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Wastewater treatment models in teaching and training: the mismatch between education and requirements for jobs

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ABSTRACT

As mathematical modeling of wastewater treatment plants has become more common in research and consultancy, a mismatch between education and requirements for model-related jobs has developed. There seems to be a shortage of skilled people, both in terms of quantity and in quality. In order to address this problem, this paper provides a framework to outline different types of model-related jobs, assess the required skills for these jobs and characterize different types of education that modelers obtain "in school" as well as "on the job". It is important to consider that education of modelers does not mainly happen in university courses and that the variety of model related jobs goes far beyond use for process design by consulting companies. To resolve the mismatch, the current connection between requirements for different jobs and the various types of education has to be assessed for different geographical regions and professional environments. This allows the evaluation and improvement of important educational paths, considering quality assurance and future developments. Moreover, conclusions from a workshop involving practitioners and academics from North America and Europe are presented. The participants stressed the importance of non-technical skills and recommended strengthening the role of realistic modeling experience in university training. However, this paper suggests that all providers of modeling education and support, not only universities, but also software suppliers, professional associations and companies performing modeling tasks are called to assess and strengthen their role in training and support of professional modelers.

Key words | education, environmental engineering, mathematical modeling, wastewater treatment

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INTRODUCTION

Mathematical models have become widely accepted tools in the field of wastewater treatment engineering and are used in design, optimization, operation and research as well as for teaching and training (e.g. Gujer & Larsen 1995; Morgenroth *et al.* 2002; Gujer 2004). At the same time, universities and industry are experiencing increasing difficulties in finding enough people sufficiently skilled for modeling work in research or consulting (authors' personal communication and perception). The situation will likely become more serious, as modeling becomes a day-to-day practice for more practitioners, and as the further-development of models, together with increasing computing power, increase the number of applications that are considered common practice in modeling (e.g. computational fluid dynamics, Monte Carlo simulation or plant-wide modeling; Gujer 2006). If the requirements for modeling in engineering practice and research are not appropriately addressed in teaching and training, then there is significant danger that models will be applied inefficiently, ineffectively or incorrectly (Takács *et al.* 2007), leading to negative experiences and a negative perception of modeling as a tool. At the other extreme, some graduates may be too specialized for typical modeling jobs in practice. In either case, the education does not fit to the requirements for various model-related jobs. Consequently, we have to ask where and why the current education system (university courses, training on the job and continuous education) seems to fail.

It is a fact that wastewater treatment modeling courses are taught in an increasing number of university programs. There is literature that outlines such modeling courses (Morgenroth *et al.* 2002; Gujer 2004) and discusses strategies for the wider field of environmental engineering education (Alha *et al.* 2000; Morgenroth *et al.* 2004). Furthermore, there exist many textbooks about modeling wastewater treatment systems (e.g. Dochain & Vanrolleghem 2001) as well as guidelines for simulation studies (Hulsbeek *et al.* 2002; Melcer *et al.* 2003; Vanrolleghem *et al.* 2003; Langergraber *et al.* 2004). Much of the literature focuses on university education. However, there is a wide range of practical modeling tasks and many different aspects of training and so consideration must be given to deciding what should be taught at university and what must be learnt by training on the job or through continuous education programs.

Appropriate measures to improve the situation can only be developed if the current state of education and the demands for different jobs dealing with mathematical models are known. Therefore, this paper provides a framework to characterize the mismatch between "supply" and "demand" of modeling know-how. Furthermore, this paper includes conclusions from a workshop held at the 1st IWA/WEF Wastewater Treatment Modelling Seminar (WWTmod2008) in Monte-Sainte-Anne, QC, Canada, June 1–3 2008, where a draft of this framework was discussed among academics and consultants from North America and Europe (list of participants in Acknowledgements section at the end of this paper, additionally the following authors were at the workshop: T. Hug, B. Johnson, E. Morgenroth, A. Shaw). This paper does not seek to provide final and complete conclusions and guidelines about the use of models in teaching; rather, it intends to promote a discussion on how to meet current and future modeling related educational requirements.

PURPOSE OF MODELING

For the discussion of model use it is important to realize that, in general, mathematical models can be applied for different purposes (Figure 1). While models are often used to design and optimize wastewater treatment plants (prognostic applications), they can also be important research tools to elucidate the functioning of processes (diagnostic applications). Furthermore, models are helpful to communicate knowledge about the behavior of the system of interest (educational purpose) which is a useful application for modeling in consulting as well as in teaching.

