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Designing a Curriculum Using Engineering Methods

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Index Terms: Curriculum Design, Learning Taxonomy, Project Management.

Abstract Engineering methods are used to demonstrate how to systematically design curricula. First of all, methods of quality management are applied to select a method of curriculum design. Next typical problems from professional life are consulted to define learning objectives. These are refined using mind-maps. Timing problems are recognized by looking into an engineering model of human memory. The collected information is processed with the aid of project-management software, which does not only help to avoid incorrect sequential arrangements of educational modules, but also supports maintenance of course program implementing the designed curriculum.

INTRODUCTION

As a consequence of the Bologna process [1], bachelor and master course programs in Europe are in a process of re-design. Institutions of Higher Education (HEIs) are challenged to use this process to improve existing curricula and to create new ones. This might be a unique opportunity to establish modern curricula that at the same time satisfy the requirements of educational science, of political demands, and of requirements from commerce and industry.

However, designers for curricula at universities are often either specialists in the particular field of the curriculum without deeper knowledge of learning theories, learning taxonomies and other fields from pedagogy and psychology, or they are experts in the theory of pedagogy and with a good psychological background, but with very limited background of the particular field of the curriculum. Combined expertise in all these fields is a strike of luck, not only for the university, but also for students.

It is thus sheer necessity to create *teams* of curricula designers, where experts of the field and pedagogues cooperate to create adequate curricula. Experience shows that in these teams communication problems between the specialists complicate work. Thus, it might be helpful to introduce tools that facilitate cooperation.

In this article, methods and tools are described that originally were developed to manage larger engineering projects for industrial or other products. They will be adapted for the design of curricula. Additionally, for the explanation of processes, in particular for quality assurance and management, methods will be applied that come from systems design, which is another field of engineering.

REQUIREMENTS AND CONSTRAINTS

Curricula for study course programs are always subject to more or less limiting conditions. Unlike academies and schools in ancient times or in the Middle Ages, modern universities do no longer serve curiosity of privileged individuals by their curricula. Their task is rather to educate a large percentage of population in a way that they are fit to contribute to the welfare of people. It is thus a legitimate interest of governments and politicians to influence curricula.

Universities are enterprises that are subject to economical constraints (even in countries, where the governments pay for the expenses). They are thus forced to satisfy the needs of the market. Therefore, study course programs must fit to public needs and to the needs of industry and commerce, which explains their interest in inspiring curricula designers.

Since constitution and maintenance of these programs is expensive, there is the need for the application of efficient methods in these programs. This is where modern pedagogy on the one hand and quality management on the other hand become important. Therefore, aspects of quality management ought to be included in curriculum design wherever it is possible.

Quality management requires that “organizations … should understand current and future customer needs, should meet customer requirements and strive to exceed customer expectations” and that “effective decisions [be] based on the analysis of data and information” [2].

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To create the basis for high quality curricula, generic customer requirements have been analyzed by expert groups, which have been established by the European Commission. These have formulated the European Qualifications Framework (EQF), which was to “make it easier for people to move between different types of education and training institutions” [3][4]. Following the European Commission,

> “The core of the EQF is its eight reference levels describing what a learner knows, understands and is able to do – their 'learning outcomes' – regardless of where a particular qualification was acquired. The EQF reference levels therefore shift the focus away from the traditional approach, which emphasizes learning inputs (length of a learning experience, type of institution).”

Since the EQF was developed under the participation of pedagogues, and since it formulates qualifications based on knowledge, skills and competencies, it might well be used to support the creation of modern curricula.

It goes nearly without saying that for applications in practice, factual constraints are given by availability of qualified teaching staff and administrative staff, of lecture rooms and labs with necessary equipment, of libraries, internet access etc.

