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A flowsheet-based model approach to reduce water consumption and improve water networks management in the steel sector

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Abstract: Resource consumption is an important topic for steelmaking industry, which is spending significant efforts to reduce its environmental impact and improve its competitiveness. Water is largely exploited in steelworks for indirect and direct cooling, specific surface treatment, and fumes washing and cooling. It is already reused and recycled after restoring its quality through treatments for temperature and/or pollutant reduction. However, sometimes water networks are not optimized due to outdated water treatments, lack of continuous monitoring, and water network management strategies often based on experience without automation. In recent years, new water treatments, simulation, and optimization tools are becoming available, together with a stronger awareness of the importance of online parameters monitoring. Therefore, improvement of water cleaning, reuse, recycling, and consequent reduction of impact related to water exploitation are potentially achievable. The introduction of innovative treatments must be tested before their implementation in steel plants and the exploration of their behavior in different operating conditions is fundamental. The presented work addresses this topic through the application of several models of operational units, developed in OpenModelica environment and aggregated into a plant simulator. The simulator was used in different case studies related to an Italian plant to assess the impact of new filtering technology for reducing suspended solids on the analyzed water networks and test the effects of different operating configurations on the treatment efficiency. The introduction of new filtration technology leads to environmental and economic advantages due to freshwater intake reduction and water management improvement.

Keywords: water management, wastewater treatment, modeling, simulation, sustainable steel production.

1. INTRODUCTION

Environmental issues and resource shortages are currently receiving increasing attention. Therefore, resource-intensive industries are ever more focused on sustainable solutions for decreasing the impact of their production processes.

Steel industry is among the industrial sectors that exploit significant amounts of energy and resources and show a not negligible environmental impact. However, the steel sector is one of the most active ones in promoting research and development activities targeting an improvement of its overall sustainability. To this aim, several projects are committed or funded, e.g. by European Union, focused on the improvement of main and auxiliary processes in terms of new operating conditions, production routes, more efficient and optimized management of the resources, and involved processes.

In steel production, besides iron and carbon, a fundamental resource is water. It is exploited for several purposes, such as direct or indirect cooling, respectively, of product or operating units, off-gases washing, etc. In all cases, pollution occurs in terms of thermal (i.e. temperature increase) or chemical/physical/biological contamination (e.g. due to suspended solids (SS), chemical compounds, bacteria).

Considering the Worldsteel Water Management Project and related member survey of 2011 (Suvio et al., 2010; Suvio et al., 2012; World Steel Association, 2020), the overall water consumption lies in the range of 1.6-3.3 m^3/ton of produced steel starting with an average uptake, respectively, of 28.6 m^3/ton of steel produced in integrated route and 28.1 m^3/ton of steel produced in electric arc furnace (EAF)-based route. This means that only a small amount of withdrawn water is consumed, as generally it is cyclically reused and recycled after treatments for cooling and/or contaminants removal.

Considering the decrease in the availability of freshwater in many countries (Bisselink et al., 2020), the increasing environmental consciousness, the ever-stricter regulations, and the fundamental role of freshwater ecotoxicity on the ecosystem quality as emerged by a work making among others an impact-oriented steelmaking water footprint assessment (Chen et al., 2022) improvements are still needed in steelworks water management. Moreover, water management in steelworks is often not optimized because of a series of factors and barriers as Branca et al. (2020) underlined, such as lack of

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monitoring and automation systems and/or out-of-date treatments. Together with barriers, the identification of bottlenecks of the status quo of steelworks water networks is fundamental for identifying and investigating improvements; this is the approach followed by Tarnacki et al. (2014) where the water balance methodology was exploited. Also, Wang et al. (2022) evaluated the transfer and loss of water in the steelmaking process by the application of a water balance network model. A similar investigation finalized to the acquisition of knowledge and identification of issues has been also the baseline for developing the work presented in the paper that is focused on the exploration of improvements achievable in a water circuit of an Italian electric steelworks by the addition of a cutting-edge treatment unit.

