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Decreasing the Use of High-Quality Make-Up Water in the Steel Sector by Coupling Enhanced Sensors Circuit with Decision and Support Tool

Ismael Matino [1], Valentina Colla [1,*], Alessandro Maddaloni [2], Silvia Cateni [1], Vincenzo Iannino [1], Alice Petrucciani [1], Antonella Zaccara [1,3], Teresa Annunziata Branca [1], Ruben Matino [1], Matteo Chini [4], Loris Bianco [4], Sergio Porisiensi [4], Luca De Cecco [4], Gianluca Tomat [4], Flavio Nodusso [4] and Guido Lepore [4]

[1] Scuola Superiore Sant'Anna, TeCIP Institute, ICT-COISP Center, 56124 Pisa, Italy; ismael.matino@santannapisa.it (I.M.); silvia.cateni@santannapisa.it (S.C.); alice.petrucciani@santannapisa.it (A.P.); antonella.zaccara@santannapisa.it (A.Z.); teresa.branca@santannapisa.it (T.A.B.); ruben.matino@santannapisa.it (R.M.)

[2] Samovar, Telecom SudParis, Institut Polytechnique de Paris, 91120 Palaiseau, France; alessandro.maddaloni@telecom-sudparis.eu

[3] Dipartimento di Ingegneria Industriale, Università di Padova, 35131 Padova, Italy

[4] Ferriere Nord S.p.A., 33010 Osoppo, Italy; matteo.chini@pittini.it (M.C.); loris.bianco@pittini.it (L.B.); sergio.porisiensi@pittini.it (S.P.); luca.dececco@pittini.it (L.D.C.); gianluca.tomat@pittini.it (G.T.); flavio.nodusso@pittini.it (F.N.); guido.lepore@pittini.it (G.L.)

* Correspondence: valentina.colla@santannapisa.it; Tel.: +39-050-882328

Abstract: Water is a fundamental steelworks additional resource; its efficient management is crucial for process reliability, product quality and environmental sustainability. Within steelworks, water is exploited mainly for direct or indirect cooling and is usually reused and recycled after cooling and treatments to eliminate contaminants. However, bottlenecks often exist, limiting water management efficiency and increasing water consumption. These issues are mainly related to water treatments efficiency, lack of water parameters monitoring and the manual/semi-manual management of water networks. Furthermore, these aspects are generally associated with the plant's service life; brownfield sites are mostly affected. In these cases, improving sensor circuits coupled with decision support tools can support human decisions and lead to significant advantages. The paper discusses a potential application of such tools after new sensors installation in a use case concerning the minimization of the use of high-quality make-up-water for the indirect cooling system of a wire-rod mill in electric steelworks. The effectiveness of the described tool is shown, and the advantages are highlighted in terms of potential savings that can reach 95% and 4% of the current consumption of well and osmotic water in the considered circuit, respectively, corresponding to a saving of about 9400 m^3/year of high-quality water.

Keywords: steel; electric steelmaking sustainability; water network efficiency; process monitoring; process simulation; optimization; decision support system

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1. Introduction

Many industrial processes require a relevant amount of water as a fundamental resource for many production steps, such as cooling and cleaning operations. On the other hand, the increase in environmental and pollution issues is reducing the availability of fresh water in many countries, including Europe, especially in the southern regions [1]. Therefore, the reduction in the water footprint is one of the most important priorities for most industries and the society as a whole, and it is an essential goal for implementing the circular economy approach. Regarding this topic, the UNESCO 2021 Water Development Report [2] focused on the responsibility of industrial companies, whose "*interests in water management should align with those of water management agencies pursuing Integrated Water*

Resources Management (IWRM) planning approaches. The circular economy will value water to the extent that each litre is reused again and again, making water itself almost become part of the infrastructure rather than a consumable resource".

In the steel sector, water is a fundamental resource for the production process; its management differs according to the type of process, plant operation, and, obviously, water availability and the nature and extent of the affected water bodies. According to the Worldsteel member survey that was published in 2011, in an integrated steel plant, the typical water intake is 28.6 m^3/ton of steel, and the discharge is 25.3 m^3/ton of steel. On the other hand, in electric steelworks, the water intake is 28.1 m^3/ton of steel, and discharge is 26.5 m^3/ton of steel [3,4].

The water networks of steelmaking industries are generally complex, and two types of water are managed: the so-called "direct water", which comes into contact with steel products, and the "indirect water", mainly used for indirect cooling. Pure or slightly contaminated water is usually required for direct usage to avoid undesirable effects on products. After usage, this water is far more contaminated than indirect water. For indirect water, generally, the only parameter modified by usage is temperature. Thus, this water typically only needs to be cooled. In both cases, optimized water management can reduce water consumption and related energy use, leading to environmental and economic advantages [5,6].

In the steel industry, water is usually reused and recycled after treatments, lowering the contaminants content and/or temperature, and only a small fraction of the enormous water volume needed for steel production is consumed. It is estimated that water losses are less than 10% of the water amount moved, and these losses are related mainly to evaporation during cooling. However, in steelworks, water management is often not optimized, and significant water recovery and reuse potentials are still unexplored. The main issues are related to the efficiency of water treatments, lack of continuous monitoring of water parameters, shortage of automation in the management of water networks, and further barriers that were analyzed by Branca et al. [7]. Optimized water management strategies can help to improve the process water quality and reduce the demand for freshwater and the amount of discharged wastewater, with significant industrial, environmental, energy, and economic benefits. This is, indeed, perfectly in line with what can be defined as water environmental sustainability, namely the use of water to ensure the current social and economic requirements and maintain the ecological balance without jeopardizing this possibility in the future. This can lead to significant direct and indirect contributions to the following sustainable development (i.e., a development meeting the present needs without compromising the future generation's needs) goals of the United Nations: 3: Good Health and Well-Being, 6: Clean Water and Sanitation, 8: Decent Work and Economic Growth, 9: Industry, Innovation and Infrastructure, 12: Responsible Consumption and Production and 13: Climate Action.

