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Ecologically Inspired Water Network Optimization of Steel Manufacture Using Constructed Wetlands as a Wastewater Treatment Process

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ABSTRACT

Traditional optimization models often lack a systems-level perspective at conception, which limits their effectiveness. Expanding system boundaries allow scientists and engineers to model complex interactions more accurately, leading to higher efficiency and profitability in industrial systems. Ecological systems have evolved for billions of years under conditions of material and energy shortage, and ecologists have defined analysis tools and metrics for identifying important principles. These principles may provide the framework to circumvent the limitations of traditional optimization techniques. More specifically, by recruiting functional roles that are often found in ecological systems, but are absent in industrial systems, industries can better mimic how natural systems organize themselves. The objective of this analysis is to traditionally optimize a manufacturing process by comparing the model with ecological and resource-based performance metrics in order to redesign the model with the addition of important functional roles that are found throughout nature. Industry partners provided data for this analysis, which involved building a water network for an existing steel manufacturing facility in China. The results of the traditional optimization model indicate a 23%, 29%, and 20% decline in freshwater consumption, wastewater discharge, and total annual cost, respectively. However, our ecologically inspired optimization model provides an additional 21% and 25% decline in freshwater consumption and total annual cost, respectively. Furthermore, no water is discharged. These results suggest that this unconventional approach to optimization could provide an effective technique not used by existing algorithms to solve the challenging problem of pursuing more sustainable industrial systems.

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1. Introduction

1.1. Motivation

The World Economic Forum listed water scarcity as one of the three global systemic risks of highest concern when surveying risk perception from business, academia, civil society, government, and international organizations [1]. Water, often viewed by industry as a low-cost, infinite resource, is largely used in an inefficient manner [2]. However, rising freshwater and treatment costs have caused a shift in focus toward water conservation. Therefore, this analysis focuses on optimization of the steel industry water network as a case study, with the aim of incorporating biological actors to fulfill the decomposer role in steel manufacturing.

Apart from iron and energy, water is the most important commodity in steel manufacturing [3]. Mostly due to evaporation losses, efficient steel making today requires approximately 4.12 m^3 of freshwater per tonne of crude steel; this water is used primarily for cooling. Therefore, reducing the amount of cooling water requiring traditional treatment and decreasing the amount of effluent generated from cooling could have major impacts on the overall amount of energy and water consumed by the steel manufacturing process. The major contaminants from cooling processes that require removal prior to water recycling are chloride compounds and suspended solids. Without such removal, the water is not suitable for processes that demand high water quality, as it could corrode mechanical equipment [4].

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1.2. Approach to optimize the steel water network

Within every natural ecosystem, there are multiple key functional roles that together result in a robust cyclic system. Primary producers, consumers, decomposers, and the physical environment are all necessary for an ecological community to harvest, transfer, and cycle materials and energy [5]. In particular, the amount of internal cycling in natural ecosystems is strongly influenced by the presence of decomposers, actors that are often called detritivores in ecology. These organisms break down waste or unconsumed biomass produced by higher level species and return it back into the system [6]. Over half of the material flows in natural food webs move through the detritivore component. However, this functional role is often poorly represented or missing entirely within industrial systems [7]. Some scientists and engineers argue that even limited connections to an actor that functions as a detritivore would greatly enhance the efficiency of industrial networks [8].

To improve the current steel manufacturing water network, this study investigates the use of constructed wetlands for phytoremediation to reduce the total amount of freshwater, operating costs, and environmental impact in the steel industry. The constructed wetlands mimic the decomposer role by reintroducing the cooling water—which would otherwise be treated by the onsite wastewater treatment plant and discarded as effluent—back into the steel industry water network. Phytoremediation is the ability of plants to concentrate elements and compounds from their environment and to metabolize various molecules in their tissues. Phytoremediation is one of the most economical ways to treat wastewater, with some studies finding it to cost 10–1000 times less than conventional civil engineering technologies [9]. After removing the contaminants from the wastewater, crop disposal scenarios include pyrolysis, composting, compaction, incineration, ashing, and liquid extraction [10]. Some scientists have identified potential to use the plants as a feedstock for biofuel production, which could then be used to further decrease energy consumption in steel making [11]. Also, when using pyrolysis as an end-use, the resulting biochar could be reintroduced as a feedstock into the steel manufacturing process. This approach should be investigated further, as this process is another way to further mimic the decomposer role in steel manufacturing.

