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Lean–Green Improvement Opportunities for Sustainable Manufacturing Using Water Telemetry in Agri-Food Industry

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Abstract: Water has become a critical resource due to increased manufacturing activities. However, there is a lack of detailed information on water management and consumption by industries. In the recent bibliography, lean–green was established as a good approach for achieving sustainability in manufacturing industries, but few studies have aimed to achieve both operational and environmental improvements in water consumption. In this paper, we present a multi-case study in the agri-food industry in which water consumption in company activities is monitored, allowing them to improve their industrial processes based on lean–green practices, leading to a zero-waste strategy for this critical resource. The aim of this paper is to demonstrate the importance of having detailed knowledge regarding water consumption in order to discover, in a lean–green context, new improvement opportunities which could remain hidden by the current way of analysing consumption.

Keywords: green production; lean manufacturing; sustainability; operation management; manufacturing; telemetry; agri-food sector

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1. Introduction

Access to water is a universal right; however, water that is fit for human consumption constitutes only about 1% of the planet's total water reserves. Water is therefore a scarce resource and can only be guaranteed through adequate management and protection [1]. Water scarcity is currently a serious problem in 11% of the European Union (EU) territory, and if no action is taken, the planet will face a 40% water deficit by 2030 [2,3]. Global trends predict that there will be a 55% growth (Figure 1) in global water use by 2050 [4] and that one out of every two inhabitants will suffer from water shortages worldwide. In the EU economy, the water sector represents 3.4 billion euros (26% of the EU's annual gross value added) and employs 44 million people [5].

Fortunately, most countries are coming to grips with the predictions of water shortages and have defined policies and initiatives to mitigate the potential effects [6]. These policies are especially aimed at the most water-consuming economic sectors: agriculture and industry [7–9]. As far as industry is concerned, knowing which industrial processes have the greatest impact on water use and how water is used in those processes would allow managers to detect improvement opportunities and achieve more efficient water management in each company.

In the manufacturing industry, some companies are using the lean–green strategy as a framework to deploy process improvements related to eliminating environmental waste [10,11]. The lean management paradigm improves quality and productivity by eliminating operational waste in organisations; the green paradigm aims to reduce environmental risks and impacts while improving ecological efficiency and eliminating environmental waste in organisations [11]. This combined lean–green approach could be useful to address the water management problem.

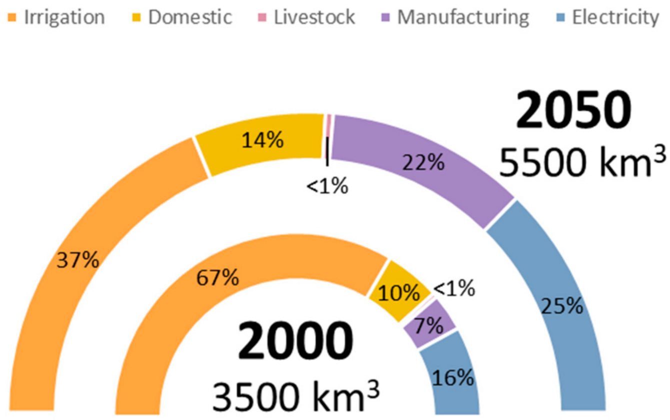

Figure 1. Predicted increase in global water use by 2050 (data source: [4]).

There is empirical evidence of the application of lean tools and methods in manufacturing processes and their positive impact on an organisation's environmental performance. However, this evidence is not always sufficiently explanatory for users. For example, some evidence of the application of those tools is based only on surveys. Other evidence focuses on describing which environmental aspects (electricity and water consumption, waste emissions, etc.) have benefitted from lean tools but do not specify how this has been achieved [12,13].

Digital technologies and their applications in industry are also considered an opportunity to increase efficiency and maintain the competitiveness of organisations [13]. These technologies are useful for knowing how much water is consumed in each process in the industry and how the water is consumed (i.e., patterns, specific activities and workers' behaviour).

The aim of this paper is to show the advantages and the potential for improvement offered by the monitoring of key process variables using digital technologies in a lean–green context. This paper presents a study of four critical processes from the agri-food sector, where clear improvement opportunities for water management were found after analysing how water was consumed based on data collected by digital technologies. These case studies highlight the importance of having detailed knowledge of how water is consumed to enhance potential improvement of manufacturing processes in the lean–green context. Unfortunately, most of the improvement opportunities discovered in the case studies had not been implemented, since achieving operational impacts requires large investments. However, the main contribution of this paper is the empirical evidence that the pattern of water consumption is necessary to discover new improvement actions hidden by the current way of measuring consumption.

