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Teaching of Complex Technological Processes Using Simulations*

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*Simulation based on mathematical modelling can be used for investigation, prediction and control of industrial processes and systems, and for educational purposes. This paper deals with the last objective. Virtual equipment can replace equipment that is unavailable or that cannot be used for educational purposes; it is of particular importance for complex technological processes and processing equipment. The technical and methodological aspects of online virtual simulations are discussed. Another challenge is to integrate virtual experiments that are based on mathematical modelling and simulation by classroom and real laboratory work in order to provide the most efficient method of mastering engineering courses. Examples of visual simulations for engineering education** and professional development as well as an approach to combining real and virtual experiments at the Department of Ferrous Metallurgy, RWTH Aachen University are presented.*

Keywords: engineering curriculum; mathematical modelling and simulation; practical work; iron making

INTRODUCTION

A TRADITIONAL ENGINEERING CURRICULUM (with both classical face-to-face teaching and using distance learning methods) is based on theoretical, often descriptive, materials that are provided in the form of lectures supported by scripts and text books and supplemented by exercises and practical (laboratory) courses. It is believed that in the future practical work, including experiments and simulations, should play an increasing role in the engineering curriculum. Online experiments based on mathematical modelling and simulation will probably become the core of higher engineering education** and will be directly linked to other online tools and resources. New types of experiments and laboratories (online virtual and remote) can support group work over the Internet and can be shared by students working from multiple distant locations, 24 hours a day. They have the potential for flexible learning, giving access to a large number of experiments and simulations and saving costs through laboratory sharing [1].

Each type of experiment has certain strengths, weaknesses and constrains. The requirements of online virtual laboratories and simulations for remote education are discussed here both from methodological and technical points of view.

The virtual replacement of equipment that is unavailable or cannot be used for educational purposes is of particular import in complex technological processes and processing equipment [2]. Experiments in a local laboratory usually simulate separate parts or zones of a process or aggregate and sometimes physically simulate phenomena by using replacement materials (e.g. water in place of a liquid metal). The construction and operation of physical models that integrally simulate real aggregates, even on a small scale, is enormously costly and time consuming, making such experiments unfeasible in a university and in the majority of research organisations. Nevertheless, students should not only practice with computer simulation software but they should also acquire the skills of working with real devices and equipment. Currently local, virtual and remote experiments and laboratories are mostly used independently. In some cases the teaching methodology comprises a real or remote experiment, which is then reproduced in a virtual simulation in order to compare the results [3, 4]. The challenge is in integrating virtual experiments based on mathematical modelling and simulations with classroom and real laboratory work. In this paper we take up this challenge.

In order to illustrate this, the iron making process has been chosen as an example of a highly complex technological system.

ROLE OF PRACTICAL WORK, MATHEMATICAL MODELLING AND SIMULATIONS IN TEACHING OF COMPLEX TECHNOLOGICAL PROCESSES

An engineer has to have adequate theoretical knowledge and be able to adapt it for use in his or her practical work. This is a necessary but not a

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** The term 'engineering education' is used in the strict sense of technical engineering sciences.

sufficient condition for success, however. Engineers actually have to control, manage, improve and develop technological processes and aggregates using their theoretical knowledge and skills. Based on this fact, the aim is that experimental and, generally speaking, practical work should become a key component in engineering curricula in the future.

On the other hand, we do not suggest a reduction in the number of lecture courses. In the case of RWTH Aachen University, a typical master's curriculum for main engineering study comprises two years of taught courses, including about 3 months' internship in industry and two thesis projects (totalling 3 months). The master's thesis takes an additional 6 months. A taught course usually consists of 50% lectures, 25% exercises and 25% practical lab work. It has to be considered that practical work (experiments and calculations using models and other software) is also the main component of the theses. We believe that this gives an optimal share of lectures and practical work but students need a clear strong motivation to attend lectures and seminars.

Furthermore two main components of the practical work—experiments and calculations—should be coupled with education and professional development. Mathematical models and simulations should be validated and tested using laboratory equipment (real or virtual). On the other hand, experimental results should be evaluated by modelling and simulation.

Therefore the idea is not to increase the number of academic hours in the laboratory but to structure and organise the engineering course better.

New tools for experiments using the Internet and multimedia technologies will become increasingly important. Currently there are various types of laboratories and experiments; they can be classified as follows:

- **Real lab**. Students and researchers work with real devices and manipulate and measure real objects while being directly co-located with the devices and objects in the same local laboratory.
- **Virtual lab**. This is based on mathematical modelling and simulations. Virtual laboratories and experiments contain software-based simulations of experiments and pre-recorded measurements, pictures and videos but do not manipulate real objects [5–8].
- **3-D lab**. Virtual Reality is generally a computer generated environment that makes the users think that they are in the real environment [9]. It is a special case of the virtual lab.
- **Remote lab**. It offers remote access to real laboratory equipment, workbenches and experiments from a remote location [10–13].

Virtual and remote laboratories can support online work via the Internet. Virtual labs can be realised as local or distributed software applications. The possibilities, characteristic features and benefits of the above mentioned experiments and laboratories are discussed in [14].

Modelling methods in process and plant simulation are particularly beneficial for reflecting the logical and quantitative relationship of complex technological processes and systems, e.g. in the chemical, metallurgical and power industries, which cannot be studied integrally in a local laboratory because of their huge complexity.

Modelling and simulation of complex technological processes, phenomena and equipment are used for:

- process investigation, to understand it better and improve it further;
- process control and optimisation;
- process prediction and automation; and
- for educational purposes, in particular for the creation of training systems for remote studies.

Modelling methods are most effective when included in a process plant simulation. Modern simulations allow the user to combine models for several unit operations into a complete flow sheet and to calculate the expected performance.