2. Materials and methods

2.1. Optimization model construction

The steel industry water network involves several typical water systems located in different plants that have various water requirements, wastewater types, and wastewater characteristics. In addition, the water networks in these plants are interconnected through utilities—that is, through a centralized wastewater treatment system (CT) and/or a desalination system (DS). Together, these aggregated interconnected water networks within steel manufacturing form a steel park water network. The total water network of the steel park is complex and involves multiscale water systems and networks, such as unit-scale water systems and plant- and park-scale water networks. To model the water network optimization of a large steel park, three multiscale efforts are performed on the model and on superstructure improvements: ① identifying all types of unit-scale typical water systems in the park, and then developing simplified unit models for them, which work as the basic elements for superstructure construction; ② establishing intra- and inter-plant superstructures to describe a potential configuration for the water network at the plant-scale and park-scale; and ③ based on these developed models and superstructures, developing a mixed-integer nonlinear programming (MINLP) problem using total annual cost as the objective in order to investigate the potential for water network optimization in the steel park.

2.1.1. Simplified models for a typical unit-scale water system

The typical unit-scale water systems in a steel park include indirect closed circulating cooling water systems (ICs), indirect open circulating cooling water systems (IOs), direct open circulating cooling water systems (DOs), DSs, once-through process systems (OPs), wastewater treatment systems (WTs), water source systems (WSs), and water demand systems (WDs). The first three types of water systems contribute to more than 97% of total water use. The IO model is presented in Fig. 1 as an example. Note that the system has two outlets: One is backwash wastewater, and the other is outlet water that is ready for recirculation or discharge. The IC and DO models are similar to the IO model; the main difference between the three systems is the water quality requirement.

Another key water system is the DS, which is used to produce the soft and desalinated water required by water-use systems. Two types of DS are commonly found throughout the steel industry: One uses freshwater, while the other uses reclaimed water from a CT as raw water. A model of such a system is shown in Fig. 2. It can be observed that this model has four outlets to include backwash wastewater, concentrate from reverse osmosis (RO), soft water, and desalination water.

These two types of water system have not been previously investigated in detail, and the corresponding models are always simplified as one-input one-output systems. However, in this study, one-input multi-output models are utilized to describe these water-use systems, which will help identify more potential for wastewater reuse in a plant. Other unit-level water systems are general, and their models have already been deeply discussed in the literature [12–14]; therefore, those systems are neglected in this study.

2.1.2. Superstructure for a plant-scale water network

A plant-scale water system denotes the water network of a single plant. A plant-scale superstructure is always established based

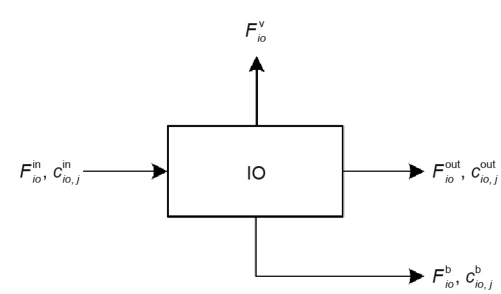

Fig. 1. Model of the IO. *F*: water flowrate; *c*: concentration; *io*: an IO system; *j*: contaminant *j*; in: inlet stream; out: outlet stream; v: evaporation; b: backwash wastewater.

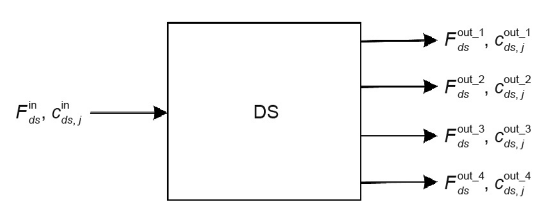

Fig. 2. Model of the DS. *ds*: a DS system; out_1: backwash wastewater in outlet stream; out_2: concentrate in outlet stream; out_3: soft water in outlet stream; out_4: desalination water in outlet stream.

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