MODELS AND TEACHING

The use of mathematical models in teaching wastewater treatment can be envisioned in different categories. In reality, the use of models in teaching involves attributes of each category.

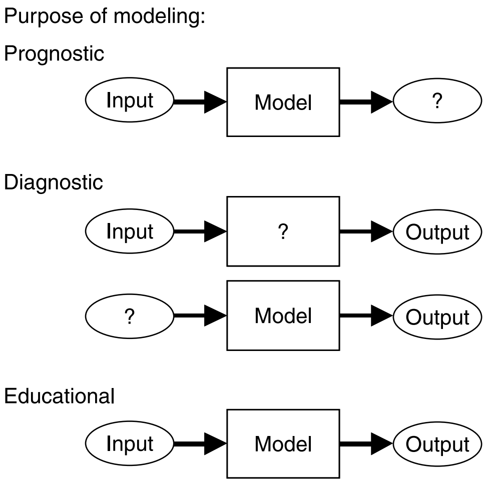

Figure 1 | Mathematical models can be used for prognostic (predicting the future values of state variables), diagnostic (discrimination between mechanisms) and educational purposes (communicating connection between input and output).

Teaching with models uses the models as tools to enable the student to learn about the behavior and process interactions of complex systems. The model could be used as a black-box; however, familiarity with the internal structure of the model allows a deeper understanding of the processes involved.

Teaching modeling involves providing instruction on the building and use of models. This goes far beyond instruction on how to run a particular model on any simulator. Responsible modeling requires familiarity with the structure of the models, as well as awareness of limitations due to data quality, calibration and validation procedures, and parameter and model structure uncertainty. It ultimately allows finding an appropriate balance of simplification and details.

Teaching models is focused on educating about specific models. This can be the actual goal of the training, but in most cases, teaching models is a prerequisite for the two aspects introduced above, namely teaching with models and teaching modeling.

THE MISMATCH BETWEEN "SUPPLY" AND "DEMAND"

Characterizing "supply" and "demand"

According to the experience of the authors and the WWTmod2008 workshop attendees, there is a lack of skilled people for modeling work in consulting as well as in academic and industrial research. It seems that there are shortages both in terms of quantity and in quality. In some cases, however, graduates are too specialized [0] for a variety of jobs.

In the following paragraphs, a structure is proposed to describe and analyze the current state of "supply" and "demand" of skilled individuals for mathematical models in teaching and training (Figure 2). Generally, education should prepare students for a specific job or a variety of tasks. Consequently, appropriate educational targets and types of education should be derived from the requirements for particular jobs (solid arrows in Figure 2). However, modeling education may actually induce new types of model-related jobs (dashed arrow in Figure 2), e.g. by establishing a new state-of-the-art of modeling technique (e.g. Gujer 2004).

"Demand"

The *"demand"*, i.e. the required skills and knowledge for jobs with wastewater treatment models, can be structured according to the categories in Table 1. It is obvious that there is a wide range of model-related jobs and activities for which different qualification levels are required or beneficial. Table 2 provides a list of skills and levels of understanding that might be important, depending on the modeling task. The list shall illustrate the wide range that has to be considered. Only the appropriate combination of understanding of the objective, the processes, the models

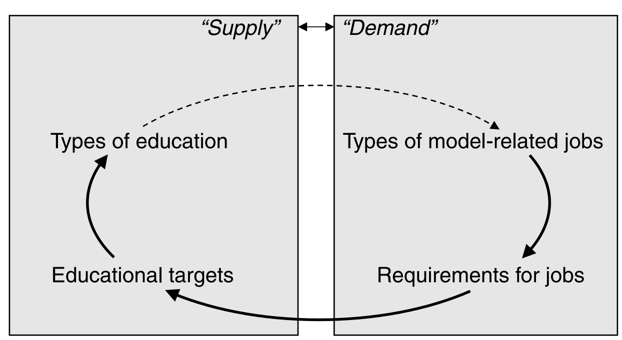

Figure 2 | Connection between the modeling education ("supply") and model-related jobs ("demand"). Education should be based on the requirements for jobs (solid arrows). However, teaching of new techniques and modeling philosophies may lead to new types of modeling activities and consequently to new demand.

