TEMPERATURE ANALYSIS OF THE WATER SUPPLY SYSTEM OF A DAIRY COMPANY BY MEANS OF A SIMULATION MODEL

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ABSTRACT
This paper describes the second part of a research project that examined, by means of simulation, the water distribution system of a dairy company located near Parma (Italy) and active for decades in the production of *Parmigiano Reggiano* cheese and butter. The first part of the research was described by Marchini et al. (2013) and focused on finding opportunities for recycling water in the distribution system of the dairy company considered. In this work, we go ahead by analyzing the thermal properties (such as, primarily, the temperature) of the water used inside the distribution system, as well as of that discharged. Specifically, the aim of the present study is to estimate the water temperature into each tank of the plant. To achieve this aim, we build upon the MS Excel™ simulation model developed by Marchini et al. (2013) and add the related thermal equations. As a result, we define the temperature trend of water inside all the tanks of the distribution system. Situations where the water temperature is higher than the boundary defined by the company (i.e., approx. 25°C) are also highlighted.

Keywords: water distribution system; thermal analysis; time-temperature trends; dairy industry; simulation.

1. INTRODUCTION
Nowadays, the world faces a wide range of ecological and human health crises related to inadequate access to, or inappropriate management of, water. The amount of water consumption in industrialized countries has almost doubled in the last two decades, making the rational use of water resources is a key issue for sustainable growth (Gleick, 1998).

Water consumption faces significant competing forces for change, which include decreasing water resource availability, developing stricter water quality regulations, decreasing federal subsidies, increasing public scrutiny, decreasing financial health, and increasing infrastructure replacement costs (Rogers and Louis, 2009). Consequently, the reuse of water has become an important issue within the process industry.

Water in food industries is primary used for two basic purposes: to be incorporated to specific products or sub-product (i.e., as a raw material) or to eliminate certain undesirable components, e.g. during cleaning operations (Poretti, 1990; Almatò et al., 1999). Recycling the amount of water used for cleaning operations can be an opportunity to combine a reduction in the costs of industrial water with an improved control of water management and a better environmental impact on natural resources (Centi and Perathoner, 1999). Indeed, the cleaning operations, besides the economic impact, have environmental impacts. In those processes, the water requirements and wastewater generation are closely tied to the sequence and schedule of the different production tasks. Discontinuous operations of the equipment generate frequent cleaning and preparation tasks, especially when product changeover takes place. Those operations are often carried out using water of different qualities at different temperatures and flows; the wastewater generated in these tasks can represent a considerable part of the total wastewater originated in a food plant (Almatò et al., 1997).

For the above reasons, the rational use of water resources has been an important research topic for many years and in different contexts. Among them, the main ones are the service processes, such as the cleaning operations (Centi and Perathoner, 1999) and the heat exchange processes (Lee and Cheng, 2012; Rezaei et al., 2010). Some authors have developed solutions for water savings, taking into account both the contamination level and the thermal properties (i.e., primary, the temperature) of the water discharged. The main purpose of those solutions is to generate savings, thanks to lower procurement and energy cost, by decreasing the amount of freshwater required, as well as to the lower cost for the treatment and discharge of waste water. Almatò et al. (1999) developed a methodology for the optimization of water use in the batch process industries. Al-Redhwan et al. (2005) address the problem of uncertainty in optimizing wastewater networks in the process industries. They start from the assumption that waste water flow rates and levels of contaminants can vary widely as a result of changes in operational conditions and/or feedstock and product specifications; therefore, an optimal water network design should be robust against those uncertainties. De Faria et al. (2009) address a similar topic, i.e. the optimization of water flows in industrial processes, by means of a non-linear programming model, whose objective function is to minimize the freshwater consumption. Kim (2012) introduces a system-wide analysis of water networks, grounded on the graphical design method, to help consider waste water charges in the water network design and making decisions about water regeneration and recycling. Looking at the food industry, some further contributions can be found, addressing both the general problem of water consumption in that industry (Casani and Knochel, 2002; Casani et al., 2005), as well as examining specific industrial segments, e.g. the sugar industry (Bogliolo et al., 1996) or the dairy one (Marchini et al., 2013).