Some past projects funded by the European Union (EU) tackled wastewater management and minimization of water consumption in the steel industry, acting on different aspects related to improved wastewater treatments and exploitation of process simulation for assessing process integration solutions. In REFFIPLANT [8], wastewater reuse and treatment in integrated steelworks were investigated through a process integration-based approach exploiting ad-hoc water networks models. MODELCOR [9] focused on the simulation of cooling water circuits. KNOWATER II [10] aimed at improving wastewater treatment by applying Artificial Intelligence (AI) methods. EIRES [11] is concerned with evaluating the overall environmental impact of electric steelworks and considered wastewater management, among other aspects.

In the literature, Sun et al. [12] investigated the impact of wastewater discharge and the concentrations of different wastewater pollutants in discharge water through a total environmental impact score method. Colla et al. [13] analyzed the implementation of ultrafiltration and Reverse Osmosis (RO) techniques to improve water quality (by reducing salt concentration). Through modelling and simulation, they investigated process integration solutions to improve water efficiency. Mahjouri et al. [14] developed an integrated methodology based on a complete list of various economic, technical, and environmental criteria and indicators to define the most appropriate method for managing industrial wastewater including the implementation of the best treatment technologies. Although this analysis is limited to the Iranian steel industry, the proposed method can represent a reference approach and a list of guidelines for any level of decision-making and for any sector. Reducing freshwater consumption is one of the objectives of the investigation proposes by Alcamisi et al. [15], where the improvement of resource efficiency through process integration was deeply analyzed. The authors developed an Aspen Plus® model of a section of a complex water network of an integrated steelworks, and demonstrated that it was possible to decrease the freshwater intake by recycling blowdown (BD) water coming from another area without significant changes in process behavior.

However, so far in the steel sector, the coupling of sensors networks (monitoring system), simulation, and the optimization of water circuits has been poorly addressed, and its potential has not been fully explored or deployed through practical tools for operators. Generally, this is strictly related to the plant's service life, and brownfield sites often have higher critical issues with respect to greenfield ones. The work presented in this paper aims at filling this gap. Such work was developed within the EU-funded project entitled "*Water and related energy Hub Advanced Management system in steelworks—WHAM*", which mainly aims at reducing water consumption. In particular, the integration of flexible online monitoring, simulation, and optimization tools and platforms is proposed. A dedicated Decision Support System (DSS) was developed to monitor, simulate and optimize water networks, considering physical/thermal/chemical water quality, energy aspects, and process constraints. A library of unit models is embedded in the DSS, which represent water users, water treatments, and other water network elements, which are commonly found in steelworks and can be combined to produce a digital twin of the water network. The DSS also includes an optimization tool.

The combination of network simulation, optimization, and online monitoring of main water parameters provides an updated picture of the status of the circuits. In this way, the dynamic of the water networks is followed, anomalous consumptions by different facilities are rapidly identified by the operators, online optimization of water distribution and/or treatments parameters is carried out, and freshwater consumption and energy required for water management can be reduced.

In the present paper, the coupling of novel sensors for improving monitoring capacity to the developed software tools is presented by showing its potential application to a case study (CS) related to a circuit of a water network of an Italian electric steelworks. The DSS allowed the optimization of the use of different make-up waters by respecting the process water quality features required by the process and has the potential to reduce the consumption of both well water and osmotic water, leading to a total saving of about 9400 m^3/year of high-quality water.

The paper is organized as follows: in Section 2, the CS is introduced and the main developed tools and models exploited in the CS are briefly described. Then, Section 3 presents and discusses the obtained results. Finally, Section 4 provides concluding remarks and introduces the ongoing work.

2. Materials and Methods

2.1. Description of the Case Study

Various issues need to be addressed to improve water networks efficiency in steelworks, also considering the management peculiarities of the different facilities. For example, the presented CS concerns the management of freshwater intake and the use of high-quality make-up water in an existing water circuit of an Italian electric steelmaking industry.

The considered water circuit supplies water to the indirect cooling system of the wire rod mills. Figure 1 shows a simplified scheme of the circuit; the pink point-line square underlines the boundaries of the CS, light blue circles represent the wells, blue blocks are the basins, yellow, violet, and green blocks are the oxygen production plant, RO and cooling towers, respectively, and the orange block indicates the user process. The make-up water sources are highlighted through dashed red squares.

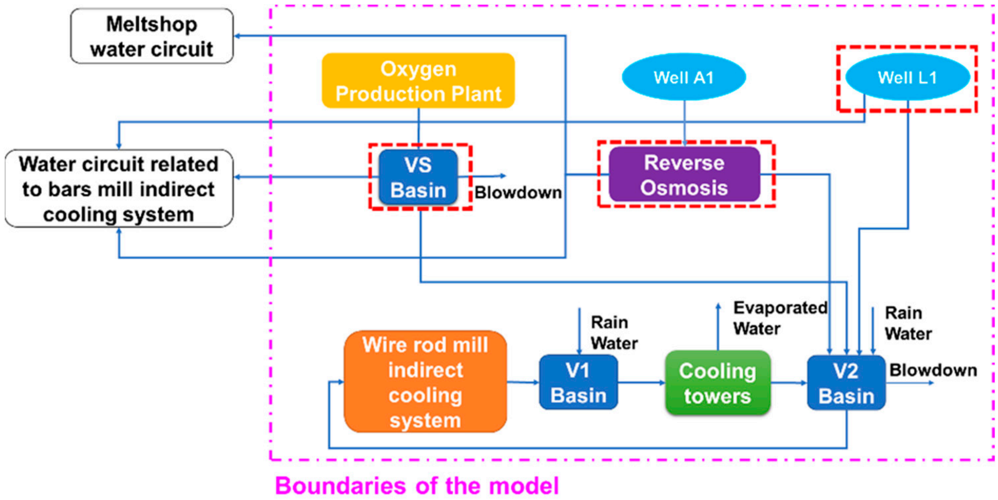


Figure 1. Simplified flowsheet of water circuit considered in the CS.