A SYSTEMATIC APPROACH TO DESIGN A CURRICULUM

The quality driven approach

Literature mentions several approaches to develop a curriculum under the given constraints (for a concise overview see for example [5]), e.g. the outcome-oriented or backward-design method, where first of all desired program objectives and learning outcomes are defined; or the problem-centered method, where a set of problems and their potential solutions are the starting point to develop educational modules for these purposes; or approaches, where existing educational modules are arranged newly. Which approach to select, is a question that is normally subject to individual preferences.

From an engineering point of view, however, one of these approaches has definite advantages. This is the outcome-oriented approach. Reasons for that are found in the necessity to include methods of quality management right from the beginning.

For engineers, quality control problems are (nested) feedback-control problems [6]. A loop for quality control might be modeled as in Fig. 1

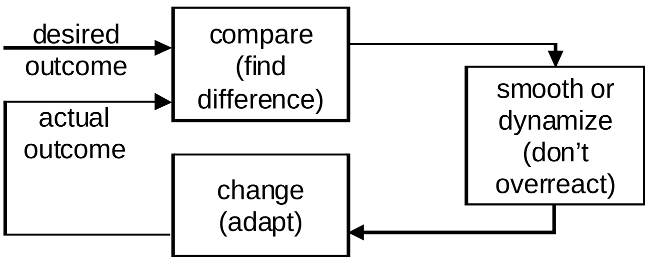

Fig. 1. Quality control loop.

Engineers have developed a detailed, mathematics based, and well-proven theory of feedback-control loops. From this theory it is known that feedback control – and thus quality control – can only work successfully and reliably, if the desired outcomes are defined clearly, verifiably and in detail. Knowledge of a carefully formulated set of desired outcomes of a curriculum is thus an indispensable requirement for high-quality curricula.

Therefore, the outcome-oriented method for curriculum design is the one that engineers might prefer. This statement coincides with the experience of specialists in learning taxonomy, who mostly use Bloom’s (revised) taxonomy of learning: Bloom and colleagues [7] have based their widely accepted taxonomy on measuring *learning outcomes*, which were classified into different types (taxa) of knowledge, skills, and competencies.

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Definition of educational objectives, their levels, and their skills

Also on a political level, educational objectives and learning outcomes are meanwhile seen as the starting point for comparability of educational programs that lead to a particular qualification. The above mentioned European Qualifications Framework (EQF), for example, gives a list [4] of eight levels of qualification, each level being characterized by a description of required knowledge, skills, and competencies.

For the design of a concrete curriculum, however, these specifications are still to general: They do not, and they do not intend to specify outcomes in a concrete, checkable way.

Meanwhile, specialists in several fields have done first steps in defining so-called sectoral qualification frameworks. The Council of schools of engineering at German universities (4ING) has given more concrete objectives [8]. Adapting their definitions for the level of bachelors (level 6) to curriculum design for *engineering programs*, the following is required:

knowledge:
Students will dispose of a scientific knowledge basis in the fields of mathematics, natural sciences, and of the specific fields of the curriculum.
They will thus develop the ability to understand the phenomena, problems, and basic principles of modeling as they occur in diverse disciplines of engineering and informatics, and to apply this knowledge in practice.

skills:
Students will develop the ability to
- identify technical problems, rephrase them abstractly and scientifically, and solve them
- systematically analyze and evaluate components, processes and methods of their discipline
- select appropriate tools and methods for analysis, modellizing, simulating and optimizing
- specify requirements for hands-on solutions of simple problems
- develop and implement convenient problem solutions subject to specific requirements
- understand and apply underlying design methods
- perform literature research and make use of sources of technical information for own work
- plan and conduct experiments or system implementations, and evaluate results

competencies:
Students will develop the
- competency to combine theory and practice in order to analyze and to solve on a methodological and scientific basis problems from engineering and computer science
- comprehension of applicable techniques and methods and their limitations
- competency to apply responsibly, and to further self-dependently their knowledge in diverse fields regarding safety-related, economical, legal, social, and ecological requirements
- competency to organize projects and to put them in execution
- competency to cooperate with experts of other disciplines
- competency to comprehensibly present results of their work either orally or in written form
- awareness for non-technical impact of their function as engineers
- generic competencies as for instance time-management, study- and work techniques, willingness to cooperate, ability to work in a team, ability to communicate
- competency to communicate with experts and laypersons in their own language and in English on content and problems of their discipline
- competency to work as an individual and as a member of an international group

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– ability for life-long learning and preparation for diverse career paths as a result of a professional, science-based education
– awareness for the consequences of own work in a social and human context
– ability to recognize and appreciate the importance of ethical standards in their work as engineers or computer scientists.

