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A tube-in-tube food pasteurizer modelling for a digital twin application

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Abstract

The process control in food industry plays an essential role to guarantee safety and quality of the manufactured food products. In order to increase the control possibility, the "Digital Twin" approach can be implemented in several food equipment, which can have a model that replies the real machine functioning. In this study a tube in tube pasteurizer has been modelled considering thermo-fluid dynamic parameters and conditions in order to simulate a beverage pasteurization process. The proposed model considers the use of possible non-newtonian fluids as it frequently happens in the food industry. After the model validation, a series of temperature and pressure probes located on the real plant and a data acquisition module will give in the future a comparison between real and simulated data in order to control the process status and avoid safety issues. In this way the operators will be able to act before something get wrong, without food product loosing.

Keywords: Digital twin, pasteurization, food processing, modelling, simulation

1. Introduction

Pasteurization is a heat treatment that stabilizes the food fluid from a microbiological point of view; contamination of the juice, caused by raw materials, the environment, and the hygiene of the processes can be reduced by means several methods, among them the thermal treatment is the most widespread used (Fellows, 2017).

In the beverage industry pasteurization can be applied before or after the filling process, depending on the number and size of possible pieces inside the beverages (Bottani et al., 2011).For beverages with small pieces (less than 10*10*10mm), a tube in tube pasteurizer could be adopted to pasteurize the beverage solution before filling. Every now and then, however, it can happen that small pieces of fruit or vegetable can aggregate and obstruct the flow. Under these circumstances, if the pressure reaches a high value, usually a safety valve discharges the flow avoiding safety problems in the system. This action however implies that a certain quantity of the product is thrown away and causes non-optimal treatment for the remainder of the beverage (Gottschalk et al., 2019). Furthermore, this possible obstruction can damage the handling and pumping systems, which must be managed accurately to ensure integrity of the components, reduced cost and easier cleaning and sanitizing of the processes.

To avoid these problems, recently the concept of digital twin has been introduced as a tool to control a system before something get wrong and safety is compromised (Bevilacqua et al., 2020).

In a digital twin approach, a key factor is the simulation model that has to reproduce the real process (Lu et al., 2020). Based on this model, sensors should then check whether the process is under control or if something is getting wrong. The reliability of the model should then be very high, meaning that it should allow to faithfully replicate the real process and interact with it, based on the comparison among real and simulated data.

On the basis of these premises, this work aims at developing a model of a pilot tube-in-tube pasteurizer for beverages, which is expected to be embodied in a digital twin system, designed on LabView environment (Bottani et al, 2020). Besides the thermo-fluid dynamic modelling of the heat exchanger, analyzing the rheological properties of the food product is a further important step of the model. In the food sector, many fluids are not Newtonian, which should be taken into account in modelling them, so as to be fully representative of different conditions. The type and shape of the particles, their concentration and interaction with the fluid phase must be considered as well (Sun-Waterhouse et al., 2014). For instance, the food particles can be cylindrical or cubic, causing the fluid to remain longer in the pipes. As the concentration and viscosity increase, the residence time of the fluid inside the pipes is more variable.

2. Pilot plant description

It is important to preliminary describe the characteristics and components of the pilot plant in which the tube-in-tube pasteurizer is inserted, for a better understanding of its modelling.

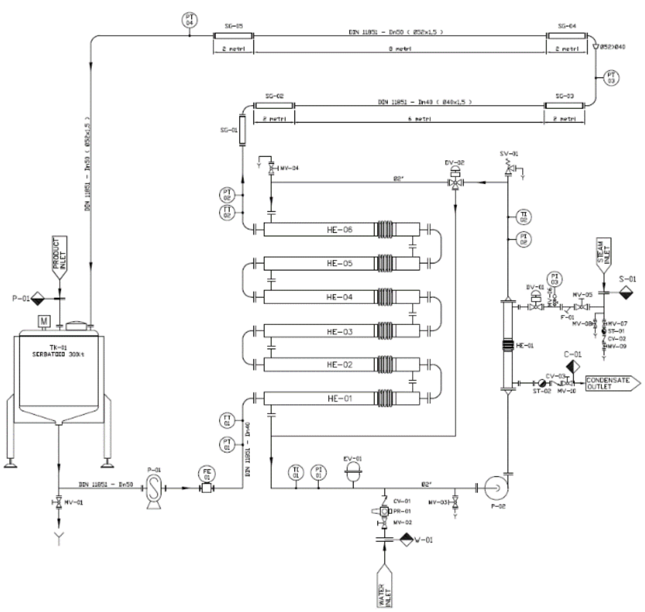

Figure 1: The pilot plant with the tube in tube pasteurizer

The pasteurization pilot plant under examination consists of the following elements:

1. supply tank;
2. double screw pump;
3. heat exchanger for heating;
4. electromagnetic flowmeter;
5. pressure transducers;
6. temperature probes;
7. data acquisition system.

