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Assessing combined Water-Energy-Efficiency Measures in the Automotive Industry

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Abstract

Water and energy represent two essential and interrelated resources for manufacturing systems. Thus, measures to increase resource efficiency have to take a joint analysis of both resources into account. Common methods of analysis focus on one of both resources only. A combined approach considering especially the interrelation between water and energy is insufficiently addressed. Against this background, the paper proposes a water-(energy) flow model comprising all relevant water flows as well as manufacturing, supply and disposal areas of a factory. An integrated simulation enables the evaluation of dynamic effects of production subsystems, e.g. cooling towers. The application of the model is demonstrated using a case study from the automotive industry.

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Keywords: Water Efficiency; Water Flow Model; Efficiency Measures; Simulation

1. Introduction

The world's current development in terms of resource consumption per capita already exceeds the planet's natural bio-capacity [1]. Due to a growing population with changing lifestyles and evolving consumption patterns, this trend is expected to continue moving upwards entailing an increased demand for energy and water by 40% over the next twenty years [2].

A survey of the OECD (Organization for Economic Co-operation and Development) further predicts an increased global water demand by 55% in 2050, including an increase in manufacturing's share by 400%, which is strongly influenced by leading emerging nations [3]. This prediction is based on the understanding that energy and water are two closely interlinked resources in terms of resource use. On a general level, energy generation needs water, whereas water treatment and distribution consume energy [4]. This implies that choices made in one resource domain have direct and indirect consequences on the other, as well as further multifaceted repercussions on often unforeseen developments [5].

At a factory level, water is often used in multiple ways. It may be used for steam generation, for heating and cooling, as a solvent, for cleaning as well as a means of transport for waste and particles. Energy is used to move, heat, cool, treat, discharge, or recycle the water [6]. Yet, industry often fails to make use of technological enhancements which can account for significant improvements in water productivity and its related energy efficiency [7].

For that reason, it is important to acquire information as well as a deeper understanding of potential water-energy measure interdependencies. This may reveal amplifying and attenuating effects of the chosen measures on the overall system. Thus, effects of combined measures do not merely add up but rather show an interdependent behavior.

Against this background, there is a strong need to assess combined water and energy improvement measures and their interdependencies. This includes an enhanced understanding as to why certain effects either have an amplifying or an

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attenuating impact on the environmental performance in terms of water and energy demand of a company. Therefore, it is this paper's objective to establish an integrated modeling approach, which enables the assessment of water and energy interdependencies. The initial section of this paper emphasizes the interrelation between water and energy and what is commonly known as the water and energy nexus and prevalent modeling approaches in that context. The subsequent section presents the proposed integrated modeling approach subdivided into the system structure and the mathematical modeling of the data structure. The last section presents a case study from the automotive industry assessing joint water and energy measures in a cooling tower.

2. Literature Review

2.1. Water-Energy Nexus

While prior initiatives and developments have rather focused on securing the supply of energy and water in an isolated manner, there is an emerging understanding for the necessity of conjoined analyses of both resources [2,3,5,7]. This is not only because water and energy represent two indispensable resources for modern economics, but also due to their intrinsically bound relationship to each other [7]. A first concept of this relationship was developed by Gleick in the 1990's [8]. It describes what is commonly known as the water-energy nexus including the two links *water for energy* and *energy for water*. They are connected to the climate system through the water cycle [9]. This nexus is illustrated in Fig. 1 for the water and energy domain. It is based on their interdependence in such a way that one resource cannot be provided, acquired, or utilized without the other.

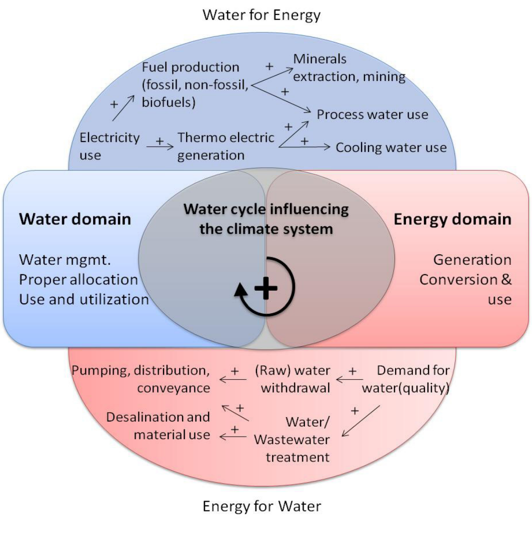

Figure 1: Relationship between water and energy (adapted from [10])

In the water domain, energy is used for water extraction from groundwater, desalination of brackish or seawater, water conveyance through different areas, water distribution, water treatment by removing chemicals of emerging concern (CECs), as well as wastewater treatment [11].

