

DEVELOPMENT OF TECHNOLOGY ENHANCED VIRTUAL LABORATORIES FOR ENGINEERING EDUCATION BASED ON MATHEMATICAL MODELS

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Abstract- One of the most modern approaches for using TEL and specifically eL in engineering education is the creation of Virtual Laboratories (VL). A VL is a set of different educational tools, the most characteristic one of which is a visual simulation model, enabling computer experiments with the target to enhance a possible new way of intuitive understanding.

Development of online laboratories offer an additionally possibility for creation of Virtual Remote Laboratories, as a tool for e-Research options in engineering, enabling sharing of research resources in real laboratories by many participants.

The objective of this work is to present a systematic basis for the creation of Technology Enhanced VL's for engineering education in general, based on mathematical modelling, and to demonstrate some options, based on this VL concept, enabling creation of Virtual Remote Laboratories, when not only process models but also process control models are involved into the VL concept.

Introduction

eLearning (eL) as one of more usable possible forms of Technology Enhanced Learning (TEL) is employed more and more in educational context. It is used to support educational targets with the help of modern Information and Communication Technology achievements, like internet a.o. TEL is an option for saving money in the short-to-middle term educational objectives but to maintain and improve the quality of education of engineers is a long-term objective. Involving TEL tools into the curricula of engineering education has then to consider the aspect quality too in order to be able to fulfil the requirements of both aspects.

One of the most modern approaches for using TEL and specifically eL in engineering education is the creation of Virtual Laboratories (VL). A VL is a set of different educational tools, the most characteristic one of which is a visual simulation model, enabling computer experiments with the target to enhance the way of intuitive understanding.

The benefits of creating and using a VL are:

- Involvement of the best teachers over the world
- Involvement of the best methodological concepts over the world

-Availability to anyone who has internet access

Development of online laboratories offer an additional possibility for creation of Virtual Remote Laboratories, as a tool for e-Research options in engineering, enabling sharing of research resources in real laboratories by many participants.

The objective of this work is to present a systematic basis for the creation of Technology Enhanced VL's for engineering education in general, based on mathematical modelling, and to demonstrate some options, based on this VL concept, enabling creation of Virtual Remote Laboratories, when not only process models but also process control models are involved into the VL concept.

Development of the curricula in engineering education is determined through two driving forces:

-societal needs, like industrial needs and economic constraints, employment context

-sustainable development needs in nearly all areas of human activities, like production, research, recycling, environment and services.

Educational policies in different countries are oriented towards these two needs more or less explicitly, respectively are driven by these two forces. They try to combine or complement or at least to consider and finally to optimise these tendencies in the curricula and to elaborate and support the frame into which engineers have to be educated in order to meet these two demands, named here shortly "societal" and "developmental". The first one is oriented towards short and medium term objectives, the second towards long term objectives.

Mathematical considerations

To a model in general the following aspects are inherent:

-Variables: which variables are essential for mapping the apparent behaviour?

-Area of validity: Domain of definition and domain of values for the model variables

-Parameter: Which parameters could be changed in order to achieve at (relative) "congruence"?

To a set of models: the following aspects are essential:

-Coupling between their- or some of their- variables

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To a VL: the following aspects belong to:

- A set of models
- A relation for their “overlapping” and “coupling”
- A conceptual platform for the VL’ s realisation
- A software platform (set of software instructions and of conditional (IF-THEN) relations)

In methodological context, in creation of VL for engineering education – one wide area of those disciplines, which are “mathematisable” – an equilibrium must exist between

- inductive reasoning and
- deductive reasoning

It may be called a “synergistic equilibrium” as its target should be to enable creating synergy by a balanced inductive to deductive activities relation.

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

-Reduction of number of facts

-Replacing facts by rules

-Replacing rules by laws

-Replacing laws by principles

Methodologically, this evidently should be generic replacement and generic deduction.

The next level in this VL- concept is to extend the VL from metallurgical engineering to all other technical-engineering (i.e. where mathematisation is today possible) educational context. This Meta-VL should be named a “Generic Virtual Laboratory” (GVL) and its creation requires multidisciplinary and deep knowledge of the fundamental principles of the respective educational content to be adapted, transferred or modified for DL purposes, e.g. for electrical engineering, energy engineering, environmental engineering, mechanical engineering, chemical engineering and other.

Formal structure for a model based Virtual Laboratory

General formulation for a coupled material and energy exchanging process:

model 1:	material charging	(Set of
variables:	M=(m ₁ , m ₂ , ...,m _N)	
model 2:	energy delivery	(Set of
variables:	E=(e ₁ , e ₂ , ...,e _L)	
...		
model r:	coupling relations	(Set of
variables:	R=(r ₁ , r ₂ , ...,r _K)	

In general:

VL = Set of r models (M, E, ..., R), if additional entities are exchanged or have to be taken into consideration (e.g. information).