These descriptors help to define the level of knowledge, skills and competencies of a bachelor. For the design of a concrete curriculum, they are still too general, since they might be applied to design any engineering curriculum, for civil engineering as well as for electrical engineering or for computer science. Therefore, further specification is necessary.

To that aim, a specific field must be chosen. Assistance in determination of this field might be given by explicit requirements of the market. In order to find appropriate and detailed learning outcomes, it might be helpful to identify typical problems as they occur in professional life and in the specific field of the curriculum. In contrast to the problem-centered method of designing a curriculum [9], however, it is suggested that *curriculum designers* use these problems as the core from which more detailed types of knowledge, skills, and competencies will be extracted. It goes without saying that practitioners are needed to identify appropriate problems and methods for solution.

If practitioners are requested to solve problems that are critical in terms of time, and that are complex with respect to their structure, then they use methods known from project management. This might also be done when dealing with the definition educational modules.

What normally is done first to obtain a survey on interrelationships is to visualize the problem by means of a mind map [10]. An example for a (strongly simplified) mind map concerning a typical problem to be solved by engineers in the business of communications engineering is given in Fig. 2.

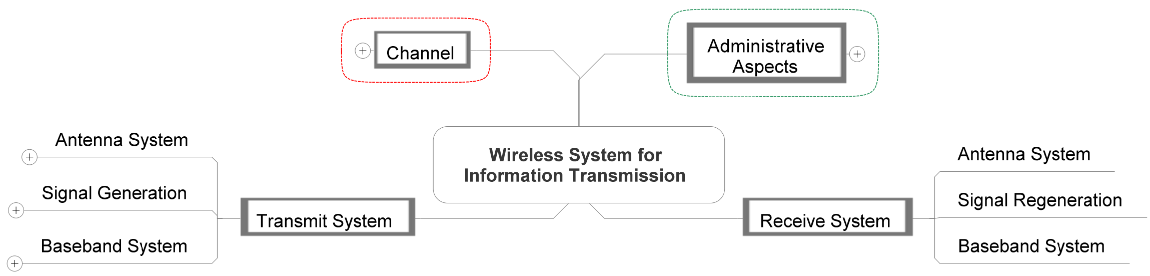

Fig. 2. Mind map of a typical problem (educational module) in communication engineering.

For the purposes of this article, it is not so important, which particular field of engineering is covered by this map. It is more important to see the structure, and to see how experts in the field might extract more useful information for the curriculum design.

First of all, it is seen that this problem might be separated into four work-packages, these are here the transmit system, the receive system, the channel and administrative aspects. It is also seen that work-packages might have a finer structure. Each work-package might be interpreted as a more or less large chapter or sub-module in an educational module, e.g. a lecture.

It is not sufficient to roughly characterize the content of each level, since this would not provide information on skills and competencies to be imparted. A better idea is to characterize each work-package by its learning objectives following Bloom's (revised) taxonomy of learning [7], which distinguishes three domains of learning:

- The cognitive domain, which classifies the whole of stored knowledge and the learnt processes to handle that knowledge [11], sometimes shortly referred to as *knowledge*. This domain is subdivided into two "dimensions", the *knowledge dimension*, and the *cognitive process dimension*.
- The affective domain, which classifies those areas of learning that are related to emotions, systems of values, motivation and (social) behaviour [12], sometimes referred to as *attitude*.

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- The psychomotor domain, which classifies those areas of learning where physical movement and/or coordination are involved [13], also referred to as *skills*.