The energy domain needs water for the extraction and mining of natural minerals such as coal or natural gas, first-generation biofuels and the generation of thermoelectric energy for cooling purposes [11]. Fig. 1 also indicates the existence of a reinforcing cycle based on water and energy demand as a consequence of the coupling between water and energy. Therefore, an increase in water consumption will also trigger a higher energy demand resulting then again in further water demand, creating a speed-up of resource consumption. Consequently, joint water and energy reduction can also exhibit a greater impact.

2.2. Modeling approaches

To model both domains, there are numerous approaches. Many efforts have focused on assessing and optimizing the water supply as well as the water use in manufacturing. Starting with a broad perspective, some approaches use Life Cycle Assessment (LCA) to estimate the use of water from a scarcity perspective in LCA analyses [12]. In that regard, there are only a few approaches incorporating combined energy and water assessments which rather focus on energy-efficient water supply systems [13]. Similar approaches such as the Life Cycle Impact Assessment (LCIA) and associated characterization models consider the environmental impact the water withdrawal may cause on the location [14], but do not indicate any relations to energy demand. Another approach that focuses on the raw material extraction and manufacturing phase predicting the amount of used water is called water footprinting. This approach is typically based on multiple databases and applied to agricultural products. However, it does not include the specific water and energy demand, wastewater treatment and/or different manufacturing processes [15]. The approach has been extended to consider the water inventory of machining processes (milling, turning, and drilling) as well as impacts resulting from differently defined scopes [16]. A broader water minimization framework, yet neglecting energy demand, has also been presented with respect to food manufacturing [17]. With regard to the automotive industry, activities mainly address separate improvement measures for water and energy savings [18], but there is no methodology for assessing the interdependent effects from a combined analysis of both resources so far.

Alternative approaches initially originated in the field of process engineering/integration, and commonly known as pinch analysis, deal on a graphical basis with defining performance targets and optimizing energy and mass (e.g. water) allocation [19]. This approach has been expanded to derive recommendations for a new optimal system design as well as to retrofit existing systems [20], including mathematical optimizations for multiple purposes [21]. Extensions of that approach also consider combined energy and water minimizations, primarily setting targets for minimum water use while taking heat recovery arrangements into account [22]. In addition to that, joint optimizations of superstructures of water and heat exchanger networks [23] as well as optimal heating and cooling flows for decreased water and energy demand have been examined [24]. Another field of approaches looks at optimal electrical pumping strategies and control settings required to withdraw and dispatch water within a system [25].

Apart from that, several recent activities focus on smart power and water grid coupling with respect to a simultaneous, economic dispatch of both resources [26], also incorporating plant ramping behavior and impacts of electrical energy and water storage alleviating demand constraints [27]. Further activities just started to model the water-energy nexus as an integrated engineering system [28] to facilitate quantified planning and management of this topic. Yet, these approaches are merely the starting point for the planning and integration of water and energy coupled topics into industry and other sectors. Adaptations to specific industry needs are yet to be developed and validated.

3. Integrated Modeling Approach

The energy and water flows in production systems are linked. In order to capture the effect of water-reducing measures on energy demand and vice versa, the interdependencies between energy and water flows must be determined. These interdependencies are substantially influenced by process factors. Process factors can be divided into three categories: process parameters, technical parameters of the equipment/machines, and external parameters. Process parameters can be changed easily for an existing process. Their modification allows the identification and assessment of measures to reduce energy and water consumption in existing manufacturing systems without making any structural changes. The changes of technical parameters are associated with structural changes in the manufacturing system and are generally associated with investments. The external parameters cannot be changed. To get a real estimation of the energy and water consumption, the behavior of the system must be investigated in dependence of external parameters [29].