As each one model is set-up by some equations / relations between its variables, it is possible that some relations are more than one time contained in the overall set of models. But the union of the model-sets guarantees that any one relation is contained only one time in the overall set.

Consequence:

VL: Based on a set of mathematical models, coupled parallelly, serially or networked

Model(s): set(s) of mathematical relations / equations, coupled too.

For two model systems (sets of models) M_1, M_2 containing the same number of sub- models and describing the same real system

$$M_1 : (M_{11}, M_{12}, \dots, M_{1n})$$

$$M_2 : (M_{21}, M_{22}, \dots, M_{2n})$$

let the “distance” between the two such sets be denoted by

$$d(M_1, M_2) := \sum_{k=1}^n d(M_{1k}, M_{2k})$$

i.e. by the sum of the distances between the sub-models contained in the two sets. The distance between two sub-models can be defined as the sum of the distances between all their propositions:

$$d(M_{1k}, M_{2k}) := \sum_{l=1}^m d(p_{1l}, p_{2l})$$

(p: propositions/statements)

The propositions are expressed through the values that some functions of model variables take:

$$p := f(v_{1l,1}, v_{1l,2}, \dots, v_{1l,r}) = c_{1l},$$

(l=1, ..., m)

Meaning: Propositions are defined through functions f_{1l}, f_{2l} of – not necessarily identical – variables $v_{1l,j}$ resp. $v_{2l,j}$ which receive the values c_{1l} resp. c_{2l} through equations. But f_{1l}, f_{2l} describe the same entity.

Consequence:

$$d(p_{1l}, p_{2l}) := |f_{1l} - f_{2l}| = |c_{1l} - c_{2l}|$$

The distance of the propositions of the two sub-models is defined by the positive difference between the values of the functions, thus of that real numbers the functions take. As the real numbers, equipped with their absolute difference distance, form a metric space, the distances between the model systems form a metric space too. This means that they can be equipped with a topology. This is important for assessment of the “quality” of model systems by comparison of their “distance” from a standard one or from the measured behaviour.

Example: The simulation and visualisation Lab of the “Virtual Lab Ironmaking”

At RWTH Aachen it has been developed a first VL in metallurgical engineering education (VL – Ironmaking, Fig. 1) [4,5] and there are currently developing further ones for this specific area of metallurgical engineering education.

A mathematical model of the blast furnace process was developed at the Donetsk National Technical University, Ukraine [1] and shortly described in [2]. This is a total balance model that does not require any input parameters to be assumed.

The model was developed on the base of a method of Prof. A.N. Ramm [3]. This method based on the interrelations of material and heat balances equations. Its characteristic feature is following: a system of equations of material balance of different input components according to a target hot metal chemical composition is formed; to this system one equation of heat balance is added which determines the correlation between coke rate and remaining components. The coke rate is introduced as unknown value in all equations of the material balance, rates of iron bearing and flux components in the heat balance equation.

The Main balance equations are written in generic form as follows:

Hot metal output:

$$i \cdot e_i + f \cdot e_f + c \cdot e_c + s \cdot e_s = 1$$

Slag basicity:

$$i \cdot RO_i + f \cdot RO_f + c \cdot RO_c + s \cdot RO_s = 0$$

Heat balance:

$$i \cdot q_i + f \cdot q_f + c \cdot q_c + s \cdot q_s = 1$$

“Excessive” amount of an element in hot metal:

$$i \cdot X_i + f \cdot X_f + c \cdot X_c + s \cdot X_s = 0$$

“Excessive” amount of an oxide in slag:

$$i \cdot Y_i + f \cdot Y_f + c \cdot Y_c + s \cdot Y_s = 0$$

where, i, f, c, s: consumption of iron bearing materials, flux, coke and injected

substances respectively, kg/kgHM;

e: hot metal output per unit of corresponding material, kg/kg material;

q: heat consumption, kJ/kg (m³) material;

RO: “excessive” (unused) amount of bases in a given material at a given slag

basicity, kg/kg material;

X: “excessive” (unused) amount of element in a given material at a given

content of this element in hot metal, kg/kg material;