The rest of this document is divided into five sections. Section 2 analyses the scientific literature, framed around the improvement strategies in lean–green contexts. Section 3 establishes the methodology and the framework of the project in which the case studies are developed. The case studies themselves are described in Section 4. Finally, discussion and conclusions are presented in Section 5.

2. Literature Review

Lean manufacturing (LM) is considered to be one of the most influential production management systems in the manufacturing industry, providing empirical evidence on the competitiveness of organisations by reducing inventories and lead times and enhancing productivity and process quality [14]. The general approach of green management (GM) is to define a production system that minimises environmental impact and maximises the use of resources [15]. As the main goal of LM is to reduce waste (i.e., to use fewer resources to generate the same outcome), lean tools and methods are clearly environmentally friendly due to the fact that fewer materials are used in production and less pollution is generated [16]. Therefore, for some years now, the use of both management systems (LM and GM with their principles, tools and methods) has been studied in order to achieve more sustainable organisations.

In this context, the lean–green approach is defined for those actions with positive effects on both operational and environmental performance [17]. Many papers have shown the prominence and effectiveness of lean and green integration to be sustainable. Several references in the literature show empirical evidence of the use of lean tools and methods in the manufacturing sector and their effect on environmental performance [18,19]. Other papers show their effects on the sustainable (economic, environmental and social) performance of organisations [20,21]. In addition, research on lean–green management also deals with the question of how to apply lean–green strategies [14,22]. Sometimes, once the production process has been improved using lean tools (i.e., kaizen, waste reduction and/or standardisation), the environmental aspect is analysed and improved. This is a sequential approach of lean–green strategy. In an integrated lean–green approach, both production and environmental issues are improved simultaneously to achieve the best balanced result.

While there is increasing interest in water consumption by industry, to the best of our knowledge, a limited number of papers address in detail the issue of water consumption control and improvement in industrial activities under the lean–green approach. For instance, in a recent literature review [23], 23 different indicators in water management in industry were found: 13 indicators are related to environmental performance and only 5 of them are linked to economic or productivity variables; the remaining 5 are related to social aspects. However, few studies [24] have focused on achieving both operational and environmental improvements in the water consumption management under lean–green schemes. For example, the United States Environmental Protection Agency [25] identified a case-study implementation of the value stream mapping approach to reduce up to 170,000 gallons of water per day, resulting in savings of USD 17,000, with non-cost investment. Similarly, [26] a pharmaceutical manufacturing company implemented a continuous improvement approach that achieved savings of USD 97,047 by improving the cooling tower and chilled water system. Other approaches, such as those proposed by [27], aim to link and measure the operational and environmental impact within a manufacturing facility. These authors defined a methodology to assess the value of water in terms of all its incurred costs (i.e., extraction, treatment, pumping, storage, purification and disposal) in a deionised water generation unit of an industrial facility and discovered that the total true cost of the water was EUR 26,025, versus the perceived cost of EUR 1853. In [28], a case study was presented where the aim was to reduce the environmental impacts (as well as water reduction) from a specific facility, achieving a reduction of 17% of the average consumption. More recently, the authors of [29] highlighted the usefulness of 5S practices to simultaneously improve water efficiency and plant performance. The results obtained by these authors confirmed a reduction of around 45% in water usage and a 20% growth in labour productivity with the joint implementation of lean and circular economy initiatives.

In all the examples presented above, water savings were obtained using average or net consumption values (output minus input). However, none of them considered the temporary behaviour of water consumption.

In addition, the authors of [30] reviewed the approaches and methodologies for implementing lean and green management in the agri-food sector. These authors highlighted the importance of the implementation of adequate process control techniques to correctly quantify and improve both operational and environmental performances. As control ensures successful and sustainable improvement [31], the adoption of digital technologies to monitor production mitigates challenges related to waste and improves batch traceability [32]. The key factor in monitor and control, in both operational and environmental performance, is to define and retrieve critical indicators for machines and/or processes so as to make the correct decisions after analysing the right data [33]. Regarding other water consumption studies in industry, in [34] were presented new technologies for measuring water consumption with the aim of increasing the information available about the use and/or consumption of this resource. Real-time monitoring of water consumption activities is presented as an effective mechanism to efficiently manage the water network [34].