The object of the digital modeling is the tube-in-tube heat exchanger, with the associated temperature and pressure probes.

The heat exchanger is an equipment that allows for the heat transfer from a hot fluid to a fluid at a lower temperature.

Water and juice (or any other fluids at different temperature) flow into two concentric tubes, which form the tube-in-tube exchanger. The innermost tube is made of stainless steel, a material with high thermal conductivity, so as to allow a significant heat exchange between the two fluids, at the same time reducing wear. The exchange surface is very limited, as it is necessary to reduce the overall size of the system. The external tube, on the other hand, is made of a low thermal conductivity material, to limit heat dispersion.

The tube-in-tube pasteurizer consists of smooth surface tubes and is capable of processing viscous products, containing pulps and fibers. It is also compatible with almost all filling technologies. It is characterized by a pasteurization temperature (tolerance ±1°C) and an outlet temperature (tolerance ±1°C) that can be controlled by Human Machine Interface (HMI).

Among the major benefits it entails, here are interesting savings in terms of water and energy, as well as the possibility of connecting homogenizers, redosing tank and vacuum deaerators, to recover odors.

The pressure transducer is the S-11 model, with wire diaphragm, designed for the measurement of viscous, particle-filled fluids. It is a facing diaphragm pressure transmitter (WIKA manufacturer: https://en.wika.com/s_11_en_co.WIKA), chosen based on cost and taking into account the need for data acquisition and processing. Its optimized design avoids obstruction, due to solid particles, of the connection channel to the conventional process: indeed, the diaphragm in contact with the fluid facilitates cleaning. In this way a good estimate of the pressure is guaranteed even in critical conditions, without losing sight of quality and flexibility.

The transmitter is connected by fully welded stainless steel wires upstream and downstream of the pipeline, in order to avoid the formation of dead spaces between the process connection and the S-11.

Pressure is essential for setting the system and diagnosing possible failures; therefore, the Flush Pressure Transmitter features:

1. Flexibility
2. Reliability
3. Precision.

The temperature probe, on the other hand, is a platinum resistance thermometer. It is made of platinum (R0, Pt100=100 Ω), by virtue of the fact that its electrical properties remain constant as the temperature varies, and is connected to the connector wires by means of an electrical conductor. An electric voltage can be measured while a constant flow passes through the thermometer.

The linear relationship between the electric resistance of the platinum conductor and the temperature allows to estimate the fluid temperature.

Further components that are needed to control the status of the system are as the electromagnetic flowmeter, which measures the flow in the tube-in-tube pasteurizer, and the inverter, which acts on the double screws pump to control its rotation.

3. The tube-in-tube pasteurizer modelling

The heat exchanger model was built using the language code in LabView software. This programming environment makes use of a graphic language, which allows to define algorithms and data structures using graphic objects, equipped with particular functions and connected to another. This system requires testing, measurement, quick evaluation and continuous inspection.

Hardware integration is simplified and also the data acquisition methodology is effective. LabView allows the visualization in a quick time of the results, thanks to the drag-and-drop creation of user interfaces: the acquired data becomes value-added information through control algorithms, which are based on mathematical functions and process signals.

The tube-in-tube exchanger, with the relating sensors, has been represented by means of the DSC Module, a software tool that develops HMI/SCADA data logging applications. The LabView Datalogging and Supervisory Control Module allows to sketch the machine and the user can therefore connect what he sees on the screen with the physical object, to reproduce what happens in the system.

The TT01 and PT01 sensors, located at the inlet of the exchanger, read the inlet temperature and pressure of the fruit juice, respectively. The TT02 and PT02 detectors, positioned instead at the exchanger outlet, read the temperature and pressure of the food fluid.