The visualisation of the simulation experiments is the next component to set-up, thus adapting the fundamental technological content to the learning technology.

PRINCIPLES OF MATHEMATICAL MODELLING AND SIMULATION FOR ENGINEERING EDUCATION AND TRAINING

When using modelling and simulation methods for educational purposes, it is necessary to clarify the fundamentals of the training in the different engineering professions. The basic components in many technological sciences, such as chemical, metallurgical, power, environmental engineering are thermodynamics, chemical kinetics and mechanics.

Thermodynamics helps one to find the stable phase modifications in multiphase multi-component systems of high complexity. This is done by minimising the free energy of formation of those phases, which derives from the principle that in thermodynamic equilibrium the energy of the system is at a minimum. The fundamental relation is the expression for the free reaction enthalpy to become the minimum. The principle of conservation of energy provides the basis for formulating energy balances for metallurgical reactions.

Chemical kinetics allows one to calculate the behaviour of the chemical components due to chemical reactions over time. The fundamental relation is the mass action law stating that, in any chemical reaction, chemical equilibrium is achieved only if the rate of production equals the rate of destruction of the species. The rates are usually calculated using Arrhenius kinetics.

By combining these two components, the formation and behaviour over time of the phases and chemical components existing or created can be monitored and quantified.

Usually a movement of the existing phase (liquid, solid, gas) requires the explicit presence and use of the third component, the *mechanics*. The fundamental relations used to quantify the motion of the system is the principle of conservation of momentum, equivalent to Newton's second law; in general for fluids these are the Navier–Stokes equations.

Combining the above three components allows one to quantify the most essential technological problems and situations starting from fundamentals.

A basic principle for adapting the learning content for engineering education is to write down the equations in strict causality relation between the physical and chemical entities and the variables representing them in an agreed causality direction.

The methodological principles for creating and using mathematical models in DL technology are:

- reducing the number of facts;
- replacing facts by rules;
- replacing rules by laws;
- replacing laws by principles.

Methodologically, this is evidently a generic replacement and a generic deduction.

ESSENTIAL TECHNICAL AND PEDAGOGICAL COMPONENTS OF ONLINE SIMULATIONS

Online simulations for engineering education and for professional development should fulfil the following requirements.

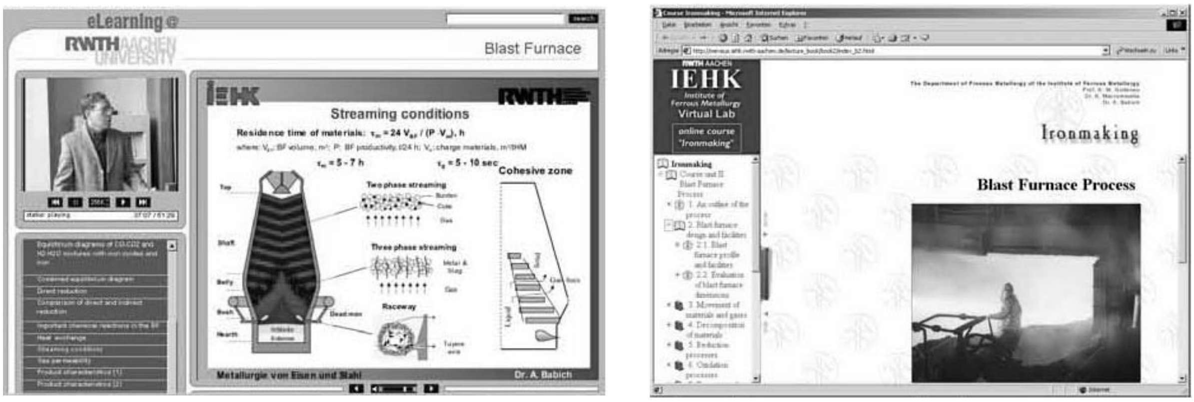
Links to theory and support resources

Online experiments based on mathematical modelling and simulation should be directly linked to other online tools and resources (text and reference books, recorded and live lectures, and other interactive and instructive material).

The most typical approaches that could be recommended as standard ways to easily integrate theoretical information and supplementary material into online experiments are interactive information and virtual laboratories.

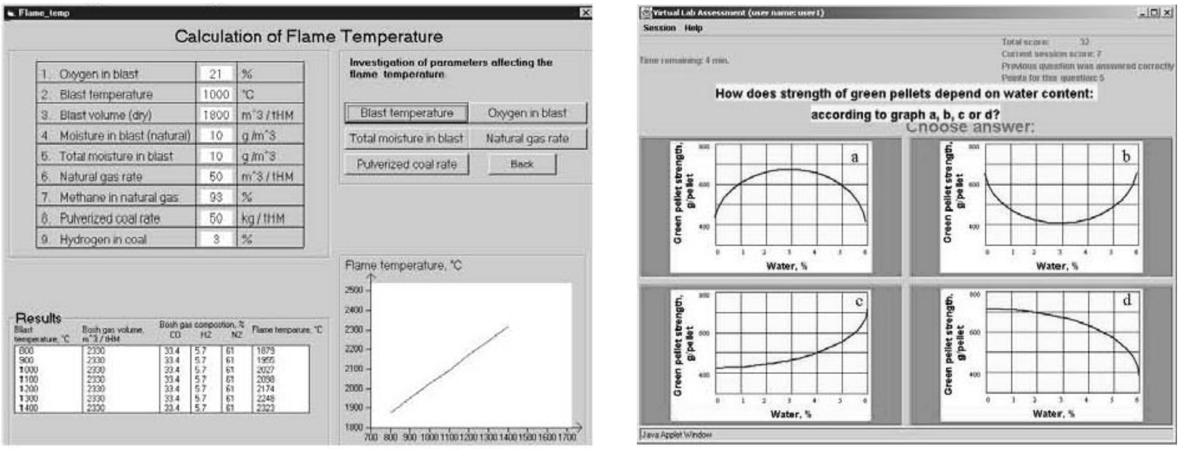
Interactive information that illustrates essential basic principles and theoretical concepts can be integrated directly into a simulation.