With the aim of contributing to research on the operational and environmental improvement of industrial processes by adopting lean–green strategies through the use of detailed information on water consumption, this paper will illustrate the telemetry of four critical processes—monitored in a small set of companies in the agri-food sector—aimed at reducing water consumption. Monitoring the use of this resource in real time will provide the following outcomes:

1. Real-time measurements. This will make it possible to simultaneously study the operation process with water consumption telemetry. Operations managers will be able to analyse consumption in detail to identify new improvement process opportunities that had not yet been detected due to lack of detailed information.
2. Real estimations of economic and environmental impacts. Having this detailed information on the water consumption of different activities in a process will make it possible not only to identify these improvement opportunities but also to estimate their profitability from an operational and environmental point of view, since the impact of the improvements would be attributed to the real water consumption of each process and activity.
3. Lean–green strategies. Only by having this detailed information associated with the most critical activities of the process (the ones that consume the most water) will it be possible to propose new integrated lean–green strategies based on responsible and sustainable water management.

The results of these cases highlight the importance of having detailed knowledge of how water is consumed (consumption behaviour) in industrial production processes.

3. Materials and Methods

Following the literature on case study methodology [35–37], this article uses different case studies to achieve the objective mentioned above. The companies in this study have flow meters, sensors and probes (temperature or conductivity) that activate or deactivate valves, dose chemicals or control their cleaning systems. Data from these electronic elements is often not recorded or not monitored and it is only used in aggregated form (e.g., daily water consumption, average conductivity value, maximum pH value).

1. In this paper, we would like to compare this data with real-time monitoring records. In gathering the real-time data, we used a device for monitoring called Plug&Lean [33], which was adapted [38] in a research project (Figure 2) to integrate a set of commercial probes, sensors and commercial devices (such as ultrasonic flow meters or transducers). The device is easy to install and it allows real-time monitoring at low energy consumption.

Figure 2. Plug&Lean monitoring kit.

Qualitative information was gathered through direct observations by one of the members of the research team and meetings with the different process managers of the companies analysed in these case studies.

The processes presented in this paper as case studies are four of the most common in the agri-food sector: cooling cycles (two cases), the autoclave sterilisation process (three cases) and two cleaning processes: one manual (three cases) and one based on a clean-in-place (CIP) system. These processes are present in practically all agri-food sector companies, so the conclusions drawn from this study could be generalised to any company in this sector. For confidentiality reasons, neither the companies nor the products will be mentioned.

The first case will show, from the analysis of a cooling process, the importance of telemetry to identify potential for improvement. The three cases involving the autoclaves show, first, two examples of sequential lean–green application (first lean, then green) focused, respectively, on water consumption and costs; the third autoclave case study is a clear example of integrated application (lean and green simultaneously). The manual cleaning study identifies an initial situation in which there is no habit of controlling water consumption. In an effort to avoid this waste using a new technology, a solution was found that also reduces water consumption. Finally, the case of automatic cleaning shows how the synchronised analysis of two environmental variables (water consumption and conductivity) can reduce not only water consumption but also the cleaning cycle. The cases are analysed in detail below.

4. Case Studies

4.1. Importance of Telemetry: Cooling Process Case Study

The washing and cooling processes work in a similar fashion: clean cold water is added to the product, usually in a counter-current, to clean or cool it. The water flow is usually high, and many companies analyse the feasibility of installing recirculation systems based on two fundamental design parameters: water flow and water quality. Frequently, companies use water consumption average values to analyse potential recirculation opportunities. This example, based on a monitoring campaign carried out in a company, will show how the use of average values could lead to an erroneous analysis.

Figure 3 shows the behaviour of two cooling cycles (two different days) for the first production line. An initial transitional period and a long period of constant water supply were observed, with an average flow rate of 250 L/min during this second period for both days. Consequently, the overall consumption during the whole cycle is 160 m^3 per cycle, with an average duration of 10 h.

Figure 3. Telemetry for the first cooling process.

Figure 4 shows the behaviour of two cooling cycles (two different days) for the second production line. In this second production line, after filling a vat with approximately 5000 L, an average flow rate of 350 L/min only during the first part of the process was used. The water supply during the rest of the process was 40 L/min. In this second production line, the overall consumption during the whole cycle was 27 m^3, also for a duration of 10 h.

