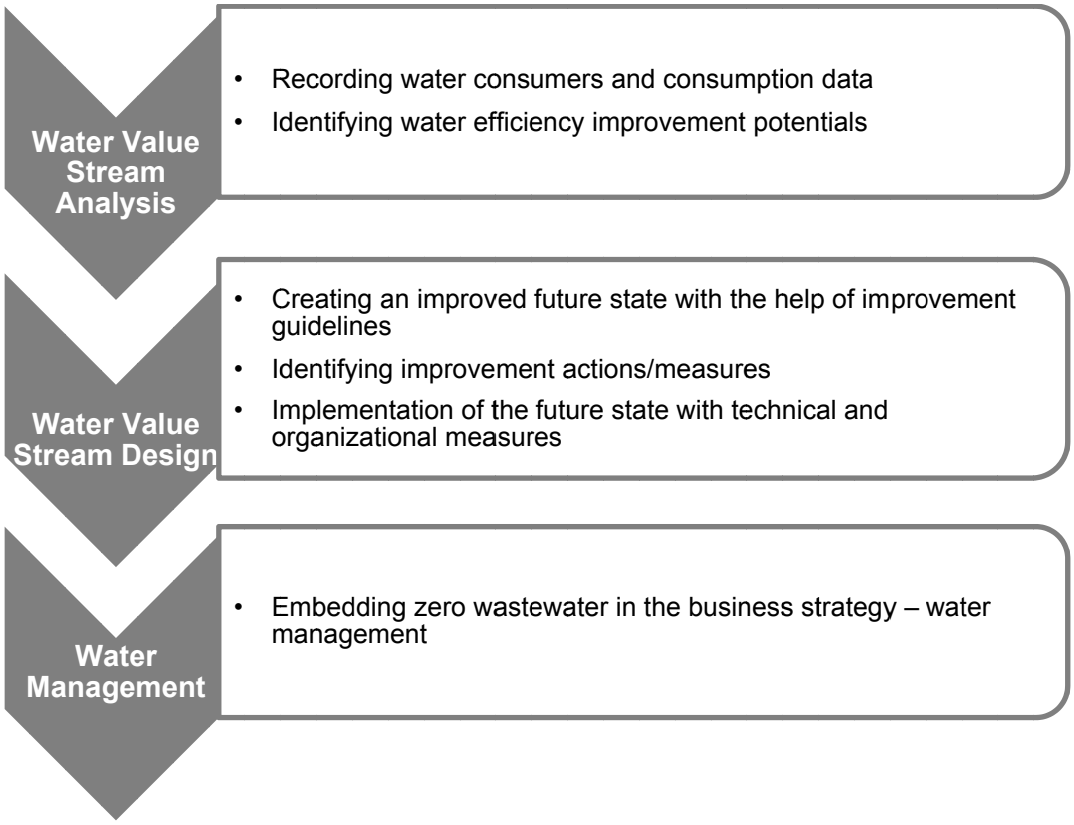


Figure 5-1: Structure of water value stream mapping to achieve zero wastewater discharge

Chapter 5.2 deals with water value stream analysis. Creating a product family including all product variants with resources, is shown in chapter 5.2.1. This is the first step in identifying water-related production in the plant. Then an investigation of detailed current water use in the factory will be undertaken. The collection methods of various water related data will be presented in chapter 5.2.2, namely by interview of workers, drawing from literature or the company's database, metering and estimates. In chapter 5.2.3, analysis of these water data plays the most important role. This helps planners to identify critical areas of freshwater use and wastewater generation in the factory. A current water value stream map will be drawn in chapter 5.2.4, which also points out the potential for water efficiency improvement.

Chapter 5.3 shows the design guidelines to improve the water use in the factory based on water value stream analysis. There are eight guidelines taken from a comprehensive viewpoint for freshwater abstraction to water use in production and plant purpose, and wastewater reuse in chapter 5.3.1. Raw improvement measures will also be identified. As a result, a future water value stream map will be established in chapter 5.3.2. The implementation of improvement measures will also be addressed.

In chapter 5.4, water management strategy consists of the continuous improvement of the water efficiency and a business strategy, with the goal of zero wastewater discharge, based on the Zero Emissions Concept of PAULI described in chapter 3.5.2.3. A layer model of

wastewater parameters will be created in chapter 5.4.1 to provide an overview of the quality situation. Finally, detailed work flow will be presented in chapter 5.4.2.

All of the production processes with the related material flow, information flow and corresponding water consumption will be integrated into the water value stream. The corresponding water consumption includes all the direct water used in production processes, supporting processes (for example transport and conveying), and other direct water use for plant purpose, e.g. plant cleaning, human use.

5.2 Water value stream analysis

5.2.1 Creation of a product family

At the beginning of each water value stream analysis, a decision must be taken as to which product family should be included in the water value stream. According to the original value stream analysis, the product range of the factory under observation is broken down into production-relevant similarity criteria. A product family includes all product variants produced in identical or similar production procedures using identical resources. The observation of product characteristics such as types of raw material, geometry, weight, manageability, and/or work content facilitates the creation of product families.

Each product family is mapped in a value stream depiction of its own. It is recommended to start with a product family of high quantity and low variance of the percentage of reasonable sales. Firstly, the respective product family's customer demand in annual quantity is identified, and then all previously determined water and water-related resource consumption figures are placed in relation with this customer's demand.

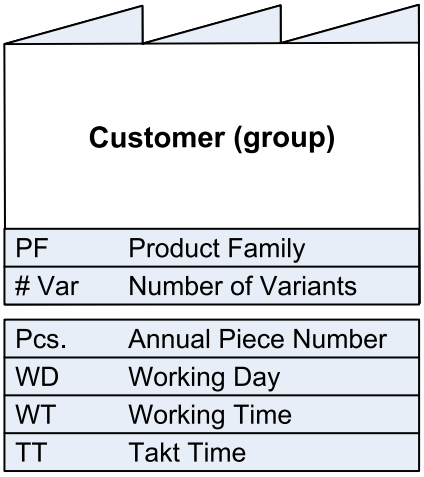


Figure 5-2: Customer symbol with data box and takt time

The customer is allocated in the symbol in Figure 5-2. The production performance requirement is calculated according to the customer's demand, and then expressed as the minimum achievable production rate. The takt time (TT) is calculated by division of the available work time by the customer demand:

$$Takt\ Time\ (TT) = \frac{Available\ work\ time\ per\ shift}{Customer\ demand\ rate\ per\ shift} = \frac{WD \times WT}{Pcs}$$

The work time results from the working day (WD) in the factory and the actual daily working time (WT) taken for the production process – in manual processes these represent attendance times minus break times.

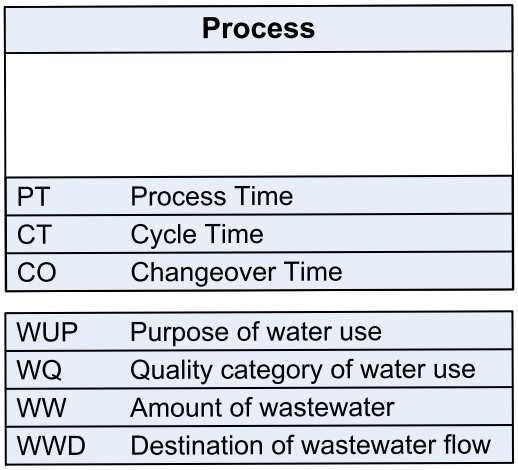
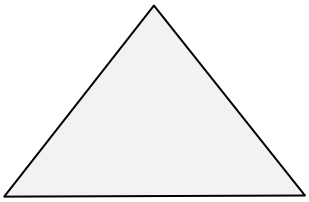


Figure 5-3: Process symbol with data box of process and water use

The production in water value stream analysis is represented by process sequence in a symbol as shown in Figure 5-3. The symbol for the production process is a rectangle with the process name at the top and the number of people required to operate the process – symbolized with stylized head and arms. The process is described with several process data listed in the box below the process symbol. The cycle time (CT) means the time that elapses between one part coming off the process and the next part coming off [Rhe-99]. It can be calculated from the numbers of operators and the available equipment and the process time. This value specifies the efficiency of each process as a production rate per part per time unit in value stream analysis. It helps to identify, whether the process capacity is sufficient to satisfy the customer's demand. The difference between cycle time and takt time is a further measure stand-by time for the facility, which plays an important role in the evaluation of water demand. The changeover time (CO) refers to the period required to prepare a device, machine, process, or system for it to change from producing the last good piece of the last batch to producing the first good piece of the new batch.

Some water data are added to the data box for water value stream analysis. The main purposes of water use (WUP) for each process, including cooling water (CoW), cleaning water (ClW) and process water (PW) will be described. It can be with both one purpose and also with several purposes. In most of the production process cleaning water may account for the largest percentage. The categories introduced in chapter 3.2.3.2 are used for the descriptions of quality category of water use (WQ) to define further wastewater reuse potentials. The amount of generated wastewater (WW) is also recorded into the process data box. The destination, to which the wastewater flows from the process, will be presented in the data box. The possible destinations are production processes, operations for plant purpose, wastewater treatment shop or directly to the natural environment.



TW: Tap water
GW: Groundwater
SW: Surface water
RW: Rainwater
ReW: Recycled water

Figure 5-4: Inventory symbol with percentages of water sources

The points where the product's material flow stops are symbolized by a warning triangle icon in the water value stream analysis, shown in Figure 5-4. It is always allocated before the process, and shows the accumulation of sources of water, which flow into the process. The combination of water from different sources will be clearly described here as the percentages of each sources below the triangle icon. In a manufacturing plant, most of the water use comes from surface water and groundwater. Tap water takes a smaller percentage and sometimes there is also water coming from the rainwater harvesting system. Recycled water coming from water treatment shop will increase the percentage with a higher attention on sustainable manufacturing.

Specifically for water use in the process, there are two "water lines" at the bottom of a value stream map which show four types of data:

- Water intake by each process in the value stream;
- Amount of water needed by each process in the value stream;
- Water intensity to indicate the water use driver; and

- Effluent intensity to indicate the wastewater discharge causer.

The two water lines are analogous to the timeline on value stream maps, and are shown in Figure 5-5. The line above shows the potential for water saving in each process. The line below, which is based on the processing time, indicates the water drivers and the wastewater causers when producing a product. The amount of water needed can be gathered from the published literature database or the best experience within the company.

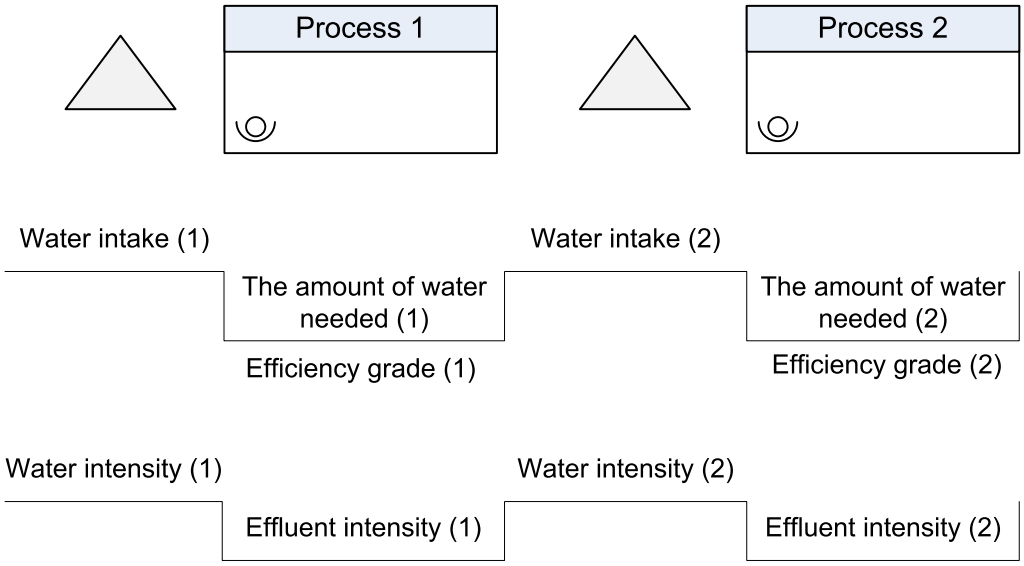


Figure 5-5: Water lines of a water value stream map

5.2.2 Data collection

5.2.2.1 Metering water flow

The water data including in water value stream are generally in two parts: freshwater flow and wastewater flow. Data collection is fundamental to the water value stream map and it should be obtained following a specific procedure which provides an accurate way to store, retrieve, and analyse the data. The best results will be achieved when the data is acquired on site, in the production area, at each individual production and operation location. When this is not possible, estimates can be made by referring to related literature, water bills, or by measuring either the intake or the discharge point of the process and comparing these.

To provide a snapshot of the current situation in the water value stream value, some measurements in the factory are essential: water intake and discharge of the whole plant; water intake and discharge of each process/operation; amounts of total reused and recycled water; and the amount of water that should be used, i.e. recommended by the maker of the machine, compared with a similar process in other machines or products, etc.

Table 5-1: Water flow meters commercially available

Meter		Types	Applicability	Water quality
Displacement	Nutating Disk	Invasive	low to moderate flow rates	Clean water
	Oscillating Piston	Invasive	low to moderate flow rates	Clean water
Velocity	Multi-jet meters	Invasive	Cold potable water where flow is in one direction	Clean water
	Turbine meter	Invasive	Sanitary, relatively clean, and corrosive liquids	Clean water
	Fire-service meters	Invasive	Fire-fighting service	Clean water
	Proportional meters	Invasive	Relatively constant but small percentage of the water	Clean water
	Propeller meters	Invasive	Main-line service with moderate flow rate	Clean water
	Compound meters	Invasive	Metering accuracy over a wide range of flows	Clean water
Orifice plate		Invasive	Continuous measurement of fluid flow in pipes	Clean water
Rotameter		Invasive	Fluid in a tube requires no external power	Clean water
Magnetic	Magnetic	Invasive	Widely used in wastewater systems	Clean and dirty water
	Electromagnetic	Invasive	All electrically conductive liquids with or without solids	Clean and dirty water
Ultrasonic	Transit time flow meter	Non-invasive	Fluid must not contain a significant concentration of bubbles or solids	Clean water
	Open-Channel flow meter	Non-invasive	Flow of liquids that are open to the atmosphere at some point in the measurement system	Clean and dirty water
	Doppler flow meter	Non-invasive	Slurries, liquids with bubbles	Dirty water

The person analysing the water value stream has to be aware of the underlying conditions of the data records, as not all the data is 100% accurate. Some of the points mentioned are, sometimes, impossible to measure because of several constraints, i.e. lack of space to install a water meter. If this is the case, the expert must use other methods to collect the volumes of

water that are being used. Water meters are the instruments used for measuring the flow of water. It is usually calibrated in cubic meters (m^3) or litres (l), although in some countries it is in cubic feet (ft^3) or US Gallons. In practice, most of the water flow meters are installed near the incoming water mains or at the end of main sewage lines [Sac-12].