Y: “excessive” (unused) amount of oxide in a given material at a given content

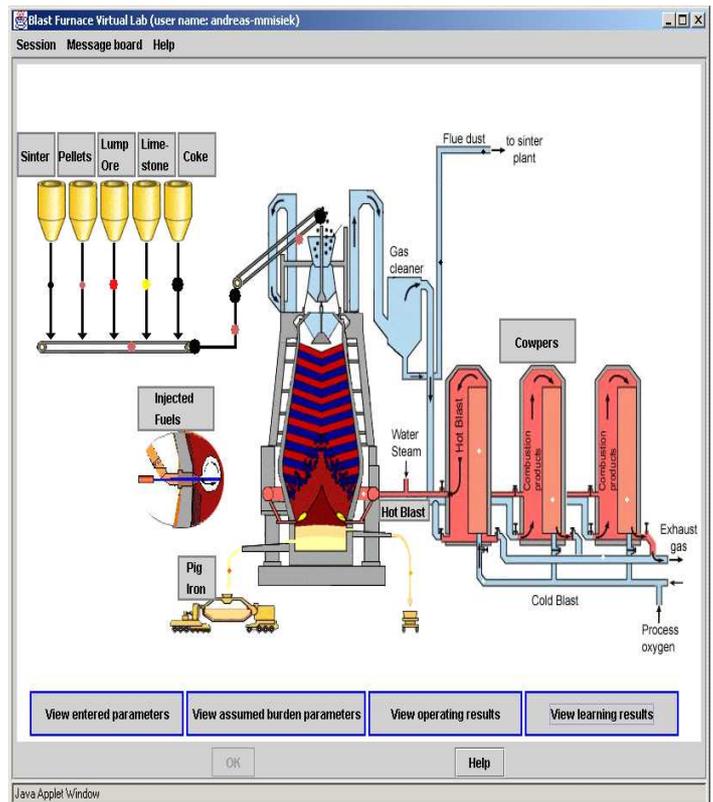
of this element in slag, kg/kg material;

The key calculations in the method determine:

- 1) amount of oxygen released during reduction
- 2) injected substance characteristics: total quantity of C, H, O and N; the enthalpy: heat released by burning in the raceway etc.
- 3) volume of bosh gas
- 4) direct reduction rate

- 5) coke and total reducing agent consumption and blast volume
- 6) flux consumption and slag volume
- 7) top gas parameter (volume, temperature, composition, calorific value)
- 8) heat balance (heat generated and absorbed)
- 9) flame temperature
- 10) change in the productivity and intensity of the coke combustion.

Virtual Laboratory – Ironmaking, Fig. 1:



Methodological basis for creating a generic virtual laboratory (GVL)

Prerequisites:

- A. Statements of a model have to be formulated as equations $f : (v_1, v_2, \dots, v_n; t) = 0$
- B. “Distance of models” is measured by the sum of distances of their statements

A Virtual Laboratory, (VL) acts on the following areas of information processing:

- Retrieval
- Storage
- Structure
- Reproduction/Generation of
 - information
 - knowledge

The VL could undertake functions (on intuitive level) which are neglected by common retrieval operations, on a new level.

- How to express the fact that derivates from the model-statement-equation $f_i(x_1, \dots, x_n; t) = c_i$: (and their possible visualisation) enhance intuitive understanding of the facts expressed in that equation?:

→ total change of f_i :

$$df_i = \sum_j \left(\frac{\partial f_i}{\partial x_j} \right) dx_j + \left(\frac{\partial f_i}{\partial t} \right) dt$$

- The model statements/functions f_i , representing the model(s)- and being presented as points or vectors in an abstract (model) space – could generate through simple parameter changes/studies a variety of statements, all lying within the limits (windows) of domain of definition and of allowed (reasonable) values, which might be able to illustrate the statements of the model(s) when visualised. The inverse way – from the simple phenomenological statement / equation to the general principle (mechanism) of the statement function f_i does not allow to induce a deeper understanding of anything else but of that parametric statement.

Example: Ohm's Law $I = \left(\frac{1}{R}\right) \cdot U$; $I = f(U; R)$

Irreversible Thermodynamics:
Flow = f(Potential, π (Parameter))

Flow: mechanical force, electric current, matter transport, ...;

Potential: mechanical potential gradient, electric potential gradient, concentration gradient, ...

Facit: VL based on models, (not on relations), which generate relations, helps better understanding

And: One measures the “quality of models” through the sum of generable relations! (and their mutual distances)

Short summary of methodological path:

- 1) – Formalisation of models comparison (“quality”)
 - 2) – VL's based on mathematical models enable (deductive!) derivation of statements
 - 3) – Starting from principles – based mathematical models enables generic mode
 - 4) – Starting from principles – based mathematical models enables better intuitive understanding
- Framework of Irreversible Thermodynamics as the “language”, could be useful, not only for a GVL, but also for the VL itself: Define an hierarchy of statements, from the most principal ones to the most specific ones!

