Web-based education in bioprocess engineering

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The combination of web technology, knowledge of bioprocess engineering, and theories on learning and instruction might yield innovative learning material for bioprocess engineering. In this article, an overview of the characteristics of web-based learning material is given, as well as guidelines for the design of learning material from theories of learning and instruction and from the bioprocess engineering domain. A diverse body of learning material is presented, which illustrates the application of these guidelines; this material has been developed during the past six years for different courses, mostly at undergraduate level, and it illustrates how web-based learning material can enable various different approaches to learning objectives that might improve overall learning. Such learning material has been used for several years in education, it has been evaluated with positive results, and is now part of the regular learning material for bioprocess engineering at Wageningen University.

Introduction
The landscape of academic learning is changing since the mass adoption of the internet in education. Most of these changes have addressed communication and distribution; however, web technology enables new approaches for content that might change the way future learning material (LM) is designed and used [1,2].

In this article we argue how the combination of web-technology, knowledge of bioprocess engineering and theories for learning and instruction might yield innovative bioprocess engineering LM. We first give an overview of the characteristics of web-based LM; then we present guidelines for the design of web-based LM [3]; finally, a variety of web-based LM modules is presented, to illustrate these guidelines and to show the various approaches that are facilitated by web-technology. The material is available online (http://fbt.wur.nl/; choose 'Content showcase' and then select any of the listed process engineering modules).

Characteristics of web-based learning material
Web-based LM is created with web-technology (Box 1) but is also a subset of digital LM; therefore, it has characteristics that are unique for web-based LM and characteristics of digital LM in general.

(i) Web-based LM requires only a web-browser (Internet Explorer or Mozilla Firefox), which are available by default on most platforms, and an internet connection, whereas digital LM, in general, might have many more requirements.

(ii) Web-based LM is directly accessible by many students simultaneously, and is independent of time and place. In contrast to digital LM that is distributed on physical media (e.g. CD-ROM), students directly access the original source of the material and, therefore, the latest version of that LM. Authors can update their LM during a course to incorporate feedback from students, even if the material is used in distance education.

(iii) Although not unique to web-technology, the hyperlink is perhaps the most well known characteristic of web-technology. The hyperlink enables one piece of web-based material to reference another piece of web-based material, such as LM from another university, literature or an online encyclopedia.

(iv) Digital LM, in general, permits various forms of multimedia and interaction. It might include formatted text, drawings, photos, animations, simulations, video, interactive applications and communication components. Web-based LM, in particular, offers various high-level components to build such rich material, where using multimedia in LM might, if used appropriately, improve learning effectiveness [4,5].

(v) Digital LM enables interaction with the student, for example, the LM can show a response to a student action, such as mouse or keyboard actions. One of the most important applications for interaction in LM is feedback – the information about progress towards a particular goal [6] – for which there are several design guidelines available [7].

(vi) Digital LM has access to computational resources, which can be used to provide simulations that can produce output from student input in model systems. In a flight simulator, for example, the inputs are the handles and the control stick, and the outputs are changes in the cockpit window and the indicators. If LM enables only a few combinations of inputs, simulation is not required because all possible outputs can be pre-calculated and included in the material [8]; however, if a wide or unlimited range of student inputs are permitted, a simulation is appropriate [9,10]. The effect of input on output is
Box 1. What is web technology?

Web technology delivers information throughout the worldwide web by way of a web browser. The information is produced or retrieved by a web server and presented on the screen of the client computer by a web browser, such as Microsoft Internet Explorer or Mozilla Firefox. Web technology can be categorized by the computer on which the processing takes place: client-side or server-side technology.

Client-side technology is technology that is processed by the web browser on the client computer. It is executed within so-called ‘sandbox’ in the web browser. This is a virtually isolated software environment that, for security reasons, is limited in both its interactions with other software as well as interactions with other computers on the internet. Because of this sandbox, client-side technology has few resources to store data; however, because processing takes place on the client computer, the interaction latency (the time between an action and a reaction) is low. Examples of client-side technology include HTML, ECMAScript, Macromedia Flash™ and Sun Java™.