A number of commercially available water flow meters with their characters and normal application areas are listed in Table 5-1, which provides a general reference for selection of water flow meters. Selection and installation of water flow meters vary for different processes or plants. However, the general criteria which should be taken into consideration are: water types, pressure, flow range, access to power, accuracy, access to meter, longevity, simple to operate and read and cost. Based on that, the water data which can be metered are: the intake and discharge of the whole plant, intake and discharge of each process and operation, see Table 5-2. Moreover, the installation of water flow meters should follow these standards:

- Installing the water meter in accordance with the manufacturer's specifications;
- Leaving sufficient straight length of pipe between gate valves, elbows etc. and the water meter to ensure there is no turbulence in the water passing through;
- The water meter should be adequate to the flow size in order to not loose accuracy.

A good water meter installation is a meter installed with sufficient distance between the meter and upstream and downstream sources of turbulence, such as elbows and valves, in accordance with the manufacturer's specifications [Hor-10]. Thus, an example of choosing the appropriate water meters and the installation locations are also stated in Table 5-2.

Table 5-2: Examples of measurement method of water data

	Type of meter	**Water types**	**Water meter location**
Intake of the whole plant	Turbine	Fresh water (municipal or from well)	Main pipe of the building
Intake of each process/operation	Compound or Ultrasonic	Combination of fresh water, recycled and, sometimes, reused water	The intake pipe of the process
Discharge of the whole plant	Electromagnetic	Wastewater from the plant	Main discharge pipe of the plant
Discharge of each process/operation	Ultrasonic	Wastewater from the process	Discharge pipe of the process

5.2.2.2 Other data collection methods

In the case where the flow meters cannot work when measuring the volume of water used by a process, a number of estimates have to be made (based on prior knowledge of the process). Such calculations must allow for partial filling or overflows. Table 5-3 exemplifies some calculations of water use in the factory. In some cases, the use of water from a tap has to be monitored (frequency of use, duration of use, and flow rate) to calculate the volume of water flow. In cases where direct monitoring is not feasible, the data could be obtained from the manufacturers' own database.

Table 5-3: Water flow rate and volume calculation [Sac-12]

Applications	Calculation	Equations
Water bath for rinsing, coating, dyeing	Volume of water in a rectangular tank	$L \times W \times D$ L: Length of the water tank W: Width of the water tank D: Depth of the water tank
	Volume of water in a cylindrical tank	$\pi \times R^2 \times D$ R: Radius of the water tank D: Depth of the water tank
Water flowing in a pipe, on a conveyor belt	Volume of water flowing through a pipe	$F_w \times T$ F_W: Flow rate per unit time T: Time per event

Table 5-4: Water consumption rates of some household fixtures [Per-09, UNEP-98, Tar-03]

Fixture	Water consumption rate
Toilets (manufactured after 2003)	5 l/flush
Kitchen sink (tap-mixer)	12 l/min
Shower (tap-mixer)	12 l/min
Bath (tap-mixer)	18 l/min
Washing table (tap)	6 l/min
Garden hose	8 – 10 l/min
Employee (full time without canteen)	25 – 50 l/day/person
Employee (full time with canteen)	40 – 90 l/day/person

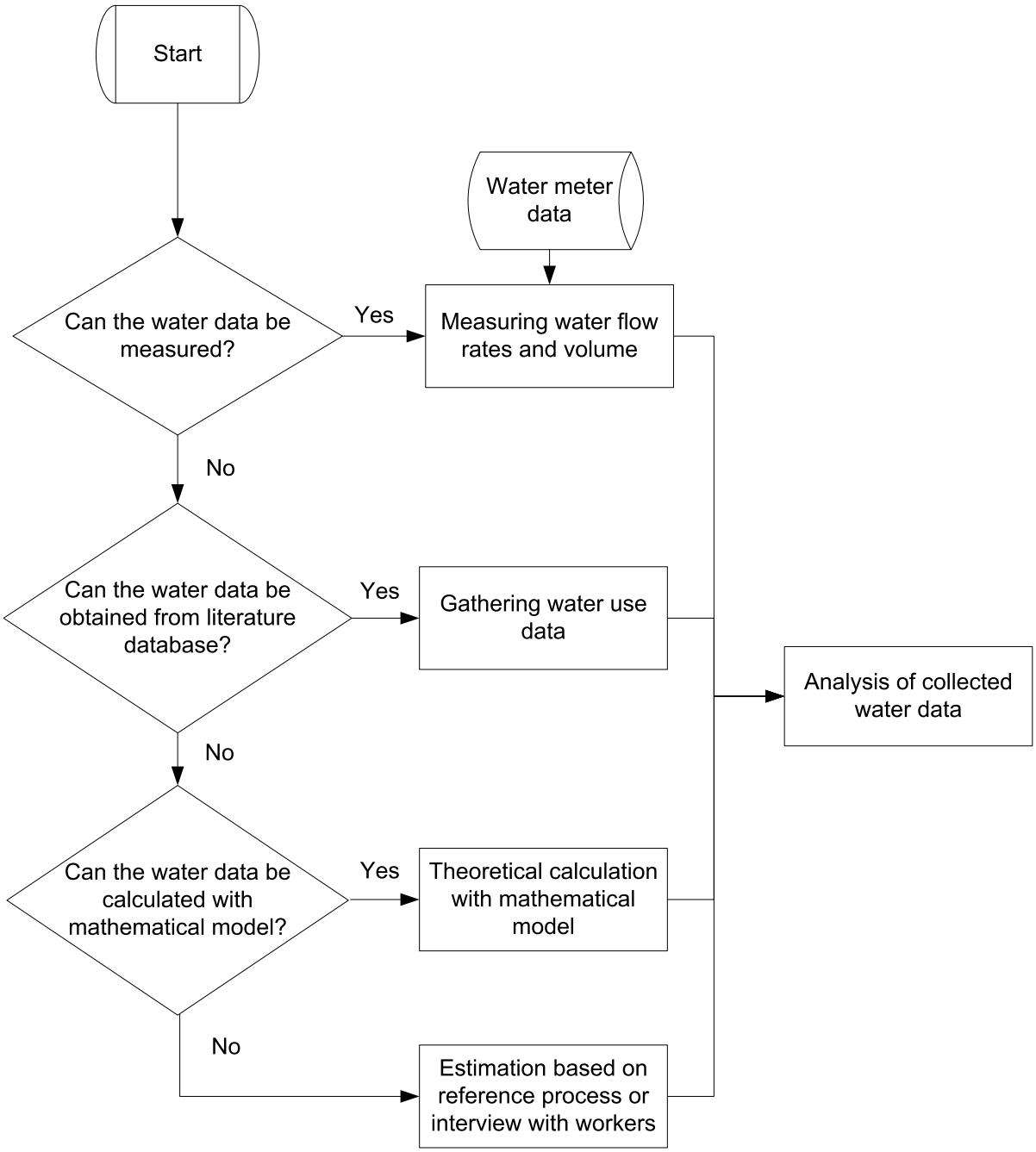


Figure 5-6: Steps of water data collection

Statistical water data collection could be used in processes and operations where direct water measurement and mathematical modelling are unfeasible, complex, or not cost effective. These methods rely on surveys and estimates, and therefore require thoughtful consideration and experiments making comparisons with water use by similar processes. This kind of method is recommended for non-production water. Typical domestic water consumption data could be used, such as those water consumption calculators provided by different organizations (a sample of which is included in Table 5-4).

5.2.2.3 Data gathering steps

Based on these feasible data collection methods, working methods of water data collection are presented in Figure 5-6. Firstly, data will be collected by metering, where this is possible, since the water data may always change. This information from water meters and the installation standard provide a reference point for their selection and installation. In case where the water data cannot be measured, planners should refer to the literature database to collect reference data. This will include published literature, commercial databases or the company's own database. If there are still some data which cannot be gathered, mathematical models can be used to estimate the data. If this is still unsatisfactory, an interview with workers or estimates based on some reference processes can be made.

5.2.3 Analysis of current water use

5.2.3.1 Water losses along water flow

To increase water efficiency, it is important to avoid water losses. Along the water flow in the factory, water losses happen almost everywhere in the plant, from withdrawal to transportation, storage, use and final discharge. In line with the seven types of waste in the original value stream mapping method, seven types of water losses are shown in Figure 5-7 along the water flow in the plant.

The *first type* of water loss happens in the collection of surface water, groundwater or rainwater, resulting from evaporation. The *second type* of water loss is mostly found in the manufacturing plant, which has a high requirement for water. The direct withdrawal of water also needs to be cleaned or filtrated. During water transport and storage, some water will be lost, because of leakages or physical losses (transmission mains, storage facilities, distribution mains or service connections) during supply (the *third type*). The water supplied at the point of consumption is then subject to further losses in day-to-day practice via evaporation and inefficient operations by machines or workers (the *fourth and fifth types* of water loss). Some wastewater generated from the process will be directly transported for further reuse in the process. Most of the wastewater will be treated before recycling and discharge. Without recycling, there will be considerable water waste from the factory, and this belongs to the *sixth type* of water loss. Furthermore, there are large losses during the wastewater treatment, such as evaporation, wrong treatment methods (the *seventh type*). Finally the useless wastewater will be discharged from the plant.

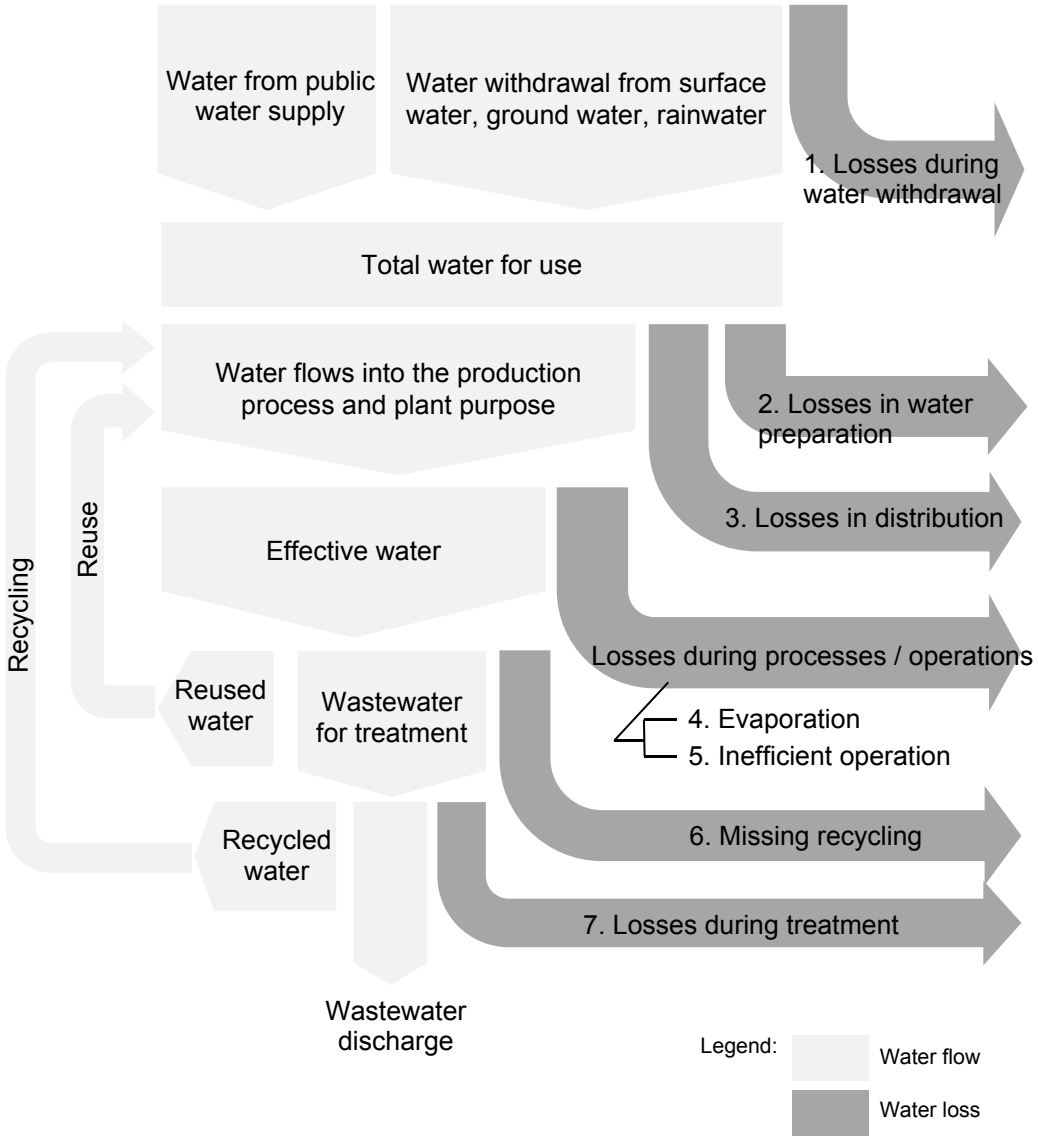


Figure 5-7: The seven types of water losses in the water flow model of factory use

By measuring water losses along the water flow through the factory, water losses can be analysed within the water value stream map. Regarding potential improvement measures, the seven water losses inside the factory can be further categorised into three parts: latent loss, real loss and functional loss, see Figure 5-8 [Tor-09].