In Bloom's (revised) taxonomy, four different levels of the ***knowledge dimension*** are defined:

1. *factual knowledge* (basic knowledge on facts),
2. *conceptual knowledge* (interrelations between facts),
3. *procedural knowledge* (how to act in order to make use of conceptual and factual knowledge),
4. *meta-cognitive knowledge* (knowledge on cognition and on one's own knowledge).

Additionally, six levels of the ***cognitive process dimension*** are given:

1. *remember*,
2. *understand*,
3. *apply*,
4. *analyze*,
5. *evaluate*,
6. *create*.
7.

The affective domain and the psychomotor domain are only rarely used to characterize learning objectives for engineering purposes. However, by adaptation of the last domain, a ***skills-dimension*** [14] might be defined, which includes the following levels:

1. *recognition of tools, methods and materials*,
2. *basic operation of tools and methods*,
3. *competent operation of tools and methods*,
4. *expert operation of tools and methods*.

Using these three dimensions and their levels, each educational sub-module might be characterized by a triple of numbers, the *level-triple*, in which the first element describes the level of the knowledge dimension, the second element describes the level of the cognitive process dimension, and the last one describes the skills level.

The triple (2,3,2) for example would describe a sub-module, where conceptual knowledge is imparted in a way that it might be applied, and that tools (e.g. software tools) might be used for basic operations. In the example-module following Fig. 2, the sub-module of administrative aspects might be classified by such a triple.

Another example would be the triple (3,5,3) that describes a (sub-) module, in which not only factual and conceptual knowledge is imparted, but also procedural knowledge, on a level that includes comprehension at such a level that this knowledge might be applied, also to analyze difficult situations, and to evaluate these situations, and where professional tools might be applied competently. By such a triple, the sub-module on the "Channel" might be classified in the example-module following Fig. 2, provided this module would be part of a master-course program, while it should perhaps be (3,3,2) or (3,3,3) for a bachelor-course program.

For a specification of the learning outcomes of a complete course program, *a set of typical problems* must be analyzed and characterized in these terms to form a *set of educational modules*.

Time dependency

Time dependency of learning is not often taken into consideration adequately when designing a curriculum. The reason for it is that most curriculum designers do not consider the dynamics of forgetting learnt information, which is due to the fact that novel insight into learning processes are not yet common knowledge. Meanwhile, models on cognition, memory, and learning are available, which are significantly improved as compared to the well-known Atkinson-Shiffrin model [15]-[17], the latter going back to the sixties and seventies. Neuroscientists have found much more detailed mechanisms of human information processing.

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Concerning information storage, engineers would model human memory as in Fig. 3. Perceived information is buffered in a coded form [18] in the sensory register [19]. It is then stored in the short term memory, which holds information up to 20 seconds [20]. Depending on whether attention is given to this piece of information, it might be held in memory by buffering it and refreshing it in the short-term memory. This process is controlled by the so-called central executive. Short-term memory, short-term buffer and central executive together form the working memory [21]. Medium-term memory is fed by the working memory. It keeps information for some minutes to some few hours [22]. If information is not retrieved from medium term memory, then it will be deleted. Otherwise, it is fed to a consolidation buffer, where it will be processed by a subconscious process [23]-[25]. Recent results from neurology [26] show a "progressively decreasing, retrieval related activation of the hippocampus over the course of 3 months", which is made responsible for memory consolidation. Other reports demonstrate that it is necessary to retrieve information from the consolidation buffer repeatedly [27] in order to store information reliably in the long term or remote memory.