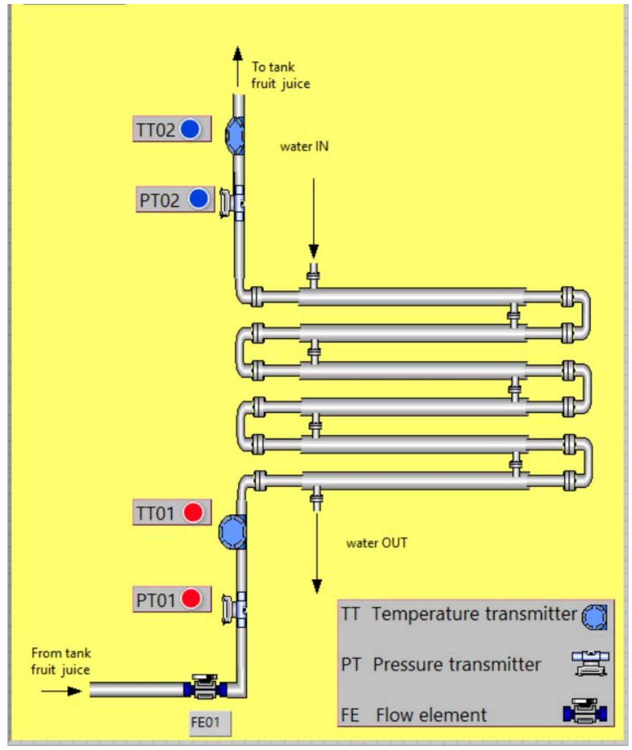

Figure 2: the modelled tube in tube section

3.1. Heat transfer modelling

The heat exchange modelling is entirely based on two fundamental rules:

1. Heat is transferred from the warmest to the coldest body. The heat released by the hottest body is absorbed by the coldest body without dispersion and loss of energy.
2. The second rule is the first principle of thermodynamics: "Energy can be converted from one form into another, but it can neither be created nor destroyed".

The equation of the above concept can be indicated as follows:

$$\Delta U = Q - L \tag{1}$$

where ΔU is the internal energy variation observed by the system, Q is the amount of heat exchanged by the environment, L is the work involved in the transformation.

The first principle of thermodynamics forms the basis to describe the operation of the heat exchanger: it is according to this principle that the water transfers its heat and increases the temperature of the fruit juice.

In general, the temperature of the fluids flowing in a tube-in-tube exchanger is not constant; rather, it varies, point by point, due to the heat exchange from the hottest fluid to the coldest one.

The thermal power, or the energy needed to make the exchange take place, varies throughout the exchanger:

$$\dot{Q} = \frac{\Delta T}{R_{TOT}} \tag{2}$$

In eq.2, ΔT is the temperature variation between the two fluids in Kelvin (K) and R_{TOT} is the total thermal resistance of the exchanger, which is assumed to be constant.

Eq.2 is used to derive the heat exchange and the surface sizing. For the energy calculation, however, it is possible to write the thermal power using two equivalent formulae, one for the juice (i.e., the process fluid, called fluid A for simplicity), and one for the water (i.e. the service fluid, called fluid B):

$$\begin{cases} \dot{Q} = \dot{M}_A \cdot c_{PA}(T_{A2} - T_{A1}) \\ \dot{Q} = \dot{M}_B \cdot c_{PB}(T_{B1} - T_{B2}) \end{cases} \tag{3}$$

In the above system $\dot{M}$ is the flow rate of the fluids, c_P is the specific heat, subscripts 1 and 2 respectively indicate the inlet and outlet sections. Having discretized the exchanger, the relative methods will allow identifying each point as the inlet section or the outlet section of the previous point.

This allows to predict the heat exchange along the whole piping and to calculate the final temperature of the juice exiting the exchanger.

3.2. Fluid dynamic modelling

First of all, a specific viscosity model has to be fixed. For non-Newtonian fluids, such as fruit juices, there are a number of mathematical models for describing their behavior. For the modeling of the pilot plant, the Herschel-Bulkeley model was chosen, better known as the "Power Law", for which the viscosity $\tau / \dot{\gamma}$ is closely related to the deformation rate (Steffe, 1996):

$$\tau = \tau_0 + \eta \left(\frac{d\gamma}{dt}\right)^n \tag{4}$$

In eq.4:

η is the consistency factor;

n is the behavior index;

τ_0 is the yield point;

τ is the shear stress;

$\dot{\gamma} = \frac{d\gamma}{dt}$ is the velocity gradient.