In this section, an approach for modeling the energy and water flows in dependence of the process factors is given. First, the development of the system structure is described. Second, the mathematical modeling of the data structure for individual processes is shown. Finally, the system and data structure of the individual processes is integrated into a water and energy flow model of the manufacturing systems. This model can be used both to derive and to assess energy and water saving measures.

3.1. System structure

Manufacturing systems include a multitude of different processes. The different processes represent mechanical, thermal, or chemical transformation processes that convert inputs such as energy, water, and other raw materials into outputs such as products, waste water, waste, and emissions. The transformation processes depend on several process factors and are interconnected by energy and material flows of the manufacturing system.

The first step in the development of the system structure is the definition of system boundaries and the division of the system into reasonable modules. Since measures usually affect the system on the process level, the next step is to specify the main modules into sub-modules, up to the process level. Then, the input and output flows need to be identified for each sub-module on the process level. As an example, Fig. 2 illustrates the system structure of a component plant in the automotive industry. The manufacturing system is divided into five main modules: power station, cooling system, fabrication, waste treatment, and waste water treatment. The module fabrication is composed of the sub-modules foundry, paint shop, and transmission manufacturing. The paint shop has, for example, the process cathodic dip painting. Cathodic dip painting is specified by the inputs raw parts, energy, water, chemicals, and paint and the outputs painted parts, waste water, emissions, and waste. The advantage of the modular structure of the model is the transparency and easy adaptation of the modules to other manufacturing systems with similar processes [30].

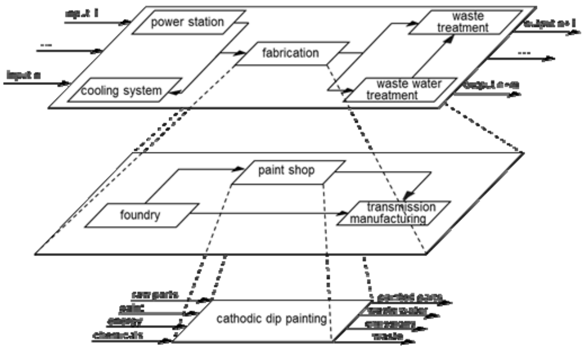

Figure 2: System structure of a component plant in the automotive industry

3.2. Data structure

For the modeling of the data structure of individual processes the input/output relations and their reliance on process factors must be known. Measures to reduce inputs and outputs may usually affect inputs as well as process parameters, technical parameters, and outputs. The impact of measures on inputs and outputs is determined by external parameters. To model the transformation processes, all interdependencies between inputs, outputs, and process factors must be considered. In general, this leads to input functions (1) and output functions (2), that Schmidt and Keil [31] extended by the process factors:

$$x_i = f_i(x_1,...,x_{i-1},x_{i+1},...,x_n;y_{n+1},...,y_{n+m};p_1,...,p_s) \quad (1)$$

$$y_j = f_j(x_1,...,x_n;y_{n+1},...,y_{j-1},y_{j+1},...,y_{n+m};p_1,...,p_s) \quad (2)$$

The function value x_i is the amount of an input material i and the function value y_j is the amount of an output material j. The variables $x_1, \dots, x_n$ represent the quantities of other input materials and $y_{n+1}, \dots, y_{n+m}$ the quantities of other output materials of the process. The variables $p_1, \dots, p_s$ denote the process factors. For an existing manufacturing system, the data required for the modeling of the transformation processes are available from process data sheets and specifications of the equipment manufacturer. Further necessary data can be generated by using simulation. The definition of the input functions (f_i) and output functions (f_j) depends on the underlying manufacturing process and must be determined individually for each process. The result of the modeling is a system of equations for each process, which describes the relations between inputs, outputs and process factors.

In the next step, the equation systems of the individual processes need to be incorporated into an integrated model. For the incorporation of individual process models into an overall model, Petri Nets notation is typically used. With the Petri Nets notation, the individual models can be encapsulated into a material flow network [32]. The implementation of the model in simulation systems such as Umberto or STAN provides a tool for the derivation and assessment of measures in the context of scenario and sensitivity analysis [33].