This paper describes the second part of a research project, addressing the problem of optimizing the water consumption in the water supply system of a dairy company, whose main products are *Parmigiano Reggiano* cheese and butter. The first part of the research was described by Marchini et al. (2013) and focused on modelling, by means of a simulation tool, the water flows of the plant, so as to gain a precise knowledge of that system. Once the simulation model was validated, it was used to identify opportunities for recycling water in the distribution system of the company considered. In this work, we go ahead by analyzing the thermal properties (such as, primarily, the temperature) of the water used inside the distribution system, as well as of that discharged. Specifically, the aim of the present study is to estimate the water temperature into each tank of the plant. To achieve this aim, we build upon the MS Excel^{TM} simulation model developed by Marchini et al. (2013) and add the related thermal equations.

The remainder of the paper is organized as follows. In the next section we provide an overview of the water distribution system examined in this study. Section 3 describes the model developed to assess the thermal properties of water inside the distribution system. The model is validated in Section 4. Section 5 provides the results of the simulation runs, in terms of the time-temperature curves of water at different points in the distribution system. Countermeasures for critical situations, i.e. those situations where the temperature turned out to be excessively high, are also discussed. Section 6 summarizes the contributions of this study, the related limitations and implications, and describes future research directions.

2. WATER DISTRIBUTION SYSTEM AND PROBLEM STATEMENT

2.1. Overview of the water distribution system

As mentioned, the research described in this paper targets a dairy company located near Parma, Italy. This company has been active for decades in the production of *Parmigiano Reggiano* cheese and butter and is one of the greatest *Parmigiano Reggiano* producers of that area, with a production volume of about 60 wheels of cheese and more than 10 tons of butter per day.

The factory is equipped with two independent water circuits, one for the cheese and the other one for the butter production line. In the study by Marchini et al. (2013), the initial (AS IS) operating conditions of the plant lines were examined, through simulation, and their performance (in terms of water consumption) evaluated. On the basis of the findings from the AS IS analysis, the authors developed two reengineered (TO BE) scenarios for the plant, with the purpose of decreasing the overall consumption of water in the plant. One TO BE configuration, in particular, offered interesting savings in terms of water consumption. In that configuration, the authors proposed to increment the storage capacity of the central tank of the plant, called TK901, by adding a new tank, named TK902, working in a complementary manner to the first one.

The introduction of the new tank would avoid wasting a significant amount of water, by recovering the outputs from the fermenters of the “cheese section” and the discharge water downloaded by the TK105 (in the “butter section”) when it reaches its maximum capacity. Therefore, the tank would work as an inter-operational buffer, with the purpose to decouple water recovery and water withdrawals from the various plant lines. The optimal capacity of the new tank was estimated to be approx. 30 m^3. By introducing the new tank, the factory could save a total of 211.58 m^3 of water over two weeks (14 days) of functioning. If compared to the daily water consumption of the plant, this saving appears as particularly relevant, accounting for approx. 7.2% of the total amount of water used in the plant. In this work, the TO BE configuration of the water supply system described above (as it was derived from the previous study) is taken as the reference scenario. A scheme of that configuration is reported in Figure 1. The reader is referred to Marchini et al. (2013) for further details.

2.2. Problem statement

In this study, the reference scenario described in the previous section is subject to further analyses, with the purpose to evaluate the water temperature at different points in the water supply system and its trend in time. Additional aims of the analyses carried out include:

- The evaluation of the amount of freshwater and recycled water used in the plant;

- The identification of those points in the plant where the water temperature is excessively high and should be lowered.

With respect to the aims listed above, it should be mentioned that each tank if the plant can be filled:

- by means of freshwater, picked from the wells, depicted in the left side of Figure 1. Usually, the temperature of that water is approx. 16°C;
- by water flows arriving from other tanks in the plant, with the related temperature;
- by recycled process water. That water has been already used in the plant for some processes, and discharged, but is free of microorganisms and can be reused in subsequent processes. Compared to the remaining flows, recycled water is, usually, at high temperature.

