Systems analysis in environmental engineering: how far should we go?

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Abstract Systems analysis is identified as a unifying topic of environmental engineering. Based on a questionnaire sent out to peers and based on the experience with an advanced systems analysis course the possible content and association of the content with bachelor and master’s programs is discussed. At the bachelor’s level it is concluded that an array of topics should be introduced more in an inductive way, going along with the discussion of examples. At the master’s level it is suggested that a substantial course, which systematically introduces a broad variety of systems analysis tools, is provided. Such a course should go along with the introduction of a simulation tool, which supports application of systems analysis methods.

Keywords Bachelor; curriculum; environmental engineering; lecture outline; master; systems analysis

Introduction
Environmental Engineering has developed initially from civil via sanitary to environmental engineering. First topics were primarily related to water supply, control of flooding and hygiene in urban areas and possibly the handling of solid waste was considered. Today environmental engineers deal with all engineered interaction of our (urban) society with the environment. The profession is characterized by the fact that it has to deal with rather complex systems based on lacking, scarce and inaccurate or uncertain information. This requires us to make extensive use of mathematical models, which relate theoretical, a priori understanding to empirical observation and allow for extrapolation into unknown territory.

The tools that we use to develop and identify models, plan experiments, make predictions, support decisions, etc. all relate to systems analysis, a discipline common to the ever broader field of environmental engineering.

The rapid expansion into new fields such as air pollution, groundwater management, soil protection, materials flux analysis, noise-, vibration- and light-pollution etc. did not really allow us to develop methods and language common to the entire profession. Our curricula typically are broad and may cover several of the typical areas of activity. We thereby repeatedly expose our students to similar, related methods but based on entirely different terminology. What is a process here may be a state there, what results in a linear increase of a reservoir may elsewhere be described as steady state, etc.

Reorganizing the diploma curriculum in environmental engineering at ETH Zurich from a 5 year diploma curriculum (Gujer, 2000) into separate bachelor’s and master’s degree programs, we are planning to introduce two courses in systems analysis (we will call them “Methods of environmental engineering”), one at the bachelor’s, one at the master’s level. Introducing a new course is one thing, planning and designing it something else. This paper reports on a first step in the preparation of these courses.

Evaluation of a questionnaire
In order to obtain some feedback from professional peers, I started a little questionnaire, relating to the requirements in education in systems analysis at different levels of
environmental engineering education. The questionnaire was sent out to all applicants to the second IWA international seminar on environmental engineering education in Zurich 2003. This report will provide a combination of my personal evaluation of the replies to the questionnaire as well as my own experience with teaching systems analysis on different levels.

A total of 12 peers replied to the questionnaire, which was sent out, their experience differs quite widely. Some teach at university level, some at the level of universities for applied sciences (German Fachhochschule, without PhD programs). Some teach systems analysis themselves, some others just rely on courses taught by others. From the answers it appears that most of the replies are based on experience in the water if not more narrowly in the field of sanitary engineering. This goes along with the limited environmental engineering focus of IWA (International Water Association) and makes it difficult to extrapolate to disciplines such as water resources management, materials flux analysis or soil and air pollution, not to talk about noise and light pollution.

Table 1 is a summary of the interpreted results. Some topics relating to systems analysis are introduced in the basic engineering education and should be available in all academic curricula. These principles are taught in mathematics (analysis), linear algebra, statistics, mechanics, physics, chemistry and informatics.

In Europe there is a trend towards the attitude that in engineering the bachelor’s degree should not be a professional degree but rather an intermediate degree, which allows one to change university, major field or to refocus further education. My interpretation of the questionnaires accepts this attitude (which is general policy at ETH in Zurich). This may result in some bias in my interpretation. Also I consider it appropriate to offer a bachelor’s curriculum in environmental engineering. This too is not necessarily the opinion of all peers. Some have serious doubt about this concept and prefer to offer environmental engineering at the master’s level only.

Table 1 relates to curricula of technical universities and may have to be adjusted if applied to courses taught in universities of applied sciences (Fachhochschulen).

I conclude from Table 1, that a specific course in systems analysis is inappropriate at the bachelor’s level. The few topics where a professional level should be reached can be integrated into another sanitary engineering course. The many topics, where basic, introductory knowledge should be provided are best introduced in an inductive way, related to examples of application.

The broad array of topics, which is suggested for the master’s level, appears to justify a specific course in systems analysis. Examples provided in such a course could broadly cover as many aspects of environmental engineering as possible and thereby introduce this discipline as basic for environmental engineering in general. Unfortunately I do not know a textbook, which could support such a course.

Almost all professions have a central issue or topic, which characterizes their work. Environmental engineering is still rather young and poorly consolidated (Alha et al., 2000). What is the common issue that this profession is dealing with? Asking relevant professionals would possibly result in a wide array of answers. Could the development and use of models for the description of rather complex systems based on scarce and inaccurate data be a valid focus? The prime tool in fulfilling this task is systems analysis supported by a process understanding in many scientific disciplines. If systems analysis is accepted as a (the?) central, unifying topic of environmental engineering, the title of a substantial course in systems analysis for environmental engineers could well be “Methods in environmental engineering”.

