3D Simulation of Industrial Large-scale Ceramics Furnace in SIMIO Platform Environment

Georgios Tsaousoglou and Stamatis Manesis
Department of Electrical and Computer Engineering, University of Patras, Eratosthenous Str., Rio, Greece

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Abstract: This article presents a 3D simulation of an industrial large-scale furnace operating in the NGC (Northern Greece Ceramics) ceramics industrial plant. The 3D modelling and simulation of the long industrial furnace is based on the SIMIO software platform the capabilities of which are explored and tested in such a complex production plant. After the understanding of the real system operational characteristics, its macroscopic behaviour has been extracted and modelled; then a 3D model was created. Using the model, matters concerning the production process optimization are explored, while also alternative production scenarios are simulated, so that conclusions for the system's behaviour at value variation of the functional parameters of the real system can be extracted, without experimenting on the real process. In the four main sections of this article, the following aspects are presented: the modeling approach of the furnace operation, the SIMIO model of the furnace, its operation, examples of possible model applications and utility of the developed model and further modeling of the whole production procedure preceding the furnace.

1 INTRODUCTION

Ceramic industry is considered to be among the most ancient industries (Ameida et al., 2013). As the production facilities and techniques are up-to-date evolving, the production of bricks and tiles in the modern era is supported almost entirely by industrial large-scale production units. The major reconstruction and the global adoption of the use of ceramics in building architecture brought the requirement for large-scale production as well as for quality control, standardization, modernization of methods, production cost reduction and innovation (Bleininger, 1917) with one of the latest fields of research being the production of ceramics from waste materials (Jahangirian et al., 2010).

In a modern ceramics production unit, the entire production process is automated. In normal operation of the system no interference of human hand is needed in any stage of the process, from mud mixing, to shaping to drying (Lianyang Zhang, 2013), to baking. Human employment is oriented at supervision, prevention and correction of errors, planning and production organization etc. The manual labor is replaced by integrated automated systems formed by the cooperation of conveyors, machinery processing, robotic arms, etc. The production capacity of modern units totals more than 1000 tones of product per day. Industrial furnaces are used, whose length is approximately 100 meters while the maximum temperature of the interior, are of the order of 1000 degrees Celsius.

1.1 The Profits of Simulation in the Industrial Ceramics Furnace Application

Simulation represents important elements of the real system, thus has long been used to help designers, engineers and investors, experience exposure to circumstances both routine and unexpected and explore the behavior of a system under certain conditions. In the last decades a very large amount of simulation techniques and applications have been published (Terzia et al., 2004). The simulation model can be used to investigate possible changes and alternative choices in a low risk environment, as opposed to the risk of experimenting with the actual furnace plant, which could result not only in inestimable cost but also in accidents of high danger. Hence, ceramics production units are too expensive or dangerous to make live tests. Simulation provides a cheap, safe way to check the changes that may be either a simple revision to the existing production

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line, emulation of a new control system or redesigning the entire production chain. The “best guess” is usually a poor substitute for an objective analysis, while now we can accurately predict system behavior under different conditions and reduce the risk of a bad decision.

Moreover, here the prediction of variability of the process is important. A quick analysis cannot capture the dynamic aspects of the system and issues that can have a significant impact on system performance. Through simulation we can be provided with a better understanding of how different parts interact and how they affect the overall system performance.

Finally, with the modeled developed we are given the capability of communicating ideas. We can help partners, customers, employees or investors to better understand the system. The modern 3D modeling promotes communication and understanding to a wide audience.

1.2 SIMIO Simulation Software

SIMIO is a SImulation Modeling framework based on Intelligent Objects. It is a modeling tool that combines the simplicity of objects with the flexibility of procedures for the provision of a rapid modeling without requiring programming (Oba et al., 2014). It can be used to predict and improve the performance of dynamic, complex systems (Pegden, 2014). The software prototypes and displays a three-dimensional illustration of the behavior of the system over time. Although simulation and visualization tools have existed for many years, SIMIO makes modeling extremely easy by providing a new object-oriented approach. One can select (http://www.simio.com/index.html) objects from libraries and place graphics in the model. Objects represent the physical components of the system, such as tiles, conveyors, wagons etc. One aspect that is often overlooked in the analysis of systems performance is the role that randomness plays in determining the behavior of the system. By randomness we mean the idea that things that happen in our system occur with some differences from one another. Classic examples of randomness are: the time between the arrival of a system entity until the arrival of the next, the time between failures of equipment or the time it takes to complete an activity. If we want to understand and improve our system we need to model accurately the variations relevant to the randomness in the system. In the model developed, the randomness factor was implemented for the production line preceding the furnace. The model of the furnace itself is deterministic, as is the actual system due to control techniques applied.