Although changing the plant configuration or the addition of novel units leads to modification of the existing "equilibria", potential improvements could be achieved. Therefore, it is common practice to explore in advance the effects of the implementation of new units (e.g. a new treatment), the change of the layout of a network (in this case the water network), or process integration (PI) solutions. Tools that can highly help to carry out these explorations without directly affecting the involved plant operation belong to the modeling and simulation (M&S) area. Their potential is demonstrated in several works that can be found in literature. Concerning improvements in steelworks water management, M&S were used for different purposes. Porzio et al. (2014) presented a conceptual work, where an integrated approach for designing an optimally industrial water system was described and tested demonstrating the interesting potential of water saving. More applicative works were focused on the exploration of the suitability of some processes to remove contaminants, the behavior of treatment efficiency depending on operating conditions variation, and PI solutions. Aspen Plus® simulations of PI solutions (not only of water) are provided for instance by Matino et al. (2015) where different interesting results are presented belonging to the project entitled "*REFFIPLANT*" funded by the EU and that can be considered a precursor of the project "*WHAM*", in which the work presented in the paper was developed. Among others, the reuse of blowdowns belonging to a steelworks plant area in another one where less water quality was required was tested and a significant freshwater decrease was demonstrated without having issues in the involved water network. The optimized design of a water network finalized for the reuse of coke-making area wastewater thanks to the implementation of ultrafiltration and reverse osmosis was achieved using Water-Int software and minimizing the operating costs (Colla et al., 2017). A further interesting simulation study was carried out by Matino et al. (2018), who extended the pilot tests of an ozonation process with Aspen Plus® models and assessed its suitability for removing cyanide from blast furnace gas washing water for different operating conditions and water quality.

The present paper follows this line and aims at presenting the application of a general-purpose simulation tool developed in the WHAM project with a particular vision on transferability. A steelworks water network simulator was developed in an open-access environment avoiding license issues of the commercial software used in the cited literature. It contains a library of common water network units (e.g. cooling towers, tanks, pumps, wastewater treatments, and water users) and novel treatments allowing the simulation of water networks belonging to different steelmaking facilities in current and innovative scenarios. To demonstrate the tool's potential, different configurations were simulated for studying the effects of the introduction of a novel filtering technology for the removal of SS in complex water networks.

The paper describes the application of such tool for Dalmine S.p.A. water circuit area of medium pipes rolling mill (called in Italian Fabbrica Tubi Medi, FTM), that produces seamless pipe by Mannesmann process (Degarmo et al. 2003). The global flowsheet of the IDRO-FTM circuit and its implementation for different case studies are presented to find the best configuration in terms of water and economic saving.

The paper is organized as follows: Section 2 describes pursued approach and developed model; Section 3 discusses the results of the analyzed case studies. Finally, Section 4 provides concluding remarks and hints for future work.

2. MATERIAL AND METHODS

The flowsheet model of the water circuit analyzed in the paper was built by exploiting a general-purpose simulation tool for simulating steelworks water networks. It was developed with the open-source development environment OpenModelica, which is based on the Modelica modeling language; it is a high-level declarative language for describing mathematical behavior and is usually applied to engineering systems (https://openmodelica.org/). Modelica can be used to simulate different engineering components, which can be easily combined into subsystems (or subprocesses), complex systems, and architectures. Models consist mainly of a declaration of parameters and variables and a set of equations described in a purely mathematical way, which the Modelica compiler transforms into something that can be simulated numerically. One of the most important features of Modelica is that the user does not describe how to solve the equations (even differential equations) and only focuses on the behavior. The solution process can be handled entirely and automatically by Modelica. The definition of a model on Modelica can contain one or more linear or differential equations.