In this case study, it is important to evaluate the flow of the non-Newtonian fluid, which flows through the circular pipes that form the exchanger with a flow rate equal to:

$$\dot{M} = \rho \, \dot{V} = cost \tag{5}$$

The juice flows with the following average speed on the section:

$$W = \frac{\dot{V} \, \rho}{\frac{\pi}{4} D^2} \tag{6}$$

where ρ is the density of the fluid, $\dot{V}$ is the volumetric flow rate, D is the diameter of the pipe. Since there are steady state conditions, the following equality holds true:

$$\pi R^2 p_1 - \pi R^2 p_2 - \pi D L \tau = 0 \tag{7}$$

In eq.7, p_1 and p_1 are the entry and exit points of the fluid in the duct, respectively; therefore, the equality can be rewritten as:

$$\tau = -\eta \left[\frac{du}{dn}\right]^n |r \; = R = \frac{\Delta p * R}{2L} \tag{8}$$

The velocity trend can be explained as:

$$u(r) = -\left[\frac{\Delta p}{2L\eta}\right]^{\frac{1}{n}} * \frac{n}{n+1} * R^{\frac{n+1}{n}} * \left[1 - \frac{r}{R}\right]^{\frac{n+1}{n}} \tag{9}$$

Considering then the mean velocity on the tubular section as:

$$W = \frac{1}{A}\int_A udA = \frac{1}{\pi R^2}\int_0^R u(r) 2\pi r dr = \left[\frac{\Delta p}{2L\eta}\right]^{\frac{1}{n}} \frac{n}{3n+1} R^{\frac{n+1}{n}} \tag{10}$$

it is possible to define the pressure drop as:

$$\Delta p = 2L\eta W^2 \left(\frac{3n+1}{n}\right)^n R^{-(n+1)} \tag{11}$$

For non-Newtonian fluids the viscosity value is not constant; a generalized Reynolds number Re' should thus be calculated to make the following relationship true for a fluid in laminar motion:

$$\xi = \frac{64}{Re'} \tag{12}$$

knowing that C_f is also equal to:

$$C_f = \frac{\xi}{4} = \frac{64}{4Re'} = \frac{16}{Re'} \tag{13}$$

it is easy to obtain the generalized Reynold number, as follows:

$$Re' = 8\left(\frac{n}{3n+1}\right)^n W^{2-n} R^n \frac{\rho}{\eta} \tag{14}$$

Obtaining Δp form eq.11 and using Re', it is possible to derive the distributed pressure drops as follows:

$$\Delta p = \rho \frac{64}{Re'} \frac{L}{2R} \frac{W^2}{2} \tag{15}$$

Apart from the distributed pressure drops, we define also the concentrated ones starting form the following definition:

$$\frac{\Delta p}{\rho} = \beta \frac{W^2}{2} \tag{16}$$

where β is the friction coefficient, which depends on the particular geometry of the object; for a 90° angle it is tabulated and scores 2.2.

4. Model discretization

Several discretization methods exist, such as the finite volume method, the finite element method or the finite difference method. The latter was used in this study to discretize the heat exchanger of the pilot plant and is based on the solution of differential equations, mainly ordinary, by approximating the derivatives with finite differences. In doing so, the differential equations become finite difference equations.

By finite difference we mean the difference between the values assumed by a function in two specific points. It is possible to calculate the finite difference, forward or backward, for the first derivative, for the second derivative or for derivatives of higher order, or even for partial derivatives, with constant step or not. The finite difference differs from the derivative by a term called the discretization or approximation error.

In the case under examination, the focus is on the forward finite difference, calculated by considering the series development of the function $u(x)$ sufficiently regular in the interval of h of point x:

$$u(x+h) = u(x) + hu^{'}(x) + \frac{h^2}{2}u^{n}(x) + \frac{h^3}{3!}u^{m}(x) + \frac{h^4}{4!}u^{iv}(x) \quad (17)$$

Hence:

$$u^{'}(x) = \frac{1}{h}[u(x+h) - u(x)] - \frac{h}{2}u^{''}(x) - \cdots \quad (18)$$

The following expression, that can be derived from the previous formulae:

$$\frac{1}{h}[u(x+h) - u(x)] \quad (19)$$

represents the forward finite difference of the first order, which differs from the first derivative as it does not take into account further (infinitesimal) terms of h, denoted as $O(h)$.