According to the indications of the dairy company investigated, the water temperature in the plant should not exceed 25°C, because of safety reasons as well as to limit energy consumption. This point is particularly relevant for cleaning in place (CIP) operations. Therefore, the analysis described in this paper is particularly focused on those tanks that provide water to the CIP process, i.e. TK601 and TK605 (cf. Figure 1); indeed, these tanks should provide cool water, used to wash the plant components, with the purpose of avoiding the growth of microorganisms.

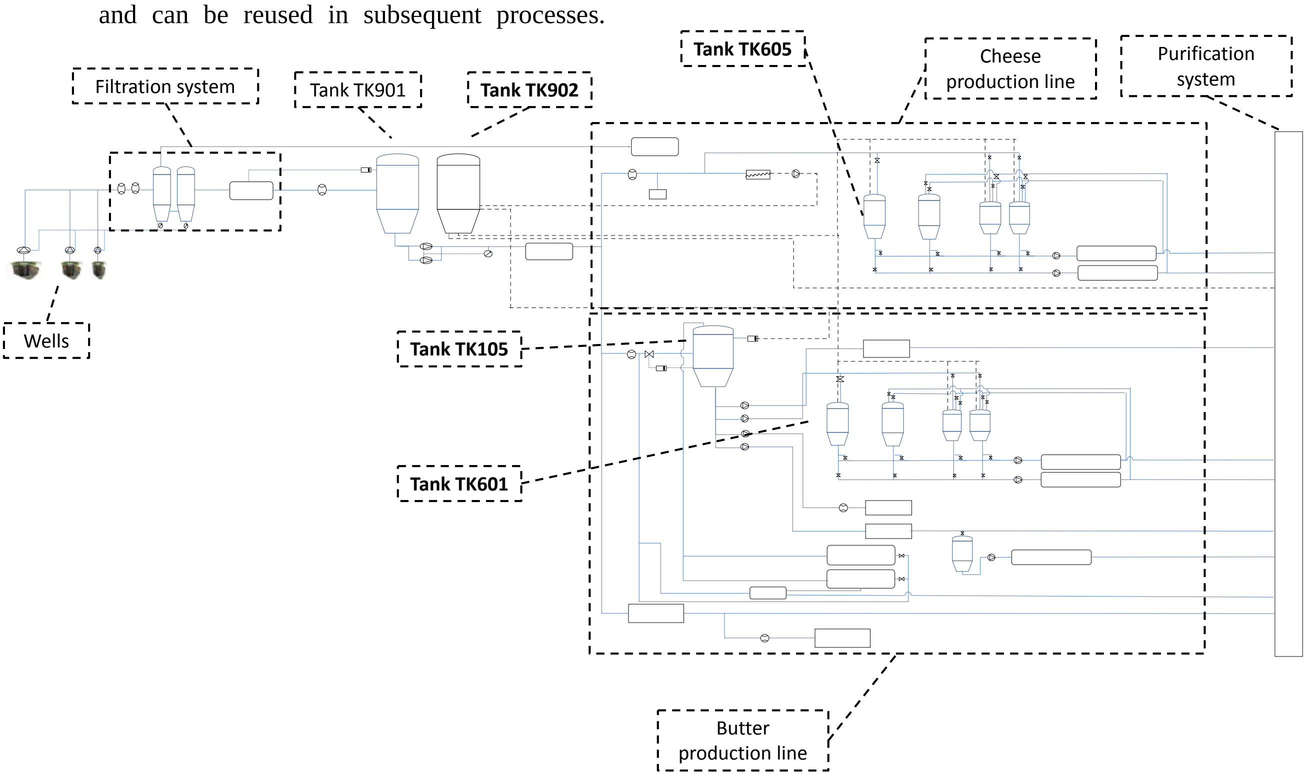


Figure 1: Reference scenario of this paper: the water distribution system of the factory after the introduction of the tank TK902 (source: Marchini et al., 2013).

3. THE THERMAL MODEL

3.1. Data input and main assumptions

As mentioned, in the previous study, the overall water flow and consumption of the dairy company were reproduced using a simulation model, developed under MS Excel™. More precisely, discrete-event simulation has been used to reproduce the flows of the water supply system.