Most water is recirculated and reused. More than 900 m^3/h of water is generally demanded by wire rod mills and provided through the V2 basin. After use, the water is sent to basin V1 and then again to the V2 basin after cooling in the cooling towers.

The main water losses are related to evaporation and to basin V2 blowdown, which is used for the cooling of existing section meters and of novel installed pH and electrical conductivity (EC) meters (see Section 2.2) or for mitigating an eventual increase in contamination. In addition, some minor losses are related to pipe leakages. These water losses are compensated for by pumping and mixing make-up water coming from the following three water sources with different qualities:

- Water from the well treated by RO (ROW), which shows the highest quality;
- Fresh water from the well (WFW) with a medium quality;
- Water from the oxygen production unit (WO2), which shows the worst quality.

The water coming from the three water sources is mixed to ensure a hardness (H) level in the range of 14–20 °f in the V2 basin. Currently, this water replenishment is not optimized. It is performed empirically, and, before the installation of new sensors, it was supported only by discontinuous laboratory analyses. The sporadic and empirical-based monitoring/management entails unstable water quality and leads to an increased water consumption and losses due to excessive preventive high-quality make-up water usage and to the need to purge V2 water if its quality does not meet the given constraints.

Therefore, the CS focuses on finding the best combination of the three water sources flows through time by minimizing WFW and ROW while maximizing use of WO2 (with consequent promotion of process integration), which is otherwise purged, resulting in further environmental impacts. In addition, compliance with process constraints (i.e., water availability for processes and required water quality) need to be ensured in this optimization task.

The acquisition of detailed and continuous information on water features, flows, and amount (considering basin levels) through newly installed sensors (i.e., flowmeters, level, and electrical conductivity sensors) and application of ad-hoc correlations (e.g., between electrical conductivity and hardness) are combined to simulation potential, and optimization approaches to reach the aimed goal.

2.2. Novel Structured Sensor Network

Improved management of industrial water circuits needs a structured sensors network to monitor the main water parameters and a correct monitoring procedure. Before the beginning of the present study, in the considered water circuit, only some parameters were continuously monitored (e.g., some flowrates, temperatures). In contrast, other ones were discontinuously measured through manual sampling and ad-hoc laboratory analyses (e.g., electrical conductivity, hardness) or not measured at all. Therefore, a series of novel sensors were installed to improve the monitoring of the involved water circuit as well as to provide helpful information to the optimization tool (e.g., features regarding make-up waters). The laboratory analyses are continued, as they are helpful to check the reliability of the new measuring system.

The monitored variables in the circuit of Figure 1 are listed in Table 1, where pre-existing and new sensors are specified. The obtained sensors network is completed with a Programmable Logic Controller (PLC) and a Server where data are stored and accessed remotely through an ad-hoc developed database (DB). This DB provides the data to the optimization tool (see Section 2.4), which computes set-up water values to be sent to the V2 basin from various sources (make-up water and V1 basin water). Figure 2 shows some installed sensors.

Table 1. Monitored variables in the considered water circuit.

ID	Variable	Sensor Installation
Basins Level		
L_{V1}	V1 basin level	Already installed
L_{V2}	V2 basin level	Already installed
L_{VS}	V4 basin level	Novel
Temperature		
$T_{V2toUsers}$	Temperature of water sent from V2 basin to users	Already installed
$T_{V1toCoolingTowers}$	Temperature of water going to cooling towers	Already installed
Electrical Conductivity and pH (Figure 2b)		
$EC_{V2toUsers}$	Electrical conductivity of water sent from V2 basin to users	Already installed
$pH_{V2toUsers}$	pH of water sent from V2 basin to users	Novel
EC_{Osm}	Electrical conductivity of osmotic make-up water	Novel
pH_{Osm}	pH of osmotic make-up water delivery flow	Novel
EC_{O2p}	Electrical conductivity of make-up water from oxygen plant through VS basin	Novel
pH_{O2p}	pH of make-up water from oxygen plant through VS basin	Novel
EC_{L1}	Electrical conductivity of make-up water from L1 well	Novel
pH_{L1}	pH of make-up water flow from L1 well	Novel
Cumulative Volume		
CV_{Osm}	Cumulative volume of make-up osmotic water	Already installed
CV_{O2p}	Cumulative volume of make-up water flow from oxygen plant through VS basin	Already installed
CV_{L1}	Cumulative volume of make-up water from well to indirect water network	Already installed
Flowrate		
$F_{V2toUsers}$	Flowrate of water sent from V2 basin to users with pumps P2	Novel (ultrasound flowmeter, Figure 2a)
$F_{V1toCoolingTowers}$	Flowrate of water going to cooling towers with pumps P1	Novel (ultrasound flowmeter, Figure 2a)

(**a**) (**b**)

Figure 2. (**a**) Installed ultrasound flowmeters; (**b**) electrical conductivity and pH sensors.

2.3. Auxiliary Simulation Models Developed for the Considered Case Study

The description of all the unit models included in the WHAM library is out of the scope of the paper. Only the auxiliary models for the optimization related to the reported CS are described here. In particular, two main kinds of models are used:

- Soft sensors models;
- Models of the treatments involved in the circuit.

These models provide the optimization tool with information that is not directly collected through the sensor network.

Balances on the basins and variations in the electrical conductivity and hardness due to water mixing are also considered through well-known and widely adopted equations, which are not reported here, as the focus is on the most innovative component of the system.