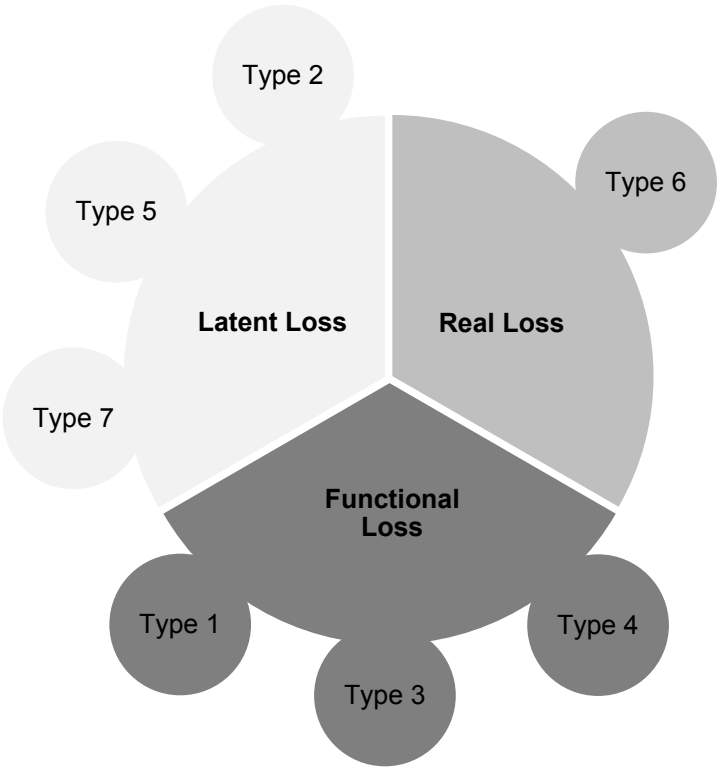


Figure 5-8: Water losses within the factory

Latent loss comes from the difference between the amount of water used by the process and water integrated to the product. It refers to the amount of water which enters the process but is not integrated into the output product. After discharging from any treatment process, water should return to its original state (the quality). Any losses will depend upon the quality of the untreated water. If the water can be returned to its original state, it can be captured or used within the factory again. This loss would belong to the latent loss. This kind of loss does harm to both the environment and the economy since it costs money. It does not add any value to the product, when it is discharged outside, and will have a negative impact on the environment. The water loss during water filtration and operations in production and water treatment (type 2, 5 and 7), which can be reused but flows directly out of the factory, belong to the latent loss. Methods to avoid this kind of loss could be improvement of the process or operation to a more water efficient status.

Real loss refers to the amount of water which is treated in water treatment processes. The quality does not return to its original physical-chemical state, so that it cannot be used in the process again. Although it can be used in a different process, where the quality demand on water is lower than in the process from which it generates. This kind of water loss is classified as real loss. This loss has an influence on both the costs and wastewater treatment, although the environment is not adversely affected, because the wastewater does not discharge to the natural source from where it was withdrawn. The cause of real loss is

water treatment technology. Ideal water treatment returns the quality of water to its original state. Water losses during treatment (type 6) belong to real loss. Obviously, the remedy to avoid real losses is improving and looking for appropriate water treatment technology.

Functional loss is the portion of the water that has been withdrawn, but not used, because it is lost in leakage, evaporation or physical or chemical alteration. Before the detection of leakages, this kind of loss is a permanent loss. Usually it happens because of the production process itself or a lack of maintenance. It exists in almost every place where water is used within the factory, from water withdrawal, distribution and storage, filtration to production processes and plant use. Therefore, water loss during water withdrawal, distribution and operation and because of evaporation (type 1, 3 and 4) fall into this category. Measures to avoid functional loss are monitoring water in different locations and regular maintenance.

5.2.3.2 Assessing water use

After recording the related water data into water value stream, an evaluation of these data should be done at the end of the analysis to identify the critical water use activities. Four key numbers – wasted water, efficiency grade, water intensity and effluent intensity – will be introduced into the evaluation of water value stream analysis.

The amount of *wasted water* refers to the difference between the amount of water used and the amount needed for the product processing. This number can help target the optimal water intake for improvements.

$$Wasted\ water\ =\ Water\ intake\ -\ Needed\ water \qquad [m^3]$$

The *efficiency gradient* compares the water intake of each production process with the needed water data and thus specifies a proportion of the process value. It represents a degree for the performance of process.

$$Efficiency\ grade\ =\ \frac{Water\ intake}{Needed\ water} \qquad [-]$$

The *water intensity* (WI) of a production process is the water required to produce one product from the product family. It refers to the litres of water spent on each product and is calculated by multiplying the water intake for a process and the takt time (TT) and divided by the process time (PT):

$$Water\ intensity\ (WI)\ =\ \frac{Water\ intake\ \times\ Takt\ time\ (TT)}{Process\ time\ (PT)} \qquad [m^3]$$

The water intensity of a value stream is the sum of the water intensities of all the production processes. It shows how much water is consumed to produce one product in the factory. A process with high water intensity is the water driver in the value stream, as shown in Figure

5-9. The highest water intensity occurs in the washing of parts. It means this process has a higher improvement potential on water use than milling.

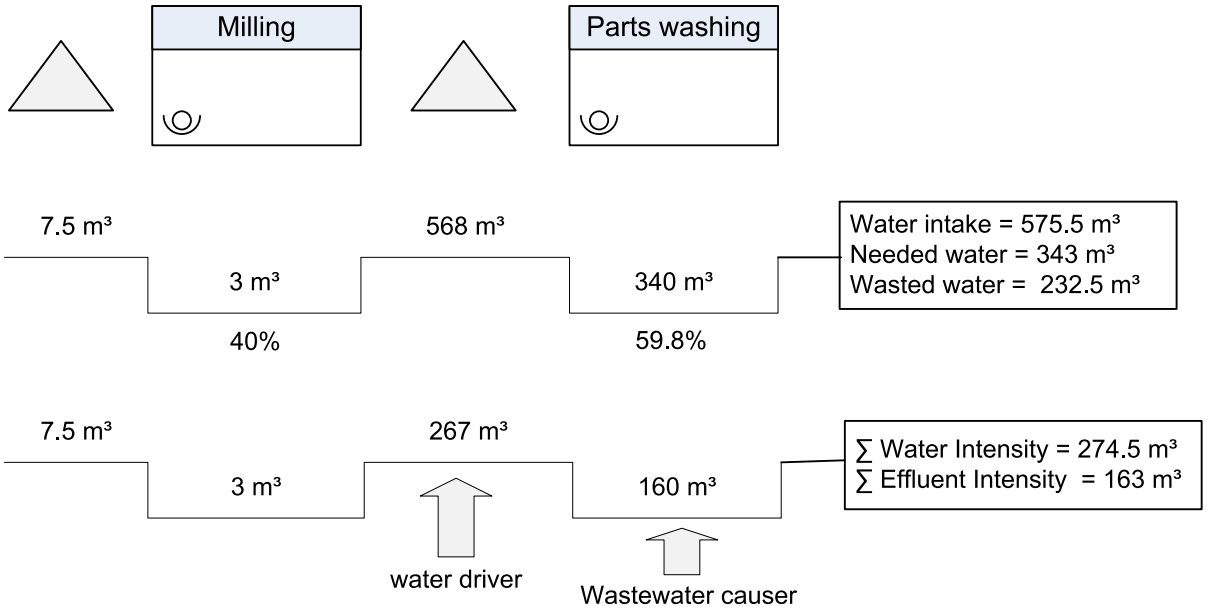


Figure 5-9: Identification of water driver using water intensity

Similar to the water intensity, the effluent intensity (EI) of a production process identifies the effluent when producing one product from the considered product family. It refers to the litres of water generated from each product and calculated by multiplication of wastewater amount of a process and the takt time (TT) divided by the process time (PT):

$$Effluent\ Intensity\ (EI)\ = \frac{Effluent\ \times\ Takt\ time\ (TT)}{Process\ time\ (PT)} \qquad [m^3]$$

The effluent intensity of a value stream is the summation of the single wastewater intensity of all the production processes. It shows how much wastewater is totally generated to produce one product in the factory. The process with high effluent intensity is the wastewater causer in the value stream, as shown in Figure 5-9. The highest effluent intensity happens in the process of parts washing. It means this process has a higher improvement potential on wastewater generation than milling. This number also has great value when analysing the composition of the wastewater.

The final stage of water value stream analysis is to conduct an evaluation from two viewpoints: water saving potential and water wastage.

- With the water intensity in a time line, the water driver in the production process will be identified in the value stream.

- With the degree of efficiency shown in a diagram, the values of production processes in the value stream are presented clearly.
- In the value stream map, the water wastage in the factory will be identified.

A so called *Kaizen Burst Icon* is used to highlight improvements on the water value stream map. Planners mark those icons with a specific description of improvement measures directly at the critical place of the current state map during the execution of improvement guidelines, see an example in Figure 5-10.

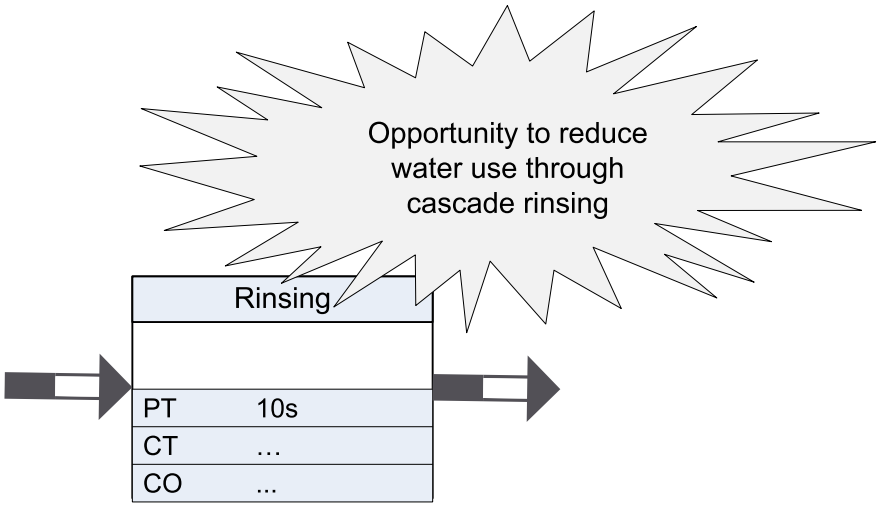


Figure 5-10: An example of marking kaizen for rinsing process

5.2.4 Current state of water value stream map

With the help of icons from value stream mapping, a map of the breakdown water use in a factory is presented in Figure 5-11 along the production line from supplier to customer. Legends are listed in appendix A.

At the top of the map are the water sources: tap water, surface water, rainwater, ground water and recycled water from water treatment process. The data box beyond the water treatment shows the information of recycled water which can be used again inside the factory. The grey arrow means the water flows from the sources to the process, giving an overview of water flow within the manufacturing plant. In the middle of the map is the process with production data, in particular water data in a sequence relating to the production line.

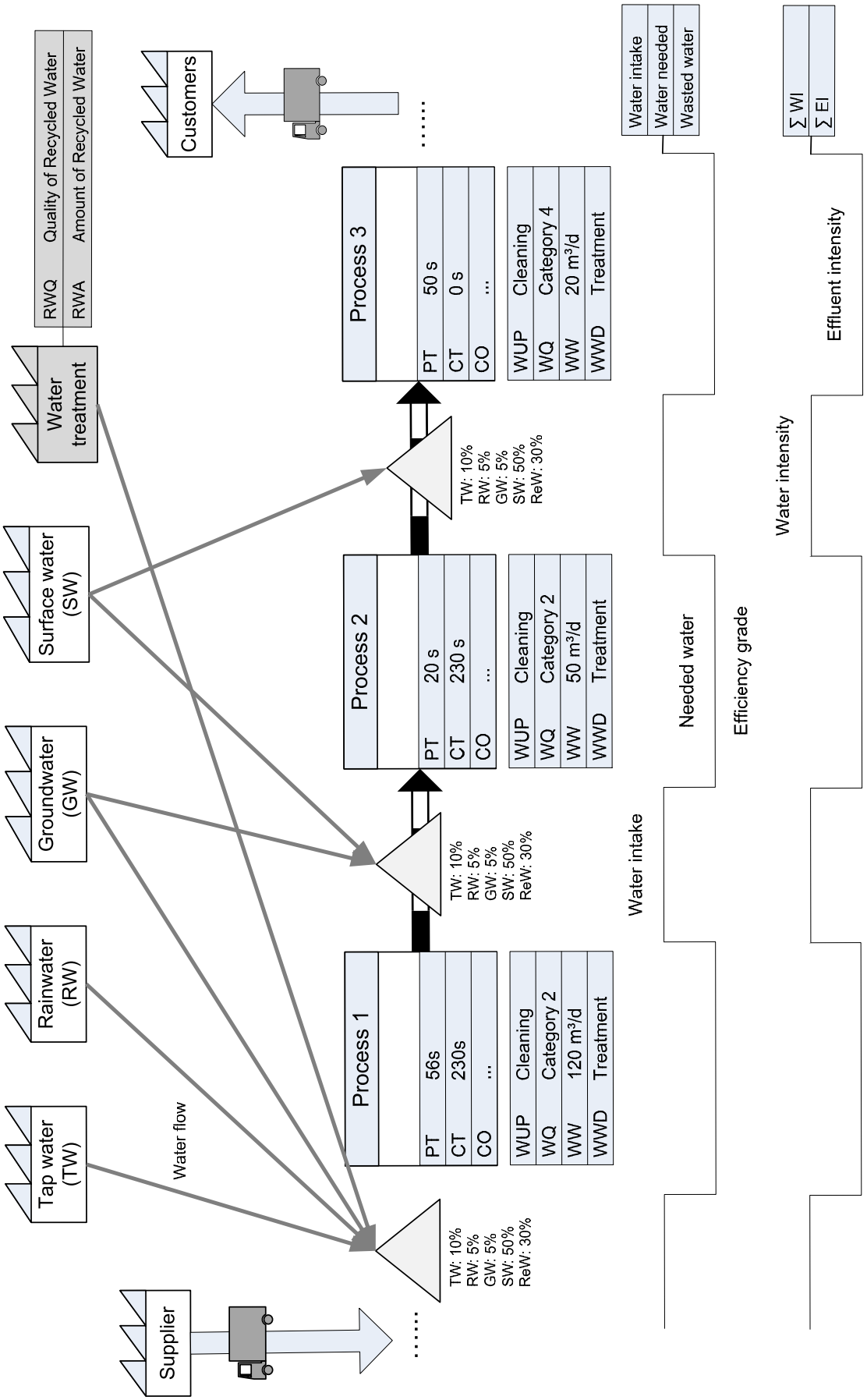


Figure 5-11: Schematic water value stream map of current state in a manufacturing factory

Each process has its water inventory which lies just before the water flows into the process, and which shows the combination of the water sources. Time lines are drawn under each corresponding process at the bottom of the map. The data box at the end of the time line shows the wastewater information which has to be discharged from the manufacturing plant, both directly from the production processes and from the treatment process. This wastewater effluent can be treated further to gain more value in accordance with a business strategy for water management.

5.3 Water value stream design

5.3.1 Improvement guidelines

Based on the results of potential improvements in the water value stream analysis, water value stream design serves as a method to achieve an improved production system in the future. Water value stream design provides a systematic approach for the identification and exploitation of potential improvements. With the design guidelines, it offers a systematic operation manual to achieve the goal of improving water efficiency in the production plant, see Figure 5-12.