The set of equations reported above must be repeated and used at any point of the heat exchanger and, therefore, can be traced back to the following differential problem at initial values:

$$u'(t) = f(t, u(t)) \quad (20)$$

$$u(t_0) = v_0 \quad (21)$$

where the first derivative leaves room for the incremental ratio and, therefore, can be taken as the forward finite difference without the approximation error. As a matter of fact, the derivative of a function is by definition the limit of the incremental ratio.

To solve this problem numerically, the explicit Eulerian method (a one-step numerical method) was used.

Consider the interval $[t(i), t(f)]$ and its element t_0, in which the solution is to be calculated and in which the conditions of existence and uniqueness of the solution $u(t)$ hold true for f.

The points t_0, t_1, t_2 are located at a distance h, called the discretization step, from each other, i.e. $t_1 = t_0 + h$ and so on.

The one-step method consists in calculating an approximation of the solution for $t = t_1$, $t_1 = t_0 + h$, knowing the solution in t_0 as provided by the initial solution. We then proceed with the solution in $t_2 = t_1 + h$, having computed the solution in t_1. The step method can find a solution for $t = t_{n+1} = t_n + h$, if the solution in t_n is known. Hence, an approximation u_n, calculated in t_n, of the exact solution $u(t_n)$ can be obtained.

The Eulerian method is the simplest method for solving the problem. In eq.21, set $t = t_0$ and replace the left-hand term with the forward approximation of the derivative and its discretization error, i.e.:

$$\frac{u(t_1 - t_0)}{h} + O(h) = f(t_0, u(t_0)) \quad (22)$$

$$u(t_1) = u(t_0) + hf\big(t_0, u(t_0)\big) + O(h^2) \quad (23)$$

$O(h^2)$ can be neglected in the computation. Being $u = u(t_0) + hf(t_0, u(t_0))$ and $u_0 = u(t_0)$, the previous formula can be rewritten as:

$$u(t_1) = u_1 = u_0 + hf(t_0, u_0) \quad (24)$$

with an error in the first step equal to:

$$e_1 = u(t_1) - u_1 \quad (25)$$

Using the same approximation, at $t = t_2$ it is immediate to obtain:

$$u(t_2) = u_2 = u_1 + hf(t_1, u_1) \quad (26)$$

with an error in the second step equal to:

$$e_2 = u(t_2) - u_2 \quad (27)$$

We proceed in this way to identify the approximations for each point in which the exchanger has been divided. 53 points were chosen as a good compromise between accuracy and speed of calculation.

It is important to underline that the explicit Eulerian method used is consistent and convergent. By consistent, we mean that the local truncation error tends to 0 as h tends to 0; by convergent, we mean that the approximation of the solution tends to the exact solution for a number of points that tends to infinity.

5. From the model to digital twin

The equations shown in the previous sections have been implemented through codes written in LabView, which allow the software to perform the calculation and, therefore, determine the temperature and pressure as a function of the values read by the sensors.

The software communicates with the pilot plant, and in particular with the related sensors, through the DAQ Device, a reliable and extremely precise data acquisition system. This device converts real data into useful value-added information, to detect problems before they occur (Figure 3).

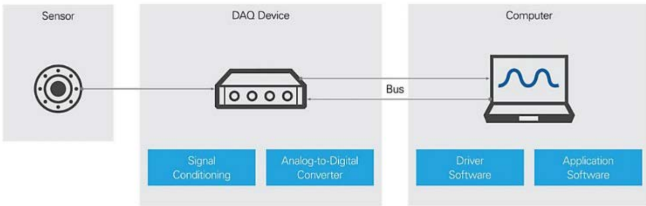

Figure 3: the Labview configuration to apply a Digital Twin model

Sensors work as a bridge between the real system and the digital world: indeed, they transform a physical phenomenon into an electrical signal, that can be easily handled. The transducers communicate with the DAQ, which digitalizes the analog signals to make them readable by the computer and then by the model created in LabView.

