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COMPUTATIONAL CIVIL ENGINEERING AT VolgGASU

The paper summarizes the intermediate results of work within the frames of the project on perspective development of information technologies in the sphere of Civil Engineering at VSUACE.

The Rector of the Volgograd State University of Architecture and Civil Engineering and the Scientific Council of the university have invited me to advise them on the future development of information technology in Civil Engineering at VolgGASU. I have pursued this project during the past 18 months in cooperation with Prof. Vera Galishnikova of VolgGASU and with Dr. Irina Bilchuk of the Moscow State University of Civil Engineering. Our activities have been sponsored by a grant of the Deutscher Akademischer Austauchdienst DAAD under the Advisors Program. This paper presents a summary of the insights which we have gained and of some of the developments which these insights have promoted.

VolgGASU has traditionally provided its students with a strong scientific background, for instance in areas such as mathematics, structural mechanics and chemistry. A new situation was created when the computer became a widely used tool in civil engineering education and practise. Rational human thought was enhanced by an instrument whose capacity to store, transform and transmit information exceeds that of human beings by a factor of more than 10^9 and is still increasing with a factor of 100 per decade. This change of dimension has made it possible to implement and to apply the scientific fundamentals in such a way that they become more widely usable in everyday engineering.

The best known example for this change is the finite element method. The ability to formulate the behaviour of trusses, beams, frames and plates mathematically existed long before the computer was invented. The problem consisted in the solution of the large set of linear algebraic equations which resulted from these formulations. Approximate iterative methods had to be applied, and different methods were developed for different tasks to minimize the computational effort. The computer made it possible to solve large systems of linear equations in short time spans. Civil engineers therefore developed a generalised method of analysis which can be applied to all types of structural systems: the finite element method. Linear analysis of structures with thousands of unknowns is no longer a challenge.

The leadership of VolgGASU came to the conclusion that the finite element method was part of a much larger development that fundamentally changes the practise of civil engineering and therefore requires a fundamental change in civil engineering education. As in the case of the finite element method, many other civil engineering problems must also be formulated in new, more rational and generalised ways before they can be solved efficiently with the computer. This leads to a revision of the theoretical foundations of most branches of civil engineering and to a new structure as well as a new content of the civil engineering curricula.

Initial attempts to treat computer applications in civil engineering as an extension of computer science did not lead to satisfactory results. This is not surprising, since

computer science deals with topics such as the design of operating systems, programming languages and data banks, whereas the problem in civil engineering is the computer-oriented formulation of tasks in civil engineering. Prof. Oleg Ignatiev was entrusted as Vice President for Education with the task of proposing a suitable approach, and decided that the concept of Bauinformatik, which has been developed in Germany since 1970, should be studied more closely.

***Bauinformatik*.** Bauinformatik is based on the concept that the beneficial application of computers is a strong component of every branch of civil engineering such as structural design, water resources, geotechnical engineering, construction management and transport-tation systems. Every branch develops computer-oriented theories and formulations for its area of expertise and prepares its students to apply computers beneficially in engineering practise. At the same time, there are aspects of computer application which are common to all branches of civil engineering and should therefore be taught only once at a university and then used in all branches of civil engineering. These common aspects are the contents of the discipline of Bauinformtik and consist of methods, models, processes and systems for the type of information whose contents and transfer are typical and of practical relevance for civil engineering. The role of Bauinformatik in civil engineering can be compared to that of other fundamental disciplines such as mechanics, which are also applied in many of the branches of civil engineering.

A *method* of Bauinformatik consists of a scientific theory which generalises and abstracts the rules for a selected topic in civil engineering, a data structure for the attributes and relations describing the topic and a set of algorithms which transform the data according to the rules of the theory. Typical examples for methods are:

- object-oriented methods for information structures in buildings
- geometric methods for computer aided design
- numerical methods for the analysis of building behaviour
- optimisation methods for the design of constructed facilities
- stochastic methods for safety and reliability
- graph-based methods for work-flow analysis and control

A *model* of Bauinformatik describes a part of the real world. Models are constructed and handled with the methods of Bauinformatik. Each branch of civil engineering needs its own models such as

- CAD models for the description of constructed facilities
- finite element models for structural, geotechnical and hydraulic analysis
- simulation models for coastal protection, transportation and construction sites
- quantity surveying models for tenders, submissions and controlling
- facility management models for the utilization of buildings

The methodology and the tools for the design, implementation and application of such models are mostly independent of the branches of civil engineering and comprise aspects such as

- description of properties of artefacts with product models
- description of events with process models
- description of relations with organisation models
- description of expertise with knowledge models
- design and implementation of persistent information bases

A **process** of Bauinformatik describes changes in a model of a part of the real world. The elements of a process are the events which occur in the real world.