Server-side technology is processed on the server and the results are sent to the client. Because a single server usually serves many clients, the computational resources are shared. A web server is usually tightly linked with other applications, such as a content management system and a database management system (DBMS). Furthermore, the server environment can be customized for a specific task. It can be configured, for example, such that processes from different users can share data. Because actions have to be sent to the server and reactions have to be sent back to the client, server-side technology exhibits a high interaction latency. Examples of server-side technology include PHP™ and Tomcat™.

Present in many learning objectives: from the operation of equipment to the discovery of system behavior. A learning objective might be the ability to detect anomalies, to identify signs of specific behavior, to predict behavior or to predict a state, or to find the combination of inputs required to obtain a specific state or specific behavior [11]. Simulations can be used to support a learning objective in a way that would be impossible or unacceptable in reality – because of danger, costs, availability of equipment, time or irreversible damage. Students might use simulations to practice situations they might never meet during their education or to prepare for situations for which access in education is limited [9,10]. Furthermore, simulations might exaggerate reality to provide more effective learning experiences [12], for example, accelerate time and thus enable students to discover how a parameter affects long-term system behaviour; or the simulation might confront the students with an important but infrequently occurring phenomenon; or the simulation might simplify reality and assume ideal behavior.

(vii) Web-based material can offer advantages for collaborative learning because collaborative learning needs communication, and web-based LM can integrate a communication component in the material.

(viii) Digital LM, in general, can support a variety of tasks and, thus, might enable an integrated learning experience [13]. An integrated learning experience means that a learning environment enables students to engage in multiple tasks related to learning without a conscious switch between these tasks. In a well-integrated environment, for example, students can move their attention from a text to a video and then to a communication component without the feeling that their attention was required for anything other than learning.

(ix) Digital LM can identify individual users, track their activities and build, retrieve and update a model of the user; therefore, it might permit adaptive LM. Web-technology, in particular, has many means for authentication, tracking, and structured data storage, and is thus well suited for implementation of adaptive functionality. Adaptive LM builds a model of the goals, preferences and knowledge of each individual user and uses this model throughout the interaction with the user to adapt to their needs [14]. Adaptive LM can, for example, present more detailed and deep information to more qualified students or suggest a set of most relevant links to each individual student. This might minimize user floundering, make the learning more goal-oriented and make the learning more efficient [15].

Six guidelines for LM design

This section lists six guidelines that have been used for the design of LM; they will further be referred to as learning material guideline (lg) 1–6.

lg1: LM should activate students

Learning is found to be more effective and yield better results if students participate actively [16,17] – LM that stimulates students to put effort into learning is called activating LM. Digital assignments are well suited to activate students: they can interact with students, display hints, and return verification of correct student input. Experience at Wageningen University shows that more students are activated by digital LM than by traditional assignments.

lg2: LM should impose only minimal cognitive load

Cognitive load theory assumes that learning is limited by the total cognitive capacity of a student. For example, extraneous cognitive load caused by an ill-designed user interface or by a non-native language should, thus, be minimized – many guidelines for user interface design to reduce extraneous cognitive load are available [18]. Intrinsic cognitive load – the load that is directly related to the learning objectives – should match the level of the students and the time available to work with the LM [19]. Unnecessary cognitive load can also be avoided by visual representation, the use of which is facilitated by web technology.

lg3: LM should be modular by design

Modularly designed LM addresses only one or a few learning objectives and requires little of the unnecessary prerequisite knowledge that would exclude some students from effective learning. For example, LM about enzyme kinetics should not require knowledge of protein structures and composition. Furthermore, feedback is more effective when triggered in a specific situation: the more
determinants an answer has, the less effective the feedback will be [7].