- A simulation can be accompanied by a user guide that includes not only instructions on how to run the simulations, a description of the user interface etc. but also an introduction to the subject and short theoretical explanations.



Video lecture

Online book



Calculation of Flame Temperature

1.	Oxygen in blast	21	%
2.	Blast temperature	1000	°C
3.	Blast volume (dry)	1800	m^3 / tHM
4.	Moisture in blast (natural)	10	g /m^3
5.	Total moisture in blast	10	g /m^3
6.	Natural gas rate	50	m^3 / tHM
7.	Methane in natural gas	93	%
8.	Pulverized coal rate	50	kg / tHM
9.	Hydrogen in coal	3	%

Results

Blast temperature, °C	Bosh gas volume, m^3 / tHM	Bosh gas composition, % CO	H2	N2	Flame temparure, °C
800	2330	33.4	5.7	61	1879
900	2330	33.4	5.7	61	1955
1000	2330	33.4	5.7	61	2027
1100	2330	33.4	5.7	61	2098
1200	2330	33.4	5.7	61	2174
1300	2330	33.4	5.7	61	2248
1400	2330	33.4	5.7	61	2323

Time remaining: 4 min.

Total score: 32
Current session score: 7
Previous question was answered correctly
Points for this question: 5

How does strength of green pellets depend on water content: according to graph a, b, c or d?

Visual processing lab

Interactive assessment test

Fig. 1. Support components of a virtual lab.

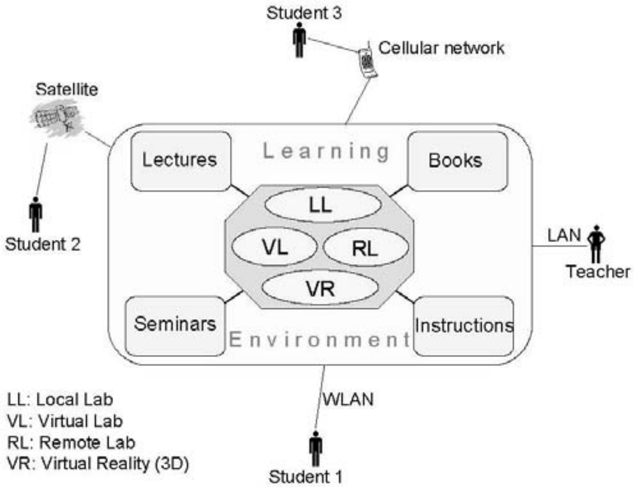


Fig. 2. Infrastructure of an engineering course with virtual and remote experiments at the centre.

- Web links to external online resources can be included.

A further approach (on a higher level) is the development of virtual laboratories based on online computer simulations and experiments that themselves include a set of multiple logically related and complementary synchronous and asynchronous learning resources and various tools (Fig. 1) [15].

The students should get more flexibility to choose the ways and sequence of steps to reach the final target (to control, manage, improve and develop technological processes, systems and aggregates). To realise this approach, a future engineering course should have an infrastructure with various kinds of experiments as the centre and lectures, etc. supporting on the periphery (Fig. 2). It means that a student taking an engineering course will be given an assignment to control, manage, and improve a real process. For this the student will make use of linked online lectures, seminars, books etc., and interact with partners and teachers; they will receive a grade based on the results of their work.

Combined modules and control functions

The simulated process or aggregate is usually a link in a chain of technological processes or aggregates. The simulation model should allow the student to investigate related processes by means of connecting sub-models and so calculate the expected overall performance (Fig. 3).

Process control is an important ingredient of a visual simulation model (VSM). Students should have the option of affecting the process results using process control functions. There are different possible modes from which they can choose to achieve this goal: change of parameters in the main menu, choice of correcting actions suggested by the model etc.

The VSM should also reflect the dynamics of the process, i.e. the delay in the change of output parameters after conducting the control actions.

Data exchange between real and virtual laboratories

The best way for students to master complex technologies that cannot be studied integrally either theoretically or experimentally and to acquire practical skills is to combine work in a real laboratory with computer experiments. Where there is a combination of experiments in a local laboratory and online simulations, measured data from real laboratories should be automatically fed into virtual laboratory engines. Information and data obtained in the local lab can, for instance, just

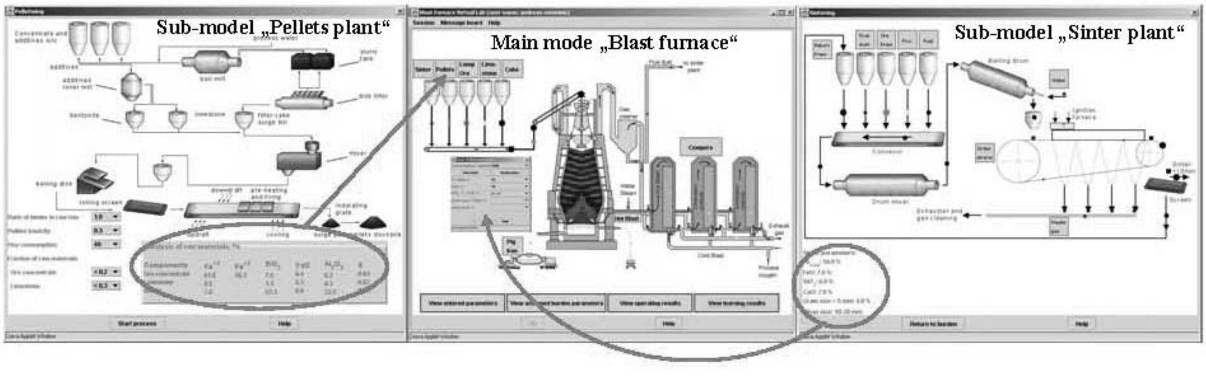


Fig. 3. Interrelation between main mode and sub-models

be passed through to the VSM engine on the fly, or imported from the files generated by data acquisition and analysis systems.