Consider a SIMIO model for a very simple system in which entities arrive, processed by a server, and then depart from the system. For this simple example in which the system makes use of a source, a server, a draw and a route from the library, the SIMIO model is shown in Figure 1. The entities entering the system from the source move to the server where they are processed one by one and then go to the draw where they leave the system.

The rate at which the source creates entities and the processing time in the server are adjusted from the user to the properties of the corresponding object and the aforementioned factor of randomness can be included (SIMIO LLC Documentation, 2011).

1.3 Overview of the Industrial, Large Scale, Ceramics Furnace

The furnace, with which we deal, is of the continuous, propulsion type. There are two gates, one entrance and one exit and the tiles are baked while moving inside the oven. In fact every time a new wagon of tiles enters, all wagons move forward to the next position, while the last wagon leaves the oven. The oven has a length of 90 meters and 33 wagon positions. In normal operation, the input rate of the heat is stable and the burners are rarely turned off. Three distinct zones along the oven are formed. First is the preheating zone starting from the first wagon until the 7th. Second is the fire zone from the 8th until the 18th wagon and third is the cooling zone from the 19th until the 33th wagon. The thermal energy flow inside the furnace is subject to extensive thermal analysis (Warren et al., 2000). In Figure 2, the temperature curve throughout the length of the oven is presented.

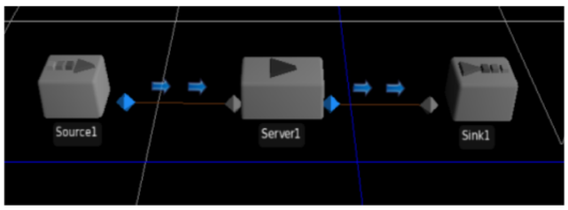

Figure 1: Simple SIMIO model.

2 MODELING APPROACH OF THE FURNACE OPERATION

Each wagon is modeled as an entity carrying the following properties which are variable with respect to time:

- Temperature: Refers to the current temperature of the tiles in the wagon
- Temperature Rate of change: Is the current rate at which wagon temperature changes. Expressed in degrees Kelvin per minute
- Ready or not: Boolean variable expressing whether the tiles are baked (ready) or not.
- Quality: Expresses the current quality of the wagon's tiles based on the quality of baking suffered. The more abruptly the temperature is altered the worse the tiles quality turns out to be.
- Damaged or not: Boolean variable which expresses whether the tiles are broken (due to abrupt temperature change).

The most important of the above is the "Temperature Rate of change", according to which, the rest of the properties are easily calculated. The rate at which the tiles temperature changes at each position depends on the temperature difference with respect to the environment (furnace position temperature) and a number of factors such as the thermal conductivity of the material, the proportion of heat absorbed by the walls of the furnace and of the metals of the wagon etc. The industrial furnace operation is thus described by a set of strongly non-linear equations, making it extremely difficult to implement them in a 3D model which needs to solve them in a short simulation time. The shortness of the simulation time is important here, so that the illustrative part of the model is valid. Based on real systems' data and the industrial furnace model non-linear equations, linear equations were built to approach the macroscopic behavior of the system and applied in order to estimate the "Temperature Rate of change" in real time for each individual wagon at its current position.

The user determines the rate at which wagons are imported in the furnace (minutes before entering new wagon). This is the same like determining how long a wagon remains at each position. As output, the user sees the current real time simulation values of the above wagon's properties, for each individual wagon. Moreover sees the temperature at which the wagons leave the furnace (exiting temperature) and the total number of wagons produced.

3 THE SIMIO MODEL OF THE FURNACE

We have now a first version of the model. At the entrance of the furnace, wagons arrive at a rate set by the user as shown in Figure 3.

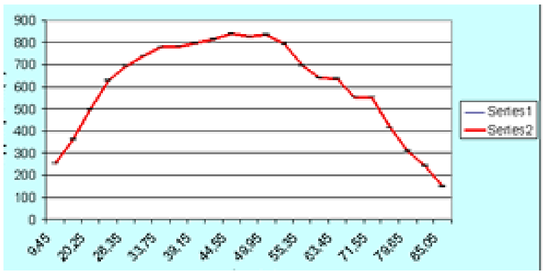

Figure 2: Temperature throughout the length of the oven.