Starting from this model, a new simulator is developed in this work to evaluate the water temperature inside all the tanks of the plants, even though this study is particularly focused on two specific tanks.

As it can be easily realized, the input data of the thermal simulation model are the output data of the previous one. In particular, for each tank, the thermal model needs all the flows of water which entered it; examples of those flows can be the water flow from the well (usually at 16°C), the flow arriving from other tanks, or other flows from other processes (with the related temperature). Moreover, for each tank, the model takes into account all the water flows exiting it, i.e. the water required by the processes and for the CIP operations. All the values related to the water flows obtained during the first study were recorded in a database, which details the final results obtained from the simulation at each time step.

For the sake of clarity, we describe, as an example, the water flows in the main tank of the butter production line (TK105). As inputs of this tank, we consider the water flows from TK901, and the reusable water coming from the pasteurizer and the whey cooler. With respect to the outputs, TK105 provides water to several plant processes and to other tanks, including, e.g.: (1) sanitary water, (2) tanks of the butter CIP line, (3) process mixture, (4) faucets, (5) tank used from CIP 3 and (6) the discharge of water by TK105 to TK902 when it reaches its maximum capacity.

As a further input to be included in this analysis, the temperature of each flow is required. The temperature from both the well and all the processes involved was directly provided by the plant's manager of the company, and is shown in Table 1.

Process	Temperature [°C]
Well	16
Pasteurizer	40
Whey cooler	25
Fermenters	25

Table 1: Water temperature at different point in the plant (source: data provided from the company)

Obviously, the model starts to calculate the temperature in those tanks which do not receive contributions from other tanks. Operating in this way, the temperature of water flows arriving from other tanks will be calculated by the model.

Starting from those data, the thermal model is able to derive the water temperature into each tank of the plant, at different time steps. It should be mentioned that the thermal model was developed under the main assumption of "whole and immediate miscibility" of the fluids in the water distribution system. Considering a tank containing a given amount of water, such assumption means that any water flow entering this tank would generate a new water amount (obtained as the sum of the two original flows) with a new (average) temperature in any point of the water mass. As a further assumption, we did not consider the heat transfer by thermal convection between the wall of the tank and the external environment, since all the water tanks are sealed. For the same reason, the thermal conduction between the insulating material and the wall of the tank, as well as the thermal exchange between the wall of the tank and the fluid inside, can be neglected.

Applying the assumptions described above, the thermal model become quite simple, as it is based on the well-known physical relation that describes the final temperature resulting from two different fluid flows, at different temperatures, when those flows are mixed. That relation is as following:

$$M_1 * Cp_1 * (T_f - T_1) = M_2 * Cp_2 * (T_2 - T_f) \qquad (1)$$

Where:

M_1 = water mass of the first flow

M_2 = water mass of the second flow

Cp_1 and Cp_2 = specific heat coefficients of the fluids (in our model, $Cp_1 = Cp_2$ = specific heat coefficient of the water)

T_1 = temperature of flow 1

T_2 = temperature of flow 2

T_f = final (common) temperature of the mixture.

Solving the equation above by T_f, it is easy to find that:

$$T_f = (m_1 * T_1 + m_2 * T_2) / (m_1 + m_2) \qquad (2)$$

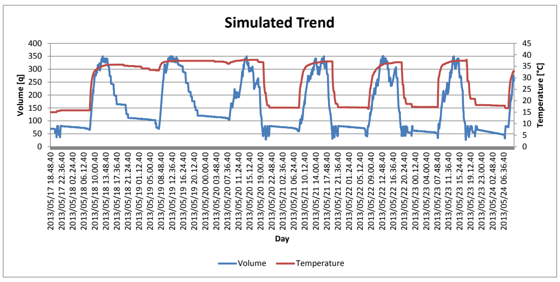
By means of the last formula, the final temperature of the water in each tank can be easily derived. By including that formula in the simulation model, and by computing the water temperature at different points of the plant, it is also immediate to identify those tanks whose temperature is higher than about 25°C, which was indicated as upper bound by the company examined.