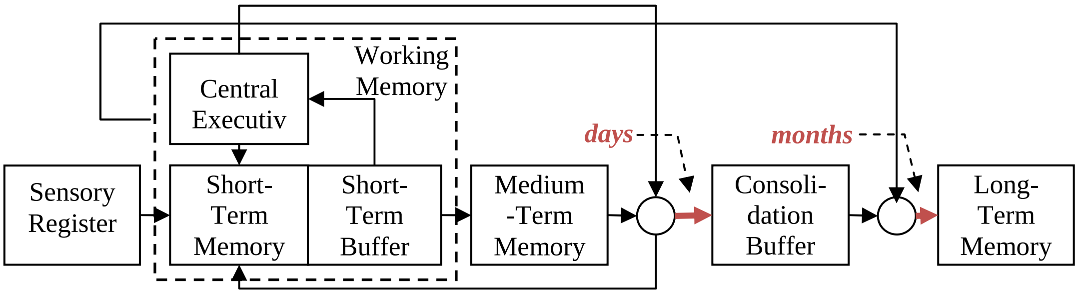

Fig. 3. Model of human memory (without fine-structure).

Since consolidation is virtually finished approximately 3 months after the process of learning [26], it is crucial that repeated retrievals are performed within this time-span. However, experiments [24] show that incomplete or erroneous retrievals might even be destructive!

These observations explain why students, who prepare for a written examination in a fortnight, may perform very well during the exam. However three months later they might have forgotten much, unless they have used their acquired knowledge several times during these months. Therefore, the best way of learning for the long-term memory is to apply recently learnt knowledge within the following three months, and in a way that enough time is given to avoid errors.

A good curriculum must therefore avoid "learning gaps", i.e. periods must be avoided where recently acquired knowledge does not need to be applied. For a proper curriculum design, it is thus advantageous to link each educational module with at least one other module that immediately follows it, and that uses knowledge, skills, and competencies of the first.

In order to be able to perform such a design, it is necessary to clearly define for each module the cognitive prerequisites that a student must be able to apply for successful execution.

There is another reason for the necessity of this definition. Each engineer knows that even simplest systems (like linear systems) cannot possibly be defined by their output alone. Rather, either the system input or the transfer matrix (information how input is transferred to output) must be known. Since curriculum design aims at finding out how to transfer knowledge, it is the transfer matrix that is looked for. Therefore, detailed information on cognitive input is necessary, which – in a way – means that the curriculum must be oriented at the *cognitive* input.

Unfortunately, the term "input orientation" has also another meaning. In the context of the European process of creating a "higher education area", it denotes the (unwanted) orientation of admission procedures for access to an educational institution [3], the *institutional* input. Therefore, due to a confusion of terms, many curriculum designers avoid to include input requirements in general into curriculum design, which is certainly not a good idea. Including *cognitive* input requirements into curriculum design is a *must*.

Taking into account the above described learning model, it is obvious that learning takes as more time as more learning steps have to be done between a given level of input cognition and the desired level of learning objectives. In other words: learning needs time, which is known to every experienced lecturer.

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Therefore, if learning outcomes could not be achieved within one semester (term) due to the number of learning steps to be performed, the course program must be subdivided into several educational modules, which is not a novelty, either.

What might be a point to think about, however, is the necessity to avoid learning gaps. Therefore, from a point of optimization of time-consumption, two important tasks must be performed:

1. Appropriate educational sub-modules must be defined, each including a definition of the level of cognitive input, the learning objectives and a skills-level.
2. An arrangement must be found to combine sub-modules in a way that learners are neither overloaded nor underchallenged, and that no learning gaps occur.

These tasks appear to be simple on a first glance; however, they need a very careful analysis. The future success of the course program strongly depends on them. Though many positive examples of module-handbooks and course programs might be found on the web-pages of universities, detailed level analyses and diagrams showing critical interdependencies are often missing.

Applying methods of project management

Comparing the requirements of curriculum design with those of managing a large engineering project, many similarities are seen. These are shown in Table 1.

Table 1: Correspondence between curriculum and project management

Curriculum Design	*Project Management*
definition of learning objectives	definition of the project objectives
separation of a course program into educational modules and sub-modules	definition of work-packages
collection of learning outcomes of a module	specifications sheet
credit points for learning	costs
availability of lecturers and tutors	availability of staff
availability of lecture halls and labs with equipment	availability of machines

Therefore, it is obvious that software for project management might be used to facilitate curriculum design. Such software is available for educational institutions at a moderate price or even free of costs.