**lg4: LM should provide authentic context and tasks**
A range of theories on learning and instruction assume that authentic contexts and authentic assignments are essential for effective learning. Thus, biotechnology students should learn about mixing in the context of cell cultivation instead of, say, paint mixing. Correspondingly, a task for mixing should be to calculate oxygen transfer instead of calculating liquid velocity. An interactive simulation of a real system is an accepted way to provide an authentic context [20]. In practice, authenticity can conflict with cognitive load guidelines [20] and, in such cases, it is the opinion of the authors that the latter should have precedence.

**lg5: LM should use personalized support where possible**
Academic courses are typically attended by a heterogeneous student population. The same LM will not be effective to the same degree for every student in the population. Adaptive material automatically changes to the needs of the users, based on assumptions made by the system about student requirements.

**lg6: LM should be motivating**
Attention, relevance, confidence and satisfaction (ARCS) determine a set of guidelines for motivation [21]. First, LM should capture the attention of the student; second, it should be relevant for the student; third, the student should be confident that he or she can handle the assignment; and last, the material should stimulate a sense of success and satisfaction.

**Guidelines for bioprocess engineering education**
In this section, four bioprocess engineering guidelines (bg) for LM that have been used are listed. These guidelines are derived from the bioprocess engineering learning objectives at Wageningen University.

**bg1: LM should balance quantitative and qualitative practice**
An experiment by McDermott [22], in which a large group of undergraduate students with adequate quantitative skills in using Ohm’s law failed on an assignment to make qualitative inferences based on Ohm’s law, showed that success on quantitative exercises implies no evidence for qualitative understanding. Students should thus practice qualitative reasoning in parallel with quantitative exercises.

**bg2: LM should use multiple ways to connect model theory to physical reality**
Many bioprocess engineering textbooks feature assignments in which students are asked to make a given calculation, for example, \( \mu = 0.1 \text{ h}^{-1} \) without any verbal reference to specific growth rate. Numerically, such an assignment might not be completed satisfactorily without any conceptual understanding. There are, however, more aspects of the connection between model theory and physical reality, and students should be confronted with all of them. Table 1 lists example assignments with different aspects of the connection between model theory and physical reality.

**bg3: LM should enable students to practice design skills**
Design assignments state objectives, specify requirements and enable the student to combine methodical steps and personal decisions to achieve a result that meets these objectives and requirements (adapted from [23]). Because each design is unique, grading is time consuming; furthermore, students find it difficult to judge their own results and require much assistance. Even experiment design is rarely done by students themselves; in practical courses, students often follow a recipe [24,25].

<table>
<thead>
<tr>
<th>Table 1. Example assignments with different aspects of the connection between model theory and physical reality</th>
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<tbody>
<tr>
<td><strong>Mechanism/phenomenon</strong></td>
</tr>
<tr>
<td>Estimate parameter values for a given model from given experimental data.</td>
</tr>
<tr>
<td>Choose the most appropriate mathematical representation given a set of experimental data and a set of possible mechanisms</td>
</tr>
<tr>
<td>Reason the behavior of a system after a given parameter change.</td>
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<tr>
<td>Adapt a mathematical representation to include some assumption.</td>
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<tr>
<td>Calculate a steady state given a mathematical model and parameter values</td>
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<tr>
<td>Give the model domain for a model and its underlying assumptions</td>
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<tr>
<td>Choose a mathematical representation for a system described in natural language.</td>
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Design can be practiced with web-based LM. This LM can assist the student with frequently occurring problems. It might, for example, force a step-by-step structured approach, in which every step is checked for compliance with previous steps. Students can also learn from simulations that show how their design is behaving.

**bg4: LM should confront students with uncertainty in parameters and models**

Students, particularly undergraduates, falsely assume that models and parameter values are perfect and are seldom confronted with uncertainty [9]. Many textbooks do not show the uncertainty in parameter values, nor do they mention the limited applicability of models. With respect to a model, LM should notify students what the relevant numerical ranges of its input variables are, to what degree the system, in reality, exhibits ideal behavior, how large the uncertainty in parameters and variables is, and how sensitive the system is to changes in both. When learning how to design new models, students should be informed that models with parameters that cannot be measured accurately, or not at all, have a limited applicability.