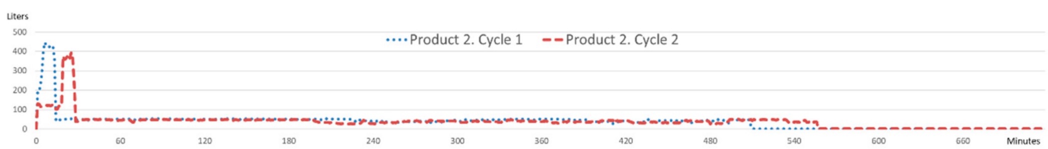

Figure 4. Telemetry for the second cooling process.

If the company were to consider investing in a water recirculation system based on these estimated average flow rates, this approach could lead to an erroneous decision. The average value accurately represents the behaviour of the process shown in Figure 3, but it is not representative of the behaviour of the process shown in Figure 4.

As mentioned, this is the example that verifies the importance of analysing in detail how the water is consumed in each activity of the process (and not only knowing the average consumption of the process with respect to the entire facility) to find new opportunities for improvement.

4.2. Sequential Lean–Green Strategy

4.2.1. Autoclave Case Study I

Although the companies studied manufacture different products (pâté, canned vegetables or canned tuna) and use different packaging systems (cans, jars or bags), their autoclave operations are similar. The autoclave is filled with water, the sterilisation cycle is carried out according to the recipe and water is added (normally through showers) to cool the product so it can be handled. Some autoclaves use temperature sensors to provide water until the target temperature is reached. In other cases, the water supply is kept constant for a period determined by experience. Finally, some autoclaves are not always loaded with the same amount of product, which is placed on trolleys.

Normally, companies use a total volume of water consumed per cycle to determine the cost of the process and define a cooling strategy based on experience (no data). Under these conditions, it is very difficult to evaluate which strategy is best in terms of volume of water supplied, cooling time or autoclave loading.

The first example (Figure 5) shows two sterilisation cycles in the same autoclave, consisting of three phases: initial load, sterilisation cycle and cooling. It is also possible to identify how the program used to cool the autoclave consumes a different amount of water, even though the company, the autoclave and the cooling time are the same. Specifically, both cycles share the same pattern at the beginning of the cooling phase to prevent the thermal shock from exploding the jars or breaking the bags. However, the first cycle consumed 800 L more than the second cycle because the water supply was constant throughout the cooling phase. In cycle 2, the water supply varied throughout the cooling phase. In both cases, the same sterilisation and cooling of the product was obtained, but in one of them, a greater quantity of water was consumed.

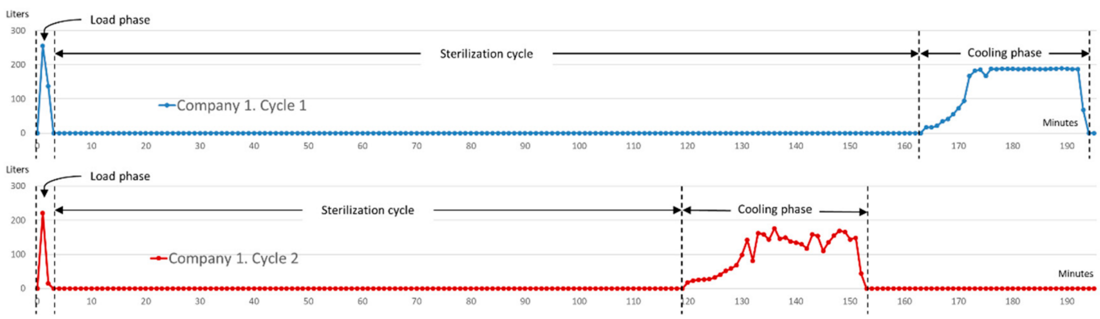

Figure 5. Autoclave telemetries for company 1.

This difference between cycles highlights the need to better understand water consumption for optimal use at the cooling stage. Using this information, the process water consumption could be standardised once the operating cycle is defined, showing how a sequential Lean–green strategy will lead the company first to a standard working cycle (lean manufacturing) and then to reduced water consumption (green management).

As a take-home message from this study, for the same process performance, a comparative analysis of the consumption of resources (water, energy, etc.) must be carried out in each treatment unit and/or each cycle.

4.2.2. Autoclave Case Study II

The second company (Figure 6) used average consumption data to calculate the production costs of the process under the assumption that all the programs used in the autoclave consumed a similar amount of water. However, the telemetries show that the program used in the cooling process was quite different depending on the product, estimating the difference between the two cycles at almost 3000 L.