These events must be mapped to processor operations in the computer. Each branch of civil engineering possesses its own processes such as
- processes of project planning
- processes of design
- processes of analysis
- processes of detailing
- processes of construction management
- processes of building approval
- processes of controlling

The methodology and the tools for the design, implementation and application of such processes are mostly independent of the branches of civil engineering and comprise
- identification, description and classification of events in buildings and systems
- aggregation of events to process graphs for classes of applications
- design and implementation of transaction-oriented user interfaces
- construction of algorithms for design and control of work flow and information flow
- delayed updates of information bases

The *systems* of Bauinformatik for the handling of civil engineering projects or the operation of building companies usually contain many methods, models and processes. In addition to the computer-based tools of civil engineering, they use the general methods of information processing such as office systems, data banks and internet. Most of these systems are so complex and multi-disciplinary that they cannot be treated adequately on the basis of common sense and heuristic knowledge alone. Through the consistent application of scientific methods, our ability to master complexity in the engineering processes for systems is gradually improving, as is our ability to produce efficient software in reasonable time spans and at reasonable cost.

Unity of Research and Teaching. The transition from the traditional education in civil engineering to a computer-related education is a great challenge. It poses particular problems to the faculty of the university, who are excellent specialists in the traditional aspects of the disciplines which they teach, but may not have had the opportunity for adequate computer-related experience. Good acquaintance with commercial engineering software is usually not an adequate foundation for the computer-oriented teaching of theories. A mechanism must therefore be introduced which permits the faculty to update their scientific knowledge in systematic fashion before they pass it on to the students.

Fortunately, the traditional Russian and German university systems contain the tool which solves the problem. It is called the principle of the unity of research and teaching and postulates that a professor must be free to do a significant amount of independent personal research in order to be able to maintain a level of teaching that is up to date. The dissolution of the Soviet Union was accompanied with conditions at the universities which weakened the principle of research and teaching significantly, so that today a renewed strengthening of the principle has become necessary.

It was decided early in the advisory program to concentrate on activities that show the potential of the unity of research and teaching when the principle is applied to the introduction of Bauinformatik and to the computer-related restructuring of

traditional branches of civil engineering. The following areas of investigation were selected:
- enhancement of structural mechanics with computational mechanics
- enhancement of construction management with computational management
- modelling of constructed facilities on the computer

The area of *computational mechanics* is the subject of cooperation between Prof. Galishnikova in Volgograd, Prof. Pahl in Berlin and Prof. Dunaiski in Stellenbosch. The research is focussed on the geometrically nonlinear analysis of structures. The aim is to develop a generalised and unified approach that can be used for all types of structural components as found in trusses, frames, membranes, plates, folded frames and mixed structural systems. The general nonlinear theory of elasticity has been reformulated for this purpose and augmented with special theories for trusses and frames. A highly efficient and reliable numerical method has been developed for the solution of the nonlinear algebraic governing equations. For the determination of snap-through and bifurcation points, where the structure looses its stability, a basically new approach was taken that has led to a highly reliable and accurate algorithm. The investigation of the post-critical deformation yielded new insights into structural behaviour. The algorithms have been implemented on the Java-platform with appropriate data structures and interactive graphic user surfaces. This research will be presented in a paper by Prof. Galishnikova.

The results of the research on nonlinear behaviour have been recorded in a set of lecture notes. The theory and its implementation have been presented in compact courses to advanced students at VolgGASU. These students are now engaged in research projects of their own which will expand the area covered by the research. Nonlinear structural analysis will be one of the subjects of the new M.Sc. Program on Computational Civil Engineering which will start at VolgGASU in October 2007. In this manner, the interaction of research and teaching is illustrated. In addition, the principles of the nonlinear approach are used by Prof. Galishnikova for a revision of the undergraduate courses on structural mechanics.

Computational management is a particularly interesting consequence of the efforts to use computers beneficially in civil engineering. It is well known that control of the high level of complexity of the modern planning, design and construction processes is a particular challenge to the building professions. Only recently has it become apparent that this challenge can be addressed by applying powerful new mathematical tools. Thus the traditional mathematical background of engineers in differential and integral calculus is being augmented by an equally important background in discrete mathematics, particularly in set theory, relational algebra und graph theory. The introduction of this new sector of mathematics leads to significant change in the civil engineering curriculum, which is ongoing world wide.

The research which prepares the faculty at VolgGASU for the introduction of these new aspects of civil engineering education is the subject of cooperation between Prof. Oleg Ignatiev at VolgGASU, Prof. Beuke at Weimar and Prof. Huhnt at Berlin. An important topic of research is the modelling of constructed facilities, engineering processes and organisations of the building industry in suitable graphs in order to permit the rational planning, optimisation and control of engineering projects. The mathematical tools are path algebras, work flow analysis and Petri nets. Computational management will also be one of the subjects of the new M.Sc.

