TEACHING PROCESS MODELLING AND SIMULATION AT TOMAS BATA UNIVERSITY IN ZLIN USING MATLAB AND SIMULINK

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KEYWORDS
Modelling, Simulation, Education, MATLAB, Simulink.

ABSTRACT

This paper summarizes author's experiences of teaching a course on process modelling and simulation at Faculty of Applied Informatics, Tomas Bata University in Zlin, Czech Republic. It briefly presents contents of the course in both lectures and tutorials together with adopted methodology and used software tools. Requirements for the students to pass the course are also given as well as some statistics concerning their results. At the end of the contribution one of the final students' projects is also briefly presented.

INTRODUCTION

Modelling and simulation plays an important role in the process of education nowadays, e.g. (Kincaid et al. 2003; Stoffa 2004; Lean et al. 2006; Andaloro et al. 2007; Zavalani and Kacani 2012). It saves time, money and even prevents from injuries that could happen e.g. during some hazardous real-time experiments, e.g. (Jenvald and Morin 2004; Skarka et al. 2013). Thanks to the rapid developments in the field of computer hardware and software it is now possible in a safe place of simulation labs, offices or even at home perform experiments that could not be realized in the past decades without a proper hardware models. This places high demands on the process of education for experts in this field, in order to produce reliable (simulation) models and reasonable results (Kincaid et al. 2003).

The skills related to process modelling and simulation are useful in most engineering disciplines and applications, including also control engineering, e.g. (Ljung and Torkel 1994; Thomas 1999; Severance 2001; Egeland and Gravdahl 2002, Bequette 2003). Most of the control methods is based on some knowledge of a process model, therefore a control engineer must be able to obtain a proper model of the process to be controlled. In addition, it is advisable to test the designed control system properly using simulation means before real-time implementation in order to prevent from possible problems.

This contribution summarizes experiences related to teaching process modelling and simulation at Faculty of Applied Informatics, Tomas Bata University in Zlin, CZ, during studies of Master's degree programme "Automatic Control & Informatics" (FAI TBU in Zlin 2017). Here, in the first year of follow-up Master's studies during the winter semester students have to complete the course "Analysis and Simulation of Technological Processes" which is focused on the deepening of the knowledge in the field of modelling, computer simulation and analysis of common technological processes. All the things taught here are oriented so that they can be subsequently used easily for further control system design.

The paper is structured as follows: after this introductory part the contribution presents detailed structure of the presented course, including contents of both – lectures and tutorials (labs). Further, methodology of teaching and used software tools are discussed, next part introduces requirements for the students to pass the course and presents also some statistics for recent 10 years. Final section enables to see briefly the results of one of the simpler students' final projects. Some concluding remarks give insight into possible future directions of the course.

STRUCTURE OF THE COURSE

This part starts with some information on prerequisites of the students starting the course "Analysis and Simulation of Technological Processes" and follows by detailed description of contents of both – lectures and tutorials (labs). The course has 2 hours of lectures and 2 hours of tutorials (labs) per week and is donated by 5 credits after its successful completion. In our institution, there are 14 weeks of lectures per semester, followed by 5 weeks of examinations.

Students' Prerequisites

Students starting the course "Analysis and Simulation of Technological Processes" in the 1st year of their follow-up Master's studies (lasting 2 years) should already have some basic knowledge of university mathematics, physics, programming and computing software from their Bachelor's degree studies (lasting 3 years), e.g. they should complete the following courses that can be further useful for modelling and simulation in control engineering:

Proceedings 31st European Conference on Modelling and Simulation ©ECMS Zita Zoltay Paprika, Péter Horák, Kata Váradi, Péter Tamás Zwierczyk, Ágnes Vidovics-Dancs, János Péter Rádics (Editors)
ISBN: 978-0-9932440-4-9/ ISBN: 978-0-9932440-5-6 (CD)

- Seminar of Mathematics; Mathematic Analysis; Differential Equations;
- Physical Seminary; Electricity, Magnetism and Wave Motion; Electrotechnics and Industrial Electronics; Microelectronics;
- Programming; Object-oriented Programming; Programs Theory; Algorithms and Data Structures; Matlab and Simulink; Programmable Logic Computers; Microcomputer Programming; JAVA Technology;
- Automation; Optimisation; System Theory.

These courses above are just a part of their Bachelor's studies and were selected as ones giving some basics that can be further exploitable in the field of process modelling and simulation for control engineers.