The general approach of the present work is the implementation of individual unit models (i.e. tanks, water treatments, and process units) and connectors that jointly form a more sophisticated water network. Each water network element simulates the effects of the corresponding unit's internal processes (e.g. changes in pressure or composition) on the variables describing the state of the water network. Each water network element may have additional variables to be simulated internally or which may be inputs/outputs to upstream or downstream units. Individual unit models are composed of three main parts: input and internal variables, equations, and output variables. Input and output variables are applied to convert port variables into the right units or adapt them to the internal equations. The equations were developed starting from the mathematical/literature theory of the generic unit and then tuned considering the particular analyzed case study. Connectors are used to connect and exchange information between the units of the water network. Particular attention was paid to modeling these connectors, which represent the interfaces among the defined models to guarantee a modular approach and the usage of the single model in different case studies. More deeply, basic connectors including all common state variables and flow variables are built to create input and output connectors. The ports (the blue squares in each unit of Figure 1) are added to all units defined in WHAM networks to link the units through the connectors. Input and Output variables in the ports are directly connected with the internally defined input and output variables.

The specific variable types, functions, and units were developed and grouped in a common library (*Modelica package*) shared by all simulation and optimization use cases.

In this work, a digital twin (DT) of the entire Tenaris Dalmine IDRO-FTM plant (see Section 1) was designed to obtain a system able to monitor and simulate the water network considering physical, thermal, and chemical quality of the water. In the first step of modeling, data and documentation related to the plant were collected and analyzed. Tenaris information and data were then used for tuning and testing the single models of water network units. When data were not available, literature data and assumptions were exploited. This step was required to close the material balance of single units. Finally, all the units were connected to reproduce the IDRO-FTM, whose model **Errore. L'origine riferimento non è stata trovata.**flowsheet is depicted in Figure 1. a.

Some sections were assembled in macro-blocks identifying specific plant and wastewater treatment sections. Furthermore, the flowsheet is equipped with auxiliary units (e.g. tanks, pumps).

The plant section (i.e. the water user) is composed of the FTM unit and the LAM unit. FTM demands water for descaling purposes and thermal regulation; consequently, the water inside the circuit is polluted by SS (e.g. iron oxide), chemicals (e.g. boron, used as lubricant), and it is heated. LAM is a basin receiving water from a lot of sources.

The main wastewater treatment macro-blocks are listed below:

- FS-01, this macro-block removes scale and oil from wastewater through the pit scale and the oil separator units.
- S_F section contains six sand filters that are used to separate very fine solids particles.
- CH-01 section removes the SS from the backwash water coming from tank V-04 and it includes the flocculation-coagulation system, settling unit, and filter press.
- CT-01 represents the cooling section and is constituted by three cooling towers.
- Boron Plant (Figure 1. **Errore. L'origine riferimento non è stata trovata.**b) is composed of four units: flotation and bag filter, which remove SS from wastewater; softener that modifies the properties of wastewater to permit the reduction of pollutants and to reach suitable properties for water reuse or discharge; ion exchange process that replaces unwanted ions dissolved in solution with other similarly charged ions. For the regeneration of the ion resins, pure water is employed after the reverse osmosis step.

The main model setup considerations were: most of the units work in continuous; minimum and maximum water levels were considered for the water tanks; the output mass flow from the tanks was defined by pumps according to Tenaris data and the requirement of the subsequent units.

In order to reuse the water in the plant and reduce well water consumption for special users (i.e. several plant units that need very clean water) and resins regeneration, it was necessary to improve the quality of the water coming from the boron plant section; the suitability and advantages of innovative filtration technology, namely SOFI filter (www.sofifiltration.com), was tested. To select the optimal IDRO-FTM configuration, five scenarios were offline tested through the developed DT. In particular, it was crucial for understanding the right disposition of the SOFI technology inside the boron plant section and all possible water recirculation.