4. Case Study

The case study demonstrates the application of the developed methodological framework to a cooling system as well as the validity of the approach. The modeling of the cooling system is illustrated using the above introduced input and output functions. The model is applied for the assessment of water and energy saving measures. While the cooling system represents only one module of the entire production system in Fig. 2, further modules could be easily added using the proposed approach but are neglected here for a simplified comprehensibility.

4.1. Cooling System

The examined cooling system consists of five components: one pump, one filter system, one heat exchanger, and two open cooling towers (see Fig. 3). The pump is responsible for the circulation of the cooling water in the cooling circuit. The filter system cleans the cooling water from the pollution caused by the air. The heat exchanger transfers the thermal energy from the fabrication to the cooling system. The warm water from the heat exchanger is transported to the top of the cooling tower, where it is distributed over the wet deck. On the way down, the water is cooled by the contact with the opposite air flow, which is drawn in through the air entrance grid at the bottom of the cooling tower using an axial fan. The cooling of the water is caused by the direct heat exchange between water and air (transmission of sensible heat) and the evaporation of a small part of the water (transmission of latent heat). The cooled water is transported to the cooling water tank and then fed back into the cooling circuit [34]. While the pure water evaporates during the transfer of latent heat, it leaves salts and other impurities behind. To ensure the conductivity of the water, a part of the cooling water must be blown down and replaced with fresh water. The thickening factor is the ratio of the total salt concentration of the circulating water and additional water and defines the amount of cooling water to be blown down. Evaporation and blowdown lead to water emissions out of the cooling system. These water emissions must be replaced with fresh water and represent the water consumption of the cooling system. In addition, water is consumed to clean the backwash filter. Electrical energy is required in the cooling system to operate the pump, the fans, and the filter system.

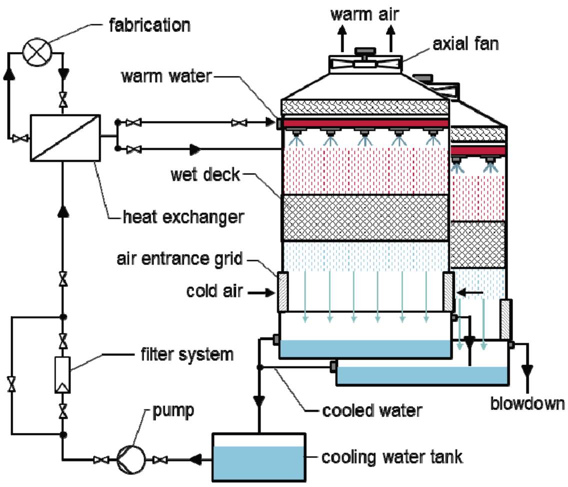

Figure 3: Cooling system

4.2. Model

The module cooling system includes the five components **pump**, **filter system**, **heat exchanger**, and **two open cooling towers**. Significant impacts on the energy and water flows in the cooling system are the external parameters outside temperature and relative air humidity. These parameters change in the course of a day. Because the changes of these parameters are relatively small within one hour, it is sufficient to normalize all energy and water flows in the cooling system to one hour. Table 1 provides the inputs and outputs of the four components of the cooling system as well as their mutual dependencies and their dependencies on the process factors. Table 2 contains all relevant process factors.

The settings for the parameters pump speed (p_1^p), fan speed cooling tower 1 (p_1^{ct}), and fan speed cooling tower 2 (p_2^{ct}) depend on the external parameters outside temperature (p_1^{EF}), relative air humidity (p_2^{EF}), cooling capacity required in secondary circuit (p_3^{EF}), and the regulation of the cooling system. They must be chosen in such a way that a constant temperature (p_4^{ct}) can be maintained in the cooling water tank, for example 23 °C.

To calculate the energy and water demand, a load profile for the cooling tower must be determined based on the temperature records of the past year and using a simulation. The load profile indicates how many hours per year the cooling tower must be operated with which parameter settings for (p_1^p), (p_1^{ct}) and (p_2^{ct}). The integration of the model described above in Umberto and the simulation of the model for a determined load profile provides the energy and water demand of the cooling system for a period of one year. The model is validated with regard to data, behavior and structure, with adequately accurate results [35].