Figure 3: User defines the input rate.

The first wagon inserts at the first position, where it stops and begins to alter its properties based on the model equations and the parameters of the position (environment temperature). When the second wagon arrives, inserts at the first position, "pushing" the first wagon to the second position, where its properties continue altering, based now on the parameters of the second furnace position.

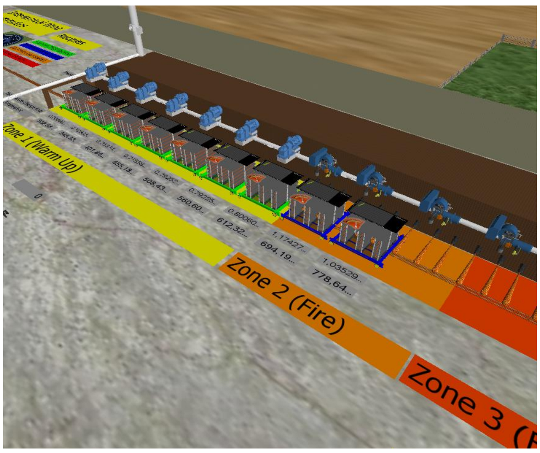

Figure 4: Wagons processing through the furnace.

The process shown in Figure 4 continues until the user presses the Stop button. When a wagon arrives at the last position (33h), on the next wagon arrival, it exits the furnace, its temperature is recorded at the "output temperature by which the wagons leaving the oven" and leaves the system.

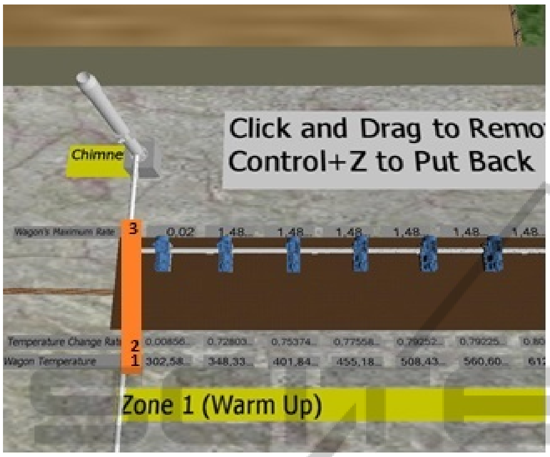

Figure 5: Indication of outputs.

The model illustrates all the outputs that the user needs to see as shown in Figure 5.

1) Current temperature in each wagon
2) Current Temperature Rate of change for each wagon
3) Maximum temperature rate suffered by each wagon
4) For each wagon if it is ready or not
5) The current quality of tiles of each wagon. This is depicted by the color of the base of the wagon. Interpreted as:
   Green: High quality
   Blue: average quality
   Orange: Poor quality
   Red: broken tiles (Figure 6)

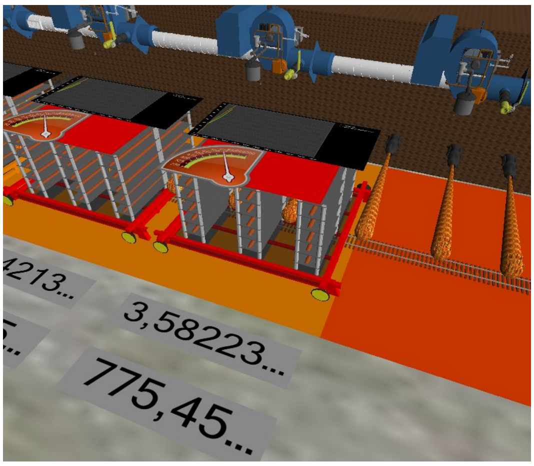

Figure 6: Wagons turn red when tiles are broken.

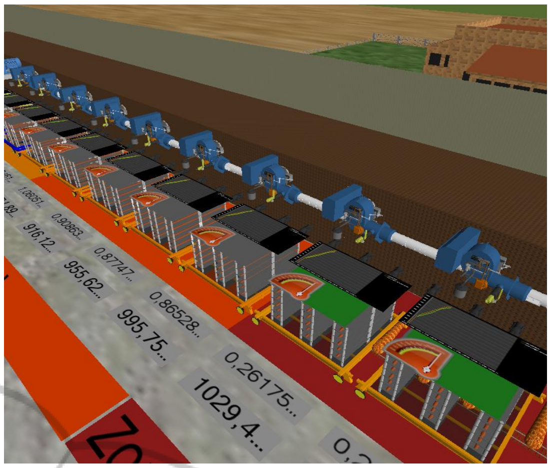

Figure 7: Wagons turn green when ready.