Table 1 | Categories to structure the demands on modelers for different jobs with wastewater treatment models

Objective of model work	Type and level of model work	Environment for model work
Academic research (as graduate student, research staff or faculty)	*Basic model users* (performing simple simulations without need for in-depth understanding, possibly advised by advanced model user)	Universities and research institutes (learning, teaching, research)
Industrial research and development of processes and equipment		
Plant design and optimization		Water engineering companies such as consultants and equipment suppliers of different specialty and size
Process control	*Advanced model users* (performing complex simulation studies requiring sound knowledge of potentials and limitations)	
Model-based support for plant operation		
Model-based support for strategic and political decisions		Wastewater treatment plants
Communication of complex or dynamic system behavior	*Model developers* (developing or adjusting model equations and structure)	
Sales of e.g. a specific design		Software developers and suppliers
Software development	*Software programmers* (implementing models into software, possibly dealing with user interfaces or with numerical solutions)	Governmental agencies
Approving modeling studies (e.g. as governmental agency)		Professional associations
Teaching and training with different targets at different levels	*Instructors* (training one of the above listed groups of modelers)	

and the nature of the involved uncertainties allows effective and efficient working with models. For most applications, it is important to be able to understand why the model is doing what it is doing. It is crucial for the modeler to realize the difference between models and the real world, and to be aware of uncertainties and limitations. Furthermore, most modelers should know that a wastewater treatment plant model consists of several sub-models. Finally, the state-of-the-art is constantly changing and will consequently push the requirements for modelers and instructors further ahead (Gujer 2006).

At the WWTmod2008 workshop there was consensus about the most important skills and knowledge of modelers for consulting as well as for academic jobs (Table 3). Not surprisingly, process understanding and awareness of the limitations of models were considered crucial, while knowing the actual tools had a lower priority. Some very important skills, such as creativity for problem solving, cannot be easily taught and are often missing in education. Similarly, in literature about environmental engineering education, problem solving skills are considered central (Bishop 2000; Morgenroth *et al.* 2004) and have been identified as important requirements in job advertisements for environmental engineers (Fettig 2004). At the workshop it also was argued that model use in consulting firms requires particular skills that are typically not taught in university courses (and maybe cannot be taught there effectively), e.g. the ability to find an appropriate level of model use due to budget and time constraints and the required accuracy or to focus on reactor volumes and operating costs rather than on minimizing effluent concentrations way beyond the discharge license requirements.

Table 2 | Possible requirements for wastewater treatment modeling jobs and targets for modeling education

Being able to apply a simulator for the intended use
Being aware that every model is a simplification of the real world
Understanding the difference between the model (equations and parameters) and the simulator (software)
Understanding the structure and equations of the model, e.g. being able to read the Gujer (Petersen) matrix
Understanding the meaning of the model parameters including possibly lumped processes
Understanding the difference between model compounds and measured data, e.g. wastewater fractionation
Being able to extend an existing model
Being able to appropriately calibrate and validate a model, following guidelines
Thoroughly understand appropriate calibration and validation procedures
Knowing how to effectively and efficiently use modeling to support the design or optimization of a wastewater treatment plant (rather than using the simulation for purely illustrative purposes).
Finding an appropriate balance of simplification and accuracy to complete a particular task
Understanding the importance of data quality and the sources of data uncertainty
Understanding causes of model uncertainty
Knowing how to appropriately use sensitivity analysis
Understanding different parameter estimation approaches
Understanding that a wastewater treatment model consists of several sub-models (bio-kinetic, hydraulic and others)
Understanding numerical procedures and how to identify and reduce errors caused by numerical effects
Knowing different models for a specific application (e.g. for biological processes or sedimentation)
Knowing different purposes of model use and its particular potentials and limitations
Being aware of current model developments and changing state-of-the-art (e.g. two-step nitrification-denitrification, computational fluid dynamics, plant-wide modeling, Monte Carlo simulation)
Having practical experience with the real-world system (wastewater treatment plant) that shall be modeled
Understanding reactor hydraulics, understanding the biochemical process kinetics
Being able to deal with time and budget constraints

"Supply"

The "supply", i.e. the training of people working with models and the use of models to teach process understanding, can be divided into two main categories:

- "*in school*" (learning about modeling and processes without using it for the current job) and
- "*on the job*" (learning about modeling and processes while using the knowledge for the current job; this includes graduate students working with models).