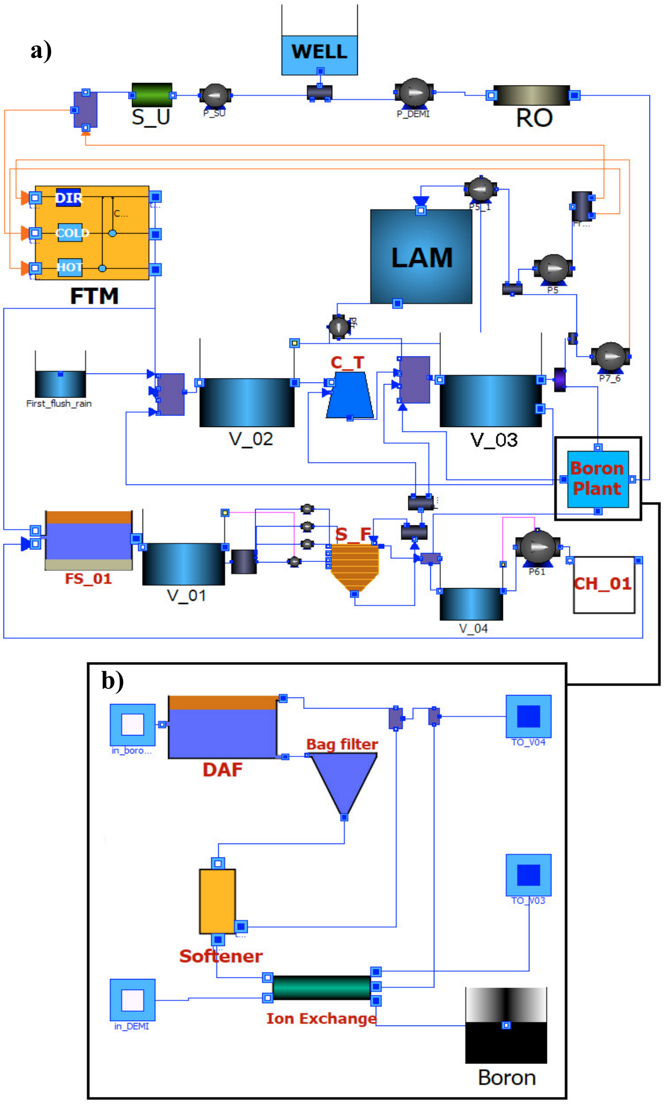

Figure 1. a) IDRO-FTM flowsheet where: S_U is Special Users, FTM is Medium Pipe Mill, RO is reverse osmosis. b) Boron Plant flowsheet.

3. USE CASES DISCUSSION AND RESULTS

The five case studies (base case + 4 innovative ones) are depicted from Figure 2 to Figure 6, where only the crucial part of the plant affected by the improvement is represented.

3.1 Base case study

The first part of the work was focused on the representation of the current situation in a Modelica flowsheet. Final tuning was tricky and it was done with collected historical data and with data coming from new installed flowmeters. A simplified base case flow diagram is shown in Figure 2, while Modelica implementation is depicted in Figure 1. Unfortunately, some measurements, like the boron concentration, were not collected in a continuous manner and were measured by sampling the water from tank V03 every time it was possible (a weekly trend is shown in Figure 7). The FTM plant works five days per week, from Monday to Friday, while the boron plant works seven days per week. Thus, the boron concentration in the water circuit raises along the week but decreases along the weekend.