Program on Computational Civil Engineering which will start at VolgGASU in October 2007, so that again the interaction of research and teaching is illustrated.

The *modelling of constructed facilities* on computers is the centre point of the computer applications in civil engineering. By mapping the objects and attributes of a constructed facility to the computer before it is built, it becomes possible to predict its behaviour and to investigate alternatives in its design. If the modelling is extended to include the full life span from the conception of a project over the preliminary planning to the final design of its facilities, to the construction process, to the facility management and to the eventual removal and the reuse of materials, a very powerful engineering tool becomes available which can be used to great advantage in achieving high design and construction quality and economy, proper utilisation and maintenance of the facility and good environmental control.

The research which prepares the faculty at VolgGASU for the introduction of the modelling of structures into the teaching is the subject of cooperation between Dr. Bilchuk at Moscow, Prof. Galishnikova at VolgGASU and Prof. Pahl at Berlin. Due to the extremely large volume of data, particularly for the time-dependent life-span models (4D models), highly efficient and compact topological and geometrical models of the constructed facilities are essential. The research is therefore centred on the fast identification of geometric objects in graphic displays by means of region trees and on efficient Boolean operations for polygons with an outer contour and an arbitrary number of inner contours. By means of strongly object-oriented methods and new definitions for polygons, it was possible to reduce the time requirements for the fundamental operations significantly. This research will be presented in a paper by Dr. Bilchuk.

Computational geometry will also be one of the subjects of the new M.Sc. Program on Computational Civil Engineering which will start at VolgGASU in October 2007, so that once again the interaction of research and teaching is illustrated.

Curriculum Development. The civil engineering curriculum in Russia in general and at VolgGASU in particular is in a process of adjustment to the bachelor and master structure inherent in the Bologna process. The new national standards are still under consideration. In order to avoid delay in the transition at VolgGASU to a new computer-oriented curriculum, a M.Sc. Program in Computational Civil Engineering has been formulated. Its goal is to educate a generation of civil engineers who have the scientific background and experience that are necessary for the beneficial use of computers in engineering practise and in research, and in addition to prepare some of the graduates of the program to proceed to related doctoral programs and thus to become the academic leaders of the future.

Computers are already being used extensively in civil engineering education at the universities. The intention of this program is not just to intensify this trend. The main obstacle to the beneficial use of computers in civil engineering is not a lack of familiarity with the readily available hardware and commercial software for tasks such as structural analysis and dimensioning, computer-aided design, transportation engineering or hydraulic engineering. These tools are today available in a quality that makes it possible to become familiar with their use without significant formal training.

The main obstacle to further progress is the inability of practising engineers and researchers to formulate their concepts for the description and solution of civil engineering tasks in such a way that the huge capacities of computers and communication networks can be utilized to handle these tasks efficiently and

reliably. These engineers frequently are capable of programming and of using computers efficiently for standard tasks such as office management or technical drawing. The problem is that they are not sufficiently familiar with the scientific fundamentals required for mapping civil engineering tasks to a computer environment, and with the handling of such tasks in the computer environment.

The proposed M.Sc. Program is concentrated on the general scientific fundamentals which form the basis for

- mapping problems from different branches of civil engineering to computers
- simulating behaviour of constructed facilities and their environment on computers
- managing processes in the life cycle of constructed facilities with computers

The fundamentals are independent of specific programming platforms and provide the basis for continuing education throughout the professional career of the practising engineer or researcher. They enable him to participate in continuous innovation and thus to contribute to the overall development of his society.

The M.Sc. program is to be as interdisciplinary and as international as possible. The interdisciplinary character is to be strengthened by opening the program to students from both the civil engineering and the information technology area and specifying the curriculum accordingly. The international character is to be strengthened by offering selected courses both in English and in Russian, having courses conducted by lecturers from other countries and including parts of the program in the activities of the International Department of VolgGASU. The following three subjects form the core of the Program:

Computational Geometry: The subject covers topics which are frequently treated in classical analytical geometry, but are now approached from the point of view of numerical geometry, which can require different algorithms to achieve the necessary robustness and efficiency. Typical topics are line segment intersection, polygon triangulation, orthogonal range searching, point location, Voronoi diagrams, Delaunay triangulation, windowing, space partition, robot motion as well as quadtrees and octtrees Typical applications of these methods are computer aided design, interactive graphic engineering surfaces for analysis and design on displays, robotics, geographic information systems, facility management and pattern recognition.

Computational Mechanics: Computer-based finite element models are widely applied in civil engineering. Commercial software packages are used as platforms for finite element analysis of projects in engineering practise. The purpose of this subject is not the application of such black-box systems in education. Instead, the students become familiar with the full cycle that is required to initiate computer-supported innovation in a branch of civil engineering, starting with the mathematical formulation of a physical problem, continuing with its reduction to an algebraic form that is suitable for computer application and ending with the implementation of the application on the computer, including the data base and the algorithms for the internal computer model as well as the presentations and editors for an interactive graphical engineering interface. This experience prepares students for research and for innovation as a part of practical engineering.