A course outline with a focus on sanitary engineering

At ETH Zurich environmental engineering education today consists of a 10 semester diploma curriculum (Gujer, 2000). After the 4th semester the students choose 2 out of 4 credit packages which lead up to the most advanced courses from the following four fields:

- Sanitary engineering
- Water resources management
- Materials flux analysis and solid waste handling
- Soil pollution control

The credit system is based on 30 credit units per semester in accordance with the European credit transfer system (ECTS).

At the moment (beginning in 2003) we are in the course of reorganizing this curriculum into a bachelor’s and a master’s course. The following experience relates to the old situation of the diploma curriculum.

I teach a course in systems analysis for sanitary engineering in the 5th semester.

Table 1  Summary of interpreted results from questionnaire. Basics of engineering include courses such as analysis, linear algebra, statistics, mechanics, physics, chemistry and informatics. BS, MS and PhD relate to the relevant level of education. X indicates basic knowledge, XX stands for professional level, XXX for in depth understanding with possible own contributions. ? indicates specific requirements or capabilities, depending on major, research topic or faculty experience.
The course is compulsory for all environmental engineering students choosing sanitary engineering as one of their two majors (see above). Previous to the course, all our environmental engineering students have to follow an introductory course in mechanical process engineering (3rd semester, 3 credit units) and an introductory course in sanitary engineering (broadly covering aspects of the field based primarily on static, empirical models, 4th semester, 5 credit units). The systems analysis course is based on two lectures per week and a two-hour exercise class supported by teaching assistants (PhD students) during a semester of 14 weeks. The outline of the course is given in Table 2.

**Evaluation of the course**

The following evaluation is based on anonymous questionnaires and open discussions with the students who have followed the course.

5 credit units (ETCS) indicate that the students have about 7.5 hrs available per week for preparation, lectures, exercise classes and final solution of exercises. The students obtain a text (about 200 pages) and copies of all overheads from the lectures.

For average students the course is overloaded, primarily with topics from Part II (after week 9, Table 2), they rely on solving the exercises in groups and for some topics they cannot see the immediate value or application, which reduces motivation. Weak students copy exercises to be handed in from stronger peers. For strong students this is a challenging, interesting and motivating course, which introduces many different tools and theoretical approaches. We have not yet optimised the use of the simulation tool, Berkeley Madonna (BM) (Macey et al., 2001). For some students even programming a simple tool like BM becomes a major obstacle and they seem to concentrate on programming rather than on structuring the problem and analysing results. Even though the basic use of BM may be learnt within less than 1 hour and the code to be developed for most examples is only 5 to 20 lines long, the application of such a tool must carefully be planned and supported.

Two exams are based on written tests, where typically some simple system has to be analysed and a model has to be developed. The solution to this part of the exam is then handed in and a correct solution is given to the students. In the second part the students may have to implement the model in a simulation tool (BM) and then they may have to analyse some simulated results for uncertainty, sensitivity, error propagation, etc.

Until now the course was taught three times in this form and the performance of the students in the final exam was surprisingly good. If compared with the performance of students from before this course was introduced in this extensive form, there is a clear improvement in modelling and analytical capability.

The models and methods that we introduce in the systems analysis course are later used in the advanced courses in urban hydrology as well as physical-chemical and biological treatment. Further we may use the simulation tool BM in order to develop specific models in the project and design classes.

Since we have introduced the systems analysis course, the understanding in the advanced courses has improved too. The students now typically report that it becomes easy (easier than in earlier reports) to read and understand some of the more complicated models that we introduce. They have experience with possibilities to actually apply the models even in dynamic form, they use sensitivity analysis in order to better evaluate the importance of parameters and they consider performing Monte Carlo simulation if uncertainty is an issue.

In the individual or group projects the tasks, which require developing or adapting models for new process designs became more popular than those where dedicated professional programs have to be applied. Earlier we were stuck with dedicated programs, which are frequently limited in scope and adaptability.
A recent example of such a project involved the development of a simulation model for the combination of an activated sludge plant for carbon removal, followed by an RBC for nitrification. The task was to improve nitrification performance in the context of rain events, when large volumes of ammonium-rich wastewater were flushed from the activated sludge plant into the small volume of the RBC. Model identification was followed by simulation of adapted operating conditions.