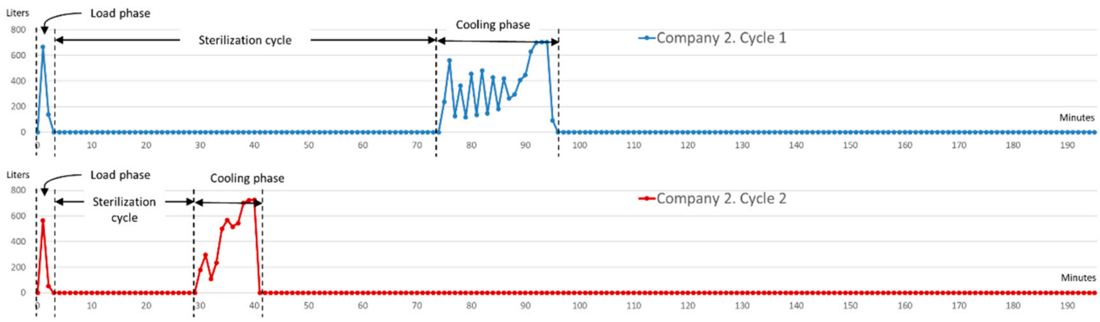

Figure 6. Autoclave telemetries for company 2.

During the campaign in this second company, the consumption measured by telemetry varied between 6 m^3 and 17 m^3 per cycle, depending on the cooling program. The process managers' hypothesis was that consumption was similar in all cases (around 6 m^3), and they used this value to allocate the costs of water consumption to the process. This erroneous hypothesis can lead to under or overestimating the production cost of each product and thus result in wrong and inaccurate production/sales strategies.

In this case, the take-home message is clear. Even though a continuous monitoring of this process is not implemented (this being the best option), it is necessary to estimate the consumption of resources for each product produced. As in the previous case, compression and quantification will help to implement correct strategies.

As a result of this study, the company is going to review and modify the cooling programs to standardise consumption where possible and adjust the cost allocation in line with real consumption. This second case study shows how a sequential lean–green strategy will lead the company first to a standard working cycle and then to allocate water cost to minimise the use of this resource.

4.3. Simultaneous Lean–Green Strategy

4.3.1. Autoclave Case Study III

Figure 7 shows water consumption in two cycles carried out in the same autoclave. Although the water supply in the autoclave was constant in both cases, the second cooling phase was shorter and therefore the water consumed was reduced by 750 L. In this case, the amount of product in the autoclave was different in each cycle, which could influence the amount of water provided for cooling.

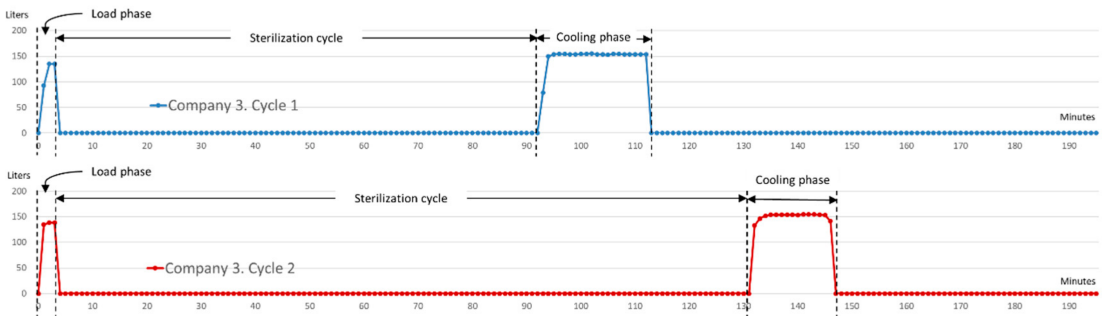

Figure 7. Autoclave telemetries for company 3.

This information may be relevant in optimising the relationship between load and cooling time; thus, an integrated lean–green strategy would optimise the autoclave and water use.

4.3.2. Manual Cleaning Case Study

Manual cleaning of facilities is usually one of the most water-consuming processes in the food industry. Water consumption follows a known pattern in production processes, but in cleaning processes, the lack of a systematic approach to cleaning or the state of dirtiness of the installations makes it difficult to define a standard consumption pattern. However, the following graphs (Figures 8–10) show the usefulness of analysing these cases.