2.3.1. Soft Sensor Models

As described in Section 2.2, most of the information required for the optimization task is provided by physical sensors. However, concerning hardness measurements, only discontinuous laboratory analyses are available. Therefore, correlations were extracted from the available data to provide continuous estimates of hardness in the main water streams. Synchronized laboratory data of electrical conductivity and hardness were used for this aim, and the following equations were obtained:

- Water in basin V2:

$$H_{V2}[^{\circ}\mathrm{f}] = 5.31{\cdot}10^{-2}{\cdot}EC_{V2}\left[\frac{\mu\mathrm{S}}{\mathrm{cm}}\right] \tag{1}$$

- Water in basin VS:

$$H_{VS}[^{\circ}\mathrm{f}] = 6.00{\cdot}10^{-2}{\cdot}\mathrm{EC}_{\mathrm{VS}}\left[\frac{\mu\mathrm{S}}{\mathrm{cm}}\right] \tag{2}$$

- Well water:

$$H_{W}[^{\circ}\mathrm{f}] = 5.56{\cdot}10^{-2}{\cdot}\mathrm{EC}_{\mathrm{W}}\left[\frac{\mu\mathrm{S}}{\mathrm{cm}}\right] \tag{3}$$

Concerning ROW, no correlation was found, but its variation is limited; its average measured value is H_{ROW} = 1.38 °f, and the standard deviation σ_{ROW} = 0.32 °f.

2.3.2. Models of Treatments Involved in the Circuit

Two main treatment units are involved in the circuit: the cooling towers for the "thermal treatment" of the water in the circuit and RO, whose permeate corresponds to the best make-up water available.

This last treatment, due to its stability, was modelled in a straightforward way, as it is used only for considering the ratio between the permeate ($\dot{P}_{RO}$ [kg/h]) and retentate ($\dot{R}_{RO}$ [kg/h]) starting from water coming from well A1 ($\dot{Q}_{A1}$ [kg/h], see Figure 1). Therefore, the following equations were implemented, considering an averaged amount of 18% of retentate with respect to the treated water, which the technical operators of the steelworks provided:

$$\dot{R}_{RO} = 0.18 \cdot \dot{Q}_{A1} \tag{4}$$

$$\dot{P}_{RO} = \dot{Q}_{A1} - \dot{R}_{RO} \tag{5}$$

The considered permeate properties (i.e., EC and H) are generally almost stable, and EC is continuously monitored through the newly installed sensor. At the same time, hardness is computed as a stochastic variable with Gaussian distribution.

The cooling tower model simulates the behavior of this treatment by calculating the outlet cooled water volume flow rate and the water losses linked to evaporation and windage.

The model is based on the following mass and energy balances and on literature recommendations [16–22]:

$$\dot{M}_{in} = \dot{M}_{cooled} + \dot{M}_{windage} + \dot{M}_{evaporated} \tag{6}$$

$$\dot{M}_{in} \cdot cp_w \cdot T_{W_{in}} - \left(\dot{M}_{cooled} + \dot{M}_{windage}\right) \cdot cp_w \cdot T_{W_{out}} = \dot{M}_{air} \cdot \left(Hn_{air_{out}} - Hn_{airin}\right) \tag{7}$$

where $\dot{M}_{in}$ [kg/h], $\dot{M}_{cooled}$ [kg/h], $\dot{M}_{evaporated}$ [kg/h] and $\dot{M}_{windage}$ [kg/h] are, respectively, the mass flow of inlet, cooled, evaporated water and of water windage; cp_w [J/[kg·K]] is water-specific heat that is assumed constant due to the low differences between the inlet and outlet water temperatures ($T_{W_{in}}$ [K] and $T_{W_{out}}$ [K], respectively); $\dot{M}_{air}$ [kg/h], Hn_{airin} [J/kg], and Hn_{airout} [J/kg] are, respectively, air mass flow, specific enthalpy of moist air at inlet and outlet temperatures. Outlet air temperature is computed as $T_{airout}[\mathrm{K}] = 0.5 \cdot \left(T_{W_{in}} + T_{W_{out}}\right)$ according to Leeper [16].

Water windage is assumed as a fraction (WF) of inlet water considering the literature indications [17,21,22]:

- $0.003 \le WF \le 0.01$ for a natural draft cooling tower without windage drift eliminators;
- $0.001 \le WF \le 0.003$ for an induced draft cooling tower without windage drift eliminators;
- $WF \le 0.0001$ for cooling towers with windage drift eliminators.

The WF value considered in the present case is 0.003.

The correlation between $\dot{M}_{evaporated}$ and $\dot{M}_{air}$ is expressed as follows:

$$\dot{M}_{evaporated} = \dot{M}_{air} \cdot \left(h_{abs_{out}} - h_{abs_{in}}\right) \tag{8}$$

where $h_{abs_{in}}$ [$\mathrm{g_{water\ vapor}/g_{moist\ air}}$] and $h_{abs_{out}}$ [$\mathrm{g_{of\ water\ vapor}/g_{of\ moist\ air}}$] are, respectively, the absolute air humidity at outlet and inlet air temperatures; it is essential to highlight that outlet air was considered saturated.

The main features of cooled water are estimated considering the concentration of cooled water with respect to the inlet water.

2.4. Optimization Algorithm

An approach is pursued to optimize the water circuit, which is widely used in the literature and was already adopted in the steel field to model the gas networks. Such an approach is based on representing the water circuit as a digraph with n nodes (units) and m arcs (pipes connecting two units).

When a cost function is applied to the circuit's arcs, the circuit's minimum cost flow can be investigated through a wide variety of algorithms [23,24].

The digraph of the considered circuit is depicted in Figure 3. Blowdown streams (i.e., originated from VS and V2 basins) are not directed to a unit. However, their destinations are still represented as nodes (i.e., *BD VS* and *BD V2*) in the digraph. The digraph shows the different variables of arcs and nodes: $Q_{i\text{-}j}$, $H_{i\text{-}j}$, and $C_{i\text{-}j}$ representing the flowrates, hardness, and electrical conductivity of the arc from node i to node j, respectively, and L_v representing the volumetric level of the v node.