The order of guidelines for improvement is not random. Rather, it sets out methods for the purpose of designing an ideal map for a water efficient factory. In other words, it creates a target vision. Therefore, the single process will be checked initially and then the interaction between each other along the whole value stream will be tested. However, some measures, even though being recognized as particularly efficient in saving water, may be rejected for economic reasons or because they cannot be financed. Various other restrictions also need to be considered. Nevertheless, since these restrictions might disappear over time, it is good to know the direction in which a company is heading in order to improve.

Improvement guidelines aim at increasing the water efficiency of the whole factory. Thus they concern all the water related activities within the factory. Three aspects are considered when designing the guidelines, namely, how to increase the water availability for industrial use, how to increase water efficiency in each production process and plant operation and how to raise water utilization within the factory.

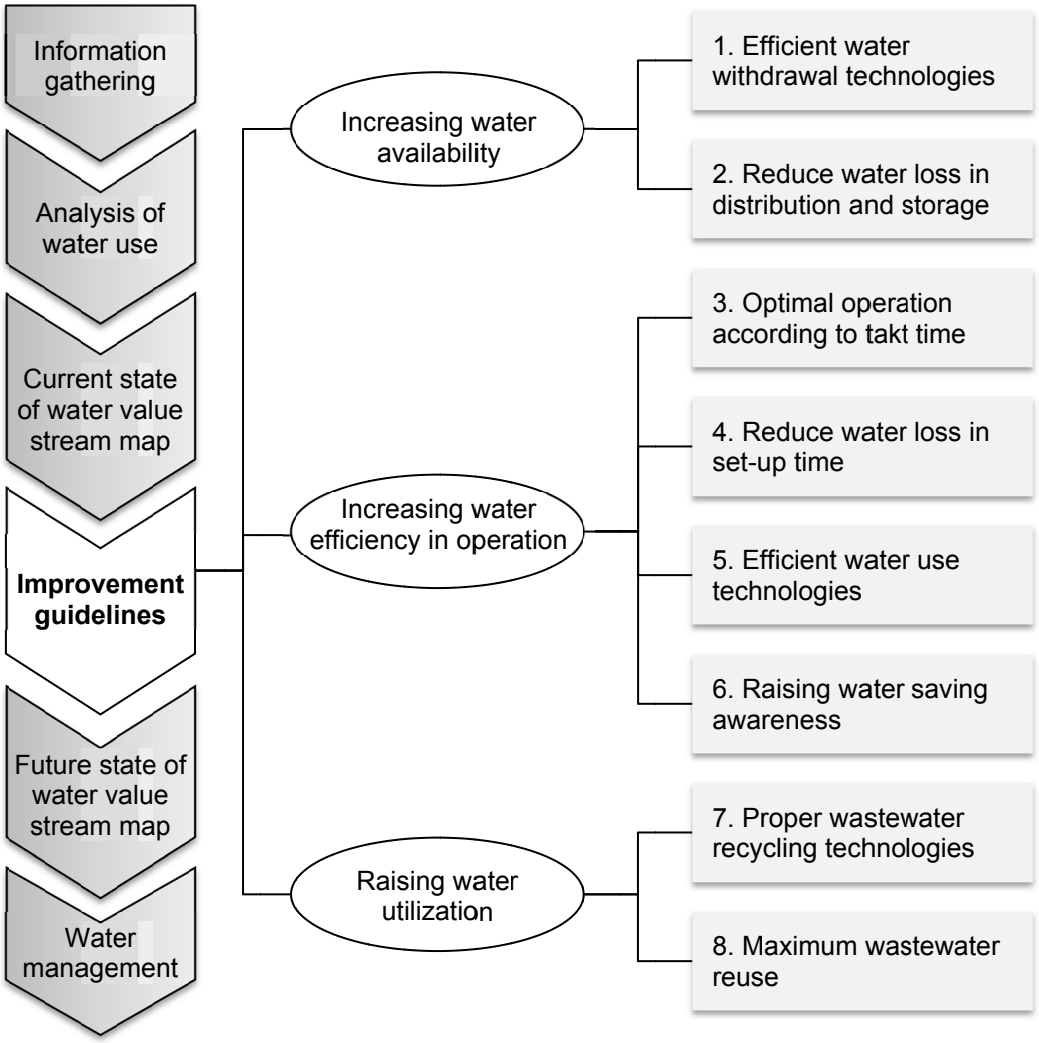


Figure 5-12: Improvement guidelines to increase water efficiency in a production plant

Guidelines 1 and 2 belong to increasing availability, 3 to 6 belong to increasing efficiency of each operation and 7 and 8 raise utilization. The eight guidelines with detailed descriptions are explained as follows:

Improvement Guideline 1: Increasing the available water resource by way of efficient water withdrawal technologies

Water for industrial use has four sources: drinking water, groundwater, surface water from river, lake, or steam, and rainwater, varying according to the factory's geographical location and local regulations. Table 5-5 lists the corresponding water withdrawal methods of these four sources and its costs.

Tap water, groundwater and surface water have widely been used in the industry. However, there is a great potential to collect rainwater to increase the water availability. According to DIN EN 12056-1, rainwater is defined as water from natural precipitation that has not been

contaminated by use. Rainwater harvesting systems can be installed in industrial companies, for use in flushing toilets, for cooling purposes, for washing and cleaning systems and for watering green areas [DIN-EN-12056-1].

Table 5-5: Water sources (without wastewater) and withdrawal methods for industrial use

Water sources	Withdrawal methods	Equipment
Drinking water (Tap water)	Public water supply system	• Pumps
Groundwater	Groundwater abstraction	• Wells and galleries • Pumps
Rainwater	Rainwater harvesting	• Rainwater collector • Filter
Surface water from river, steam, lake	Water abstraction	• Pumps

Choosing the most economic combination of water sources according to its current situation should be the key task, and always adjusted according to the change of water price. At the same time, industry planners should also think about the ecological aspects of water use.

Improvement Guideline 2: Increasing water availability by reducing water loss in distribution and storage system

Water loss occurs in the distribution and storage system within a factory. This has a strong similarity with water loss in the public water distribution system. Leakages in pipelines and storage tanks contribute to the largest amount of water loss. In addition, overflow from water storage tanks can be a cause of losses. To avoid this kind of waste, water loss control requires a comprehensive audit in the distribution system and interventions. Typical steps include:

- Gathering water information;
- Determining flows into and out of the distribution and storage systems based on estimates or metering;
- Establishing performance indicators (e.g., what parameters will be measured and how);
- Assessing where water losses appear to be occurring, based on available metering and estimates;

- Analysing data gaps (e.g., determining if more information is necessary to make comparisons and informed decisions);
- Considering options and making economic and benefit comparisons of potential actions; and
- Selecting and acting on the appropriate interventions.

According to the practical situation, including budget constraints, benefits and other scheduled capital improvements, the interventions should include detecting and locating leaks, repairing or replacing pipelines or other equipment, etc. To maintain the water distribution and storage system in good condition, regular maintenance or even real-time control should be undertaken by means of effective sensors and data processing systems.

Improvement Guideline 3: Suitable measurement through alignment with the optimal operating point according to the takt time

In order to make the water use in production as efficient as possible, it is necessary to know firstly, which product will be produced, and in what quantity. The production should be geared to customer demand. In the water value stream analysis, customer demands are expressed as customer takt. When using a target figure for sales development, this water value stream interpretation can also be considered for current and future water demands on production. To reach the average customer demand, how much water should be consumed during the production process have to be considered. From that, the production processes are expressed as being operated to achieve the customer takt with optimal water use.

Production at the optimal operation point consumes the minimal water for one product, i.e. has the minimal water intensity. A decline of production takt means the production is operated at part load. If the water use does not decrease proportionally, the water intensity will be increased. Similarly, the increase of the production takt from the optimal operation point will lead to a growth of water intensity, if the water demands increase disproportionately under conditions of production overload. Production resources and machine capacity should be designed in such a way as to allow the production takt at minimum water intensity to coincide with the customer takt time.

Figure 5-13 shows a schematic changing of water intensity with different production takt time. The guideline is particularly suitable for the situation where the curve of water use per item produced shown in the figure is very flat or horizontal.

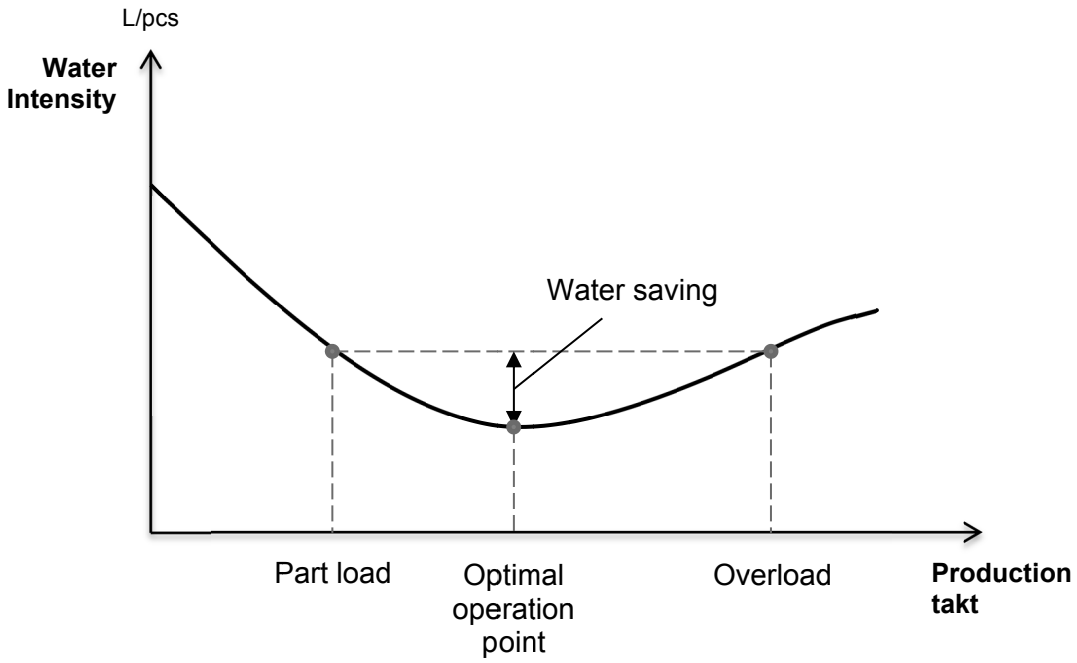


Figure 5-13: Schematic diagram of water saving at the optimal operation point

Improvement Guideline 5: Reducing the use of water in single operation by way of efficient technology

The water demands of a production process depend very much on the applied production technologies. Technical improvements to single facilities may therefore have a strong impact. Accordingly, this guideline concerns the application of alternative, highly efficient technologies and methods for the reduction of water demands.

This may be achieved through application of alternative, more efficient technologies with lower or no water requirements. For example, ozone sanitization of equipment can be used as an alternative to water based disinfectants. Use of dry ice blasting, and ablation technology can be another option to clean the machine tools after manufacturing. Conventional wastewater in industry may be generated from washing and cooling. Applying more efficient and environment-friendly processing technologies like dry cutting without any coolant and conventional dielectric fluids used in wet electrical discharge machines, replaced by a gaseous liquid in near dry electrical discharge machines, belong to this guideline.

Improvement Guideline 6: Minimum freshwater use by raising awareness of water use

Increasing workers' awareness of water use can save large amounts of freshwater use. Since more than half of the water use in a manufacturing plant is for cleaning and 40 litres

water is used for every full time employee where there is a canteen, raising the awareness of efficient water use is very important in establishing a water efficient production factory.

Industrial customers should be shown the effect of potential cost savings in product price and competitiveness. Examples should be distributed, and individual visits made to the larger water-using industries to carry out water audits and advice or how water can be saved. Waste minimization programs may also be promoted, showing that more water-efficient plant and better housekeeping can reduce water consumption and quantities of wastewater.

This promotion of awareness includes both water use in production and plant service. Factories should first develop a broad strategy for water conservation. The following steps in a top-down approach are recommended to prepare a detailed strategy for promoting water conservation awareness:

- STEP 1: Setting up a management committee inside the company to manage the promotion of water conservation. Employees with skills in social marketing, public relations, education and communications are required in addition to water professionals. This committee may carry out water audits under the guidance of water experts.
- STEP 2: Identifying water conservation awareness promotion activities. Detailed activities can be planned using a logical planning framework - –hat are the issues to raise with each audience, which messages are important to deliver, and what are the most appropriate ways to deliver them.
- STEP 3: Awareness dissemination activities, e.g. newsletters, regular training programs, publication of pocket guides, instructions for use of water appliances.

Improvement Guideline 7: Recycling of contaminated water using appropriate wastewater recycling technologies before reuse

Water treatment technology plays the most important role to increase the water use times. Recycling of contaminated water with appropriate wastewater treatment technologies relates not only to the cost of water but also to environment protection and local policy regulations.

Choosing an appropriate treatment method is depends upon a precise analysis of wastewater contaminants, experience of wastewater treatment and a comprehensive database of wastewater and its treatment. An appropriate treatment method doesn’t mean the wastewater can be treated as rigorously as possible, but rather to the degree which the reuse requires at the lowest cost. For example, normally we use biological treatment methods to treat pharmaceutical wastewater, and use physical and chemical treatment methods to treat wastewater from paper and pulp industries.

Improvement Guideline 8: Maximum wastewater reuse and recycling through elimination of wastewater and/or reuse of water without the need for any recycling process

Use of wastewater from a process in various downstream operations, like cleaning facilities, can increase the number of times water is used. This leads to a reduction in the amount of water consumed in the whole factory. To maximize the water use times calls for a comprehensive analysis of water demands in each water-related activity. This will determine the choice of treatment methods. To plan water reuse and recycling systematically, planners should carry out the optimal plan to maximize wastewater reuse and recycling with the greatest economic benefit.

5.3.2 Definition of measures for a future state of water value stream map

After the improvements according to the eight improvement guidelines, a practical implementation plan should be then undertaken for those improvement measures. The water flow on the map will be changed accordingly. The practical application will show whether or not other relevant factors need to be taken into consideration in addition to the guidelines mentioned above.

The application of the guidelines enables the systematic generation of improvement measures for processes, resulting in an ideal future state value stream with reducing water consumption. These measures are necessary for the realization of an ideal future state, which must be prioritized in accordance with the respective corporate strategy.

Once the suitable procedure of improvement measures has been determined for the realization of future state of water value stream map, the targeted implementation can be undertaken aligned with the corporate strategy. Important is, there should be an awareness of the effects of each individual measure with a view to economic, ecological and social aspects.