Computational Management: The scientific foundation for management in civil engineering has reached a level of abstraction and generality which is comparable to the theoretical foundation for the treatment of physical tasks. The new area of expertise includes such topics as relational algebra, graph theory, Petri nets, operations research, workflow analysis, safety theory, decision theory and process analysis. While all of

these topics have been studied in the past, the analysis of the practical demands of the tasks, the theoretical foundation of their solution and the computer implementation of the management models seldom form a unit in civil engineering education, research and practise. Suitable models for engineering design processes, project management, facility management and organisation management are under development. Research on the control of the increasing complexity of construction in dense urban and industrial areas with the methods of computational management will remain a significant task for a long period of time. The subject prepares students for both practical engineering and research activities in this innovative area.

In addition to these three core subjects, students will be able to specialise with the following courses:

- Technical English for civil engineers
- Models of Bauinformatik
- Linear finite element analysis of structures
- Dynamic structural analysis and design
- Lifecycle engineering and project management
- Computer-aided facility management

The specialisation is augmented by the following electives:

- Nonlinear finite element analysis of structures
- Computer-based dimensioning and detailing of structures
- Numerical methods in geotechnical engineering
- Earthquake-resistant structural design
- Lifecycle-engineering and project development
- Lifecycle-engineering and building management
- Information and communication technology for lifecycle-engineering

As the new national standards become available, this process of curriculum development will be extended to the undergraduate education. As in the case of the graduate curriculum, the names of the subjects alone are not adequate to describe the new concepts. The computer-orientation of the theories is an essential component that must be acquired through research and introduced systematically in the teaching.

Strategic Research Areas. The advisors propose that information technologies in civil engineering be chosen as one of the strategic research areas of VolgGASU. The following list describes the main topics that could be treated in the next ten years of research. Each topic would require several research projects. A significant number of the scientists who could perform this research still remain to be identified and trained.

Computational Mechanics

Unified geometrically nonlinear analysis for all types of structural components
Theories for bars, beams, membranes, plates, and folded plates
Physically nonlinear structural behaviour
Computer implementation of data bases, algorithms and user surfaces
Systematic testing of the efficiency and accuracy of the methods
Systematic analysis of the behaviour of various types of slender structures
Computational Management
Description of projects, facilities, processes and organisations with graphs
Path algebras, Petri networks and workflow analysis
Data bases, computer algorithms and user surfaces for management
Engineering cooperation in computer networks with information platforms

Transactions, versions and updating of data bases in the building industry
Modelling of Constructed Facilities
Computational Geometry
Design and construction of graphic engineering surfaces
Life span modelling for constructed facilities (4D-models)
Transition from a document structure to a model structure of information
Computer-aided facility management: spaces, equipment, persons, tasks

Development of the following software is expected to contribute strongly to the interaction of VolgGASU with planning and design offices, with the building industry and with government agencies:

- Software for the unified nonlinear analysis of load bearing structures
- Software for the modelling of the life-cycle of constructed facilities
- Software for facility management
- Software for engineering cooperation in computer networks

It is expected that the experience gained in the strategic research area will also benefit new research activities in the traditional areas of civil engineering, since the object-oriented technology as well as the basic structure of the data bases, the core models and the presentation models in the traditional areas are similar to those in the strategic area.

*Conclusions***.** The research and the curriculum development which have been performed during the 24 months of the advisory program at VolgGASU demonstrate that the unity of research and development is an excellent tool for the enhancement of computational civil engineering at VolgGASU. In the areas on which the activities of the advisory program were concentrated, the progress through research has laid the foundation for sound curriculum development and has prepared the ground for strategic research on three topics.

The main factor which retards the speed of development at VolgGASU is inadequate funding for regular research on adequately paid full-time university appointments, particularly for young faculty. It is highly desirable that sufficient funding be made available so that the required large number of new faculty members can be prepared through unified research and teaching projects in a sufficient number of focal areas throughout the university. These projects should be selected and planned strategi-cally and independently of their immediate fund raising capabilities.

If the financial difficulties can be overcome, it will be possible to develop a faculty that is well prepared for Computational Civil Engineering. This faculty will be capable of formulating the required curriculum and to create an educational environment in which it will be attractive for the students at VolgGASU to develop their talents and skills.

Through its research and the high quality of its alumni, the national and international prestige and recognition of VolgGASU will be enhanced and the interest of industry, government and the private sector to benefit from cooperation with VolgGASU will be strengthened. VolgGASU will be able to compete with the best universities both nationally and internationally in Computational Civil Engineering, just as it has been able to compete in other areas of civil engineering in the past.