4. MODEL VALIDATION

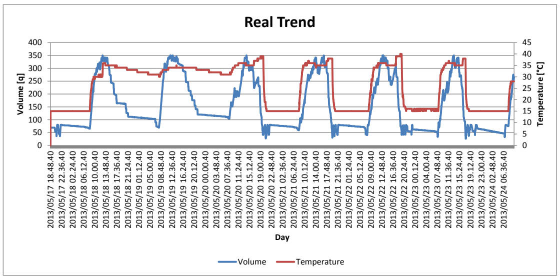
Once the model was developed, we identified a method to validate it, before its use to measure the water temperature inside each tank.

Specifically, for validation purpose, tank TK105 was equipped with a specific instrumentation able to measure the flow of water and the current temperature each day, with a time step of one minute. The real flow of that tank was then used as input of the thermal model, in order to compare its results to the real values provided by the measurement tool.

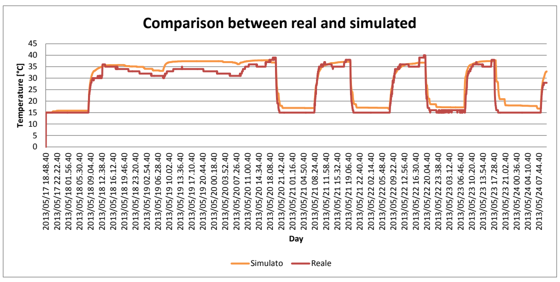
As shown in Figure 2, considering the same flow rate, the time-temperature trends obtained from real measurements and those simulated are quite similar.



(a)



(b)



(c)

Figure 2: simulated time-temperature trend (a), real temperature trend (b) and comparison (c).

The main difference between the simulated temperature trend and the real one is due to the fact that the simulated values are affected by the assumption of whole and complete miscibility of fluids. Because of this assumption, the resulting temperature profile is more regular than the real one. Anyway, taking into account that the simulation is expected to provide an estimate of the real result, the model could be considered validated.

5. SIMULATIONS AND RESULTS

The thermal model was launched to obtain the main outcomes in terms of the water temperature.

As previously mentioned, the plant includes two main critical elements, used during the rinsing phases of both the CIP lines, i.e. TK605 for the cheese production line and TK601 for the butter one. However, we started with the analysis of two other tanks, which supply water to the critical tanks and contain a relevant amount of recycled water: TK105 and TK902. As described earlier, tank TK105 reuses water coming from the pasteurizer and the whey cooler, plus the incoming water from the well when its total volume is lower than its safety level.

Figure 3 shows both the trend of the water flow (blue line) and its temperature (red line) over a two-week period (14 days).

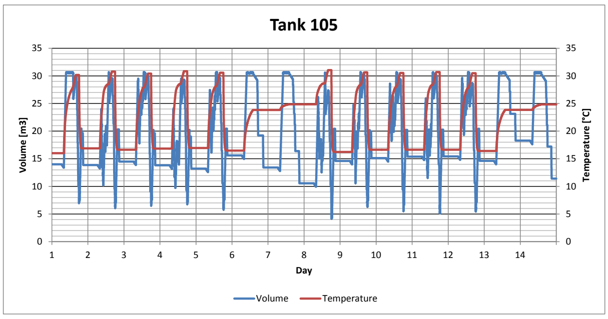


Figure 3: trend of the water flow (blue line) and related temperature (red line) for tank TK105.

As we can see from Figure 3, from Monday to Friday, the temperature increases in the morning up to reach about 30°C and it decreases in the second part of the day. This trend is due to the recycling of hot water arriving from the 2 processes of pasteurization and cooling. Indeed, from 8 a.m. to 2 p.m. both processes are working, providing, overall, 18,000 liters of water at 40°C and 54,000 liters at 25°C. Moreover, from 2 p.m. to 4 p.m., the pasteurizer continues to supply 6,000 liters of water, causing a sudden increase in temperature, up to its maximum. On Saturday and Sunday, the butter production line is not operating (only some washing cycles are carried out); therefore, the water requested is considerably lower compared to the other weekdays. Moreover, only the cooler operates; thus, the water temperature is always lower than 25°C.