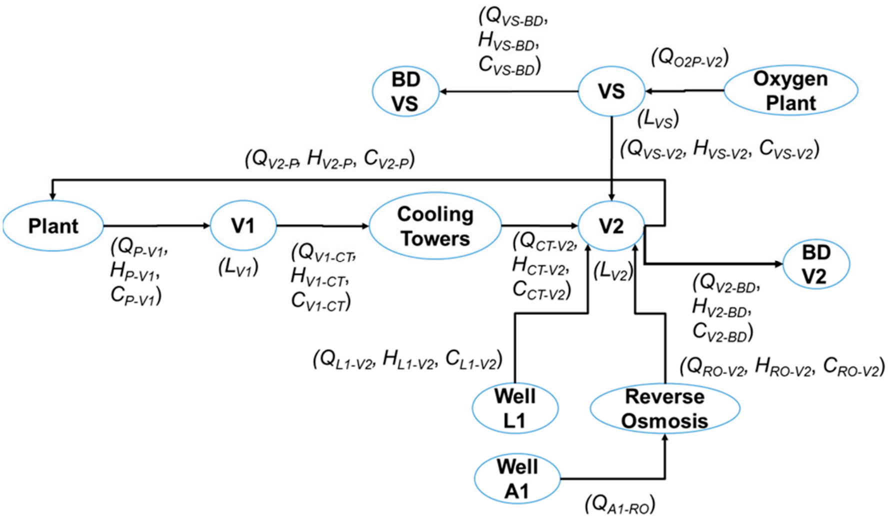


Figure 3. Digraph representation of CS water circuit.

The proposed algorithm is a discretization of the continuous time process. First, a time unit is chosen, and the flow variables $Q_{i\text{-}j}$ represent the total amount of water flowing (along the corresponding arc) in the entire time unit.

The optimizer is configured to set the value of the flow variables so that they satisfy the operational constraints (i.e., water demand, water quality, basins levels, and maximum annual amount of water that can be withdrawn from the two wells A1 and L1) while minimizing the following objective function:

$$J(Q,P) = Q_{L1-V2} \cdot \alpha_{well} + Q_{RO-V2} \cdot \alpha_{osm} + Q_{V2-BD} \cdot \alpha_{V2BD} + Q_{VS-BD} \cdot \alpha_{VSBD} + P \cdot \alpha_{penalty} \quad (9)$$

where Q is the vector of flowrates of the different water streams as represented in Figure 3, P is a penalization variable fundamental to keep basin levels within their threshold limits, α_{well}, α_{osm}, α_{V2BD}, α_{VSBD}, $\alpha_{penalty}$ are the costs, respectively, for well and osmotic make-up water, for the two blowdown streams and the penalty cost.

Although not reported in the digraph of Figure 3, rain water contributions were also considered in the calculation; however, their impact is low, so they are not included in the previously reported formulas.

The optimization procedure was implemented in *Python*; *PuLP* package and related *Cbc* solver were used to solve a linear program, which constitutes the present optimization problem.

Most of the variables and parameters the optimizer requires are provided through the sensors network described in Section 2.2, otherwise by the models described in Section 2.3 or by the user (e.g., for limit parameters).

3. Results and Discussion

3.1. Sensors Functionality Check

Before the optimization tool application, the correct operation of installed sensors was checked by monitoring the registered data and making data analysis. All the sensors were correctly operating, except for the one devoted to measuring the $F_{V1toCoolingTowers}$ flowrate; unexpected peaks were found in the measurements. Although some anomalies can be directly observed by the user, in view of an automatic industrial deployment, outlier detection was implemented through different outlier detection methods, such as the fuzzy approach described in Cateni et al. [25] to verify the frequency of anomalous measurements and to arrange for outlier removal and substitution. The results of outlier detection are shown in Figure 4 for two periods of about one month each.

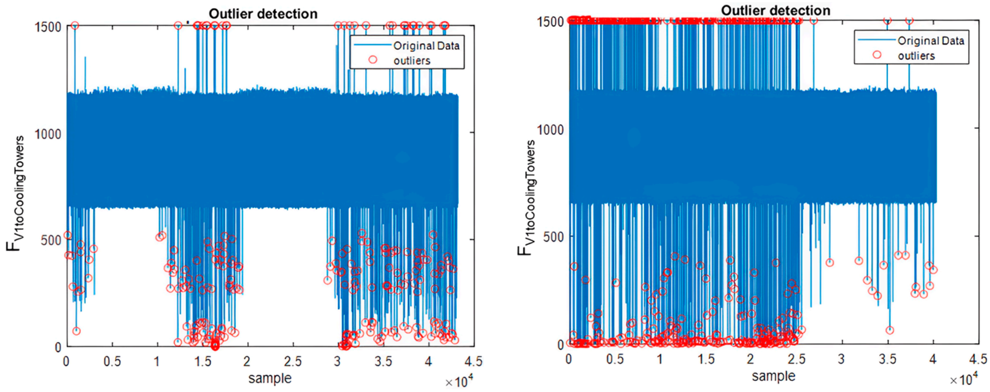
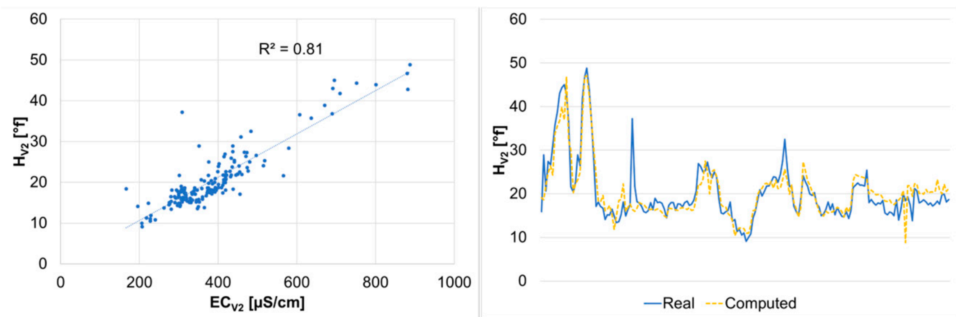


Figure 4. Outliers detection for $F_{V1toCoolingTowers}$ flowrate in two different periods; outliers are highlighted with red circles.