For example, a system comprising a microscope combined with image analysis software stores images and data sets with analysis results in MS Excel spreadsheets, which can be imported by a VSM [16].

Collaborative work support and interactive tutoring

The possibility of collaborative work support and interactive tutoring when using online experiments and laboratories is very important. Students on geographically dispersed sites can collaboratively operate the same process or aggregate, solve a problem in human interaction with remote partners and in this way can experience and learn from teamwork. A variety of tools—distributed models, video conference systems, grid-technologies etc.—can be used for this.

Interactive tutoring and supervision are important features of virtual laboratories. The remote tutor has to be equipped with visual front-end software to monitor the activity of the students, answer their questions, and analyse the learning results. For better analyses of the students' work, the tutor can view the log of their actions (Fig. 4).

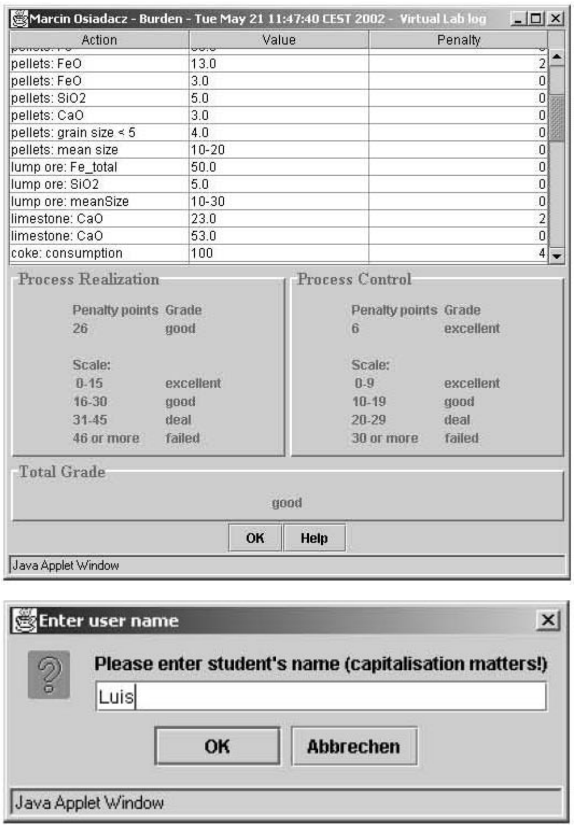
The teacher's graphical interface for editing the simulation model can, for example, be a Java applet that runs in a web browser. The teacher has a series of icons, organised in libraries, and a working area. Through simple drag and drop operations, the teacher can put the icons in the working area and link them to each other in order to build the simulation mathematical model in a visual way. Learners use the simulation through another graphical interface. The simulations are executed at the server side and then the results are sent to the applet.

Software reuse

From the experience with the virtual lab that has been developed at the authors' institution, the following components have been identified as being the best for reuse:

- communication tools (message board etc.);
- tutor support tools (logging and assessment of student actions in different models);
- visualisation elements;
- certain models of processes and aggregates that can be used either as stand-alone models or as sub-models of more complex processes or plants.

There are numerous technological solutions that can carry the simulations on the web, using web browsers both with and without the use of plug-ins, e.g., Java applets, AJAX, ActiveX components, VRML virtual worlds and interactive movies. All these solutions have positive as well as negative features.



Marcin Osiadacz - Burden - Tue May 21 11:47:40 CEST 2002 - Virtual Lab log

Action	Value	Penalty
pellets: FeO	13.0	2
pellets: FeO	3.0	0
pellets: SiO2	5.0	0
pellets: CaO	3.0	0
pellets: grain size < 5	4.0	0
pellets: mean size	10-20	0
lump ore: Fe_total	50.0	0
lump ore: SiO2	5.0	0
lump ore: meanSize	10-30	0
limestone: CaO	23.0	2
limestone: CaO	53.0	0
coke: consumption	100	4

Process Realization

Penalty points	Grade
26	good

Scale:

0-15	excellent
16-30	good
31-45	deal
46 or more	failed

Process Control

Penalty points	Grade
6	excellent

Scale:

0-9	excellent
10-19	good
20-29	deal
30 or more	failed

Total Grade

good

Java Applet Window

Enter user name

Please enter student's name (capitalisation matters!)

Luis

Java Applet Window

Fig. 4. Student session log and opening a student session from teacher front-end.

For reasons of reuse, platform independency and interoperability between different computers over the Internet, the Java programming language has proved to be a suitable choice. Software implemented in Java is able to run on nearly any platform and communication over the Internet is possible, for example, with the Remote Method Invocation mechanism.

Development of the virtual laboratory as a client–server architecture allowed the product to be used either locally or as a distributed application.

Pedagogical scenario and assessment

Typical educational activities usually include:

(a) Directed Learning

- Introductory session (e.g., videoconferencing)
- Demonstration of the computer simulations by videoconferencing or synchronous VL mode

(b) Self-directed Learning

- Individual work in an asynchronous processing laboratory
- Individual work with real-time computer simulations, supplemented by an interactive assessment test and enhanced by real-time online remote tutoring
- Linked resources: individual learning of online, packaged educational material, enhanced by asynchronous remote tutoring

(c) Synchronous Group Collaborative Learning

- Collaborative work with computer simulation models supplemented by interactive assessment tests and enhanced by real-time online remote tutoring.