These major categories can be further divided into:

- general or specific (targeted) modeling know-how,
- formal or informal education and training, and
- different types of instructors (university teacher, professional associations, software supplier, supervisor at work, colleagues, self-education, book)

Most combinations of the main categories "in school" and "on the job" with sub-categories are possible, although some are more likely. Typically, a professional modeler has gone through a series of different steps of education. Some examples are: formal general education about activated sludge models at university, informal training by a

Table 3 | Priorities of skills for model-related jobs in consulting and research (conclusions from workshop at WWTmod2008)

1st priority	2nd priority	3rd priority
Process understanding	Being critical	Knowing models and design tools
Practical process experience	Creativity	
Knowing limitations of modelling	Holistic thinking	

supervisor or more experienced colleagues, formal continuous education course by a software supplier or a professional association, formal self-education based on a book, informal "training" of a consultant by unguided learning-by-doing. All of these types of education have their own strengths and risks, for targeting a particular task or considering quality control.

It is obvious that non-university types of training exist. Indeed, according to a recent survey by the IWA Task Group on "Good Modelling Practice–Guidelines for Use of Activated Sludge Models" (Hauduc *et al.* submitted) only 31% of model users in industry (42% in academia) have gone through modeling courses at university; only 4% in industry (16% in academia) have obtained all knowledge from university courses. In industry, training by software providers plays a more important role than university education. By far the most significant path of acquiring modeling knowledge is self-education: 81% of model users in industry (77% in academia); 31% (41%) have acquired all their knowledge by themselves.

Reasons for the mismatch

Based on the assumption that the shortage of appropriately skilled modelers is quantitative as well as qualitative, the following hypotheses may help to explain the identified mismatch between "demand" and "supply." Firstly, there might be a simple time-lag as modeling has become more widely accepted but the teaching and training lags behind. It is also possible that students believe that they do not need to understand the real-world process and the function of the model because the software seemingly knows. Teachers and instructors may fail to make students aware of the uncertainties associated with models. Teachers and instructors themselves may be inappropriately trained. Students might be inadequately prepared for the requirements of different real-life modeling projects, as teachers are not sufficiently aware of the different requirements for research and practice. Knowing that many modelers and instructors are self-educated, it is easy to imagine that they might have missed or misinterpreted crucial aspects of modeling.

Considering the variety of education paths and the broad range of possible requirements (Tables 2 and 3), it is clear that no single type of education can appropriately prepare a student to every model-related job, but that several training steps are typical. Limitations in each step may contribute to an individual's lack of required knowledge and skills. As university courses played a limited role in the education of current modelers (Hauduc *et al.* submitted), we have to ask whether this fact is responsible for the mismatch or that it is rather due to shortcomings in other means of training such as self-education and informal training on the job.

Converging "supply" and "demand"

The outline given in Figure 2 and the structure proposed above to describe "supply" and "demand" facilitate the derivation of adequate educational targets and types of training. The approach starts with an outline of model-related jobs of interest (involving the respective professionals) and the rating of the importance of specific levels of knowledge and experience. These requirements for the jobs should be the educational targets. Based on this information, various means of education can be evaluated and prioritized, or new means designed. All of them have their own characteristics, advantages and limitations. Some are particularly important, e.g. due to the number of students or the potential to specifically target the training. Some are particularly critical due to the impossibility of assuring quality standards, such as self-education. Complete analyses are beyond the frame of this paper. They have to be performed for different geographic regions and professional environments taking into account the different education systems and professional cultures as observed e.g. by Fettig (2004) and Gujer (2004). Consequently, they should be conducted by professional associations or companies with a particular interest area. Once strategies for improvements have been evaluated and prioritized, actions can be taken by providers of modeling education and training. In support of this step, many suggestions, preliminary results and practical experiences have been published (e.g. Gujer & Henze 1991; Gujer & Larsen 1995; Dochain & Vanrolleghem 2001; Morgenroth *et al.* 2002; Gujer 2004) or are currently being developed, e.g. by the IWA task group on "Good Modelling Practice–Guidelines for Use of Activated Sludge Models" (http://www.modeleau.org/GMP_TG/UP.htm). Repeating the approach outlined in Figure 2 in iterative cycles facilitates the continuous assessment and improvement of the connection between "supply" and "demand".

At the WWTmod2008 workshop there was agreement about successful teaching and training strategies. First, the fundamentals about the processes should be taught at university. In this step, models can be valuable teaching tools. Later, modeling these systems shall be learnt, again at university but in parallel with increasing knowledge and experience of the real-world processes. This may include data quality issues and non-modeling experience with the systems. Preferably this is done with case studies based on real problems and real data, including natural variation, errors and incomplete data. Realistic project-based courses allow the students to improve in all three main levels of requirements for modeling jobs (Table 3). Similarly, Bishop (2000), Schilling & Hagen (2000) and Morgenroth *et al.* (2004) stressed the value of such projects to develop important skills such as problem solving, project management and team work. Early and repeated exposure to models and modeling (teaching with models, teaching modeling in different fields) is beneficial.