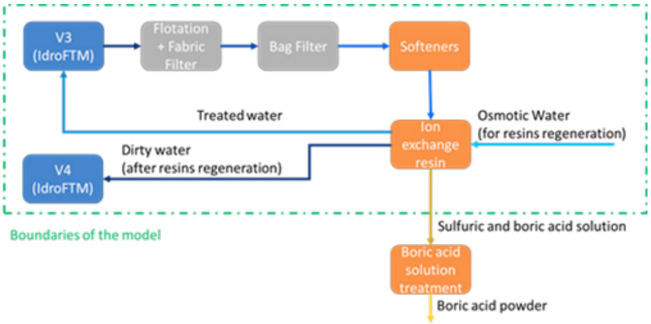

Figure 2. Base case: flotation and fabric filter, no recirculation

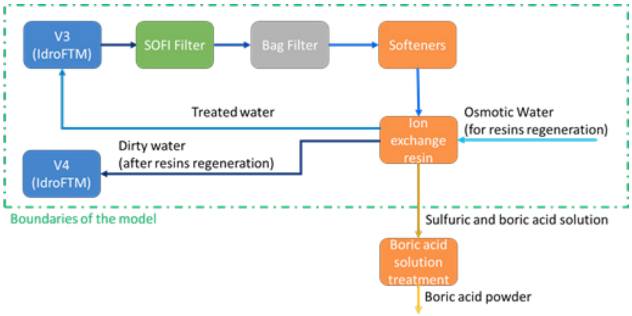

Figure 3. SOFI case: SOFI filter, no recirculation

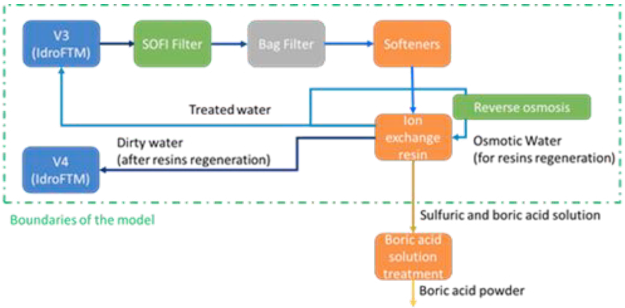

Figure 4. SOFI+REC case: SOFI filter, water recirculation for resins regeneration.

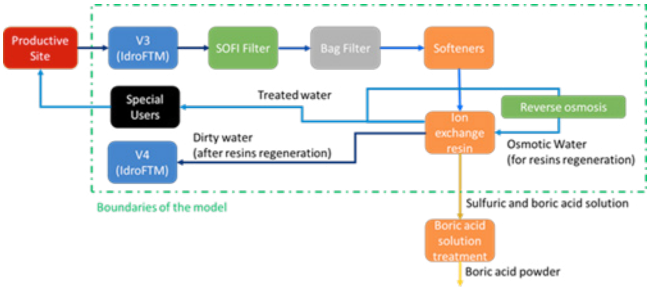

Figure 5. SOFI+REC+to SU case: SOFI filter, boron plant send water to Special Users.

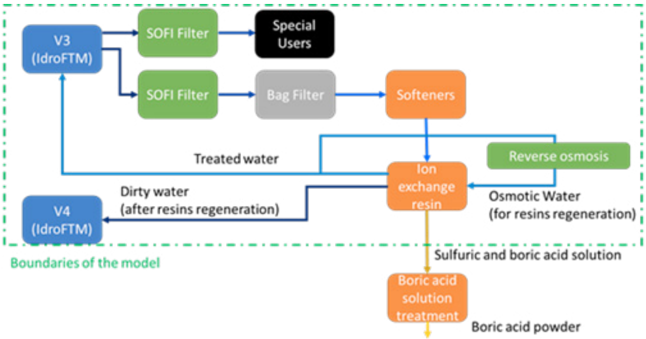

Figure 6. SOFI+REC+SOFI to SU case: SOFI filter, boron plant sends water to V03, second SOFI filter sends water to Special Users.

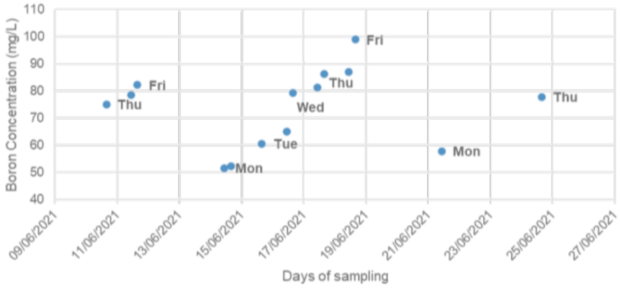

Figure 7. Measurements of Boron concentration

The Base model considers the water contamination increases constant during the week and can predict the trend of boron concentration in each plant tank (Figure 8). The accuracy decreases when a sudden increase in pollution occurs due to a rise in pipe production, as shown in Figure 8. The V-03 real measurements are indicated with the blue dots, while the green line represents the V-03 simulation results. Contamination of the water (e.g. by total SS (TSS), boron) is taken into account in the FTM model, which is considered a “contaminant producer”. The model is tuned by modifying a specific parameter that regulates the "contaminants production” for all pollutants.