The “staircase” should be parametric studies and changing of the “domains”.

- Definitions of “principal” mathematical models and of derivable mathematical models are possible for any technical discipline.
- Understanding what is “causa” and what is “actio” (effect), what are model variables and what operational parameters, explicitly in the VL – model, is necessary for clarifying the fundamental relations of the specific technical area.

As

$$\begin{aligned} d(M_1, M_2) &:= \sum_{k=1}^n d(M_{1k}, M_{2k}) = \\ &= \sum_{m=1}^n \left(\sum_{l=1}^m d(p_{1l}, p_{2l}) \right) = \\ &= \sum_{m=1}^n \left(\sum_{l=1}^m |f_{1l} - f_{2l}| \right) = \\ &= \sum_{m=1}^n \left(\sum_{l=1}^m |c_{1l} - c_{2l}| \right), \end{aligned}$$

where $c_{ij} \in R^1$, the model space, thus the space of model distances is the 1-dimensional-real-numbers-space R^1 . Adapting the framework of Irreversible Thermodynamics, the relations between (generalised) Forces and Flows is

$$J_i = \sum_{k=1}^n L_{ik} X_k, (i = 1, 2, \dots, n)$$

X_i : “Forces”

J_i : „Flows“

L_{ik} : Phenomenological Coefficients (Their matrix is according to Onsager symmetrical)

It is easily shown from the above relation that:

$$\left| J_i - J_j \right| \leq \sum_{k=1}^n \left| L_{ik} - L_{jk} \right| \left| X_k \right|$$

The implication of this relation is that in adopting the formalism of Irreversible Thermodynamics for formulating a GVL for a mathematisable technical discipline as basis for eLearning – educational tools, the distance of the flows in comparing two models is simply bounded by the sum of the distances of the phenomenological coefficients. This gives a methodological tool for using mathematical models in creation of a GVL, as well as specific VL's, and for measuring their quality.

In the following a (possible) set-up of a G/VRL is schematically presented (first in general form and then for the specific case of Ohm's Law).

$$Flow = L * Force$$

Constraints:

$$Flow_{min} \leq Flow \leq Flow_{max} \rightarrow Force_{min} \leq Force \leq Force_{max}$$

Parameter Study: $L_{min} \leq L \leq L_{max}$

Loops:

$$Force \Rightarrow Force_{\phi} \rightarrow Flow(Force_{\phi}) = Flow_{\phi} \rightarrow \begin{cases} Flow_{min} \leq Flow_{\phi} \leq Flow \rightarrow OK \\ Flow_{min} \rangle Flow_{\phi} a / o : Flow_{\phi} \rangle Flow_{\phi} \rangle Flow_{max} \\ \rightarrow new : Flow_{\phi} := Flow_{\phi\phi} etc \end{cases}$$

This scheme can be continued down the level with detailing out L

Example: Ohm's Law

$$I = \frac{1}{R} * U$$

I: electric current

U: electric potential

R: resistance

Constraints: $I_{min} \leq I \leq I_{max} \rightarrow U_{min} \leq U \leq U_{max}$

Parameter study: $\left(\frac{1}{R}\right)_{min} \leq \left(\frac{1}{R}\right) \leq \left(\frac{1}{R}\right)_{max}$

$$U \rightarrow U_{\phi} \Rightarrow I(U_{\phi}) = I_{\phi} \Rightarrow$$

Loops: $\begin{cases} I_{min} \leq I_{\phi} \leq I_{max} \rightarrow OK \\ I_{min} \rangle I_{\phi} a / o : I_{\phi} \rangle I_{max} \Rightarrow new : I_{\phi} := I_{\phi\phi} etc. \end{cases}$

In detail:

$$R = \rho \frac{l}{q} \rightarrow \frac{1}{R} = \frac{1}{\rho} \cdot \frac{q}{l}$$

ρ : specific resistance

l: length

q: cross section

Keeping the same material ($\rho = const$) one has two possibilities to study parametrically the influence of $\left(\frac{1}{R}\right)$,

through q or l (or both).

This scheme can be formulated in a set of (IF-THEN) – relations which could enable to control (on a first, simple step) the process.

Given that the mathematical model equipped with the above conditional relations constitutes a simulation-based Virtual Control Lab, its set-up could be named a Virtual Remote Lab as it would enable to control the (physical) process remotely, doing simulations and parametric studies.

A Generic Remote Lab (GRL) is then defined through the set-up formulated above in generic terms (Force, Flow).

Literature

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