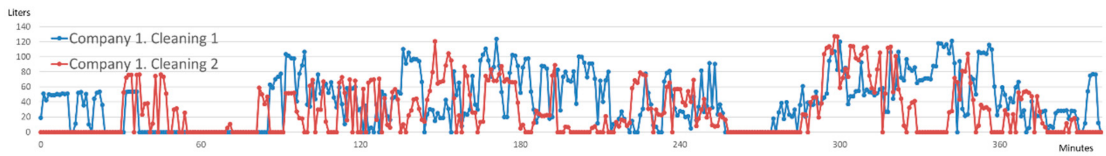

Figure 8. Telemetry for manual cleaning of a plant with old nozzles.

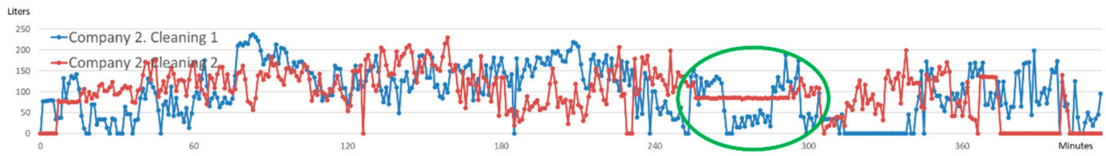

Figure 9. Manual cleaning telemetry identifies waste patterns (green circle).

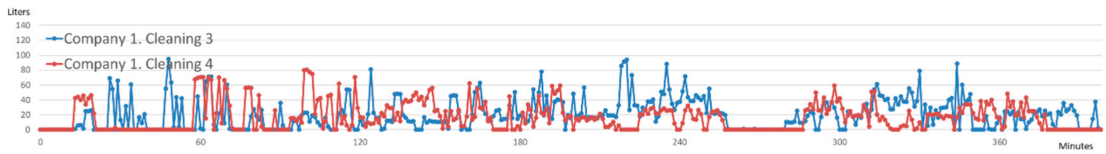

Figure 10. Manual cleaning telemetry of a plant with new nozzles.

Figure 8 shows a manual cleaning processes for two days, obtained from a fifteen-day campaign carried out in the same company. Some periods where flow rate value equalled zero and others with values ranging from 40 to 120 litres per minute could be observed.

The following graph (Figure 9) shows two cleaning cycles from a second company which allowed managers to identify and quantify the effect of a leak during rest when a shut-off valve was not closed (green circle). As a consequence, 3 m^3 of water was wasted over 37 min.

By showing workers a simple graph, the company was able to make them aware of the impact that this type of undesired situation has on the total consumption during cleaning cycles. In this case, the presence of a constant consumption pattern helps identify errors or misunderstandings. These charts could be included in the 5S panels to encourage the development of good habits according to an integrated lean–green strategy.

Seeing the opportunity to assess the water consumption behaviour during the cleaning of its installations, the company decided to test a different cleaning nozzle. According to the supplier, the nozzle offered lower consumption by increasing the water pressure, thereby reducing the flow while maintaining the result and the required hygienic conditions. The following telemetries (Figure 10) certified a water saving of 40% in the cleaning cycles (in the campaign, each nozzle was tested for one week and the same savings were certified). The graph shows that the level varied between 20 and 80 L per minute. This is a clear example of a new improvement opportunity provided by information from the telemetry of this cleaning activity.

Monitoring the consumption of cleaning water can serve as a follow-up or control of the work carried out. It can help to identify inefficiencies and establish good company practices that minimise water consumption. It is therefore an indirect optimisation derived from the quantification and knowledge of the system.

4.3.3. CIP Cleaning Case Study

Many facilities employ clean-in-place (CIP) systems for pipe cleaning. Most of them operate similarly: an initial rinse of the pipe is performed with water that is subsequently discarded; caustic soda and other chemical products stored in tanks are then circulated in a closed circuit. Next, the products are recovered by pushing clean water through. This water is also discarded along with the water used in the final rinse.

In this type of process, the amount of water used at the beginning and end of the cleaning process is unknown, as is the extent of the liquid interfaces (water–soda and soda–water). Therefore, it is impossible to assess whether it is profitable to invest in a new tank to collect the final rinse water to be used in the initial rinse during the next cycle.

In one of the campaigns carried out at a company, the signal from a conductivity meter was combined with the signal recorded by the flowmeters (indicating when caustic soda was circulating) to link the water flow and conductivity in each phase of the cleaning cycle. The flowmeters recorded both the soda and water flow. In this case, the data was collected every second.