In their follow-up Master's studies, besides having the course "Analysis and Simulation of Technological Processes" students have to study simultaneously e.g. Mathematical Statistics, Process Engineering, Discrete Control System, Sensors, and others. Those students coming from different study programmes or different universities can also choose the course "Matlab and Simulink" besides some obligatory courses that equalize students' entry level.

Contents of Lectures

This course is primarily focused on modelling common continuous-time technological processes and their simulation/solution using the apparatus of numerical mathematics. The 14 weeks of 2-hours lectures/per week are divided into 2 main blocks – while in the first half students learn to derive analytically (simplified) first-principles mathematical models of common industrial processes, in the second block they study how to solve these models using the methods of numerical mathematics. After some introductory information where students gain motivation for studying this course, learn basic approaches to process modelling, become familiar with basic terminology and classification of models, these typical process models are derived step-by-step using the first-principles analytical modelling:

- liquid tanks with constant and non-constant cross-sections;
- processes with heat transfer, mixed and tubular heat exchangers;
- processes with mass transfer, distillation and staged processes;
- processes with chemical reactions, batch, semi-batch and continuous stirred tank reactors.

In the presented list of processes there are both linear and non-linear representative models as well as lumped and distributed parameters systems. If they are non-linear, a subsequent linearization and transformation into deviation models is also given. From the derived dynamical models, also their steady-states models are obtained and analysed, all with respect for subsequent control system design.

The second part of the lectures is focused on numerical solution of such models as obtained in the first part of the course. It begins with introduction into general approximation of functions, followed by polynomial approximations and then common numerical methods of solving introduced models are presented, from the simplest problems to more complex ones.

First, simulation/solution of steady-state behaviour of lumped-parameters processes is studied, resulting in the solution of sets of linear and nonlinear equations. For this purposes the principles of following common iteration methods are presented: simple iteration method, Jacobi, Gauss-Seidel and Relaxation methods, Newton method, and others, with obvious discussion on the conditions of convergence of all these algorithms.

Further, the problem of simulating/solving dynamic behaviour of lumped-parameters systems is explained, resulting in the solution of ordinary differential equations. Principles of both, simple one-step and more complex multi-steps methods are presented, including e.g. the simple Euler method, popular Runge-Kutta methods, and others, with further analysis on their numerical stability.

Finally at the end of the course, also the most complex problem in this field – simulation of steady-state and dynamics of distributed parameters systems is briefly presented, resulting in numerical solution of partial differential equations. Here, boundary value problems are discussed, together with the practical usage of the finite difference methods.

Contents of Tutorials

Tutorials (or laboratory exercises/practices/labs) are oriented more practically while following the course of more theoretically oriented lectures. In the first part of the semester students, with the help of a teacher, derive mathematical models of common industrial processes, followed by their practical simulation in a popular simulation software. They derive, e.g.:

- liquid-storage tanks with cylindrical, spherical and funnel-like shape, tanks in series;
- mixed and tubular heat exchangers;
- continuous (flow) stirred-tank reactors,

while learning the typical procedure of modelling and simulation:

- schematic picture,
- definition of variables (inputs, outputs, states),
- simplifying assumptions,
- energy/material balances,
- steady-states analysis,
- (classification of the model),
- choice/estimate/determination of model parameters,

- process variables limits, singular states, model validity,
- choice of initial/boundary conditions and operating point(s) for simulation,
- implementation of the model,
- simulation experiments,
- experiments evaluation,
- model verification / corrections…

For practical solution of the models the MATLAB computing software is fruitfully exploited together with its popular graphical multi-domain simulation library Simulink. In this environment student try to solve both steady-state and dynamical models using various approaches. For example, when solving models described by ordinary differential equations (ODEs) they learn how to solve it using the standard function *ode45* (based on an explicit Runge-Kutta (4,5) formula), how to build the model in the Simulink (including building their own blocks) or are advised to use e.g. the *state-space block* in the case of linear systems.

In the second part of the semester students are more practically familiarized with the numerical methods of solving the models. They start with recalling basics of solving sets of linear equations with the focus on the iterative methods and their practical implementation, i.e. programming in the MATLAB or other software. Then they go on to solve sets of nonlinear equations and finally (sets) of ODEs, with examples from the modelling part of the course or from practice. Discussion on the numerical aspects of the methods, i.e. convergence, accuracy, initial estimate, stability, etc., is a natural part of the explanations.