Table 2  Outline of a systems analysis course in sanitary engineering. 4 lectures/exercise class per week, 14 weeks per semester, 5 credit units (ECTS). BM = Berkeley Madonna (Macey et al., 2001)

<table>
<thead>
<tr>
<th>Week</th>
<th>Topics</th>
<th>Type of exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Part I: basics</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Introduction: What are models? What is to be expected from this course?</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Systems, system boundaries, transformation- and transport-processes, states, parameters, intensive/extensive properties, initial and boundary conditions, general materials balance equation (macro-, microscopic), dimensions, units</td>
<td>Simple analysis based short verbal cases taken from everyday life Identification of parameters, states, intensive/extensive properties, etc.</td>
</tr>
<tr>
<td>2</td>
<td>Transformation processes: stoichiometry (stoichiometric matrix), composition of states (composition matrix), conservation equations, kinetics, process vs. transformation rate. Theoretical oxygen demand (ThOD)</td>
<td>Examples of stoichiometric matrix, computation of coefficients, rates, units, etc. Conservation based on elements, ThOD</td>
</tr>
<tr>
<td>3</td>
<td>Transport processes: advection, dispersion, diffusion (random walk and Fick’s 1st law), sedimentation Steady state</td>
<td>Simple mass balance equations</td>
</tr>
<tr>
<td>4</td>
<td>Ideal reactors: completely mixed, cascade, SBR, plug flow, plug flow with dispersion, considering recycle</td>
<td>Steady state example (calculator), dynamic SBR problem (BM), for “experts”: split boundary value problem in plug flow with dispersion at steady state (BM)</td>
</tr>
<tr>
<td>5</td>
<td>Residence time distribution of ideal reactors, including dispersion, statistical characterisation</td>
<td>Simulation of RTD with BM for cascades and recycle</td>
</tr>
<tr>
<td>6</td>
<td>Modelling real reactors based on tracer information</td>
<td>Statistical characterization of measured RTD (EXCEL or BM), estimation of dispersion (calculator), model identification based on observed data with BM</td>
</tr>
<tr>
<td>7</td>
<td>Dynamic behaviour of different reactor systems, time to steady state, harmonic disturbance, effect of noise</td>
<td>Simulation of ideal reactors subject to harmonic load variation and noise (BM)</td>
</tr>
<tr>
<td>8</td>
<td>Case studies: (1) Aeration with single bubble models (2) Self-purification in small rivers with biofilm model</td>
<td>Aeration model: simple applications (calculator) Simulation of a biofilm at steady state (BM)</td>
</tr>
<tr>
<td>9</td>
<td>Discussion and reserve</td>
<td>Midterm exam including simulation with BM</td>
</tr>
<tr>
<td>10</td>
<td><strong>Part II: advanced topics</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local sensitivity and parameter identification, minimization and interpretation of $\chi^2$</td>
<td>Analytical and numeric identification of sensitivity for a simple system (analysis, EXCEL, BM), parameter identification (EXCEL)</td>
</tr>
<tr>
<td>10</td>
<td>Error propagation (Gauss, Monte Carlo simulation) based on independent parameters</td>
<td>Error propagation in a simple non-linear system, small/large error (analytical, calculator, BM)</td>
</tr>
<tr>
<td>11, 12</td>
<td>Process control: PID controller, introduction into fuzzy control</td>
<td>Simulation of aeration control, based on given model of PID controller, instability (BM)</td>
</tr>
<tr>
<td>13</td>
<td>Case study: development of a nitrification model for a river, based on experimental data.</td>
<td>Application to a similar case, sensitivity, experimental design, parameter identification (BM)</td>
</tr>
<tr>
<td>14</td>
<td>Design under uncertainty, variability vs. uncertainty, case study</td>
<td>Final exam including simulation with BM</td>
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</table>

(W. Gujer)
A second example involved the development of a model, which describes and predicts re-aeration and nitrification of treated effluent in a 20 km long discharge sewer.

My conclusion of this evaluation is as follows. The course is extremely valuable in environmental engineering education. As offered today in the 5th semester, which corresponds to the last year of a bachelor’s curriculum, some topics (primarily the ones in part II in Table 2) are introduced too early, especially for average to weak students. Typically such an extensive course should be taught early in a master’s program, where students can be expected to have clear expectations and some vision with regard to their professional education. A more appropriate alternative would be to include the topics of weeks 1–5 as part of a bachelor’s course and the rest in a master’s program.

**Discussion and conclusions**

Systems analysis has the potential to become a unifying theme of environmental engineering. It provides the tools, which allow us to model, analyse and predict the behaviour of rather complex systems even if data is scarce; a situation that environmental engineers are typically dealing with. Systematic, deductive introduction of advanced systems analysis is best performed at the master’s level. Some basic topics should however be introduced in a more inductive, problem oriented way at the bachelor’s level.

This paper gives an overview of topics to be addressed in an advanced systems analysis course with a focus on sanitary engineering. Experience with such a course indicates that the students greatly profit in view of later courses in advanced process engineering and urban hydrology. However it is questionable to introduce some of the topics too early – students may not see the value of the rather demanding techniques and methods and may lose motivation.

There is merit in introducing basic topics (primarily reactor technology and kinetics) in a bachelor’s curriculum and to expand the advanced course such that systems analysis tools across the entire profession (not only sanitary engineering) are included. This might make it easier for students to realize what is common and what is different in the broad variety of technical topics addressed by environmental engineers.

The introduction of simulation tools, which support a variety of methods in systems analysis is productive but time consuming for weaker students. Care has to be taken that problem analysis and the analysis of simulation results predominates over the programming effort.

**References**