The WWTmod2008 workshop participants recommend improving the connection between university education and practical modeling jobs (consulting or research). This can be achieved by the following options: (1) developing university courses based on case-studies with real-world modeling objectives and real data sets; (2) involving professionals in university training for the design of such case-studies but also as instructors and mentors; (3) encouraging university teachers to obtain work experience in practical model-related jobs; and (4) providing internship opportunities (and encouragements) for students.

At the workshop there was also consensus that the exposure to realistic model work should start at university as it provides an error-tolerant environment. Nevertheless, further training on the job was considered very important too, particularly to efficiently obtain the specific skills and knowledge necessary for the particular job (i.e. the purchase of a specific simulation platform is only a small part of the cost required to acquire an appropriate modeling capacity within the company). There is an advantage for large or specialized companies as they have more resources for internal training and may be able to employ specialized full-time modelers. In many small companies, on the other hand, all modeling knowhow is connected to one specialist who is only infrequently doing actual modeling work. If this person leaves the company, all knowhow is lost. These facts imply that specific training should be provided for all companies by software providers, universities or professional associations. Continuous education is essential to assure quality control, and to follow up with novel modeling techniques. To guarantee that proper modeling is taught, a competent expert should guide all project-based modeling experience at university, continuous training and learning on the job. Furthermore, the awareness for responsible modeling in practice and research should be increased by widely discussing the issue in professional organizations, conferences and publications.

In contrast to the survey about environmental engineering education by Morgenroth *et al.* (2004), the individuals at the WWTmod2008 workshop suggested more practical aspects in university education. However, according to the above presented survey about education of current modelers (Hauduc *et al.* submitted) the universities do not currently play the main role in modeling education. Consequently, other providers of modeling education, such as software suppliers, professional associations and the companies using the models themselves are increasingly called to take the initiative to identify their needs and possibilities. This clearly indicates that the whole education and support system for modelers, as outlined in this paper, has to be taken into account and that common efforts of universities and practitioners are required.

CONCLUSIONS

As the use of mathematical models in wastewater engineering has become more common, a mismatch has arisen between education and requirements for modeling practice, both in the quantity and quality of skilled modelers. To address the mismatch, it is important to realize that modeling education and application is often seen too narrowly. In fact, (1) there is a wide variety of model-related jobs, not just model use for plant design by consulting companies, (2) modeling education goes far beyond university courses but includes training on the job and self-education, and (3) models in teaching involves teaching models and modeling techniques but also using models to support the understanding of technical processes and natural systems.

In a workshop at WWTmod2008 including practitioners and academics from North America and Europe it was concluded that universities should teach the fundamentals about the processes but also impart skills in problem solving and holistic thinking. Furthermore, students should become exposed to real-world modeling work including relevant questions and real data sets. On the other hand, it should be recognized that universities will not be able to fully train a modeler able to carry out every specific modeling job. Training on the job is and will be necessary in the future.

To identify, understand and appropriately address the mismatch, it is necessary to characterize "supply" and "demand", i.e. the different types of modeling education and the requirements for different model-related jobs. This paper provides a framework to support this process that consists of iterative cycles of assessing the current situation, implementing improved education programs, and exchanging and discussing the findings and experiences. Consequently, we suggest the following further actions:

- Assessing the current state of "supply" and "demand" for different geographic regions and professional environments and evaluating the role of different types of education to improve the situation. To be relevant, this has to be done by or involving professional associations and companies with particular needs.
- Designing, implementing and evaluating case studies for modeling education on different levels and involving practitioners. Professionals shall take the initiative to direct the teaching rather than just dealing with the provided education.
- Assessing and improving training on the job and continuous education which both play a crucial role in modeling education and quality control. This training is typically provided by supervisors and colleagues, as well as by software suppliers and professional associations.
- Being aware of future developments of models and modeling applications. Teaching, particularly at universities, may be ahead of the state-of-the-art in practical modeling and promote new techniques and standards. But it may also lag behind in terms of insights in the current needs/applications in the industry.
- Increasing the awareness of the mismatch and requirements for different modeling jobs, e.g. by publishing and discussing problem analyses and successful means of training.

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