EXAMPLES OF VISUAL SIMULATIONS OF COMPLEX TECHNOLOGICAL PROCESS

Blast furnace iron making

The blast furnace process is a good example of a complex multi-phase and multi-component technological process. It is characterised by numerous phenomena (physical, chemical, physico-chemical, mechanical and hydraulic) and homogeneous and heterogeneous reactions, which occur simultaneously and affect each other.

A blast furnace processes various iron bearing materials (sinter, pellets, lump ore etc.), coke as fuel and additives that are continuously charged from the top of the shaft furnace reactor. Hot air that is enriched with oxygen needed for the process is supplied from the lower part of the furnace together with gaseous, liquid or powder substances. The process runs constantly for several years but liquid products (metal and slag) are discharged periodically. The process performance, its efficiency and product quality depend on hundreds of parameters that characterise heat and mass exchange, softening, melting, drainage, movement and other phenomena.

The peculiarities of the blast furnace process as a modelling object are:

- interconditionality—every output variable depends on a multitude of input variables;
- non-linearity of relations;
- inertia and transport delay;
- ambiguity and loss of information: it is possible to generate two different sets of inputs that are adequate to the given set of outputs.

It is hardly possible to simulate this process integrally in a local laboratory due to its enormous complexity. In Europe there is only one research centre equipped with an experimental blast furnace [17]. Experiments on this unit are enormously costly and time consuming, so they are limited to a small number of selected research projects. Laboratory equipment and facilities at universities and at the majority of research organisations are designed to study separate phenomena of such complex technological processes or reactions and the behaviour of selected materials, phases and interaction of restricted groups of them.

To realise the concept of engineering education based on the enhanced role of experiments that are close to industrial conditions, practical work in a local laboratory has to be complemented by computer simulations. A suitable visual simulation model has been developed as a component of an online Virtual Lab course, 'Iron making', created at the Department of Ferrous Metallurgy, RWTH Aachen University.

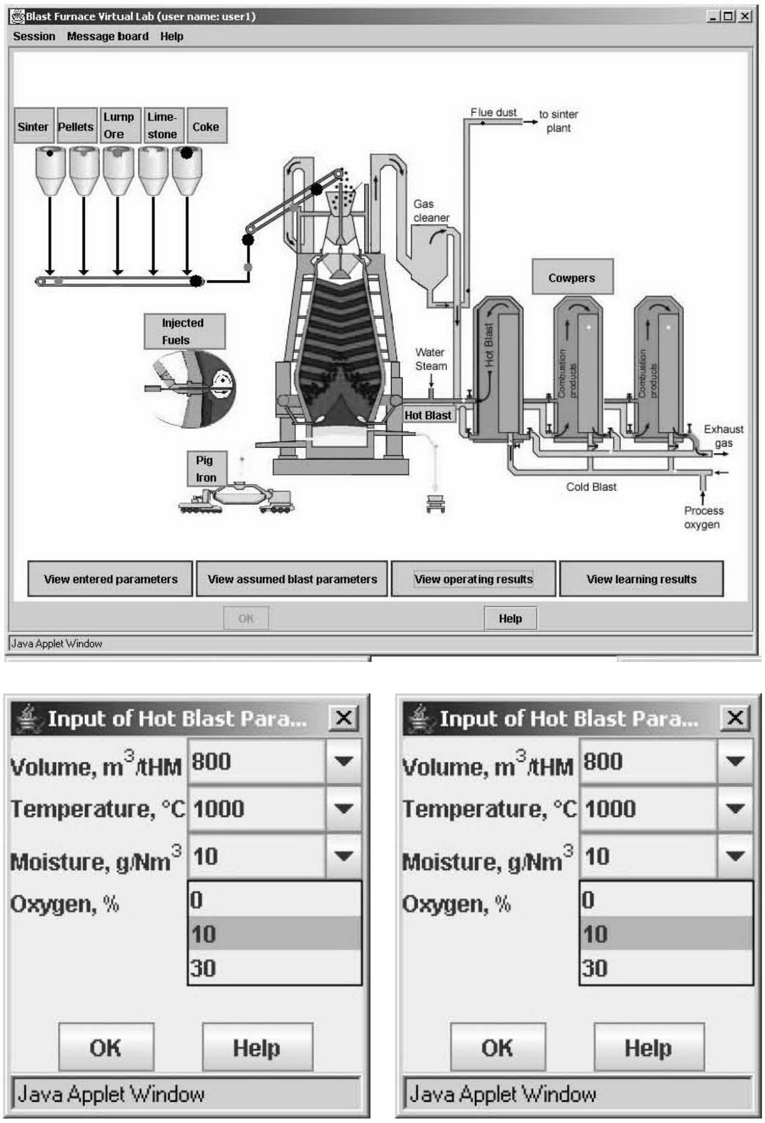
Example of simulation for educational purposes

The interactive, distributed application 'Visual Simulation Model' (VSM) enables students to study iron making technology integrally and helps to train and test their learning success [18]. The aim of the simulation is to transform the existing knowledge about the iron making process using mathematical models and to represent this complex technological process integrally (which, in a local laboratory, is possible neither practically nor theoretically), visually and dynamically.

The simulation model processes entered parameters, and outputs both operating and learning results. Currently the simulation model is being extended by the development of new scenarios. All the scenarios are based on the same mathematical model of the blast furnace process.