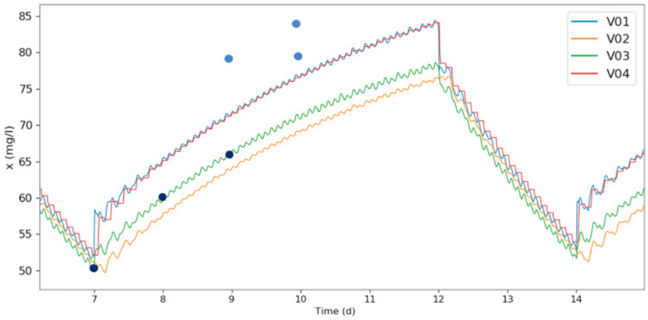

Figure 8. Boron concentration in several tanks. Blue dots represent plant measures; lighter blue dots represent plant measures after something unpredictable occurred. Measures are sampled in tank V03, the green line

3.2 SOFI case study

The Base case was modified by introducing in the IDRO-FTM a new filtration technology, i.e. SOFI filter, to assess its impact in terms of water quality and water saving. SOFI filtration is a dynamic cross-flow filter that does not need chemicals. The novelty of this technology is the frequent and rapid application of a self-cleaning technology to remove the deposit of solid particles on the membrane surface maintaining a high treatment efficiency without the usage of backwash water. SOFI filters can reduce SS in the water and can potentially substitute the step of flotation and filtration by fabric filter in the Boron plant, reducing the consumption of chemicals.

The SOFI filtering process is modeled and added to the basic model, replacing the flotation and fabric filter unit in the boron plant (Figure 3).

Results can be seen in Figure 9, Figure 10, and Figure 11. The simulation shows that Boron and TSS concentrations are very close in SOFI and the Base case. SOFI technology can be implemented in the plant without losing any efficiency (Figure 9 and Figure 10). Therefore, SOFI technology can replace the current configuration and has several advantages, such as no need of chemicals and less maintenance with consequent economic benefits.

3.4 Implementation of water recirculation

A further investigated option consists of the recirculation of the water after ion exchange resins to reverse osmosis (Figure 4, case SOFI+REC). The water was then used for the regeneration of the resins. Simulations confirmed that the water intake was reduced (Figure 11), with a negligible increase in contamination level (Figure 9 and Figure 10).

Based on the identified effect of water recirculation, new layouts were investigated to further reduce well water intake. In the case SOFI+REC+to SU (Figure 5), clean water coming from the boron plant is sent to Special Users. This is possible because the contamination level of the water is comparable to the well water. Nevertheless, some backup water from well is still needed. The last tested scenario (SOFI+REC+SOFI to SU, Figure 6), considers the installation of a second SOFI plant. In this case, the water from V03 is cleaned by SOFI technology and sent to Special Users. This configuration can simplify the control of the water circuit, and it can eliminate the demand of well water. Figure 9 and Figure 10 show that pollutant concentrations are similar and acceptable even in these cases.

3.4 Comparison of well water consumption and saving

Suspended solids are similar for all cases (Figure 9), while boron concentration increased less than 5% (maximum in boron concentration went from 83 mg/l of the Base case to 87 mg/l of SOFI+REC+to SU case) and it is always lower than the practical limit (100 mg/l); therefore, the boron concentration growth can be considered negligible.

Figure 11 shows that the rate of well water consumption is strongly reduced for the SOFI+REC+to SU case, but controlling the process is very difficult because well water changes very often. The last case (SOFI+REC+SOFI to SU) does not need any well water. The average well water consumptions on weekly basis are the following: 9152 m^3/week for Base and SOFI cases, 8467 m^3/week for SOFI+REC, 2661 m^3/week for SOFI+REC+to SU, and 0 m^3/week for SOFI+REC+SOFI to SU.

The saving of well water is depicted in Figure 12 and clearly shows that the most significant contribution is obtained by replacing the well water for SU with recirculated water: the saving water increased from 7% to 71% (+64%), while the case SOFI+REC+SOFI to SU shows a lower improvement than the previous case (from 71% to 100%, +29%).