A test campaign was carried out during the rolling mill maintenance period to understand the issue better and confirm that the problem was related only to the device measuring $F_{V1toCoolingTowers}$ flowrate. It was observed that unexpected values appeared to be randomly generated. Therefore, after further checking, the setup of the flowmeter providing anomalous measurements was changed, and outliers replacement was implemented by obtaining regular measurements of the $F_{V1toCoolingTowers}$ flowrate.

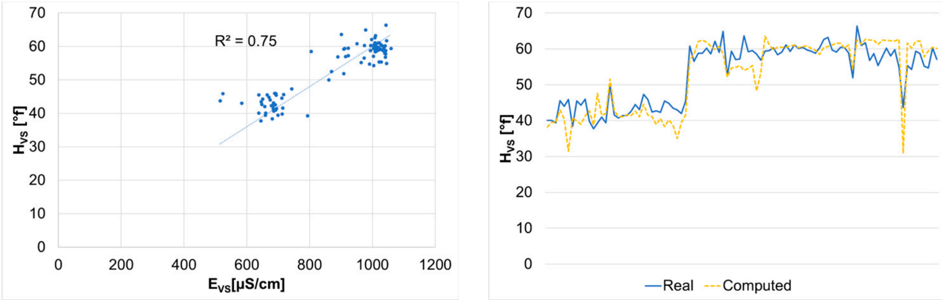
3.2. Accuracy of the Models

The accuracy of the models described in Section 2.3.1, which estimate the hardness value in the main concerned water streams based on the electrical conductivity value, was assessed. The results are depicted in Figures 5–7, respectively, for the water in basin V2, in basin VS and for the well water. In particular, the top diagrams show the correlation diagram, while the bottom ones compare actual and estimated hardness values. In particular, the correlations for the hardness of the water in V2 and VS basins show a higher accuracy, while for well water, the correlation is less accurate. However, it still allows following average values and minimum peaks of well water hardness.



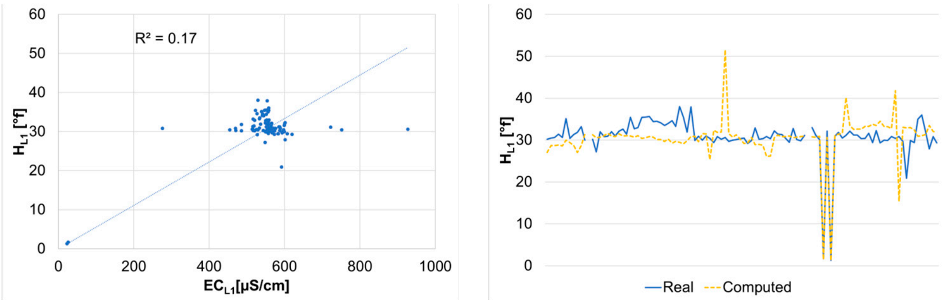
(**a**) (**b**)

Figure 5. (**a**) Linear correlation between H_{V2} and EC_{V2}; (**b**) comparison between actual and computed H_{V2}.



(**a**) (**b**)

Figure 6. (**a**) Linear correlation between H_{VS} and EC_{VS}; (**b**) comparison between actual and computed H_{VS}.



(**a**) (**b**)

Figure 7. (**a**) Linear correlation between H_{L1} and EC_{L1}; (**b**) comparison between actual and computed H_{L1}.

Moreover, the accuracy of the cooling tower model was also assessed. Considering that such a model is used especially to compute the cooled water flowrate and its main features in terms of EC and H, to determine its accuracy, the calculated amount of evaporated water is compared to the average available evaporation rate, namely about 4.2 m^3/h of evaporated water. Figure 8 provides a comparison between the calculated values and the actual average for one week, showing that the model overall provides realistic and trustable values.

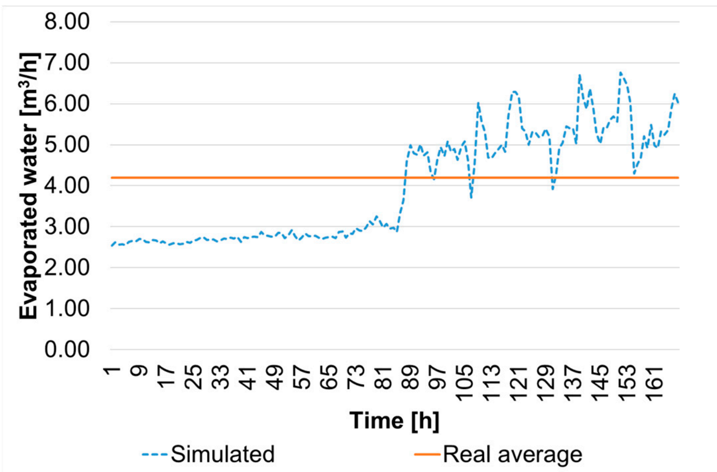


Figure 8. Comparison between one week of simulated evaporated water with real average value.

3.3. Optimization Tool Tests

After the appropriate configuration of the sensors network and optimization tool, tests were carried out. Three periods with almost the same duration were considered:

- Case A: 210 h;
- Case B: 172 h;
- Case C: 188 h.

The results were compared to the obtained values during the standard management of the wire-rod mill indirect cooling water system. In particular, the following variables were compared:

- The total amount of make-up water exploited from different sources and blowdowns from various basins (see Figure 9).
- The flowrate from the V1 basin to cooling towers before going to the V2 basin (see Figure 10).
- The hardness of V2 basin water (see Figure 11).