Completion of the Course

After successful completion of the course, students should be able to derive mathematical models of basic technological processes using the first-principles analytical modelling. Further, they should be able to analyse the models in order to obtain important information (e.g. linearity, stability, gain and time-constants…) and prepare them for subsequent control system design. Finally students should be able to solve/simulate and investigate these models using numerical methods, independent of the used simulation language.

While lectures attendance is voluntary, laboratory practices require min. 80% attendance and active students can gain “extra” points which can improve overall classification of the course. The classification is based on the unified credit system (compatible with the ECTS student mobility within European education programmes, e.g. European Union 2015) and therefore it is expressed on a common six-point scale: “A” (Excellent), “B” (Very good), “C” (Good), D (Satisfactory), E (Sufficient) and F (Fail/Unsatisfactory). The course is evaluated by 5 credits, where one credit represents 1/60 of the average annual student workload within the standard length of study. In order to obtain the credits students have to:

- have 80% attendance at tutorials/labs,
- have to elaborate and defence a “final project” on a given topic, obtaining min. 50% of points from it.

In the “final project” students show that they are able to derive simple mathematical models further usable for control system design and that they are able to analyse and solve/simulate these models effectively. So basically they try to follow the procedure they have learnt in the tutorials/labs. The final projects are assigned as soon as the students have basics knowledge and skills to elaborate it, typically after first 3 weeks. Students can come with their “own process”, if not, they are assigned randomly from a regularly updated list of projects. The list of project includes, e.g.:

- cylindrical/spherical/funnel-like tanks in series,
- mixed and tubular heat exchangers,
- room heating process in various set-ups,
- continuous flow hot water systems and boilers,
- concentration and temperature mixers,
- swimming pool heating systems,
- continuous (flow) stirred-tank reactors,
- landfill site systems,
- various current/voltage controlled motors,
- conveyor systems
- and others…

while students follow the procedure they have learnt during the course (see “Contents of Tutorials” above), deriving the process model and analysing its steady-state and dynamic behaviour using the simulation means. One such typical final project is briefly presented at the end of this contribution.

STATISTICS OF THE RESULTS

This section summarizes briefly some statistical information concerning the number of students enrolling the course and their successfulness. The presented course is a part of “Automatic Control”– oriented study programme taught at our institution for several decades. Number of students enrolling studies in this field is not big – usually 1-2 study groups, as a result, the courses can be taught more individually and tailored to the actual needs of students and practice. This is also the case of the course “Analysis and Simulation of Technological Processes”, referred in this contribution. General table with number of students enrolling this course in the last decade together with their successfulness according to the ECTS grading scale is presented in Table 1. From the table it can seen that overall number of students in the last decade was 126 and that the number of students in the last few years decreases, unfortunately, as also seen in Fig. 1. In the last several years, this is a trend in our country attributable to the drop in the population curve and also decreasing interest in technical studies, unfortunately.

Table 1: Number of Students and Their Successfulness in ECTS Grading Scale

Year	A	B	C	D	E	F	Sum
15/16	2	1	1	0	0	0	**4**
14/15	5	2	2	0	0	1	**10**
13/14	6	1	0	0	0	3	**10**
12/13	7	3	4	1	0	2	**17**
11/12	8	2	4	1	0	6	**21**
10/11	3	3	1	0	0	0	**7**
09/10	6	2	2	3	0	2	**15**
08/09	2	2	1	1	0	0	**6**
07/08	3	1	2	0	0	0	**6**
06/07	10	6	7	0	3	4	**30**
Sum	**52**	**23**	**24**	**6**	**3**	**18**	**126**
Sum [%]	**41%**	**18%**	**19%**	**5%**	**2%**	**14%**	

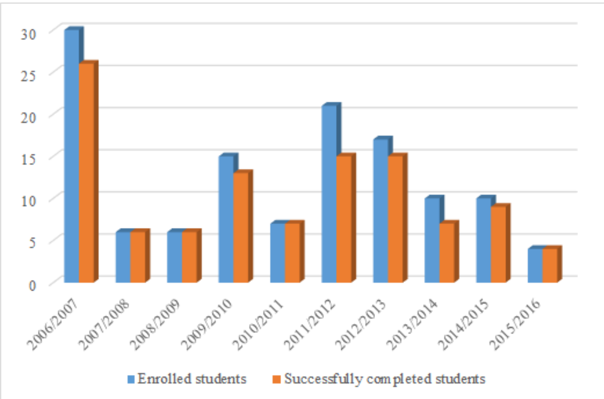

Figure 1: Number of Students and Their Successfulness

The table and graph show also successfulness of the students enrolling this course in each year, which is 86% on the whole, i.e. 86% of the students obtain the grade from "A" (Excellent) to "E" (Sufficient) according to the ECTS grading scale, and 14% of them do not complete the course successfully. Percentage in each category is presented in the table above or more clearly, in the next graph, Fig. 2.