When the temperature of the tiles of a wagon exceeds a certain value, they are considered baked (ready) and the roof of the wagon turns green as shown in Figure 7.

Each wagon, in addition to the above indications, also carries two displays on the roof. A thermometer which shows the current temperature and a diagram showing the temperature of the particular wagon as a function of time, from the time entered in the furnace until the current time.

This chart gives us a very useful illustration of temperature, from which one can understand the response and operation of the model. The red line shows the furnace temperature from place to place, such as seen by the wagon. Step increased, as the wagon moves from one position to the next. As shown, the curve of the temperature along the furnace, extracted by the model during the simulation, verifies the actual oven temperature curve (Figure 2).

The green line shows the temperature of the tiles. This generally tends to approach the red line. Whether it reaches it or not, depends on the time given to it, i.e. how much time a wagon is left to stay in each position. As we can see in Figures 8 and 9, clearly depends on the rate at which wagons are imported in the oven. Two examples are given.

In Figure 8 the wagon tiles' temperature approaches the furnace temperature quite accurately, which is logical as they are baked for quite a long time.

The curves in Figure 9 result steeper, which means high rates of temperature change of the tiles, i.e. tiles of low quality or cracked. Also, it must be noticed that the green curve does not manage to reach the red.

Practically, this means that we spent much energy to maintain the oven temperature high, without this being exploited for the baking of the tiles since they do not stay long enough in the oven to smoothly absorb this heat. Characteristic of this waste is the temperature at which the wagons leave the furnace (exiting temperature), as will be made clear in the next section.

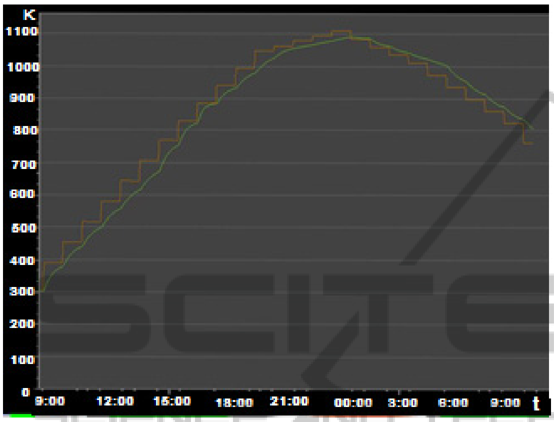

Figure 8: Wagon temperature diagram for low import rate (one wagon every 60 minutes).

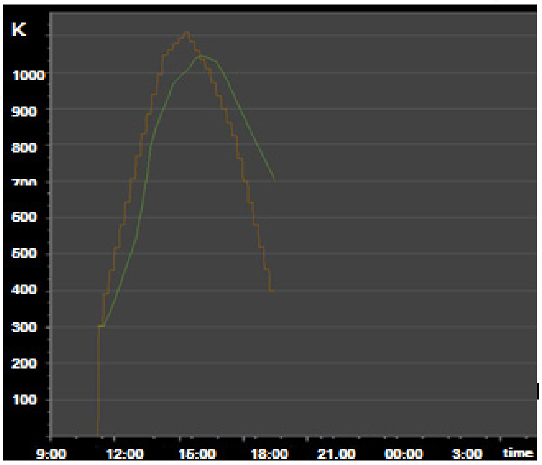

Figure 9: Wagon temperature for high import rate (one wagon every 15 minutes).

4 EXAMPLES OF POSSIBLE MODEL APPLICATIONS AND UTILITY OF THE DEVELOPED MODEL

We want to study the behavior of the model and the results for different values of operating parameters. The aim is to draw conclusions about the real system and with the experiments made on the model. Thus, to the extent that the model corresponds to the real system, we acquire knowledge about the behavior of the system in different operation modes. That would be impossible to achieve with experimentation on the actual production line, since the cost would be too high.