Table 1: Inputs and outputs

	Specification	Name	Unit	Function
Pump	Input x_1^p	Cooling water	m^3/h	$f_1^p(\boldsymbol{p_1^p}, \boldsymbol{p_2^p})$
	Input x_2^p	Electrical energy	kWh	$f_2^p(\boldsymbol{p_1^p}, \boldsymbol{p_3^p})$
	Output y_3^p	Cooling water	m^3/h	$f_3^p(x_1^p)$
Filter system	Input x_1^{fs}	Cooling water	m^3/h	$f_1^{fs}(y_3^p)$
	Input x_2^{fs}	Electrical energy	kWh	$f_2^{fs}(\boldsymbol{p_1^{fs}}, \boldsymbol{p_2^{fs}})$
	Input x_3^{fs}	Fresh water	m^3/h	$f_3^{fs}(\boldsymbol{p_1^{fs}}, \boldsymbol{p_2^{fs}}, \boldsymbol{p_3^{fs}})$
	Output y_4^{fs}	Cooling water	m^3/h	$f_4^{fs}(x_1^{fs})$
	Output y_5^{fs}	Waste water	m^3/h	$f_5^{fs}(x_3^{fs})$
Heat ex-changer	Input x_1^{he}	Cooling water	m^3/h	$f_1^{he}(y_3^p, y_4^{fs})$
	Output y_2^{he}	Cooling water	m^3/h	$f_2^{he}(x_1^{he})$
Cooling tower	Input x_1^{ct}	Cooling water	m^3/h	$f_1^{ct}(y_2^{he})$
	Input x_2^{ct}	Electrical energy	kWh	$f_2^{ct}(\boldsymbol{p_1^{ct}}, \boldsymbol{p_2^{ct}}, \boldsymbol{p_5^{ct}}, \boldsymbol{p_6^{ct}})$
	Input x_3^{ct}	Air	m^3/h	$f_3^{ct}(\boldsymbol{p_1^{ct}}, \boldsymbol{p_2^{ct}}, \boldsymbol{p_7^{ct}}, \boldsymbol{p_8^{ct}})$
	Input x_4^{ct}	Fresh water	m^3/h	$f_4^{ct}(y_6^{ct}, y_8^{ct})$
	Output y_5^{ct}	Cooling water	m^3/h	$f_5^{ct}(x_1^{ct}; y_8^{ct})$
	Output y_6^{ct}	Waste water (blowdown)	m^3/h	$f_6^{ct}(y_8^{ct}; \boldsymbol{p_3^{ct}})$
	Output y_7^{ct}	Air	m^3/h	$f_7^{ct}(x_3^{ct})$
	Output y_8^{ct}	Evaporation	m^3/h	$f_8^{ct}(x_1^{ct}, x_3^{ct}; \boldsymbol{p_1^{EF}}, \boldsymbol{p_2^{EF}}, \boldsymbol{p_3^{EF}})$

Table 2: Relevant process factors

	Specification	Name	Unit
Process parameters	$\boldsymbol{p_1^p}$	Pump speed	%
	$\boldsymbol{p_1^{fs}}$	Number of backwashing cycles	1/h
	$\boldsymbol{p_2^{fs}}$	Rinsing time per backwashing cycle	h
	$\boldsymbol{p_3^{fs}}$	Volume flow of fresh water during the backwash	m^3/h
	$\boldsymbol{p_1^{ct}}$	Fan speed cooling tower 1	%
	$\boldsymbol{p_2^{ct}}$	Fan speed cooling tower 2	%
	$\boldsymbol{p_3^{ct}}$	Thickening factor	--
	$\boldsymbol{p_4^{ct}}$	Temperature cooling water tank	°C
Technical parameters	$\boldsymbol{p_2^p}$	Maximum water flow pump	m^3/h
	$\boldsymbol{p_3^p}$	Nominal power pump	kWh
	$\boldsymbol{p_5^{ct}}$	Nominal power fan cooling tower 1	kWh
	$\boldsymbol{p_6^{ct}}$	Nominal power fan cooling tower 2	kWh
	$\boldsymbol{p_7^{ct}}$	Maximum air flow fan cooling tower 1	m^3/h
	$\boldsymbol{p_8^{ct}}$	Maximum air flow fan cooling tower 2	m^3/h
External parameters	$\boldsymbol{p_1^{EF}}$	Outside temperature	°C
	$\boldsymbol{p_2^{EF}}$	Relative air humidity	%
	$\boldsymbol{p_3^{EF}}$	Cooling capacity required in secondary circuit	kWh

4.3. Scenarios

The cooling system model has been applied in order to assess two different improvement measures compared to a base scenario, leading to four cases.