In Figure 11, the different stages of the CIP cycle can be identified: rinsing (1), water–soda interface (2), closed circuit cleaning with soda (3), soda recovery (4), soda–water interface (5) and final rinsing (6).

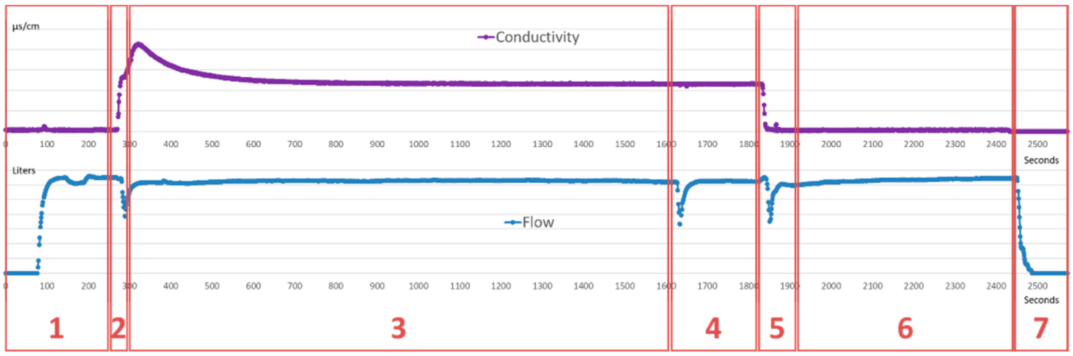

Figure 11. Combined conductivity and flow telemetry in a clean-in-place (CIP) system.

By studying the graphs and considering the width of each stage, three important conclusions can be drawn:

1. The interfaces (stages 2 and 5) are very narrow (only a few seconds), so the caustic soda and water barely mix, meaning that the water circulating in the pipe is clean water.
2. Stages 1 and 4 could be used to estimate the length of the pipe because the valves operate at the beginning of the system.
3. Taking this length of pipe into account, in the final rinse phase (6), the pipe is filled twice with clean water, which is discarded. This consumption behaviour means about 10 m^3 of water is used for each cleaning, although this data will depend on the length of the pipes being cleaned.

This example again shows that measurement and quantification are essential for correct system optimisation and decision-making. With this information, the company was able to justify the incorporation of a tank for the recovery of water from the final rinse, which was installed in other CIP systems. This water could then be used in the first rinse of the following cleaning cycle. Furthermore, reducing the final part of the rinsing would reduce the cleaning cycle, thus increasing the availability and productivity of the installation. In this case study, both the cycle and the resource usage were reduced simultaneously.

5. Discussion and Conclusions

Climate change affects many aspects of society, and the European water system (flood defences, irrigation systems, drinking water and wastewater networks) is no exception. Our water system must become more resilient to future increases in extreme weather events, including lower rainfall and more intense floods and droughts.

Different governmental organisations are addressing the need for new methodologies and innovative approaches to achieve sustainability. Current technological advances based on digitalisation, data analysis and artificial intelligence cannot be ignored in the area of water consumption, management and governance. By combining monitoring, communication and data analysis systems with the best available techniques (BREF), we should be able to reduce or at least streamline water consumption to ensure that the catastrophic forecasts being made do not come to pass. This also applies to industrial contexts.

Consequently, the development and/or implementation of new methodologies or techniques to solve real problems has become an important challenge in operations management. In this context, the Lean–green approach has become a particularly useful framework to achieve sustainability in industry. Recent bibliographic literature has found evidence that a trade-off can be achieved between operational performance and sustainability performance in manufacturing industries.

The results of the case studies presented in this article allow us to conclude the following:

1. Wireless measurement systems are increasingly being used for data capture in industrial applications. These systems allow detailed information to be collected, for example data about water consumption, with relatively low energy costs.
2. Analysing how and how much water is consumed (by relating the consumption to specific process activities) increases the information available and provides more comprehensive knowledge about processes used in relation to the consumption of critical resources.
3. The use of these wireless measurement systems for collecting detailed knowledge of process water consumption will allow industrial companies to better define strategies to establish increasingly sustainable production processes.
4. Some of the real cases analysed can be used as practical examples of the use of an integrated lean–green strategy.

Finally, the processes chosen are common processes within the food industry, so the results obtained here could easily be generalised to similar situations.

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