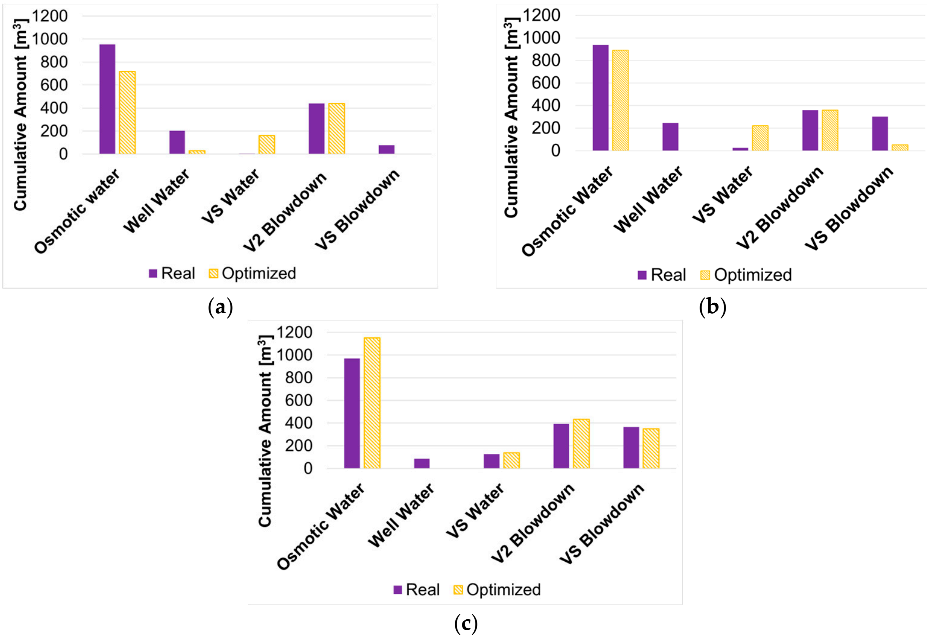


Figure 9. Comparison between global amounts of make-up waters and blowdowns in standard and optimized management for: (**a**) Case A; (**b**) Case B; (**c**) Case C.

It is essential to highlight that blowdowns are not continuously monitored and the following actions were implemented:

- Only real V2 fixed blowdown devoted to the cooling of the section, pH, and EC meters was considered. It was assumed to be 2.1 m^3/h corresponding to the value measured with a portable device during the test campaign mentioned in Section 3.1.
- Real VS basin blowdown was computed through a balance considering the available data.

Regarding the actual V2 hardness values, they were computed by exploiting Equation (1).

It can be observed that the optimizer significantly reduces the usage of well water; only in Case A (Figure 9a), a small amount of well water is used. In addition, if possible, the tool tries to decrease the use of ROW and increase the usage of VS basin water. This is achieved in both Cases A and B (Figure 9a,b), while for Case C (Figure 9c), a higher amount of ROW is required to respect the constraints on hardness (Figure 11c). Indeed, in real cases, the maximum hardness limit is not always respected, while the optimizer manages to keep the hardness at least equal to this value. Deepening on the control of the hardness of V2 basin water, the optimizer allows a smoother trend with respect to standard management; generally, the optimizer leads to an asymptotic stabilization of the water quality variable (e.g., H). Moreover, it avoids high variations in its values (see Figure 11).

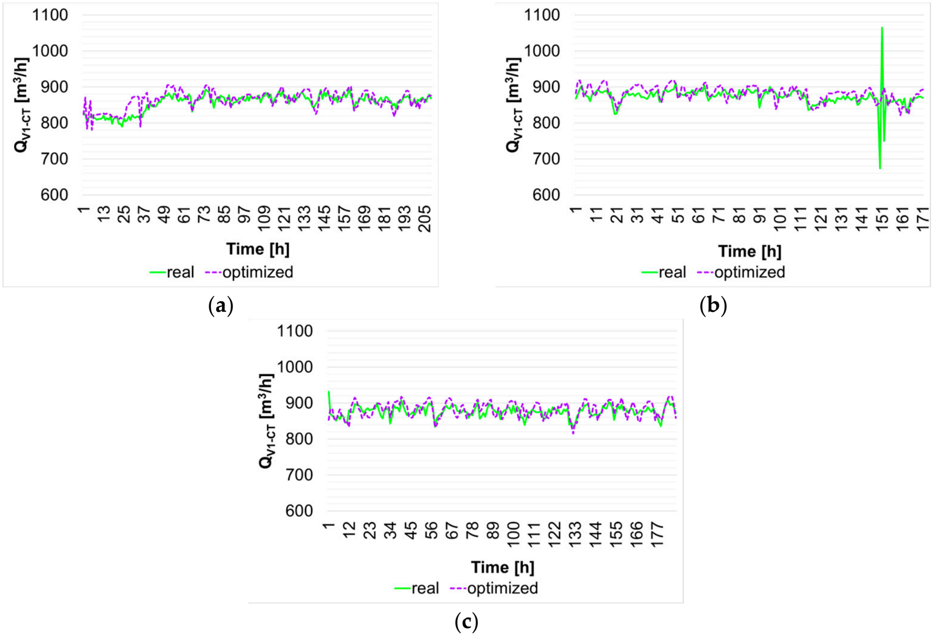


Figure 10. Comparison between real and optimized flowrate from the V1 basin to the cooling tower before going to the V2 basin for (**a**) Case A; (**b**) Case B; (**c**) Case C.