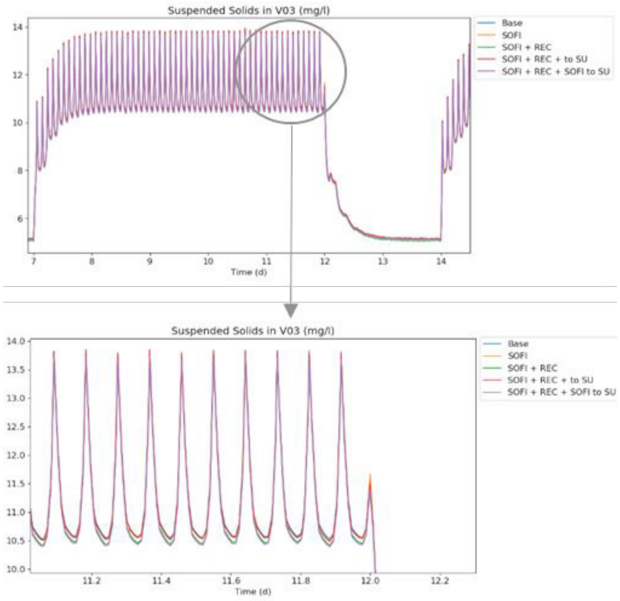

Figure 9. Comparison of Total Suspended Solids concentration in V03 (where measures are taken). Zoom in lower figure.

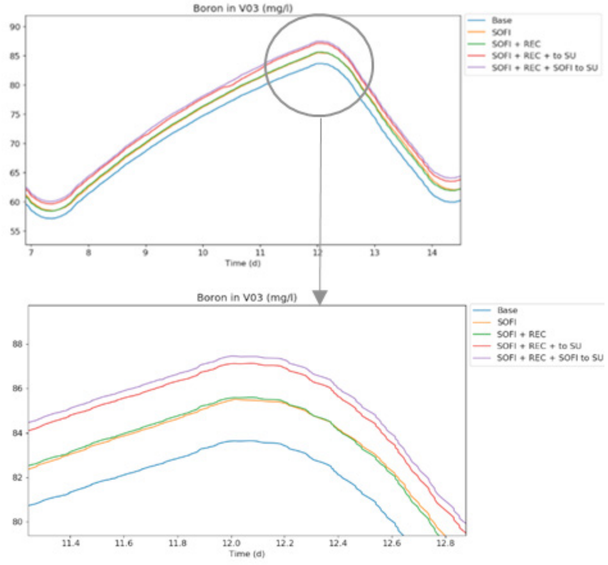

Figure 10. Comparison of Boron concentration in V03 (where measures are taken). Zoom in lower figure

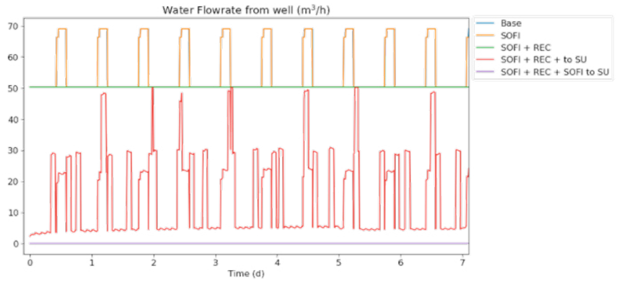

Figure 11. Well water rate of consumption, for each case

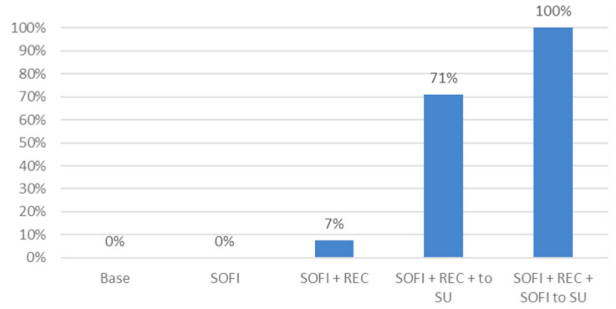

Figure 12. Saving of well water compared to the base situation in the IDRO-FTM plant

4. CONCLUSION

Modelica language was used to develop a general-purpose simulation tool of steelworks water networks, which in turn was used to build the model of a water treatment circuit of an EAF steelworks; it was proved what the tool was reliable for exploring innovative treatments and plant configurations. The model was tuned, and some difficulties in tuning procedure (e.g. the lack of continuous variables monitoring) were overcome using discontinuous sampling data. The model was then modified to assess the effect of changing FTM water network layout by including a new filtering technology (i.e. SOFI) and considering new recirculation solutions. SOFI technology was able to perform good filtering without using chemicals, and internal water recirculation was able to reduce significantly well water consumption without losing water quality.