The concept of the *learning* models for educational purposes is as follows. The complex mathematical description of the process and the basic mathematical model are invisible to the user. Students work only with the logic part (visual model), which is presented in the form of a graphical user interface. The user can choose a 'basic level' or an 'advanced level' variant. When choosing the basic level the user has to select the correct values of input parameters from a list. When a wrong value of a parameter is entered or a mandatory parameter is not provided, an error message appears (Fig. 5). When working at the advance level, all the parameters are user-defined (Fig. 6). When a value of an individual input parameter is out of its realistic range, a warning message appears. It is possible to investigate quantitatively the effect of about 100 parameters on the results of the blast furnace operation.

The operation of the simulation model is organised in steps of increasing complexity. In the first step, values of individual parameters and the list of mandatory parameters are checked. In the second step the combination of individual parameters is verified. In the third step total material and energy flows are examined and corresponding recommendations are given if necessary. The next part of the work using the VSM is the Process Control. Obtained operating results can be improved in various ways: by changing the parameters in the main menu and choosing the correcting actions suggested by the model. Before making a decision about control actions, a student has the option of forecasting the change in value of some output parameters using an add-on calculation program. Whenever errors are made (i.e., wrong or missing values for parameters), penalty points are incurred and accumulated for the final grade. The option to affect the process results and to improve them using the process control function allows the student to work with the VSM in close to real operating situations.



Volume, m^3/tHM 800
Temperature, °C 1000
Moisture, g/Nm^3 10
Oxygen, % 0
10
30

Fig. 5. Basic level of visual model: user interface and choice of input parameters.

The VSM allows the student to investigate processes (coke plant, sinter plant, pellets plant) that supply the raw materials to the blast furnace and to calculate the expected overall performance (Fig. 3).

The remote tutor is equipped with visual front-end software to monitor the activity of the students, answer their questions, and analyse the learning results. Students at geographically dispersed sites can collaboratively 'charge' and 'operate' the same simulation model and view the results simultaneously. To analyse the students' work better, the tutor can view the computer log of their actions. The VSM software is implemented in Java and therefore able to run on nearly any platform that makes use of the Remote Method Invocation mechanism for communication via the Internet. The framework of the program is kept quite general so that, on the one hand, the underlying model or the user interface can be safely changed and, on the other, models of entirely different processes can be easily added and integrated, given the conformity of the programming interface.

Example of simulation for professional development

For this kind of work, a user interface with even more input parameters has been developed (Fig. 7). Users don't work with the educational logic but directly with the basic mathematical model. They can change and affect some parameters that in the educational versions are accessible only to the teacher. This version is also suitable for the research objectives, e.g. for investigation and development of new iron making technologies both from a technical and an economic points of view. In addition, comparative study of different technological regimes is possible. All the functions of VSM versions for educational purposes (see previous sub-section) are also contained in this version.

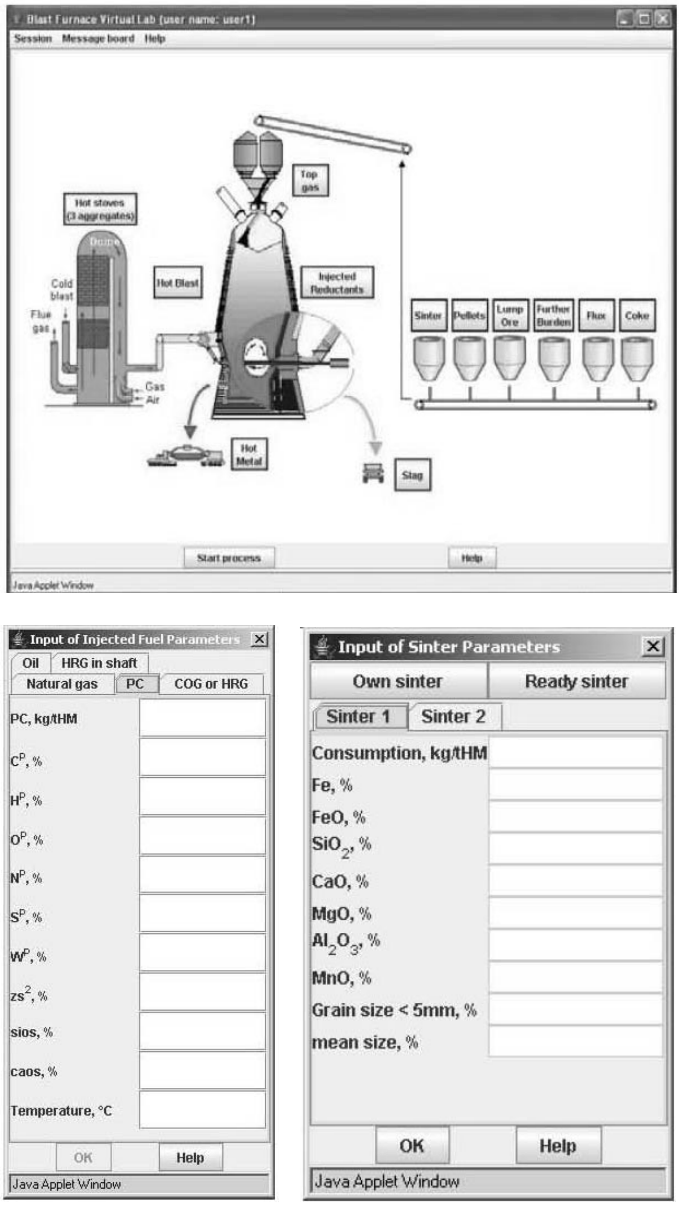


Fig. 6. Advanced level of visual model: user interface and fields for input parameters.