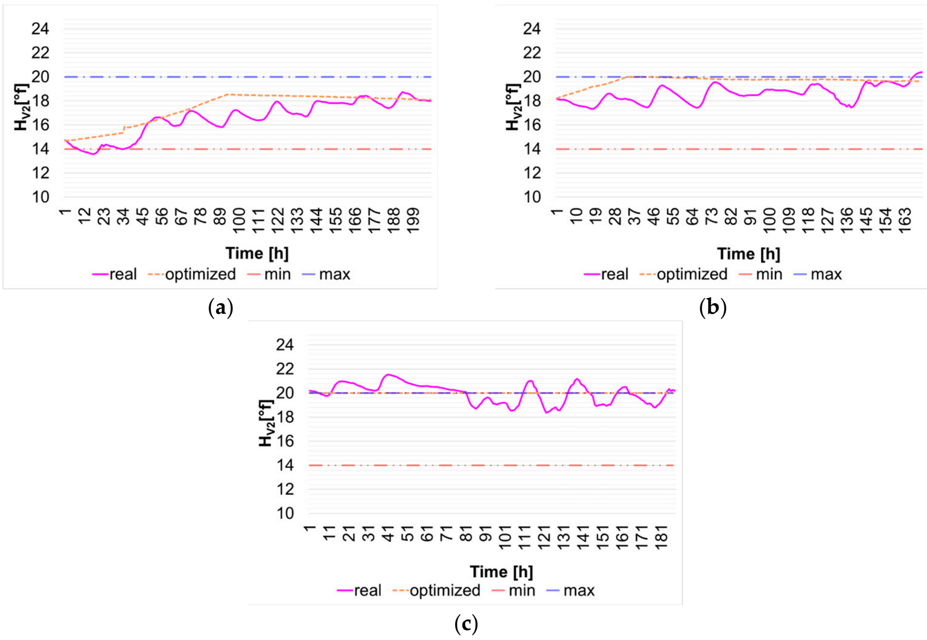


Figure 11. Comparison between V2 basin water hardness in standard and optimized management for (**a**) Case A; (**b**) Case B; (**c**) Case C.

The higher amount of VS usage leads to a decrease in the water wasted through VS blowdown and better exploitation of the available resources in a process integration concept, such as that shown in Figure 9. Also, considering the V2 blowdown, most of the time, it is maintained as the minimum required for meters cooling; only in Case C, a slightly higher blowdown is needed, probably to respect the hardness limit.

Moreover, the V1 flowrate managed by the optimizer (see Figure 10) is highly similar to the one provided by the actual management, but automatically controlling the V1 flowrate gives more freedom to the optimizer, making it more capable of finding better solutions.

Finally, it must be underlined that the basin-levels constraints and water demands were always respected during tool operation.

In conclusion, the optimizer leads to the better exploitation of water resources by respecting the constraints on water quality, request, and basin levels. The results highly depend on the quality and amount of available water from various sources, sensor measurements' reliability, and model results' accuracy.

3.4. Argumentation and Implications of the Results

Considering the three presented tests, the continuous monitoring and more stable control of the water quality to be sent to water users allow for the optimized usage of the different make-up water sources, promoting process integration solutions and reducing excessive freshwater use and avoidable purges.

In particular, the following average savings were obtained:

- Osmotic water: 4.3 m^3/die, corresponding to about 3.6% of standardly used osmotic water in the considered circuit.
- Well water: 21.3 m^3/die, corresponding to about 94.5% of standardly used well water in the considered circuit.
- Avoided blowdown from VS basin: 14.5 m^3/die, corresponding to about 45.9% of standardly purged water from VS basin.

Globally, an annual amount of about 9400 m^3 (5.7 dm^3/t of produced steel) of high-quality water can be potentially saved, and about 5300 m^3 (3.8 dm^3/t of produced steel) of VS blowdown can be avoided.

Considering that only a small water network area was considered in the CS, the results in terms of savings were considered satisfactory and high margins of further improvements exist in the whole network. Evidently, the analyzed CS constitutes a straightforward example that has the intention to act as benchmark and to pave the way to policies for the implementation of similar approaches and tools in world-wide steelmaking facilities or other water intensive industries. Starting from the presented results, the revamping of brownfield sites in terms of water circuits monitoring and management from linear, discontinuous, and manual to circular, continuous, and automatic concepts is expected. Furthermore, the design of greenfield water circuits already suitable for smart water management is promoted.

Significant water resource savings can be achieved, with consequent implications in steelworks (or other water intensive industries) economic and environmental impacts, and local economy and society, as water becomes available for further uses (e.g., agricultural), promoting well-being, and sustainable development both in areas that do and do not suffer from drought. Furthermore, the acceptance of steelworks in the international society may increase following further contributions to the sustainable transition of this sector.

It is essential to underline that the achievement of such results was possible because different techniques, which were studied separately in previous research works, such as the ones analyzed in the Introduction section and taken as reference in this work, were integrated. As already mentioned, models were used generally to carry out simulation analyses of process integration solutions [8,13,15] for analyzing the behavior and impact of wastewater treatments and management in different scenarios [9–11]. Further advanced techniques were developed exclusively for impact assessment [12] or for the selection of wastewater treatment technologies [14], and virtual sensors and AI-based technologies were proposed in [10]. However, the improvement of sensing systems for continuous water quality monitoring and impact assessment, the development and application of models and simulations tools and of optimization frameworks were performed independently and without considering an in-field deployment of a DSS to improve water management. In contrast, in this work, everything was developed based on the final goal of improving water efficiency and circularity by ensuring the satisfaction of water demand through the DSS. The synergy between the enhanced water monitoring system, modelling, simulation, and optimization techniques represents the main enabler to achieve the expected smart water management.

4. Conclusions and Ongoing Work

The application of an innovative approach supporting water management in steelworks is presented, which combines improved online monitoring of relevant variables and DSS with simulation and optimization tools. After the appropriate configuration of the sensors network, the potential of this coupling in improving water management is proven through the analysis of a CS related to a water circuit of an Italian electric steelworks. The continuous monitoring and the proposed optimized management by DSS allow significant environmental advantages by saving high-quality make-up water and decreasing discharged water. In addition, more stable control of process water quality is achieved.

The installation of the DSS has recently been performed and ongoing improvements to the software are ongoing by following the suggestions of industrial operators. The aim is to achieve a high acceptance level of the DSS to support the considered water circuit (and of the whole water network) management and achieve the demonstrated environmental advantages, as well as the more stable control of water quality, by paving the way to the more sustainable management of auxiliary processes of electric steelworks or of other water intensive industries worldwide, and to leave high-quality water to other uses that can ensure well-being in society.

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