**Case-based learning material**

In the developed case-based LM, students are set a scenario in which they have to solve some problem, the context and task of which are chosen from real problems described in the literature or by industry. These are the most authentic of all designed material (lg4), and students find them interesting and relevant (lg6). Students proceed through the scenario by answering a series of activating closed questions (lg1), and receive slightly personalized (lg5) feedback on their answers. The more tries the students need to answer the questions, the more feedback is given and the more concrete the hints in the feedback are: the questions and feedback guide students through the scenario. This approach borrows various aspects from adventure games, such as the storyline, role-play and the discovery of new information.

Several case-based modules, such as ‘mixing and oxygen transfer’, ‘membranes’ and ‘heat transfer’ have been designed for undergraduate courses. Generally, these cases start with qualitative questions and slowly move to more quantitative questions (bg1). Students do not practice design; instead, all students follow the same so-called ‘closed’ questions and therefore find the same result. The ‘open’ nature of design, in which different answers to the same question are obtained, is thus absent.

The subject is introduced in a regular lecture, followed by the modules, which are carried out in a computer laboratory. Experience teaches us that little assistance is asked for, and teaching assistants indicate they spend their time, effectively, with students who lack some prerequisite knowledge or with students who have in-depth questions. Yearly evaluation results indicate that students like these modules next to regular lectures and tutorials.

A framework for these modules that enables the quick creation of a sequence of closed questions is designed. This supports five types of closed questions: multiple choice, multiple answer, numerical value, item selection and ordering, and balance equation setup. These can be extended where required.

**Adaptive learning material**

One module of adaptive LM has been designed for ‘cell growth kinetics in reactors’. In this material, each student follows an individual, personalized path through a collection of questions (lg5), where each student will get the ‘most appropriate’ questions to answer, selected according to their history in the system [26]. An outline of this selection procedure is given in Figure 1. For example, a student who can immediately select the correct definition of the biomass yield might get more in-depth questions about biomass yield, whereas a student who needs multiple tries before selecting the correct definition will get more questions on the definition of biomass yield before any in-depth questions. Other criteria for question selections enable variation in topics between subsequent questions, variation in questions between different students working at the same time, and matching to the confidence level of the students (lg6).

The questions should be mostly independent from other questions and thus modularly designed (lg3), such that the

![Figure 1](https://www.sciencedirect.com)
adaptive system has great choice when choosing the next question. However, some questions might require prerequisite knowledge; these are only presented after students have acquired this prerequisite knowledge by working through a group of other questions.

The questions in the module about ‘cell growth kinetics in reactors’ are similar to the questions described in the case-based LM: they are activating questions (lg1), with the same staged interactive feedback (lg5); students do not practice design; and many questions in this module activate qualitative reasoning (bg1). Furthermore, the questions confront students with many different aspects of the connection between model theory and physical reality (bg2). The module does not address guideline lg4 at all, neither does it present an authentic context nor an authentic task.

Students are asked to finish the module individually, before the regular lectures. Students indicated that they liked the module by rating its usefulness as 4.4 on a scale of 1–5. Students indicated that this LM is effective and they liked the qualitative questions and the questions that connect model theory and physical reality. Compared with previous years without this material, the lecturer observed that students had fewer problems with introductory theory.

A framework for adaptive LM has been designed that enables the quick creation of these adaptive modules. It is based on the framework for case-based LM and adds a conceptually simple interface to specify the required information to use these questions in an adaptive sequence [26].

Experiment design and parameter estimation learning material

In the LM developed for experiment design and parameter estimation, students practice the design of experiments for parameter estimation, execute these experiments in a reactor simulation, and use the results for parameter estimation [9]. Figure 2 shows the virtual environment in which students obtain samples with simulated numerical data. The results include experimental error and the operational limits of analysis equipment, which are important constraints in experiment design. The task forces students to focus on model- and experiment-related learning objectives, which often receive little attention in real laboratory experiments [24,25]. Experiments are simulated with accelerated time, which enables students to practice and execute many designs in a short time and learn from their choices.