With the experience drawn by experiments, we can now make decisions concerning the production strategy, making strategic choices and not random.
Experimentation could be done by running the model separately for each case. But SIMIO provides us with a powerful simulation tool, which gives us the ability to run ***experiments.*** The designer designs the *experiment* by choosing parameters which are subject to value variation and setting the values of these for each "scenario". Then selects those outputs, which's the behavior wants to study. The different scenarios are running really fast and the software shows the results. An example of such an "*experiment"* is following.

4.1 Experiment: Study of the Import Frequency of Wagons in the Oven

As varying-value parameter we select the import rate of wagons in the oven (minutes per wagon) chosen by the operator. We want, in correspondence with it, to study the temperature at which wagons exit the furnace.

The outlet temperature is a very important parameter in the operation of the oven. It is a characteristic parameter which indicates whether we apply proper heat management of the oven and proper management of the fuel. A high value of this temperature is undesirable, mainly for two reasons. First, tiles of high outlet temperature are sensitive to cracks during further processes and secondly show us that there has been waste of fuel. This is partly because the excess heat, stored in the tiles, is released in the environment and not exploited for use in heating the tiles currently being in the stages of fire, preheating or drying. Also, the fuel spent to maintain the furnace temperature at high levels is not utilized properly, because the tiles do not have time to absorb the heat, thus resulting being baked forcibly and heat is released to the environment through the cooling tower, which in normal conditions is not used at all.

We will consider four cases for value variation of import rate: entering wagon every 19, 24, 42 and 52 minutes respectively. The results of the experiment are summarized in Table 1.

4.2 Use of the Results for Improvement of the Production Strategy

From the results we can estimate which is the cost (high temperature output) if we want to produce quickly (increase production). Hence, if there is a need for rapid production (e.g. short-notice order) we can determine the cost of meeting the demand, so that the pricing of the product can be made accordingly.

Table 1: Tiles exiting temperature to varying values of Import Rate.

Import Rate (min)	Exiting Temperature (K)
19	659.5
24	619.5
42	538.2
52	512.8

5 FURTHER MODEL EXTENSION AND APPLICATION

The whole production line (preceding the furnace) was modeled. The stages in which the soil is smoothed, mixed, stored, molded, cut, dried and loaded on the wagons are incorporated in the model and some samples are presented in Figures 10-13. With the whole production line modeled, the user can select with how many kgs per minute of soil he wants to supply the production line. The choice of the user is very important for the operation of the whole model since as we will see, so is the rate at which wagons enter the oven. That is, the user's

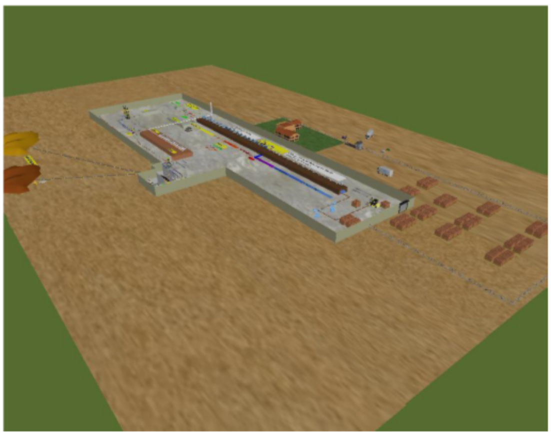

Figure 10: Panoramic view of the model.

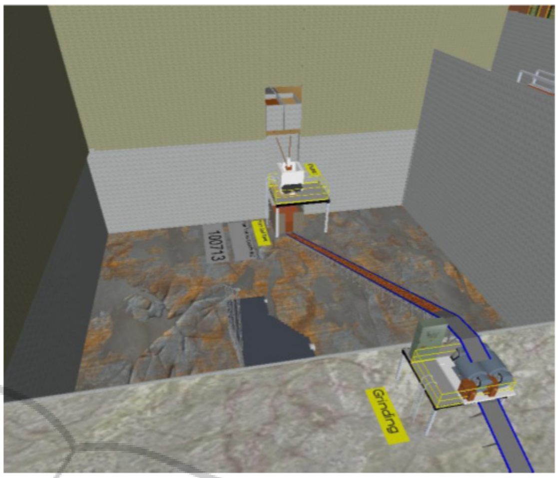

Figure 11: Grinding stage.

Figure 12: User defines kgs per min of soil sent to the production line.