In particular, the recirculation of water directly to Special Users improved the water saving of 64% (based on consumption of base case).

Summarizing, the described tool was used to assess the technical feasibility of the introduction of new technology and layout modifications for plant revamping to evaluate water consumption and quality. It can also be used for other purposes, e.g. the evaluation of chemicals reduction, and economic and investment evaluation.

This work demonstrates how simulation supports the elaboration and feasibility analysis to be used in the definition of automation and control solutions enabling sensible improvements in the water management in industrial sites. Finally, it leads to considerable environmental benefits and possible economic benefits due to the opportunity to lower the consumption of chemicals and to lower the pumping energy of well water.

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REFERENCES

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L., Feyen, L., and de Roo, A. (2020). *Climate change and Europe's water resources*. Publications Office of the European Union, ISBN 978-92-76-10398-1.

Branca, T. A., Matino, I., Colla, V., Petrucciani, A., Singh, A. K. M., Zaccara, A., & Piras, E. (2020). *Paving the way for the optimization of water consumption in the steelmaking processes: barriers, analysis and KPIs definition*. Matériaux & Techniques, 108(5-6), 510.

Chen, W., Zhang, Q., Wang, C., Li, Z., Geng, Y., Hong, J., Cheng, Y. (2022). *Environmental sustainability challenges of China's steel production: Impact-oriented water, carbon and fossil energy footprints assessment.* Ecological Indicators, 136, 108660

Colla, V., Matino, I., Branca, T. A., Fornai, B., Romaniello, L., and Rosito, F. (2017). *Efficient use of water resources in the steel industry*. Water, 9(11), 874.

Degarmo, E. P., Black, J. T., Kohser, R. A. (2003). *Materials and Processes in Manufacturing* (9th ed.), Wiley, 404.

Matino, I., Colla, V., Romaniello, L., Rosito, F., and Portulano, L. (2015). *Simulation techniques for an efficient use of resources: an overview for the steelmaking field*. In 2015 World Congress on Sustainable Technologies (WCST), 48-54.

Matino, I., Colla, V., and Branca, T. A. (2018). *Extension of pilot tests of cyanide elimination by ozone from blast furnace gas washing water through Aspen Plus® based model*. Frontiers of Chemical Science and Engineering, 12(4), 718-730.

OpenModelica, https://openmodelica.org/, https://openmodelica.org/, n.d. s.l.: s.n.

Porzio, G.; Alcamisi, E.; Matino, I.; Colla, V. (2014). *An integrated approach for industrial water systems optimal design*. In Proceedings of the 2014 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech, Washington, DC, USA, 12–15 May 2014, 529–532.

Sofi Filtration, https://www.sofifiltration.com, accessed 13.06.2022.

Suvio, P., van Hoorn, A., & Szabo, M. (2010). *Water usage in steel making: Findings from a worldsteel water management project*. stahl und eisen, 130(11), 51339-51350.

Suvio, P., van Hoorn, A., Szabo, M., & Ekdahl, Å. (2012). *Water management for sustainable steel industry*. Ironmaking & Steelmaking, 39(4), 263-269.

Tarnacki, K. M., Melin, T., & Jeschke, S. (2014). *Water Saving in a Complex Industrial System–Evaluation of the Sustainability of Options with System Dynamics*. Complex Systems Design & Management, 267-279.

Wang, Y., Li, L., He, W., Zhang, X., Li, X., Li, X., & Li, H.; (2022). *Application of networked water balance model in refined management of steel industrial park.* Water Supply, 22 (3), 2533-2545.

World Steel Association. (2020). *Water management in the steel industry*, position paper.