The aforementioned interface consists of:

- Signal conditioning circuit: it turns noisy, or unclear, signals into measurable ones;
- Analog-to-digital converter (ADC): the data detected by the sensors are in the form of analogic data, which need to be digitalized to be processed by the software devices;
- Computer bus: it connects the DAQ to the computer via Ethernet.

Among its functions, the DAQ module includes analogic inputs for analogic signals, digital outputs for digital signals, counters and timers that count the digital phenomena and generate the relative pulses.

6. Conclusions

By combining digital aspects about an equipment work and real-time aspects of its operating conditions, digital twin models are gaining increasing application potentials in industry. The food industry is not an exception, as in this context, digital twin models enable simulation, diagnostics, prediction and other advanced use cases. Obviously, to be effective, a digital twin must ensure a faithful representation of the real system or subsystem.

In this respect, the model developed in this paper is a useful support for a digital twin application in the food industry and in particular in a tube-in-tube food pasteurizer. More precisely, this model allows to predict the pressure and temperature conditions of the plant on the basis of real data taken from the sensors and on an Eulerian approximation of the heat exchange process.

It is evident that reproducing the real process is just the first step for the implementation of the digital twin model The natural future steps of the research, which are part of our ongoing activity, will focus on testing the model on the real plant and validating it on the basis of real data taken from the sensors. The precision of the sensors located on the plant will also be preliminarily evaluated to this end. After validation, the model is expected to be used for predicting possible safety issues of the plant; again, this will be tested by means of experimental campaigns on the real plant.

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References

Bevilacqua, M., Bottani, E., Ciarapica, F.E., Costantino, F., Donato, L.D., Ferraro, A., Mazzuto, G., Monteriù, A., Nardini, G., Ortenzi, M., Paroncini, M., Pirozzi, M., Prist, M., Quatrini, E., Tronci, M., Vignali, G. (2020) Digital twin reference model development to prevent operators' risk in process plants. Sustainability (Switzerland), 12 (3), art. no. 1088, DOI: 10.3390/su12031088;

Bottani, E., Montanari, R., Vignali, G., Guerra, L. (2011) A survey on packaging materials and technologies for commercial food products. International Journal of Food Engineering, 7 (1), art. no. 12, DOI: 10.2202/1556-3758.1687;

Bottani, E., Rizzo, R., Vignali, G. (2007) Simulation and analysis of fluid dynamic behaviour of foods during filling processes. Chemical Product and Process Modeling, 2 (3), art. no. 18, DOI: 10.2202/1934-2659.1084

Bottani, E., Vignali, G., Tancredi, G.P. (2020) A digital twin model of a pasteurization system for food beverages: tools and architecture. Proceedings - 2020 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2020;

Fellow P.J. (2017) Food Processing Technology Principles and Practice (4th Edition). Woodhead Publishing Series in Food Science, Technology and Nutrition Book. ISBN: 978-0-08-101907-8

Gottschalk, N., Reuter, L.S., Zindler, S., Föste, H., Augustin, W., Scholl, S. (2019) Determination of cleaning mechanisms by measuring particle size distributions. Food and Bioproducts Processing, 113, pp. 77-85. DOI: 10.1016/j.fbp.2018.10.003

Lu, Y., Liu, C., Wang, K.I.-K., Huang, H., Xu, X. (2020). Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer-Integrated Manufacturing, 61, art. no. 101837, DOI: 10.1016/j.rcim.2019.101837.

Steffe J.F., 1996. Rheological methods in food process engineering. Freeman Press - Food - 418 pages

Sun-Waterhouse, D., Bekkour, K., Wadhwa, S.S., Waterhouse, G.I.N. (2014) Rheological and Chemical Characterization of Smoothie Beverages Containing High Concentrations of Fibre and Polyphenols from Apple. Food and Bioprocess Technology, 7 (2), pp. 409-423. DOI: 10.1007/s11947-013-1091-y.

Vignali, G., Bottani, E., Guareschi, N., Donato, L.D., Ferraro, A., Pirozzi, M., Tomassini, L., Longo, F. (2019) Development of a 4.0 industry application for increasing occupational safety: Guidelines for a correct approach. Proceedings - 2019 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2019, art. no. 8792814, DOI: 10.1109/ICE.2019.8792814;