5.4 Water management to achieve zero wastewater

A sustainable water management in a factory should provide the continuous improvement of water efficiency. Therefore, constant efforts should be done to avoid water waste together with the company’s culture. In addition, wastewater can also be a value in the business chain, contributing to not only the economic profits, but also the ecological benefits. Hence, there is a need to look for potential use applications of the wastewater end-effluent use from one factory, which cannot be reused within the factory itself. It could be probably a valuable raw material for other factories, including manufacturing and agriculture-related industries. An organizational and technical combination of measures can reduce the wastewater to zero.

Wastewater flows to other manufacturing industries can be treated with the same methods as the reuse and recycling within the original factory. However, an effective combination is to use it as the raw material for agriculture-based industrial production. In this way, the nutrient contaminated in the wastewater could be beneficial.

Zero wastewater methodologies described in chapter 3.5 provide a basic know-how to develop it. However, some of them concentrate on production technologies, like Green Chemistry, and Upgrading. Some of them focus on the water use within the factory or processes, like cleaner production and recycling. Although industrial symbiosis can have the potential to use wastewater from one factory, it cannot ensure the final use of wastewater to a zero discharge. To achieve zero wastewater, the integrated biosystem and Zero Emissions Concept seem to be the appropriate methodologies. These involve not only industrial use, but also agriculture-based industries.

5.4.1 Presenting all parameters in a layer model

To find a suitable reuse area, a detailed analysis of ingredients in wastewater should be done firstly. The difference with the normal wastewater treatment is, this analysis concentrate more on the valuable ingredients, which could be benefit for other processes.

In order to present an overview of all potential methods, a layer model needs to be introduced. All related operations, influencing factors and parameters should be known before developing the layer model. They will be placed in different layers with connections to each other in the model. Such a hierarchical structure shows which parameter has a direct connection to which, and how it relates. The layer model will express clearly the following points:

- Listing all the important parameters for the wastewater;
- Systematic and hierarchical organization of the influencing factors and parameters;
- Visualizing and presenting the relationship to each other;
- Good overview of all parameters and factors
- The layer model is used as the basis for the development of a decision tree.

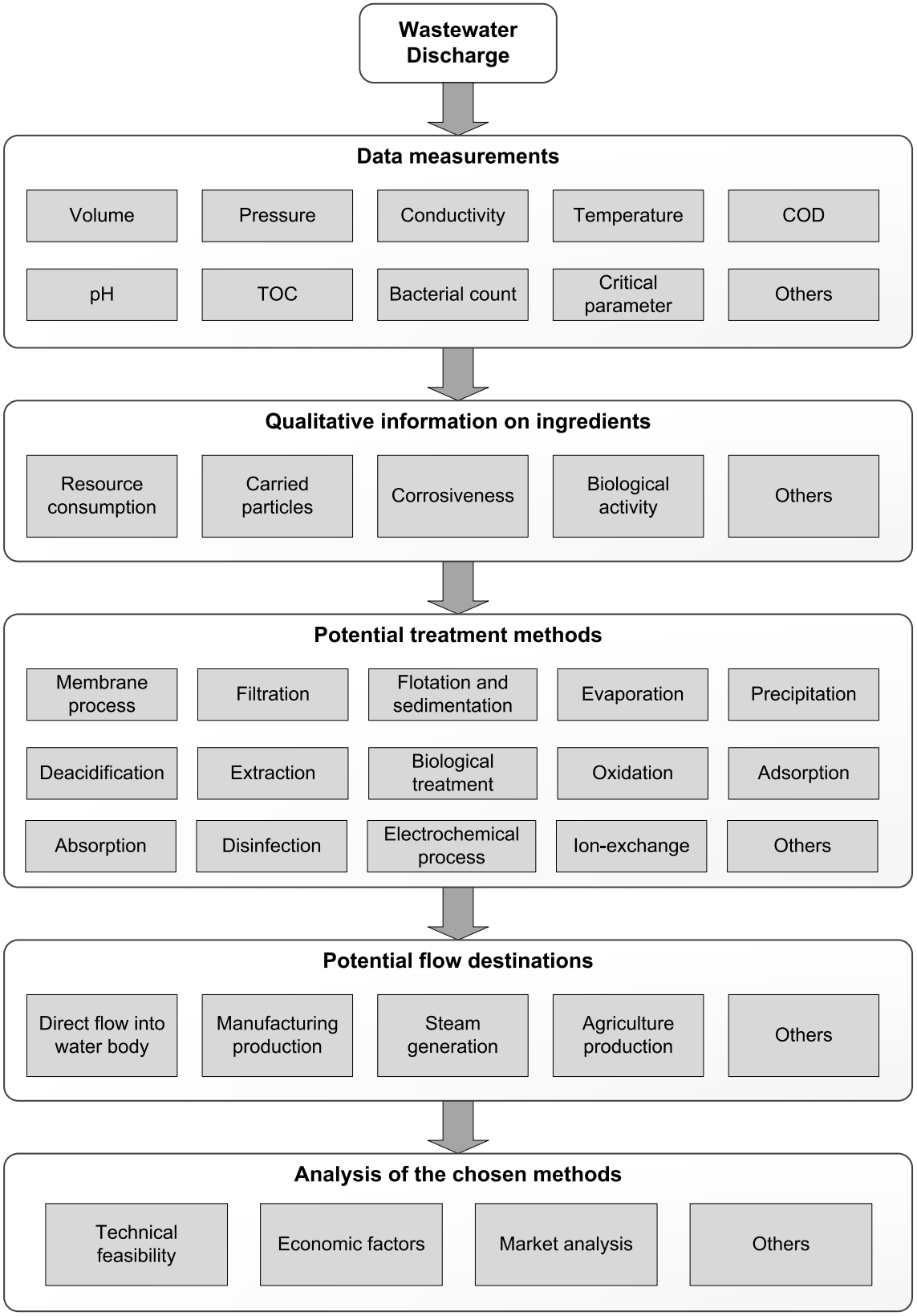


Figure 5-14: Layer model of the wastewater effluent

Figure 5-14 shows the layer model of the wastewater effluent. The first layer presents the measurement data, some of which may already be measured in operation. This will include volume, pressure, conductivity, temperature, and pH value, etc. The next layer is the qualitative information of ingredients, which is important for treatment decisions, e.g. resource consumption, particle carried, corrosiveness, biological activity. The third layer is the potential separation technologies with mechanical, chemical and biological treatment methods. The treatment methods, which are explained in chapter 3.2.3, can be used as single processes and also as a combination. An analysis layer follows to give a reference to support treatment and reuses decisions. It may include technical feasibility, economic factors, market analysis, etc. Finally comes the potential flow destinations layer, including flow into a natural water body (without treatment), flow into manufacturing production, generating steam, use as a raw material for agriculture production, and other water efficient methods.

5.4.2 Developing the work flow

The parameters which are collected in the layer model can be organized in a work flow. This procedure approach allows the users to work successfully with this structure. The work flow is used to carry out a recognition and estimation of the possibilities to operate a zero wastewater plan. Important parameters and possibilities will be applied to improve the wastewater reuse plan in business chain.

The work flow is developed based on the layer model, and includes all essential parameters and factors which are collected in the layer model. Two essential decisions, which support achieving a zero wastewater in an industry cluster, are: how to choose the wastewater treatment process or the combination of several treatment methods; how to decide the next applications of the wastewater.

Figure 5-15 shows the work steps from wastewater effluent to zero wastewater. After taking all parameters and factors, which are included in the layer model, into consideration, an Output-Input-Table can be drawn with potential external reuse applications. The Output-Input-Table will adopt the Zero Emissions Concept, which is explained in chapter 3.5.2.3. The market analysis and evaluation of these applications are carried out using, for example, feasibility analysis and economic calculation. After the deciding upon reuse applications, detailed treatment technologies will then be identified.

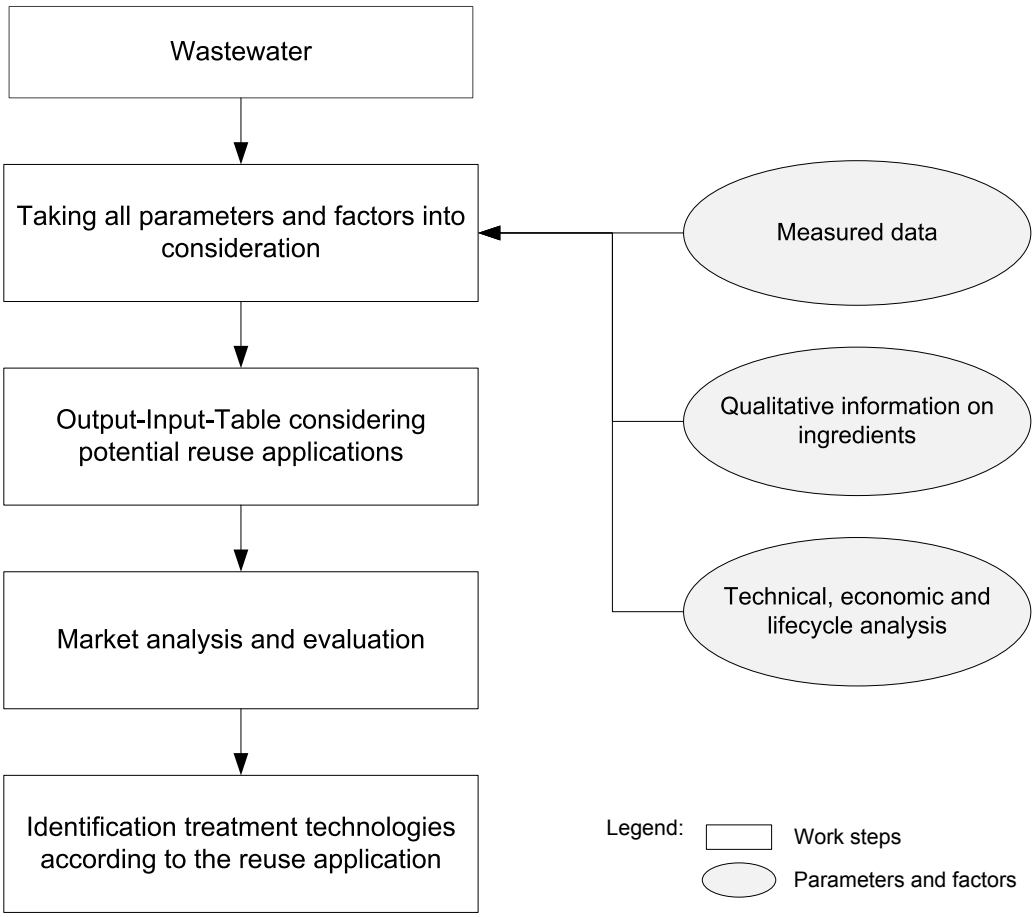


Figure 5-15: Work flow of the wastewater external reuse

6 Implementation

The implementation part of this paper will be divided into two parts according to the concept in chapter 5. Firstly, a water value stream analysis in an automobile company will be researched and improved with the example of a paint shop. Water management within business strategy will be implemented to achieve zero wastewater discharge, based on the wastewater treatment in a train service plant. The concept of zero wastewater will be tested by looking for a business plan for the total reuse of wastewater generated from the train in operation.

6.1 Water value stream analysis in an automobile industry

6.1.1 Conditions description

The automobile factory located in Germany produces important parts such as the car body. It assembles all parts, paints and checks all functions, while some parts or components have been already pre-assembled by suppliers, such as the central console and steering.

There are five workshops in the factory: press, body, paint, assembly and quality control. The car manufacturing process begins in the press shop where the body panels for cars are pressed. In the body shop, metal sheet is pressed into the shape of the body, and the body panels are assembled by an almost full-automated welding of body parts. Because of the large quantities of material, energy and water used, the paint shop has the greatest impact on the environment. Four layers of paint will be applied in this shop, and the underbody and cavities sealed. The final step in the manufacturing process of a car is the quality control. This occurs on the assembly line where all components will be checked before delivery to the customer. Industrial automotive assembly is a scheduled assembly of components, needed to make the car functional and usable for the customer. Table 6-1 shows the detailed processes description in each shop and water relations processes.

From the annual report regarding water use, 63.5% of the total wastewater is generated by sanitation facilities and 36.5% come from production processes [BMW-11]. The highest water consumption occurs in the paint shop, and large amounts of water are required in the preparation of the car body in the paint shop.

Table 6-1: Workshops description and water related processes in an automotive factory [Hon-13]

Workshops	Processes description	Water application
Press shop	• First pressing to form the panel • Second pressing to trim the panel to remove excess metal • Third pressing to bend the panel to create flanges • Fourth pressing to piercing holes for other fittings • Inspecting panels and transferring to storage	• Washing • Process cooling (water-soluble coolant)
Body shop	• Welding wheel houses • Combining engine compartment with floor assemblies • Welding all parts together to produce a completed body • Additional manual welding and door hinge installation • Fitting doors, tailgates, fenders and bonnet	• Process cooling (water-soluble coolant)
Paint shop	• Corrosion proof painting on metal surface • Sealing panel joints • Painting car bodies	• Washing • Water-soluble paint
Assembly	• Removing the doors • Fitting the wiring harness, roof lining, instrument panel • Assembling bumpers, fuel lines, exhaust • Fitting engine and suspension and steering components • Installing wheel and tyres • Installing carpets, seats and doors • Filling fluids (screen wash, coolant and brake fluid)	• Washing • Water-soluble coolant • Brake fluid (water absorbing)
Quality control	• Initial vehicle inspection • Sampling inspection • Pre-delivery preparation • Analysis • Complete inspection certificate	• Leakage testing (recirculated water)

6.1.2 Water value stream analysis

Processes in the paint shop include degreasing, phosphating, passivation and cataphoretic dip painting (CDP). The working time for one day is 16 hours with 2 shifts. Assuming the takt time is 1 min, water intake of this painting line is 480 m³/d [INCA-13]. According to the interview with employees, the amounts of wastewater generated from each process are 13 m³/d, 100 m³/d, 114.2 m³/d and 57 m³/d [Wit-03].