A useful type of diagrams used in these software packages is the Gantt-chart, which reveals time-dependencies.

A very small part out of a Gantt-chart for a curriculum is shown in Fig. 4.

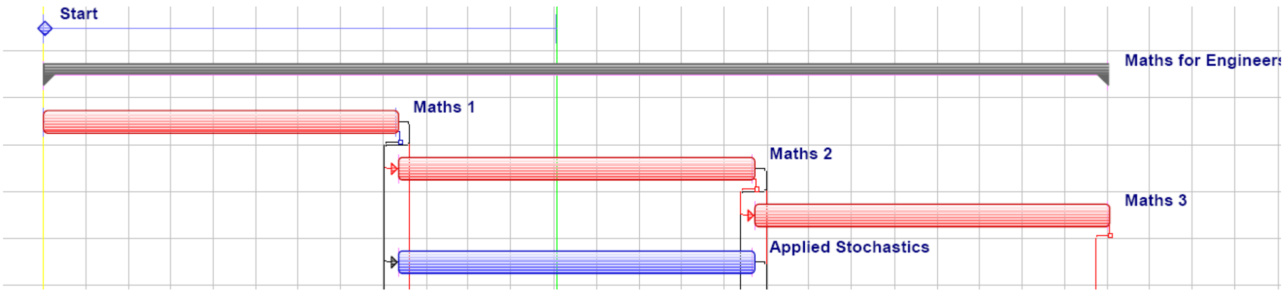

Fig. 4. Abridgement of a Gantt-chart for a curriculum.

There, the chronological sequence of four educational modules might be seen in combination with some dependencies. Since the latter are not very well visible in this diagram, an abridgement of a net-diagram is shown in Fig. 5. Net diagrams represent interrelations in general.

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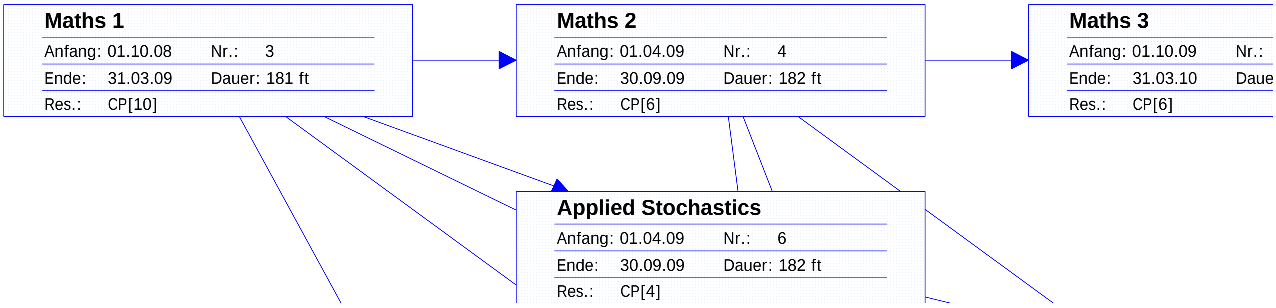

Fig. 5. Abridgement of a net diagram for a curriculum.

This latter diagram shows that there are at least five other modules that directly make use of the module “Maths 1”. There might be indirect dependencies, as it is seen by the concatenation of the modules “Maths 1”, “Maths 2”, and “Maths 3”.

These dependencies are input to the software by defining so-called “successors” or “predecessors”.

It is obvious that only such dependencies are acceptable where a successor starts after the end of its predecessors. Project-management software helps to avoid conflicts by making impossible to arrange a predecessor previous to a successor, provided these dependencies have been input to the project data.

Since dependencies can be seen by the net diagram, “learning gaps” can be discovered, which allows for optimization of the curriculum. This is demonstrated using another partial view on the Gantt-chart of the example curriculum. This view is shown in Fig. 6.