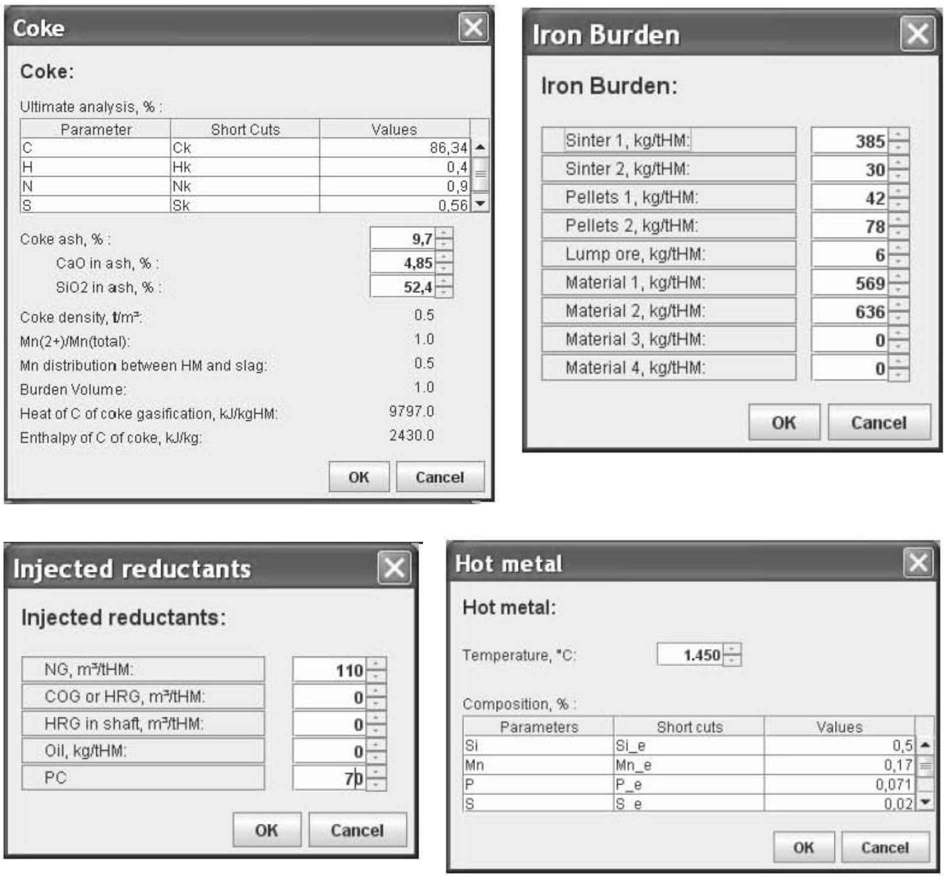
COMBINATION OF REAL AND VIRTUAL EXPERIMENTS

Experience and analysis show that, despite the numerous advantages of online experiments and other distance learning methods, they cannot cover the whole range of pedagogical elements needed for modern engineering education, at least in the medium term. Educators seem to have come to the consensus that a combination of face-to-face and online methods is the way to go. Practical work in the local laboratory should be coupled with online computer simulations to enable an integral study of technological processes of high complexity.

In the iron making study in the Department of Ferrous Metallurgy, RWTH Aachen University students work in the local laboratory, investigating selected properties of two raw materials (pellets and coke) and the behaviour of injected powder substances.

Using information and data obtained in the local laboratory, which can be imported from the files generated by the data acquisition and analysis systems, students work with the VSM to learn the interrelationships of various parameters and phenomena in the blast furnace process. The VSM allows for examination of:

- the effect of each of about 45 input parameter (plus about 15 in each of the linked sub-models) on multiple intermediate and output parameters (about 30–35 parameters only in the main mode);
- the effect of combinations of individual parameters on values of intermediate and output parameters;



Coke:

Ultimate analysis, % :

Parameter	Short Cuts	Values
C	Ck	86,34
H	Hk	0,4
N	Nk	0,9
S	Sk	0,56

Coke ash, % :	9,7
CaO in ash, % :	4,85
SiO2 in ash, % :	52,4
Coke density, t/m^3:	0.5
Mn(2+)/Mn(total):	1.0
Mn distribution between HM and slag:	0.5
Burden Volume:	1.0
Heat of C of coke gasification, kJ/kgHM:	9797.0
Enthalpy of C of coke, kJ/kg:	2430.0

Iron Burden:

Sinter 1, kg/tHM:	385
Sinter 2, kg/tHM:	30
Pellets 1, kg/tHM:	42
Pellets 2, kg/tHM:	78
Lump ore, kg/tHM:	6
Material 1, kg/tHM:	569
Material 2, kg/tHM:	636
Material 3, kg/tHM:	0
Material 4, kg/tHM:	0

Injected reductants:

NG, m^3/tHM:	110
COG or HRG, m^3/tHM:	0
HRG in shaft, m^3/tHM:	0
Oil, kg/tHM:	0
PC	70

Hot metal:

Temperature, °C: 1.450

Composition, % :

Parameters	Short cuts	Values
Si	Si_e	0,5
Mn	Mn_e	0,17
P	P_e	0,071
S	S_e	0,02

Fig. 7. Model for research purposes: selected windows for input parameters.

- the comparative effect of different control actions on the same output parameters, as well as on the total material and energy flows.

EVALUATION AND EXPERIENCE

An online simulation trial was first performed over two months with the participation of four European Universities and a research centre. Altogether there were 37 participants, including 25 undergraduates and postgraduates, 7 faculty members, and 5 expert reviewers. Student participants who met certain prerequisites were granted a course certificate, which served as one of the incentives for their participation in the trial.