Although it is hard to find the exact amount of needed water for each process, the water footprint of the product (automobile) is found from other research, namely ca. 70 m³ [Ber-12]. 3% of it is result from painting. The daily productivity of paint line is 90 pcs. Thus the amount of needed water for painting line is 189 m³/d. Therefore, the theoretical water wasted in this production line is calculated as:

$$Wasted\ water\ =\ 480 - 189\ =\ 291\ m^3/d$$

According to the process time, takt time, water intake and the amount of effluent, the water intensity and effluent intensity for each process can be calculated. Thus it is obviously that, passivation has the largest water intensity and effluent intensity. Taking the process of degreasing as an example, the water intensity is calculated as:

$$WI\ =\ \frac{Water\ intake\ \times TT}{PT} = \frac{25\ m^3/d \times 1\ min}{4\ min}\ = 6.25\ m^3/d$$

The effluent intensity is:

$$EI\ =\ \frac{WW\ \times TT}{PT} = \frac{13\ m^3/d \times 1\ min}{4\ min}\ = 3.25\ m^3/d$$

Thus, it should be specially taken into consideration when undertaking improvement from aspects of both water consumption and wastewater generation. In addition, the water intensity in phosphating is also much higher than degreasing and CDC (cathodic dichromate). Thus technology to improve it should be concentrated on how to reduce water use in phosphating.

The current water value stream is shown in Figure 6-1.

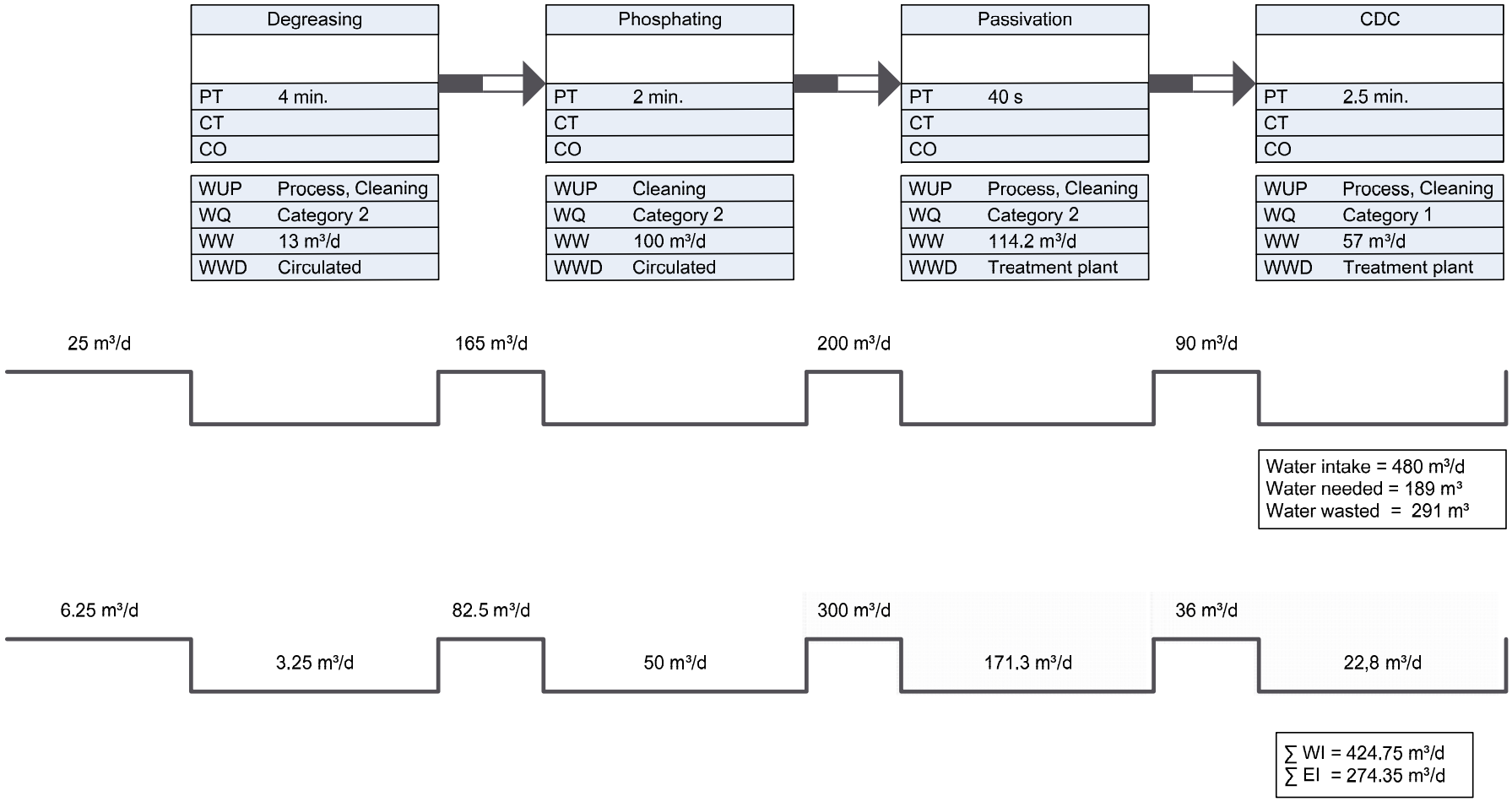


Figure 6-1: Current water value stream map of the paint line

6.1.3 Improvements

Based on these critical processes identified in water assessment, improvement options with the prediction of water saving potential and costs, are listed in Table 6-2, according to the designed guidelines. Regarding to the large amount of water use in the cleaning process, one option is directly reuse the wastewater generated from the process itself and without any freshwater input. In other words, the water is used circulated in cleaning.

Table 6-2: Application of improvement guidelines in the paint shop

Area	Guidelines	Improvement options	Water Saving	Cost
Increasing water availability	1. Efficient water withdrawal technologies	• Rain water tanks • Storm water harvesting • Groundwater	↓ - ↓↓	€€ - €€€
	2. Reduce water loss in distribution and storage	• Use alternatives to liquid ring pumps, vacuum pumps that require seal (gland) water	↓ - ↓↓	€ - €€
Increasing water efficiency in operation	3. Optimal operation according to takt time	• Production according to takt time	↓ - ↓↓	€ - €€
	4. Reduce water loss in set-up time	• Reducing water temperature	↓	€
	5. Efficient water use technologies	• Dry sweep all areas before hosing • Use water efficient nozzles for spray rinsing/hosing • Applying separation device after passivation to take the grease away	↓↓↓	€€ - €€€
	6. Raising water saving awareness	• Awareness dissemination activities, e.g. regular training programs, instructions for use of water appliances	↓	€
Raising water utilization	7. Proper wastewater recycling technologies	• Use ultrasonic cleaning processes	↓↓↓	€€€
	8. Maximum wastewater reuse	• Reuse water directly from the cleaning process	↓↓↓	€

Legend: ↓: low potential; ↓↓: medium potential; ↓↓↓: high potential;
€: low cost; €€: medium cost; €€€: high cost.

This implementation chose the paint shop in the water value stream mapping as an example, since this work shop consumes the largest amount of water use in an automobile industry. However, as the water value stream mapping focuses on the water use in the whole factory, further research should be carried out in other workshops. Finally an overall water value stream map for the factory will be drawn. Efficient and detailed improvements will be then presented.

This case study shows how the introduced concept of water value stream mapping is implemented in a painting shop of an automotive plant. The other case study presented in chapter 6.2 will show how the aim of zero wastewater is achieved in a factory cluster, with the example of the management of wastewater from a train service plant.

6.2 Zero wastewater in a factory cluster

The wastewater from several different types of train will be discharged in a train service plant. In this part, how to use this wastewater to achieve zero discharge in a business chain will be explained using the zero wastewater concept introduced in chapter 5.4.

6.2.1 Conditions description

The train service plant is located in Berlin, including a workshop, which is adjacent to the administration building, a wheelset overhaul and a washing facility for train cleaning. The water for cleaning the train is used from the treated well water. There are six types of train running into this service plant, with a total of 550 trains per week. Needed repair, drive control, regular maintenance, wheelset handling/exchange, bogie exchange, train washing and the disposal of toilets and wastewater containers will be undertaken in this plant.

The wastewater comes from sanitation (toilet, wash basin, dishwasher) and the condensation water from the air conditioning. In general the wastewater is divided into black water from toilets, wash basins and air conditioning, and grey water from kitchens.

Figure 6-2 shows the substance flow along the water flow in the service plant. Black water in the collection container is pumped within the plant, and discharged to the municipal evacuation network. In this plant, faeces are pumped by two different methods, according to where the train is parked. The train parked in the plant building, will be connected with a disposal pipe directly to the collection container. There is a macerator to shred the ingredients before being fed into the wastewater network. For trains parked outside, the faeces are fed into an evacuation truck with a volume up to 1,600 litres and then be transported to the station, where the faeces will be discharged to the wastewater network.

Since the processes in the hall area is a closed system and process changes will lead to a high cost, the improvement research concentrates only on the train outside the hall.

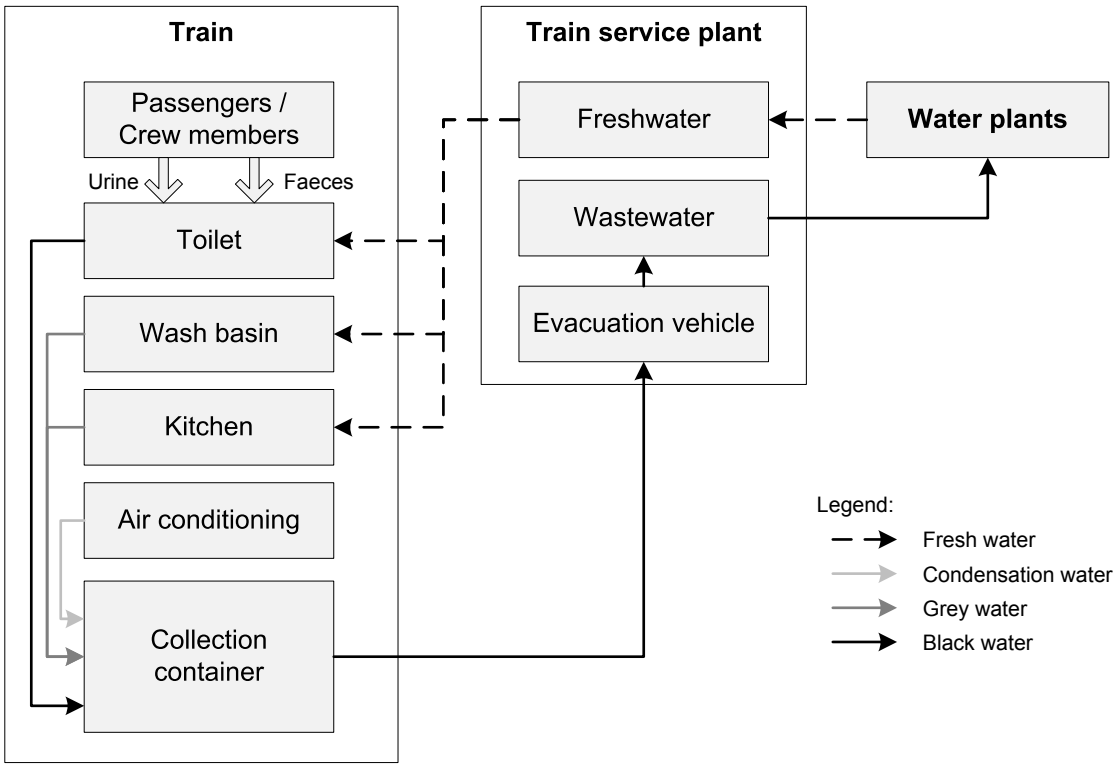


Figure 6-2: Current substance flow of water cycle in the train service plant

6.2.2 Wastewater data calculation

In 2011, a total of 108,000 wastewater containers were emptied in this plant. The average container volume is 825 litres. Based on data of the average capacity in each container, the total black water volume is calculated as being 25,920 m³.

According to the calculator of nutrient in black water (urine, faeces and toilet paper), the theoretical nutrient content from the black water containers are listed in Table 6-3.

Table 6-3: Theoretical nutrient contents from wastewater containers per year

Nutrients	Weight [kg]
Digestion of dry organic residues	90,396.7 kg
BOD	73,164.4 kg
COD	100,201.7 kg
Nitrogen (N)	42,931.7 kg
Phosphorus (P)	4,486.0 kg

Potassium (K)	10,661.6 kg
Sulphur (S)	2,989.3 kg
Amount of urine	5,456.6 kg
Amount of faeces	140.9 kg

In order to get an idea of nutrient contents, chemical analysis data of contents in faeces tanks was researched from 1996/97 to 2007. The result shows that there was a big fluctuation in the concentration of each nutrient. The concentration of phosphorus, for example, has a fluctuation range of almost 100 mg per litre, with a maximum reading of 160 mg per litre.

In research from 2007 and 2012, an average of 42,000 m³ of freshwater per year was supplied. With such a huge freshwater supply and associated wastewater discharge, the plant paid a total of 213,000 Euro per year for wastewater discharge both inside and outside of the plant building. In addition, every year the plant consumes about 2.3 million kWh electrical energy. This costs 423,000 euro, and when the electricity tax is taken into consideration, this equals 18.23 cent per kWh. For heating, in 2009, 5600 MWh were consumed, which cost ca. 650,000 euro.

As the substance flow shown in Figure 6-2, the fresh water flowing into the train comes from public water plant. The water for washing the outside equipment is extracted from a well in the plant. Passengers add faeces, urine, soap and toilet paper to the freshwater when using the toilet. Some unknown contaminants also flow into the faeces container.

Currently, black water which comes from faeces containers is discharged directly to the water treatment plant. Part of the water, however, will be treated and recycled for the use in the washer. Currently, about 70% is treated. The other 30% will also flow to the water treatment plant.

6.2.3 Output-Input-Analysis

In the Output-Input-Analysis, alternative reuse potentials will be researched to find the most appropriate method to maximum the utility of the wastewater.

The first output from faeces discharge is the faeces itself. In order to achieve an optimal reuse of every element, the solid and fluid part should be separated. The substance flow will then be separated into two different flows. The fluid part can be treated for divers reuse applications, e.g. irrigation, wash water in the train or washing the train body. The solid part can be reused for Terra Preta production. Terra Preta is a type of very dark, fertile anthropogenic soil with very high charcoal content. It is made by adding a mixture of

charcoal, bone, and manure. Detailed production processes are shown in appendix B.1. Thus it can be used as a fertilizer and soil additive in agriculture to produce energy crops, fruit and vegetables. Table 6-4 shows an almost complete reuse of ingredients through different substance flow.