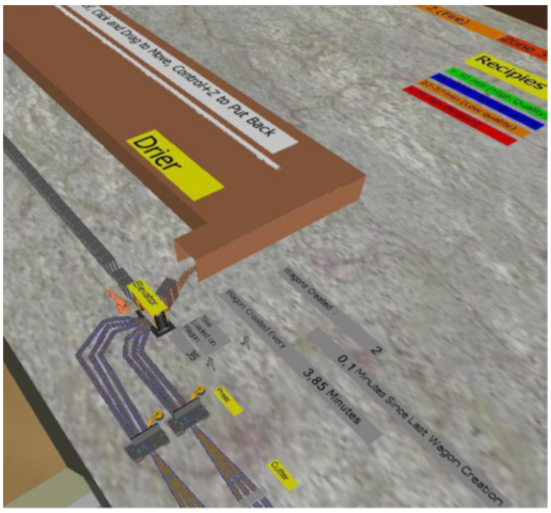

Figure 13: Wagons of tiles inserted in the Drier.

choice must be consistent with the production goals to be served. An experiment this option affects the rate at which wagons are prepared, thus designed upon the variation of the parameter value “kgs per minute” (of soil sent to the production line) explores the impact of the user’s possible choices while in this experiment the randomness factor is being incorporated in our model, representing the deviation in the value of the aforementioned parameter, “kgs per minute”.

5.1 Experiment: Study of the Wagon Production Rate

As varying parameter is set the rate at which soil is provided to the production line (kgs per minute). We want to study the time it takes to prepare a wagon and the number of wagons prepared in 24 hours with respect to this parameter.

We will study seven cases for the value of the soil supply rate from 30 to 90 (in step 10) kgs of soil per minute. A deviation is also incorporated. More precisely, the rates of supply are 7 different distributions (normal) with centers of the above values and a standard deviation of 10. The results of the experiment are summarized in Table 2, (average values of distributions). The two responses of the experiment are represented graphically in Figures 14 and 15. The supply of soil is represented on the horizontal axis in kgs per minute.

Furthermore, by combining the results of the two experiments, we can answer the question: "If you have to produce X wagons in Y days, how much soil must be provided to the line?"

Table 2: Time for Wagon preparation and Wagons produced in 24 hours, according to the soil supply of the line (model experiment results).

Soil Supply (kgs per min)	Time for Wagon (min)	Produced Wagons in 24h
30	60.89	23
40	45,76	31
50	36,47	39
60	30,33	47
70	25,95	55
80	22,82	63
90	22,10	65

That is, if we want to produce X wagons the next day, we should put wagons at a rate A, thus we provide Y soil supply at current day (about 13 hours earlier because of the residence time in the drying stage and preparation time). So depending on the

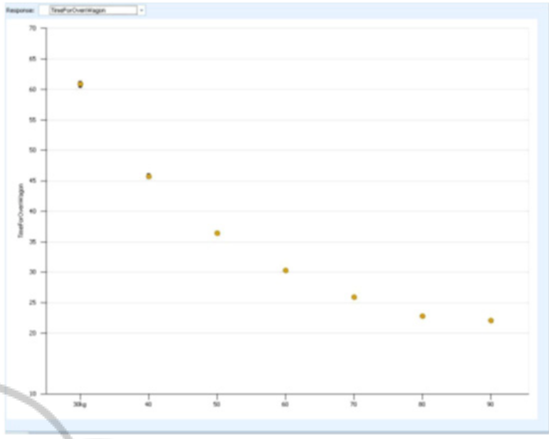

Figure 14: Time for wagon preparation (vertical axis) as a function of soil supply.

Figure 15: Wagons produced in 24 hours (vertical axis) as a function of soil supply.

value of X someone can find the appropriate value for Y from tables or rerun the experiment for the desired value of X.

6 CONCLUSIONS

A 3D model of the system and examples of experiments using SIMIO were implemented in this paper. The simulation experiments protect us from wasting resources and poor choices. In addition, it can help to investigate investment projects. For instance, it can be studied on the model a new machine installation to replace an old and with respect to the new performance of the particular stage, to study the impact to the whole production. Thus we can estimate the feasibility, viability and usefulness of the candidate investment. Results show that such a model could be proven quite a useful tool in the hands of the production organizing engineer, the investment consultant as well as the investor.

It should be noted that such models, while powerful are only used to support the decision making process only offline. It is open to future research, the implementation of simulation models that dynamically communicate with the operating furnace, predicting its sort term behavior to a possible decision so as to support a real time decision support tool.

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