Experiment design for parameter estimation is an activating (lg1) and authentic (lg4) task for students, which they find relevant (lg6). The LM does not provide an authentic context, as described in guideline lg4; only a laboratory would. The material, however, avoids cognitive overload (lg2), whereas in a real laboratory, students are overwhelmed with the number of practical details and fail to focus on design and estimation issues. The material enables students to practice the design process itself (bg3) (in an open way without much guidance), qualitative reasoning (bg1) and reconstruction of their mental model of the system. Students are confronted with the uncertainty in parameters because they will find uncertainty in their own estimates (bg4), and by estimation of such parameters, students assign physical meaning to model theory themselves (bg2). The material is modularly designed with respect to parameter estimation (lg3) and does neither include nor require a specific parameter estimation method, which enables it to be used in multiple courses.

The LM is used in the undergraduate courses Introduction to Process Engineering and Bioprocess Engineering; and despite following several practical courses...
before, students indicate that real experiment design is mostly new to them. However, students quickly learn from their first designs and continuously improve them: they rate the usefulness of the material at 3.9 on a 1 to 5 scale.

The developed material includes various kinetic models but is restricted to cell growth experiments in batch or CSTR reactors. Furthermore, a collection of Java components, which can be used to create other virtual experiments, has been developed for this material.

**Downstream process design material**

In the developed LM for downstream process design, students design a process chain that meets certain purity, yield and cost requirements. This material is used in the BSc Bioprocess Engineering course. Students see an overview of their design: the fixed composition of the starting material, the variable composition of the final purified product, and the performance of each unit operation in between [27]. Students can insert and delete unit operations or change operational settings for each unit operation (Figure 3). To activate students, the performance of each unit operation and the content of the final product immediately reflect those changes (lg1). However, to avoid a cognitive overload, the number of unit operations as well as the number of operational parameters are kept low (lg2). This also enables students to discover better the qualitative relation between the parameters and the performance (bg1).

The design task is an authentic one (lg4). Several advanced design applications exist, which would provide a more authentic context (e.g. SuperPro Designer™ and Aspen Plus™); however, none of these applications is

![Figure 3](https://www.sciencedirect.com)

Figure 3. A screenshot of the downstream process designer, showing the performance of a small downstream process chain. Unit operations can be inserted or removed, and operational settings can be changed.
suitable for education early in the BSc course because they have a long learning curve.

Students are free to design any process chain that meets the design requirements – they are not guided to a specific answer (bg3). After students have created a first design, an overview is given of how their design relates to designs from other students. The designs that achieve the highest yield, the highest purity, the lowest costs, and the lowest waste are shown. This demonstrates to students some fundamental design characteristics: different designs can all match the requirements, and different optimizations are possible within the requirements. Furthermore, this comparison motivates students to improve their own design (lg6).

Students indicate this LM is both challenging and fun, and that they like the possibilities for discovering how parameters affect unit operation performance and how unit operation performance affects the total chain performance. Many students are motivated to optimize their design to get it shown in the high score list. Assistants indicate that they concentrate on their work and often engage in on-topic discussions.

The developed material can be extended with other unit operations, or with unit operations with more operational parameters. However, the functionality of the unit operation has to be modeled on the basis of a few simple properties of the stream, such as density, pI and size.

Systematic model design material
In the developed material for systematic model design, students practice the design of a mathematical model to answer an assignment [28]. Students engage in a large number of activities, grouped into four stages: general analysis, detailed analysis, model composition, and model evaluation. The material guides students tightly through these stages but still enables students to design their model freely.