Table 6-4: Output-Input-Table for reuse of the wastewater from the trains in the plant

Output / Input	Waste-water treat-ment	Grey water treat-ment	Terra Preta	Yellow water treat-ment	Train body washing	Irriga-tion	Sum
Grey water from train body washing		70 / 100					70 / 100
Residual from grey water treatment	None						
Black water from train container	100 / 100						100 / 100
Separated faeces from black water			100 / 100				100 / 100
Separated water with urine from black water				100 / 100			100 / 100
Nutrients from yellow water			100 / 100				100 / 100
Residual waste from black water	None						
Cleaned water from yellow water treatment					50 / 100	50 / 100	100 / 100
Residual from yellow water treatment	None						

Information from the Output-Input-Table can be translated in the processes, as shown in Figure 6-3. Firstly, black water will be separated into solid and fluid parts. The solid part is treated as a raw material for Terra Preta production, which will be used to grow energy

crops. These crops could produce the material for the generation of thermal energy. The fluid parts will be treated as a nutrient source for Terra Preta production and the remained water can be used for water applications with low quality demand, e.g. irrigation and washing. Such a system could achieve the complete reuse of wastewater from the train. Application of these processes with elements depends on the production amount of Terra Preta and the wood fuel.

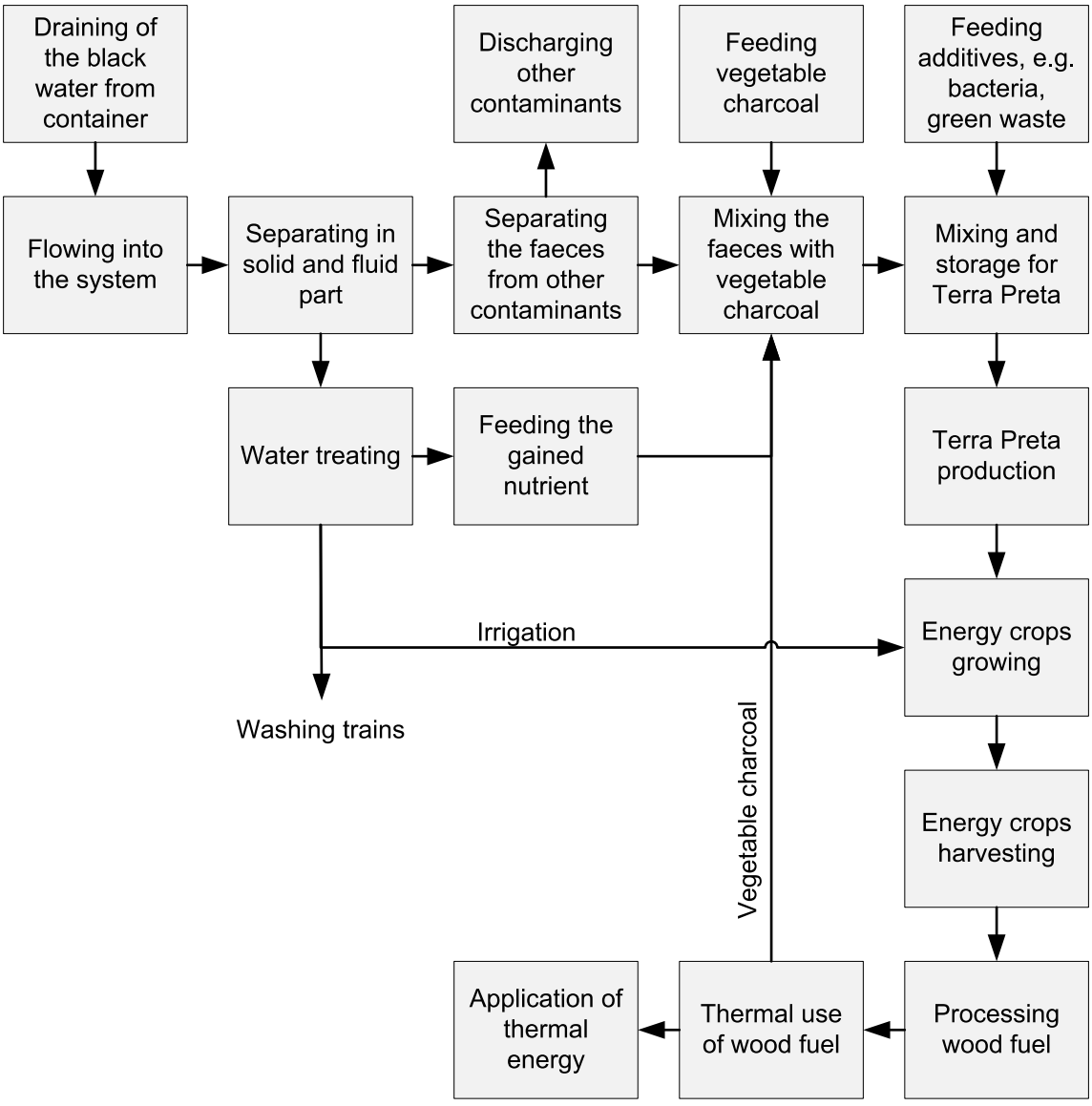


Figure 6-3: Schematic function structure of the reuse processes of the black water

6.2.4 Market analysis and evaluation

The solution potentials and products introduced in Table 6-4 should be subjected to market research. From schematic function structure, possible products which determine the dimension of the system are wood chips, vegetable charcoal and Terra Preta. Therefore, the

markets for these three products were researched and evaluated, with reference to their specification, application potential, competitive products, suppliers, demands, average price and possible market development, see Table 6-5.

Table 6-5: Market analysis of wood chips, vegetable charcoal and Terra Preta

	Wood chips	Vegetable charcoal	Terra Preta
Specification	Waste product in wood processing	Charcoal with • Conservation of structure • Storage for water and nutrients • Coal sequestration	Black earth with • Storable for water and nutrients • Coal sequestration
Application potential	• Thermal energy generation • Chipboard production	• Thermal energy generation • Enrichment of fertilizers	• Fertilization of agricultural soil
Competitive products	All thermally applicable products	All other types of coal for thermal recycling	Clays / granules with • Fertilizer with water storage capacity • nutritious
Supplier	Many	Fewer	Fewer
Demands	High in industry and private household	Low in agriculture	Low in agriculture and private household
Average price	96 €/t	ca. 1 €/l	ca. 1.52 €/l
Predict of market developing	Rising with increased use of renewable energy sources	Increasing, still in the development phase	Increasing, still in the development phase

6.2.5 Plan to achieve zero wastewater

The wastewater reuse plan takes all the elements from the schematic function structure into account. Element separation, water treatment, train body washing and Terra Preta are added to the current process flow. The separated fluid is treated further with biological particles, providing nutrient for Terra Preta production. The cleaned water with 25,000m³/a will be used to wash train bodies. In this way, a 10,350m³/a for train body washing can be saved from the well water and the remaining wastewater can be directed to neighboring train service plants. The separated solid will be used for developing Terra Preta substrate. It would ultimately produce Terra Preta in the plant when some raw materials from external suppliers are added. Terra Preta can be sold in the market to balance the initial investment in separators and

filtration equipment. The corresponding substance flow is shown in Figure 6-4. A rough layout of the Terra Preta production in the plant area is shown in appendix B.2.

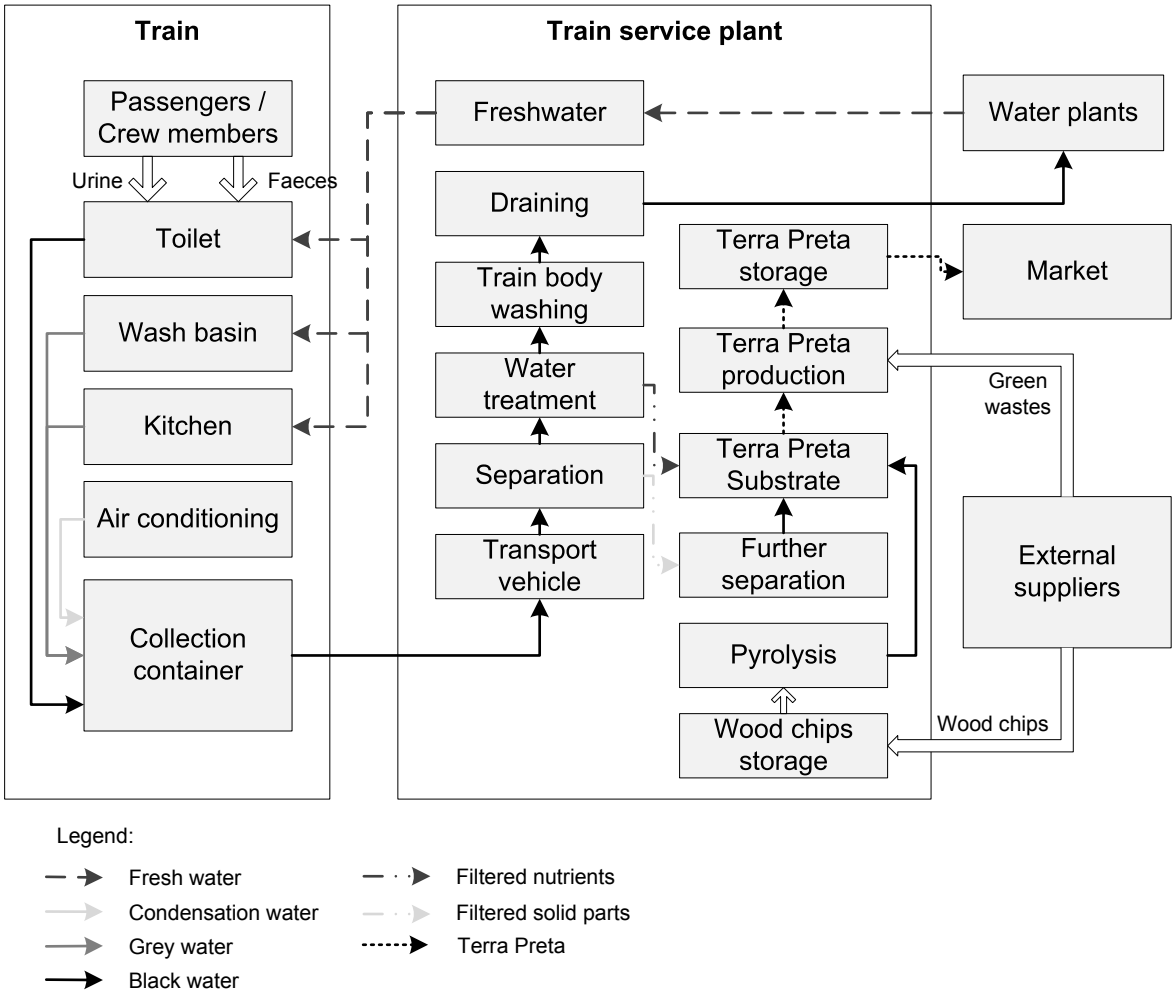


Figure 6-4: Substance flow with nutrient reuse in the train service plant

Based on the cost of raw materials, equipment, personnel, production, operation, management, maintenance, a modest calculation for the lowest sell price for Terra Preta results in 0.718 €/l. Compared to the average price of 1.52 €/l in the market analysis, the product has high potential for competition. Taking the average price in the market, further Break-Even Analysis shows that, after producing 1275 m³ of Terra Preta, i.e. over about 3 years, the system can hit the financial break-even point, see appendix B.3. However, in this calculation, personnel costs make up a large percentage. Further improvement would depend upon, whether the personnel cost can be reduced by some improved technologies.

7 Conclusion and outlook

Although water is relative abundantly available on a global scale, it is predicted that access to freshwater will be under increasing pressure if the current rate of unsustainable use and discharged pollution are not improved. This environmental pressure leads to an increase in freshwater and wastewater discharge prices, together with more and more restrictive legislation. Facing these challenges, as industry is one of the largest sectors of contaminators, it will have to minimize water use and wastewater discharge.

The review of global water availability, with a focus on industrial use and pollution, represents an overall basis for sustainable use. Industrial wastewater treatment methodologies and existing zero wastewater technologies offer the potential to minimize wastewater discharge. Available water assessment technologies and tools have highlighted their effectiveness with some specific application areas, but there is a lack of systematic approach to water flow in the factory. With these requirements, a systematic approach has been developed which would identify critical water use from processes through cells to the factory level. There is potential for improvement in both reducing water intake and reducing environmental impact in the business plan.

Water value stream analysis provides a platform, upon which all water consumers can be identified within a production related organizational connection to each other. Thus the production process with its water consumption amount would be clear. The entire water requirement of a factory can be shown with the production flow in a transparent way. Water consumption, which is normally only captured centrally, will be allocated to its consumer. In this way, it will be clear, how much water is required for which process, and in which step of the production flow.

This thesis investigates a methodology to improve water efficiency and minimize environmental impacts of wastewater in industrial factories, based on value stream mapping and zero emissions methods. Water data are collected from related processes and operations by metering, literature and estimation. Water losses and water intensity analysis is then undertaken to look for critical water use processes in a factory. Based on this, a current map of water use along the process flow in an industrial factory is presented, which provides a clearly visual representation of water use and wastewater generation within the whole factory. Eight improvement guidelines are offered to increase water availability, to increase water efficiency in operation and to raise water utilization. With a reduction of water intake to minimum level, methods to achieve maximum wastewater reuse in a business dimension are introduced. Although there are some existing methodologies to reduce the wastewater discharge to zero, much of them use efficient wastewater treatment technologies with high costs. An economic and ecological way to achieve zero wastewater can be undertaken based on the idea of industry clusters. The valuable constituents in wastewater can be profit for another production use, especially some agriculture-based production. With

a layer model for the description of the condition of wastewater, the potential for organizational reuse methodology is presented.

The operability of the developed concept is validated with two example case studies. The first example shows how the water value stream mapping method is applied in a paint shop of an automotive factory. In the example of treating wastewater from train maintenance, a method of planning a zero wastewater discharge system within the business strategy is shown.

This approach offers a starting point and a basic framework for improving water use in an industrial factory in a systematic and business way. However, still some improvement can be added to the existing model to achieve sustainable water use. Further researches should be undertaken to improve the system in the following ways:

- Updating the database of the amount of water needed for each operation as a reference point;
- More effective indicators to show critical points of water use and wastewater generation, within the factory's own situation;
- Improvements to wastewater treatment decision-making by developing new methods and improving existing technologies;
- An decision-making algorithm can be established to support the choice of external reuse areas in the business;
- Continuous improvements of wastewater application in business with the development of agriculture-based production.