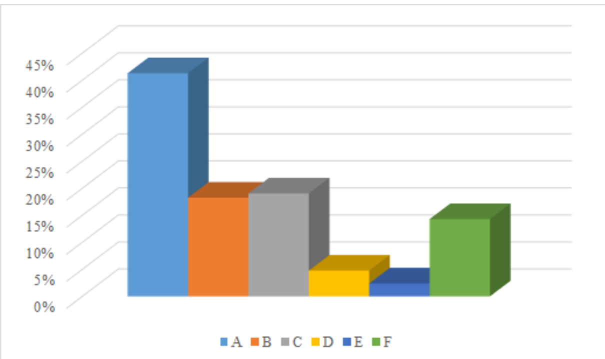

Figure 2: Students' Successfulness in the ECTS Grading Scale

Generally speaking, unsuccessful students are usually those who enroll studies and this course and for some reasons decide to withdraw from their studies, after some time during the semester.

CASE STUDENT'S FINAL PROJECT

This section presents one of the simpler final students' projects needed for the successful completion of the course. It starts with the problem assignment, followed by the elaboration including also main results and final summary.

Problem Formulation

Assume a room heated using an electric heater. Choose all the physical parameters so that they approx. correspond to real conditions.

- derive a simplified mathematical model of this system describing the room temperature $T(t)$ as a function of outdoor temperature $T_C(t)$ and heating power $P(t)$;
- derive and discuss also the steady-states model;
- determine the minimum necessary heating power to heat the room up to 20°C in case of outside temperature -10°C;
- display static characteristics $T^S = f(P^S, T_C^S)$;
- simulate a response of the room temperature to the step change in outside temperature and heating power ± 20%, compared to the chosen operating point; discuss the results;
- classify the derived model.

Simplified Mathematical Model

The modelled system can be sketched simply as presented in Fig. 3 below, where V stands for the volume and α is the average heat transfer coefficient.

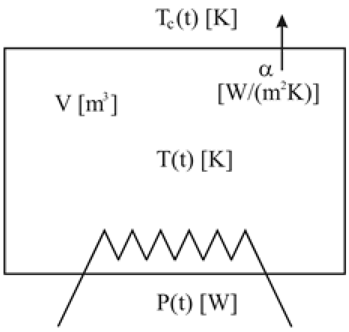

Figure 3: Schematic Picture of the Process

Definition of variables can be as follows: *input* variables are the heating power $P(t)$ in [W] and outdoor temperature $T_C(t)$ in [°C] (the latter one can be alternatively considered as a disturbance); *state* variable is the room temperature $T(t)$ in [°C], which is also the *output* variable, from the systems theory point of view, as displayed in Fig. 4.

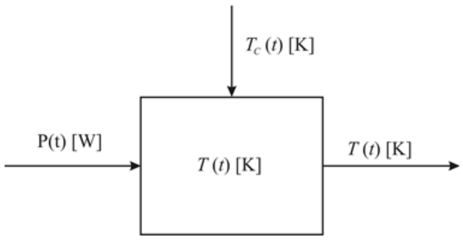

Figure 4: Process from the Systems Theory View

For the derivation of a mathematical model, the following common simplified assumptions are adopted:

- ideal air mixing,
- constant process parameters (air volume V, density ρ, heat capacity c_P, overall (average) heat transfer coefficient α, heat transfer surface area A, …),
- heat accumulation in the walls neglected.

Based on the heat balance:

heat input = heat output + heat accumulation,

the following simple mathematical model holds:

$$P(t)=\alpha A\left[T(t)-T_C(t)\right]+V\rho c_P\frac{dT(t)}{dt}, \quad (1)$$

for some initial room temperature $T(0)$. For simulation purposes, the derivative is expressed as:

$$\frac{dT(t)}{dt}=\frac{1}{V\rho c_P}P(t)-\frac{\alpha A}{V\rho c_P}\left[T(t)-T_C(t)\right]. \quad (2)$$

The steady-states model is obtained from (1) simply for the derivative equal to zero, i.e.

$$P^S=\alpha A\left(T^S-T_C^S\right), \quad (3)$$

where the steady variables are denoted with s-superscript, as usual. Therefore, the steady room temperature reads simply as:

$$T^S=T_C^S+\frac{P^S}{\alpha A}, \quad (4)$$

which is further used to generate the static characteristics.