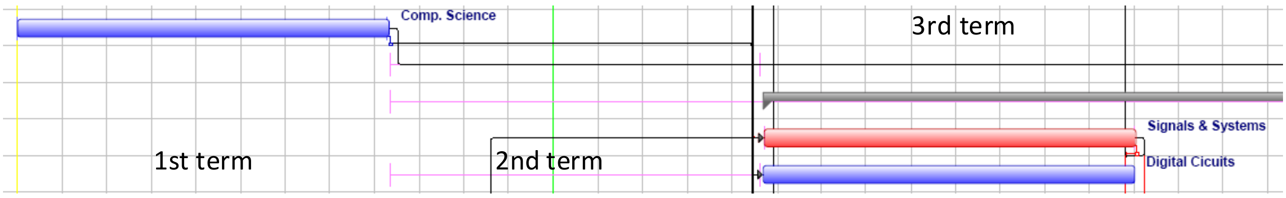

Fig. 6. Another abridgement of a Gantt-chart for a curriculum demonstrating a learning gap.

Here it is seen that the left-most bar (representing a module on introduction into computer science) has a successor (module on digital circuits) that follows only after a gap of one term. This is not optimum with respect to learning success. (In this particular case, it was necessary, since there were other needs with higher priority).

A little bit more sophisticated is the control of whether the level of a predecessor is sufficient to guarantee that the successor could be executed successfully. A simple but not very satisfying way would be just to define the above introduced level-triples as additional data that must be hand-controlled. A more complex but more comfortable method would be to code a macro that does this control automatically, and that gives a warning, if conditions are not met. It is obvious that detailed knowledge about cognitive input requirements and of learning objectives of each individual educational module is needed to perform that task.

Project-management software might also help to control the accumulated number of credit points per term. This is done by defining the given number of credit points of a module as fixed costs of that module. The sum of fixed costs (sum of credit points) per term is then easy to see either in a table that is automatically generated by the software or by a graph, see for instance Fig. 7.

Project-management software even makes possible to control staff availability for running the curriculum. If it is assumed that the nominal duration of the curriculum is four years, then by copying the project several times and shifting each copy by one year against the next, all necessary parallel instances of the curriculum might be handled by the software. Then, to each course staff resources might be assigned. Since for each individual staff member a calendar might be defined, the software might control availability of lecturers, tutors, administrative staff, etc. It would automatically give a warning, if there is a shortage of available staff, and it might help to optimize staff costs. The same might be done for the availability of lecture halls, rooms for tutorials, labs, equipment, etc.

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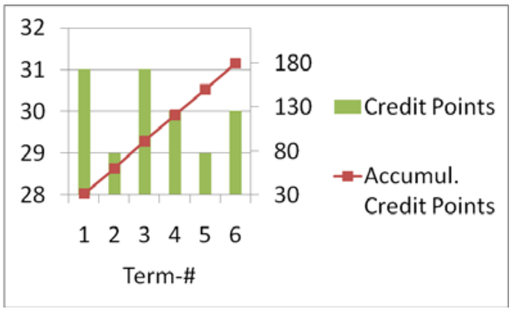

Fig. 7. Credit points of course program of six terms. (Bars: Credit points in semester #; Squares: accumulated credit points)

SUMMARY

It has been demonstrated how a systematic approach could be applied to design a curriculum that corresponds to the needs of the labor market, that gives organizers the possibility to implement a logical structure, and which is optimized with respect to students' workload, learning efficiency, and best usage of facilities.

As a novel aspect, optimizing of knowledge consolidation by avoiding learning-gaps has been addressed. Also, a better control of cognitive requirements has been introduced by inclusion of level-triples, which characterize required previous knowledge, skills and competencies.

Supporting means, in particular project-management software, were used to discover critical points and to avoid failures. Additionally, this software could help to manage successful performance of study courses.

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