The trial evaluation was divided into three phases. First, the learning system had to undergo several rounds of pre-trial tests, including usability tests of the user interface as well as the network connectivity tests of the server. The next phase was an in-trial (formative) assessment, which focused on the evaluation of the content and on how well the students could understand the content. No control groups or pre-/post tests was employed. The trial was to demonstrate the feasibility of embedding the Virtual Lab in an international CSCL (computer-supported collaborative learning) context, but the learning effect resulting from collaborative interactions was not the major concern of the Course Provider. The last phase was the post-trial (summative) evaluation. The questionnaire consisted of 5-point scale questions about content, visualisation, interactivity, support, and overall satisfaction (1 = terrible . . . 5 = excellent). Respondents were also asked to give qualitative comments on these five aspects. Questions on academic and social background were also included. In total, 21 completed questionnaires were collected. The respondents included five experts, one faculty member (majoring in physics), and 15 students (1—Spain, 6—Poland, 9—Germany). The statistical analysis of post-trial evaluation is shown in Table 1. The data indicated that the course was generally well accepted with the mean 'Overall Satisfaction' being 4.25.

Statistically significant differences between expert reviewers and students were identified in 'Content', 'Visualisation', and 'Overall Satisfaction' (Table 2). Note that the experts rated all the three dimensions higher than did the students. These findings indicate that the student ratings of

Table 1. Summative evaluation of all VL components.

Content	Visualisation	Interactivity	Support	Overall satisfaction
4.42	4.03	3.77	3.65	4.25

Table 2. Results of two-sample t-test: expert vs. student.

	Content		**Visualisation**		**Overall satisfaction**	
	Expert	Student	Expert	Student	Expert	Student
Mean	4.6	4.13	4.4	3.73	4.4	4.0
Variance	0.3	0.27	0.3	0.49	0.3	0.14
t-value	1.73		1.92		1.84	
p (one tail)	0.05		0.03		0.04	

the quality of the learning resources were not particularly valid.

Furthermore, there was no significant difference between the Polish students (penalty point count $PP = 127$, standard deviation $SD = 1.72$) and the German students ($PP = 117$, $SD = 4.67$) in the total number of penalty points accumulated in five sessions of the work with the VSM. The correlation between 'Overall satisfaction' and the total number of penalty points was moderate ($r = 0.52$) and the correlation between 'Overall satisfaction' and 'Academic level' (i.e. university 1st cycle, university 2nd cycle, and postgraduate) was very low ($r = 0.17$) and there was no correlation between 'Overall satisfaction' and 'Preferred learning/Communication modality' (i.e. face-to-face, computer-mediated, mixed) at all ($r = 0.0$).

The evaluation results showed that the users were generally satisfied with the course and had new learning experiences, especially the collaboration with international partners. In particular, the high acceptance of the VSM confirmed the assumption that visualising complex concepts can greatly enhance the students' motivation to learn.

Further trials and those reported above were held for external users and were not coupled with classroom teaching and practical work in a laboratory. This approach was realised in the scope of the iron making study of the master programme at the Department of Ferrous Metallurgy, RWTH Aachen University. Practical work in the local laboratory is complemented by experimentation with the Visual Simulation Model.

The first experience of the combined classroom study and eLearning of iron making processes in the Master programme is as follows.

The whole study of the iron making processes took approximately 34–36 hours, of which about 75% were work in class and a local lab and the other 25% were for online study.

The work in the local laboratory included the investigation of pellets, coke and injected auxiliary energy agents. Students spent approximately two hours performing each experiment and about one more hour each time to process the data obtained. It should be mentioned that the preparation work (preheating of lab furnaces, producing the raw pellets, specimen preparation etc.) was done by technicians or assistants and took extra time.

The work with the online Visual Simulation Model was divided into five sessions.

- *1st session*: The model's features and use were explained and demonstrated by a teacher.
- *2nd session*: Students investigated the effect of parameters of all burden materials (sinter, pellets, ore, limestone and other additives) and energy source (coke) on the overall blast furnace iron making performance. Another group of parameters (materials supplied from the lower part of a blast furnace) was determined by the model. Sinter and pellets (specifically their chemical and physical properties) could be chosen directly from 'available' ready products or were 'produced' at sinter and pellets plants respectively. Data collected in the local laboratory during the investigation of pellets and coke could be extracted and used at this stage of the work with an online simulation model. The session was followed by an assessment.
- *3rd session*: Students simulated the effect of parameters of materials supplied from the lower part of the furnace on the overall blast furnace performance. Data extracted from the results of injection tests in the local laboratory were used in this session. Burden parameters are determined in this regime by the model.
- *4th and 5th sessions*: Several teams (two students in each) collaborated in 'charging' and 'operating' the same blast furnace simulation model per team and received common grades. The communication was conducted using a message board tool. The difference between two sessions consisted in the examination of burden and blast parameters (as in the 2nd and 3rd sessions).

A comprehensive evaluation of the new combined teaching method has not yet been performed. The mean grade in interim assessment tests was better than the previous student group who worked only in the classroom and the local lab. Interviews also showed a higher motivation to study the complex process when students were involved in situations close to real industrial conditions, as well as a better understanding of the interrelationships between linked technological processes and related phenomena.

CONCLUSIONS

The role of practical work, experiments and simulations in engineering education will become increasingly significant.

A wide spectrum of diverse experiments and laboratory types is available for engineering education and professional development. An engineering course designed with a focus on various kinds of experiments and simulations and a combination of them will improve the quality of engineering education.

The basic components of the majority of technological systems are thermodynamics, chemical kinetics and mechanics.

Online experiments based on mathematical modelling and simulation should be directly linked to other online tools and resources (text and reference books, recorded and live lectures, and other interactive and instructive material).

The Department of Ferrous Metallurgy at the RWTH Aachen University develops, uses and offers simulation models and tools to extend the possibilities of real experiments in local labs.

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