In the designed material, students are asked to design a model to predict when oxygen becomes limiting in an aerobic cultivation, in which the biomass concentration, substrate concentration and viscosity change. The prediction of oxygen limitation in a cultivation and the design of a mathematical model are both considered to be activating (lg1), relevant (lg6) and authentic (lg4) tasks for students. There are many software applications that enable simulations of a model, such as Matlab™ or Mathcad™. These applications, however, assume the model is already available; none of them supports the model design process itself (bg3). Furthermore, these applications require a specific syntax or user interface with a long learning curve, which adds too much extra cognitive load for the students. The structured approach and the available interactive feedback provide guidance for students, reduce the cognitive load for them (lg2) and give them the confidence to handle the design assignment (lg6). The material is activating: the interactive questions continuously activate students to provide an answer or to improve their existing answer (lg1). The LM might help students to connect model theory to physical reality: students first design a model for physical reality, and then use this model to answer an assignment about physical reality (bg2).

Students indicate that they like the structuring and unit checking, and the fact that they can design a model without getting stuck in mathematical manipulation. This material is used at the end of the course. Students would appreciate it if such material were used more often in bioprocess engineering courses.

The developed material uses the closed questions from the case-based material framework and some Java-based tools for model composition and numerical simulation. These tools can be used to create LM for any model described by differential equations. Furthermore, a collection of Java components has been developed that can be used for simulation, unit checking and to search for steady states.

Discussion
Digital LM should complement other LM where appropriate. It should better prepare students for lectures and tutorials, enable more effective interaction with lecturers and assistants during tutorials, enable students to practice more challenging and motivating assignments and to engage in otherwise impossible learning activities.

The developed LM requires extensive database functionality from the learning management system (LMS). Most current LMSs, such as Moodle™ or Blackboard™, do not, at present, offer database functionality for learning objects. New standards for LM that describe some of the required database functionality have already been developed [29], and we expect that future standards will include adequate functionality.

To develop web-based LM that exploits all the possibilities of web-technology, advanced knowledge of both the specific domain and of web technology are currently required. We expect that the near future will bring high-level building blocks that are specifically designed as a basis to build LM. We also expect that applications for LM development that require less web-development skills will become available. Together, this would make the development of web-based LM more accessible to authors without a web-development background. However, such high-level components and user-friendly development applications come at the price of reduced flexibility.

To some extent, the bioprocess engineering guidelines listed above were a starting point for the development of LM. Their final shape, however, emanated from the development, usage and evaluation of the various LM presented. Experience acquired during several years has led us to believe that these guidelines are essential for bioprocess engineering education. Evaluation results of both tutorials and exams in which guidelines bg1–bg4 were applied indicate that students need more practice with LM that implements these guidelines.

The presented LM has been designed during the past six years. In view of the guidelines presented in this article, there might be several opportunities for improvement. A large part of the developed material addresses learning objectives that were applied at Wageningen University but previously not supported by specific LM. All of the LM has been used and evaluated, with positive results and satisfactory exam results, which indicates that the material is better than, or at least on par with, regular LM.
The developed material that supports previously unsupported learning objectives shows that evaluation of new technologies for LM in bioprocess engineering has also led to innovation in education in the subject. Perhaps most importantly, the development of new LM has stimulated many valuable discussions about the current bioprocess engineering education and bioprocess engineering LM at Wageningen University.

Conclusion
Web-based LM is a useful addition for bioprocess engineering education. A combination of web-technology, general guidelines for LM and guidelines from the bioprocess engineering domain enables various new approaches to learning objectives and has led to innovation in bioprocess engineering education.

A variety of LM has been designed and developed for bioprocess engineering that might serve as an inspiration to learning objectives and has led to innovation in bioprocess engineering education.

A variety of LM has been designed and developed for bioprocess engineering that might serve as an inspiration for the development of new material. Most of the LM has been used in education for several years as part of the regular LM for bioprocess engineering and has been evaluated with positive results.

References

Free journals for developing countries
In 2002, the WHO and six medical journal publishers launched the Health InterNetwork Access to Research Initiative, which enabled nearly 70 of the world’s poorest countries to gain free or reduced-cost access to biomedical literature through the internet. Currently more than 70 publishers are participating in the program, providing access to over 2000 journals.

Gro Harlem Brundtland, former director-general for the WHO, said that this initiative was “perhaps the biggest step ever taken towards reducing the health information gap between rich and poor countries”.

For more information, visit www.who.int/hinari