Model parameters were chosen as follows: A = 55 m^2, V = 70 m^3, α = 1.82 W/m^{2}K, ρ = 1.205 kg/m^3, c_P = 1005 J/kgK. Initial conditions and operating point for simulation were defined as $T(0)$ = 20 °C, P = 2000 [W], T_C = 5 °C.

The dynamical and statical models (2), (4) have no singular states and are valid in common (reasonably chosen) conditions; the heating power can vary in the interval: $P(t) \in <0; 4000>$ W.

From the steady-states model (3) it is straightforward to compute the necessary heating power to heat the room to the temperature 20°C in case of outside temperature -10°C:

$$P^S=\alpha A\left(T^S-T_C^S\right)=1.82\times 55\times 30=3003\,W, \quad (5)$$

therefore, under the defined conditions, we need more than 3 kW to keep the temperature above 20°C when outside is freezing -10°C.

Simulation Results

The steady-states model (3) displayed graphically generates the static characteristics of Fig. 5, which shows linearity of the derived model.

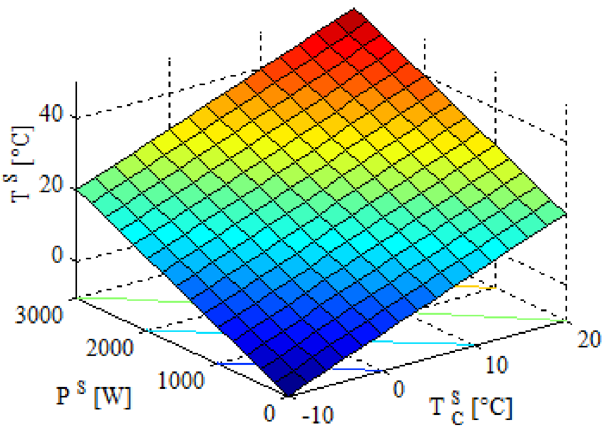

Figure 5: Static Characteristics

Dynamic step-responses obtained using the standard MATLAB ODE solver *ode45* are presented on the next graphs, Fig. 6 and Fig. 7.

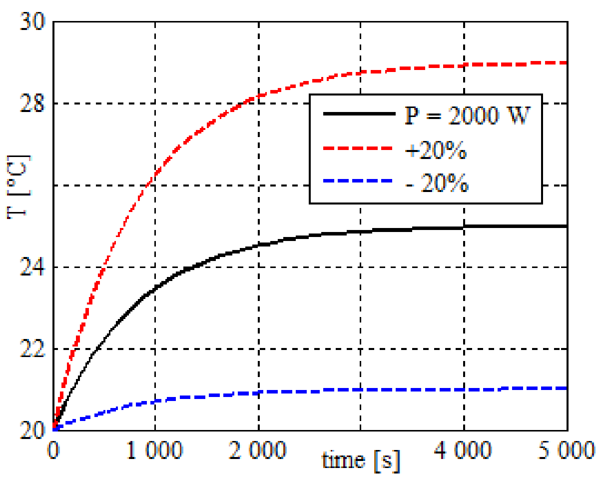

Figure 6: Step-response of Room Temperature with Heating Power

The first one shows the case of different heating power, starting with the nominal (P = 2000 W) and then small variations ± 20% from this value. As can be seen, when the outside temperature is around 5 °C, the electric heater enables to heat up the room to 25 °C approximately, when the power decreases to 1600 W, the room temperature will be around 21 °C and with 20% more (2400 W) the temperature settles around 29 °C, for the same initial conditions.