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8.2 Norm

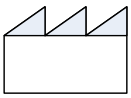
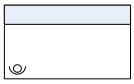
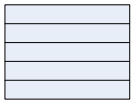
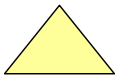
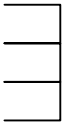
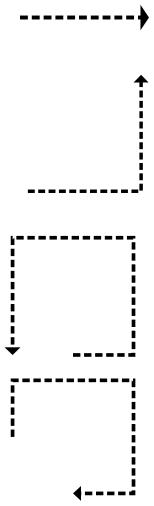
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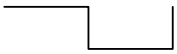
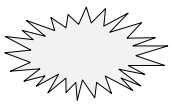
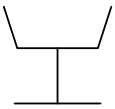
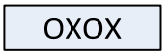
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9 Appendix

A. Value stream mapping process symbols

	**Customer/Supplier Icon** Represents the Supplier when in the upper left, customer when in the upper right, the usual end point for material.
	**Dedicated Process flow Icon** A process, operation, machine or department, through which material flows. It represents one department with a continuous, internal fixed flow.
	**Data Box Icon** It goes under other icons that have significant information/data required for analysing and observing the system.
	**Inventory Icons** show inventory between two processes
	**Shipments Icon** It represents movement of raw materials from suppliers to the Receiving dock/s of the factory. Or, the movement of finished goods from the Shipping dock/s of the factory to the customers.
	**Push Arrow Icon** It represents the “pushing” of material from one process to the next process.
	**Supermarket Icon** An inventory “supermarket” (kanban stock point).
	**Material Pull Icon** Supermarkets connect to downstream processes with this "Pull" icon that indicates physical removal.

	**FIFO Lane Icon** First-In-First-Out inventory. Use this icon when processes are connected with a FIFO system that limits input.
	**Safety Stock Icon** It represents an inventory “hedge” (or safety stock) against problems such as downtime, to protect the system against sudden fluctuations in customer orders or system failures.
	**External Shipment Icon** Shipments from suppliers or to customers using external transport
	**Timeline Segment Icon** It shows value added times (Cycle Times) and non-value added (wait) times. Use this to calculate Lead Time and Total Cycle Time.
	**Kaizen Burst Icon** It is used to highlight improvement needs and plan kaizen workshops at specific processes that are critical to achieving the Future State Map of the value stream.
	**Sequenced Pull Icon** It represents a pull system that gives instruction to subassembly processes to produce a predetermined type and quantity of product, typically one unit, without using a supermarket.
	**Kanban Post Icon** A location where kanban signals reside for pickup. Often used with two-card systems to exchange withdrawal and production kanban.
	**Load Leveling Icon** A tool to batch kanbans in order to level the production volume and mix over a period of time.
	**Electronic Information Icon :** This wiggle arrow represents electronic flow such as electronic data interchange (EDI), the Internet, Intranets, LANs (local area network), WANs (wide area network). You may indicate the frequency of information/data interchange, the type of media used ex. fax, phone, etc. and the type of data exchanged.

B. Information and data in the case study of train service plant

B.1 Production of Terra Preta and its composition

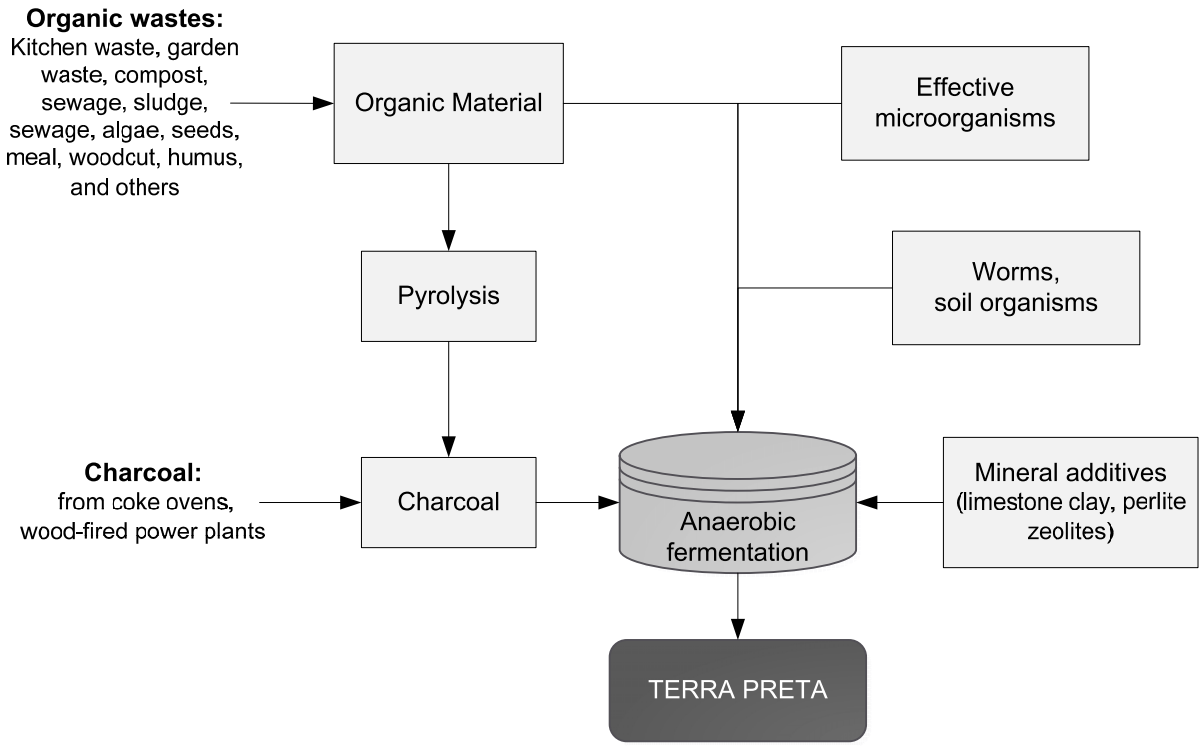


Figure 9-1: Production of soils according to the Terra Preta principle (Source: www.terra-preta.de)

Table 9-1: Comparison of the carbon efficiency of methods to produce vegetable charcoal

Method	Carbon-efficiency
Humus production through composting	5 – 10%
Charcoal production (Combustion temperature < 450°C)	25%
Pyrolysis	50%
Hydrothermal carbonization (HTC)	80%

B.2. Plan of zero wastewater application

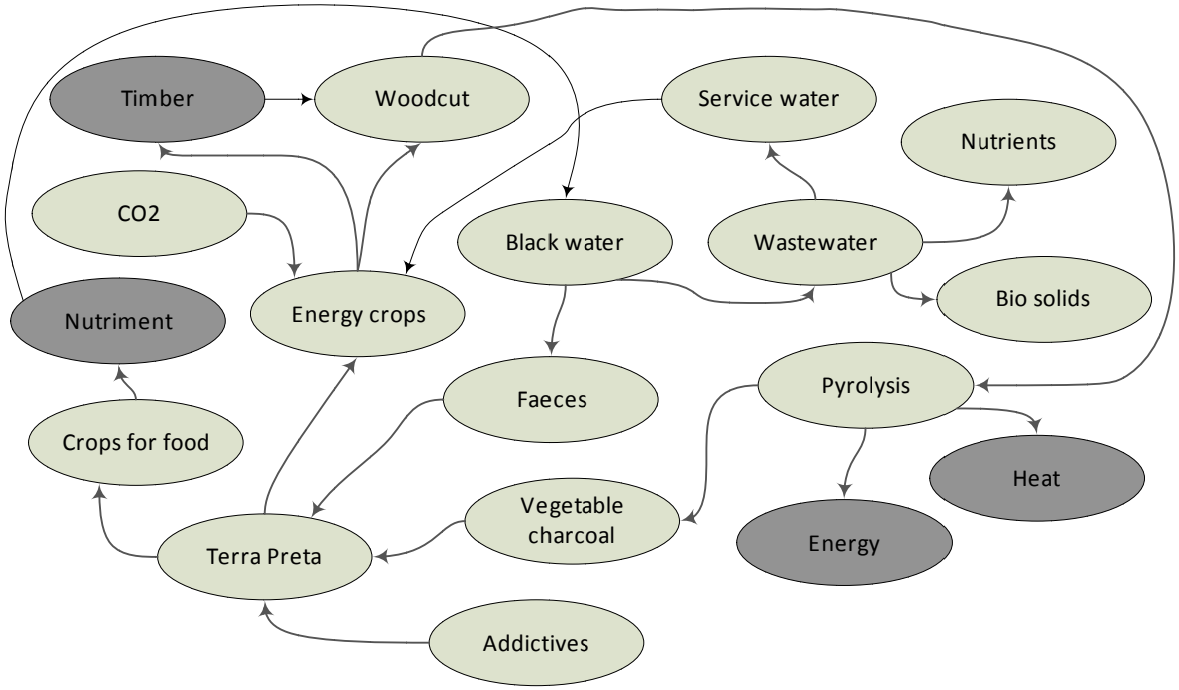
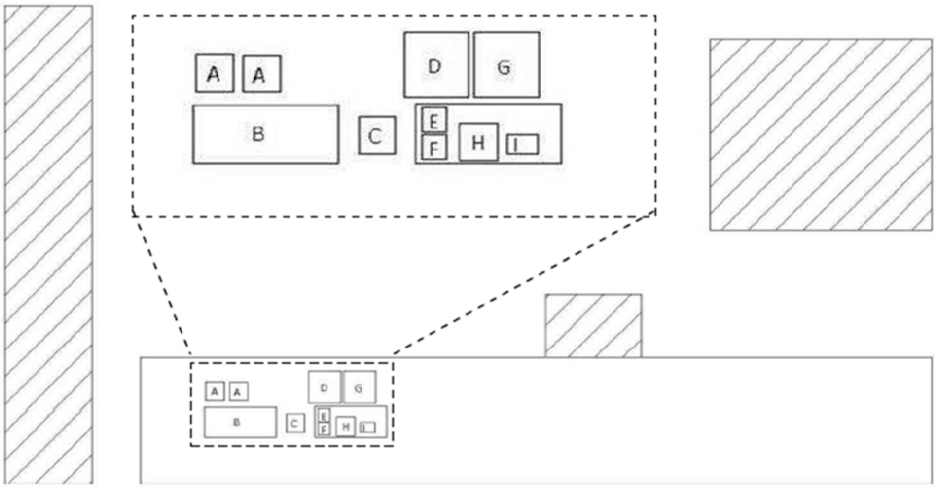


Figure 9-2: Schema of a faeces reuse process



A	wood chips storage container	F	Faeces mixer
B	pyrolysis	G	Green waste
C	vegetable charcoal container	H	Terra Preta mixer
D	Black water container	I	Terra Preta container
E	Separator		Building

Figure 9-3: Rough layout of a Terra Preta production within the train service plant

B.3 Economic calculation of the zero wastewater application

The tables and figure below shows the economic analysis of the investment of such zero wastewater application.

Table 9-2: Summarization of the important parameters for the cycle of substance flow

Process	Volume	Process time
Separation	1600 l	15 min.
Cleaning of the faeces	12.96 l	30 min.
Mixing faeces and coal plants	16.6 l	30 min.
Green wastes	37.02 l	30 min.
Storage of Terra Preta	1.13 m³	24 h
Water treatment	1600 l	15 min
Demand of vegetable charcoal	41.1 m³	per year
Demand of wood chips	137 m³	per year

Table 9-3: Process data of pyrolysis equipment under full load

	Woodchips	Vegetable charcoal	Electrical energy	Thermal energy
Amount	90 kg/h	25 kg/h	35 kW/h	110 kW/h
Cost	96.00 €/t	0.8 €/t	0.1823 €/kWh	0.11579 €/kWh
Consumed / produced amount	30,897.0 kg/a	8,582.5 kg/a	12,015.5 kWh/a	37,763.0 kWh/a
Cost/Value	2,966.11 €/a	6,866.00 €/a	2,190.43 €/a	4,372.58 €/a
Sum	2,966.11 €/a			13,429.00 €/a
Difference	10,462.89 €/a			

Table 9-4: Calculation of minimal selling price for one cubic meter Terra Preta

Calculation of cost price [€]	
Production material basic price	31.54
Material overhead (10%)	3.16
Material cost	34.70
Machine cost	150.30
Personnel cost	302.79
Manufacturing cost	453.09
Production cost	487.79
Administration cost (15%)	73.17
Distribution cost (8%)	39.02
Cost price	**599.98**
Calculation of minimum selling price [€]	
Cost price	599.98
Profit (15%)	90
Cash sale price	689.98
Cash discount (2%)	13.80
Target sale price	703.78
Discount (2%)	14.08
Minimum selling price	**717.85**

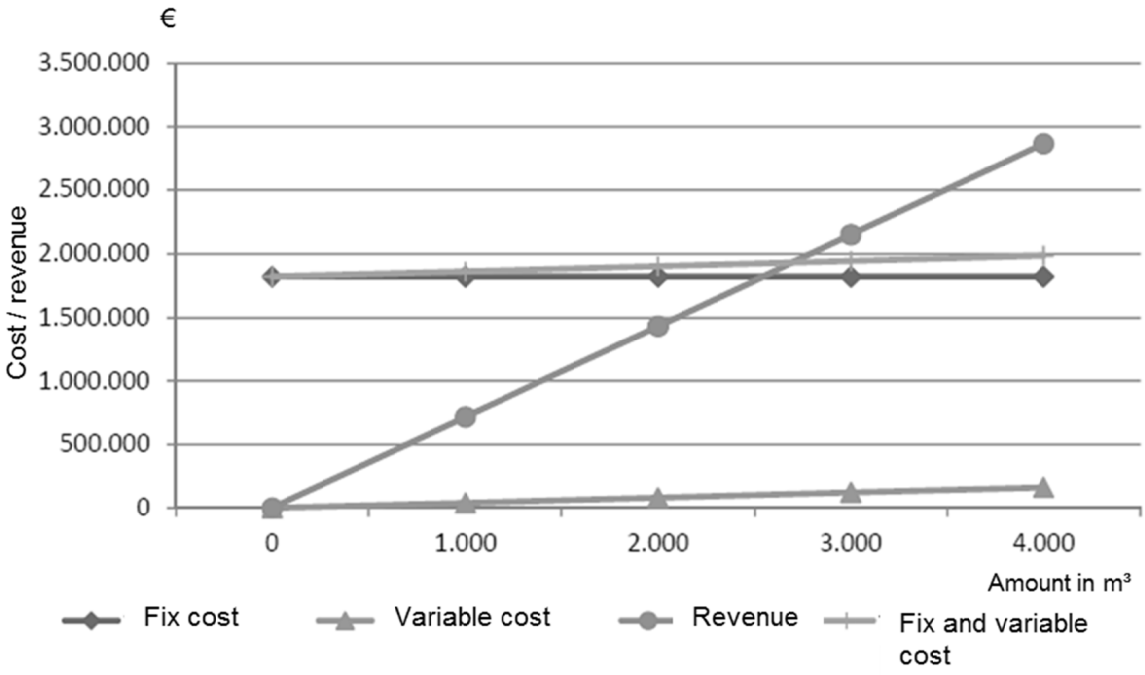


Figure 9-4: Break-Even analysis for Terra Preta production

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