Tank TK902 recovers the outputs from the fermenters of the cheese production section and the discharge of water by the TK105 when it reaches its maximum capacity. The corresponding water flow is proposed in Figure 4.

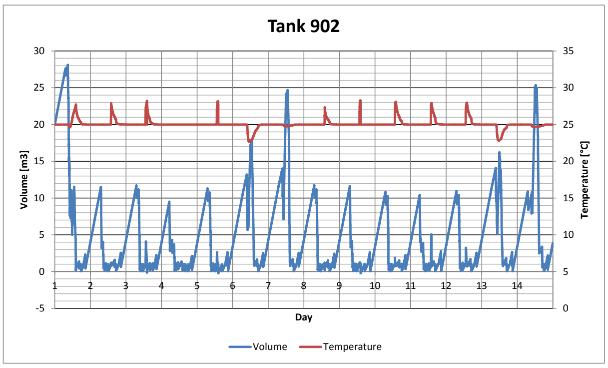


Figure 4: water flow (blue line) and related temperature (red line) for tank TK902.

From Figure 4, it emerges that the temperature is almost always higher than 25°C, with a daily peak of about 27°C, corresponding to the discharge of TK105. This is justified by the high temperature of the water flows that fill this tank. Obviously, on Saturday and Sunday, the scenario described for TK105 affects also the temperature of TK902.

As mentioned, the most important problem for the company examined is to control the water temperature inside two main elements which provide pure water to the CIPs. The corresponding results, which reflect the core outcomes of this work, are discussed below.

Looking at the cheese production line, TK605 can be filled from both the well and TK902. The corresponding temperature profile and water consumption are presented in Figure 5.

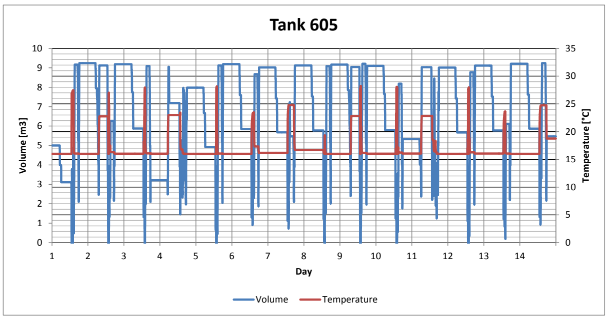


Figure 5: water flow (blue line) and related temperature (red line) for tank TK605.

From Figure 5, one can immediately see that the water temperature reaches unacceptable values, and that almost all the working days include at least one criticality. It is easy to identify the critical points looking at two specific days (i.e., Monday and Tuesday), which are particularly representative of the temperature trend across the two simulated weeks.

Figure 6 shows the behavior of the two valves (green and blue one) which regulate the CIP flow of pure water for the cheese line (1= valve open; 0=valve closed).

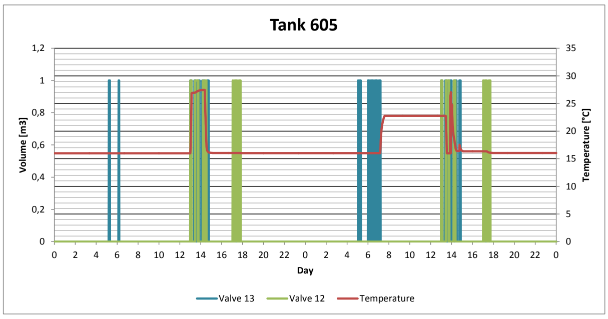


Figure 6: opening/closure of the CIP valves (blue and green lines) and corresponding water temperature (red line) for tank TK605.

Figure 6 highlights a main critical point, corresponding to the first day, from 12.30 p.m. to 2.30 p.m. If the company would like to avoid numerous washing cycles with hot water, the second critical point could be acceptable. Indeed, at about 2 p.m. of the second day, there is only a peak up to 25°C which could be ignored, considering also that the subsequent washing is at 15°C.

Tank TK601 is the last tank analyzed (Figure 7). This tank is slightly more problematic than the previous one, because it picks water only from TK105 and TK902, already studied.