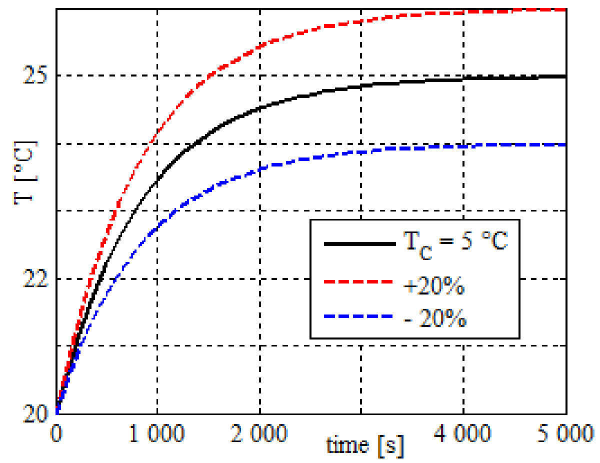

Figure 7: Step-response of Room Temperature with Outside Temperature

The second graph shows the case of different outside temperature and constant (nominal) power. As expected, lower outdoor temperature results in lower indoor temperature and vice versa.

Presented behaviour of the simplified mathematical model corresponds to the general expectation, therefore the model can be further used for e.g. subsequent control system design and analysis. More computations using the MATLAB software generated 3D plots of Fig. 8-9 with continuous intervals of heating power and outside temperature.

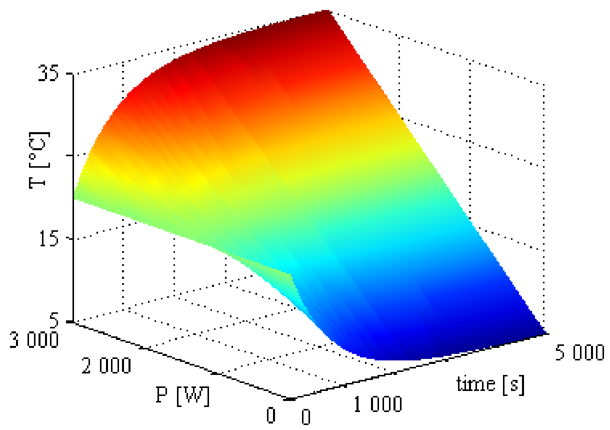

Figure 8: Step-responses of Room Temperature with Heating Power – 3D

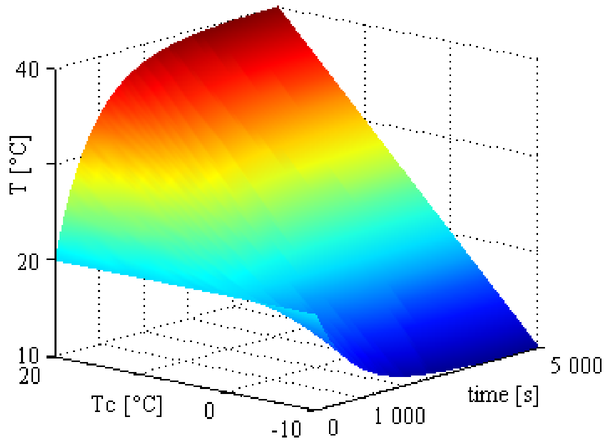

Figure 9: Step-responses of Room Temperature with Outside Temperature – 3D

Classification of the Model

Based on the adopted mathematical model and presented simulation results it is possible to classify it as:

- linear 1st order stable aperiodic system,
- with lumped parameters,
- continuous-time,
- deterministic,
- two-input and single-output,
- time-invariant,

which can further help to design a convenient control system for the adopted mathematical model, and real process as well.

Presented information and results outlined a possible form of students' final projects in the mentioned course focused on process modelling and simulation.

CONCLUSIONS

This paper has presented the structure and contents of the course "Analysis and Simulation of Technological Processes" taught in the first year of Master's degree study programme "Automatic Control & Informatics" at Faculty of Applied Informatics, Tomas Bata University in Zlin, Czech Republic. Requirements for the students to complete the course were also given together with some statistics concerning their successfulness. The presented case study has shown one of the simpler final students' projects for which the MATLAB computing system and its toolboxes for simulation and optimization are fruitfully utilized during the course. Future direction of the course aims to more practically-oriented modelling and simulation, connected to practical real-life examples and actual projects with industrial companies. There is also an obvious effort to teach the students not only to build reasonable process models but also to be able to utilize them for the next step - control system design. Therefore, in the next semester, after successful completion of the course "Analysis and

Simulation of Technological Processes" students use their built models in the next course – "State-space and Algebraic Control Theory" where they are taught how to design a convenient control systems. This course is also completed by a "final project" where students try to design and implement suitable control algorithms for their models/systems, again, with the strong help of MATLAB and Simulink.

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