Base scenario: The current regulation of the cooling system starts with the irrigation of the cooling water in both cooling towers. If the operating point is insufficient to cool the cooling water to the temperature required in the cooling water tank, the fan of the first cooling tower is additionally switched on, first at 40 percent. Depending on demand, the fan speed is raised up to 100 percent. Only if the first fan is no longer sufficient at 100 percent, the second fan is turned on. The temperature required in the cooling water tank is 23 °C.

Measure 1: The energy demand of the fan is generally related to the third power of the speed [36]. Therefore, two fans consume at the operating point of 40 percent less energy than one fan at 50 percent. Following this, the fan on the second cooling tower is already turned on as soon as the fan of the first cooling tower exceeds 50 percent. Once the speed of the second fan reaches the speed of the first fan, the speed of both fans is increased equally. Analogous to the calculation of the energy and water demand for the base scenario, a load profile of the cooling system for the new regulation is created at first. Then, the energy and water demand of the cooling system is determined using the Umberto model.

Measure 2: Better insulation of water pipes and reduction of losses allow for an increase of the temperature in the cooling water tank from 23 °C to 24 °C

Measure 1+2: In this scenario, the combination of both measures is examined.

4.4. Results

Table 3 presents the results for the calculation of the energy demand to operate the pump, the fans, and the filter system and water demand for the compensation of evaporation and blowdown. In the **base scenario**, the cooling system consumes 373,222 kWh energy and 31,732 m³ water. The implementation of a new regulation of the cooling system (**measure 1**) leads to savings of 44,768 kWh energy and 983 m³ water per annum. Increasing the temperature in the cooling water tank from 23 °C to 24 °C (**measure 2**) leads to savings of 13,389 kWh energy and 4,147 m³ water per annum.

Table 3: Results energy and water demand

	Base scenario	Measure 1	Measure 2	Measure 1+2
Energy [kWh]	373,222	328,454 [-44,768]	359,833 [-13,389]	318,014 [-55,208]
Water [m³]	31,732	30,749 [-983]	27,585 [-4,147]	26,740 [-4,992]

The implementation of both measures (measure 1+2) leads to savings of 55,208 kWh energy and 4,992 m³ water. Although the first measure aims at saving energy, water is also saved by the redistribution of the transfer of sensible and latent heat. The combination of both measures leads to 2,949 kWh less energy savings and 138 m³ less water savings compared to the sum of the individual savings. The results show the importance of an integrated approach. Measures, such as increasing the temperature in the cooling water tank, can be evaluated only with integrated models, because they affect both energy and water consumption. Furthermore, the energy saving measures may, as it is evident from the case study, not only directly influence water consumption, but also indirectly affect the effectiveness of other measures. The combination of measures does not lead to simple summation of the results. In this case, the combination of both measures leads to 5 percent less energy savings and 3 percent less water savings.

5. Conclusion and Outlook

In this paper, an integrated approach to model the energy and water flows and their interdependencies in production is presented. The model depicts the energy and water flows as a function of the relevant process factors and enables both the derivation and assessment of energy and water saving measures. The approach is applied to a cooling system from the automotive industry. Two measures to improve the systems efficiency are investigated. The case study shows the effectiveness and the necessity of the approach, since measures can easily be modeled and their effects do not simply add up.

Future works will focus on the development of additional modules of the manufacturing system and the development of a standardized procedure to close data gaps with simulation. Besides, further interdependencies such as e.g. CO_2 or VOC-emissions will be addressed as well. Moreover, the modeling will be extended to the economic evaluation of the measures, to enable in particular also an adequate assessment of the variation of technical parameters. The aim is a holistic approach for the derivation, evaluation and selection of measures to increase energy and resource efficiency.

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