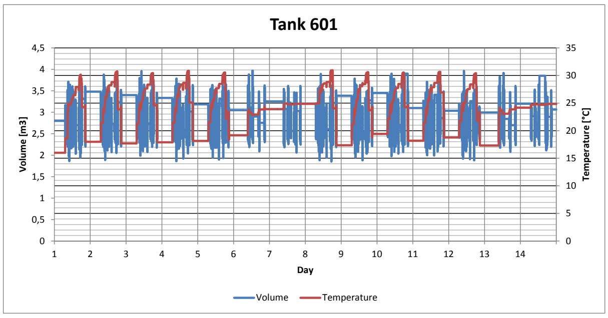


Figure 7: trend of the water flow (blue line) and related temperature (red line) for tank TK601 over a two-week period.

As Figure 7 shows, during all the working hours the temperature inside TK601 is higher than the acceptable limit of 25°C. Moreover, the time-temperature trend is very similar across the different weekdays. Therefore, we focused on a specific working day (i.e., Tuesday), obtaining the trend depicted in Figure 8.

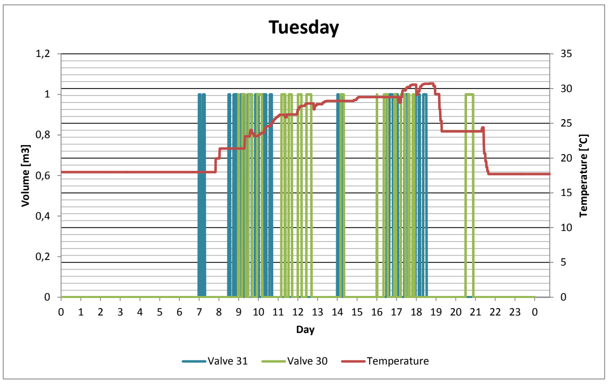


Figure 8: opening/closure of the CIP valves (blue and green lines) and corresponding water temperature (red line) for tank TK601 for a given day (i.e., Tuesday).

As it could be expected, all the washing cycles from 11 a.m. to 7 p.m. are characterized by too high temperature compared to the acceptable limit. From the theoretical perspective, only the washing cycle carried out in the early morning could exploit water from TK605; however, this solution is not feasible from the practical point of view.

6. DISCUSSION AND CONCLUSIONS

In the food industry, the issue of optimizing water consumption, by enhancing its reuse, is becoming more and more important. In this regard, this paper described the second part of a research activity, whose general aim was to optimize the water consumption in a cheese manufacturing company. In this work, a particular attention was paid to the analysis of time-temperature curves of water at different point of the water distribution system of the company, with the purpose of:

- estimating the amount of freshwater and recycled water used in the plant and the related temperature;
- identifying possible critical situations, i.e. those points in the plant where the water temperature is excessively high and should be lowered.

To achieve the aims listed above, in this paper we started by the discrete-event simulation model developed by Marchini et al. (2013), that was used in the first part of the research to describe the water flow in the plant. We added to this model the relevant thermal equations, to derive an estimate of the water temperature in the plant. Once the model was validated, subsequent simulation runs allowed to derive the water temperature at different points in the distribution system. Some critical situations, related, for instance, to water tanks TK605 were also highlighted.

This work has both theoretical and practical implications. From the theoretical point of view, our study is a typical example of how discrete-event simulation can be exploited as a powerful tool for the analysis of the water distribution system of the company investigated, and of the related performance.

Indeed, by means of discrete-event simulation, we were able to predict the operating conditions of the water supply system, taking into account the circulating flow rates, the on/off periods of pumping systems, the filling levels of the storage tanks.

From the practical point of view, we have mentioned that the whole study grounds on the analysis of a real cheese production company. Therefore, results have also a practical usefulness for that company. The identification of critical situations, or the analysis of the current performance of the water distribution system, are typical examples of practical results the simulation model can provide to the company investigated.

Future research directions that can be undertaken starting from this study include, primarily, the identification of countermeasures for the criticalities highlighted in our analysis. In this respect, the simulation model developed in this paper could represent a useful tool to investigate alternative layout configurations without the need of realizing them in practice, and to assess their performance against the criticalities identified.

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