COMPUTER TECHNOLOGIES IN STUDIES OF MECHANICAL ENGINEERING: WHAT, HOW, WHERE?

DATORTEHNOLOĢIJA MAŠĪNZINĪBU STUDIJĀS: KAS, KĀ, KUR?

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Introduction

Studies of mechanical engineering, which involve comprehensive design and analysis problems of parts, mechanisms and machines, are accompanied with great amount of engineering computations and technical drawing. While the major goals of study process are:
- introducing students with the main types of mechanical engineering objects,
- giving understanding in general principles of their behavior,
- developing skills of finding or creating appropriate methods and algorithms for problem solving,

the time-consuming calculations and drafting, as well as lack of appropriate visual and laboratory aids, can lower efficiency of the education process. Complex solution is in utilization of *e-tools* - computers, software, databases, networks etc., that provide unlimited possibilities for improvement of the education environment. Wide variety of commercial software can be used for increasing effectiveness of learning as well as teaching, nevertheless there always are possibilities to enhance students' cognition and understanding of specific problems by developing and implementation of original, object or problem oriented tools.

Besides applications of proprietary software (*MS Office*, *SolidWorks/Cosmos, Watt* etc.), this article also presents authors' experience in development and use of original e-tools – different computer

software modules intended for visualization, calculation, analysis and assessment. Developed tools are collected in educational software package *ME&TMM Toolbox* and named "problem-oriented", since are aimed at particular problems of the mechanical engineering core courses, such as Machine Elements, Theory of Machines and Mechanisms, Kinematics and Dynamics of Machinery.

2. VISUALIZATION

*"A picture is worth a thousand words [1]"*

There is no other branch of science except mechanics, whose objects and processes can be visualized in natural form, i.e. without use of assumed equivalents or analogies. Representation of physical bodies of real world in the virtual 3D space of CAD software or as plane 2D illustrations in different mediums is straightforward and the only transformations to be performed are associated with selection of scale and viewpoint. Visualization of movement, reflecting the changes of object's position, is affected only by adjusting the time-scale. These benefits in conjunction with broad gateway of human visual perception [1] make all forms of visualization to be an extremely useful and effective means for studying and teaching mechanical engineering. Appropriate visual tools ensure quick transfer of large amount of information and convey data, coding of which in written or spoken form takes much more space and time, or in many situations even is impossible. The main forms of visualization concerned here are images, animations and mechanistic simulations.

1.1. Images (static illustrations)

The beauty of literature of mechanical engineering since beginnings comes from clear and exact illustrations of objects and problems discussed. Due to properties mentioned above, sketches, drawings and schemes frequently are the main part of investigation, while accompanying text serves only as explanation. Images of this type can be classified into following categories:
  - images introducing with view of objects (photos, CAD models),
  - images showing principles of construction and / or functioning of objects (drawings, exploded views),
  - images setting the basis and illustrating principles and subjects of calculations (calculation schemes),
 - images representing results of calculations, analysis, design (diagrams, graphics, sketches).

With increased accessibility and specifications of digital cameras preparing images of stationary, special, unique or in other respects interesting technical objects depends only on mobility of educator. Remote, unreachable or even nonexisting objects can be modeled by means of 3D CAD software. Objects' realistic rendering, exploding of assemblies, section views and other powerful options of this software make it a most useful and productive technology for creating images of mechanical devices and constructions. Illustrations with higher level of abstraction, i.e. principal and calculation schemes, diagrams etc. traditionally are created by making use of word processing and graphical software (MS Word, Power Point, Visio, AutoCAD etc.). Computer technology and digital form of the product enable simple editing of created images, as well as handy management and compact archiving. Images of different categories (Fig. 1) can be shared between all types of media used in engineering education process – printed materials, on screen illustrations, files for e-learning etc.
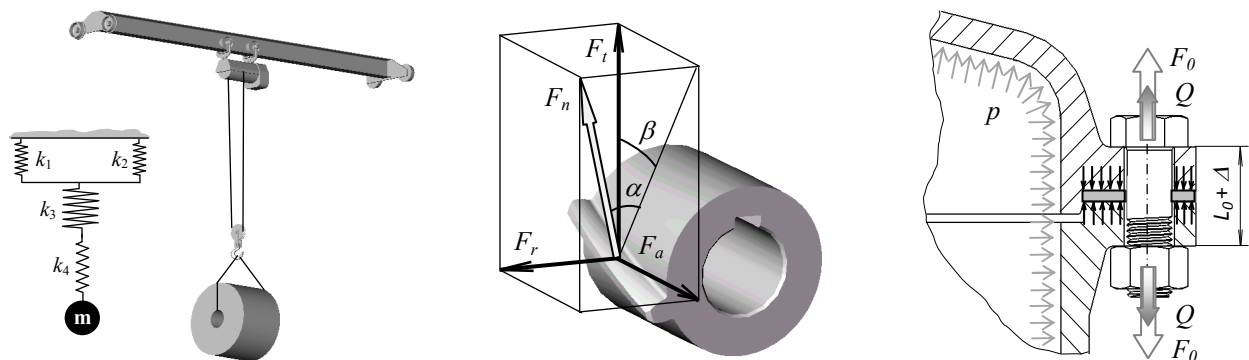
Fig. 1. Static illustrations for Machine Elements course (*SolidWorks, MS Word*)

3. Animation

Horizons of possibilities of computer animation, the newest and most powerful technique of animation [2], are obviously outlined by continuously enhancing video games and special movie effects. In technical applications requirements of the animation are less artistic, but need to be more precise instead since the main purpose of animations here is illustration of time - space succession of objects in the way, adequate to real-world processes. Particularly it means that all frames of animation sequence must be interconnected according to some governing rules, which in case of mechanical applications traditionally are of geometric or kinematic nature. Following the encoded rules, computerized animations also can visualize imagined, hardly- or non-obvious events and processes, unreachable for other visual aids. 3D MCAD software of nowadays includes animation procedure as one of the standard options. Creating assemblies by defining mutual relations of parts – concentricity of shafts and holes, coinciding of particular faces etc. - simultaneously sets the rules for animation. This software option can be double-successfully utilized in study courses, intended for learning of CAD software. Assigning a task for students to create and animate some mechanism described in literature (of type [3]), students, firstly, have practical and professionally oriented problem to solve, and secondly, get full insight into details and functioning of the particular mechanism that, in turn, can serve as a visual aid for other courses (Fig. 2).
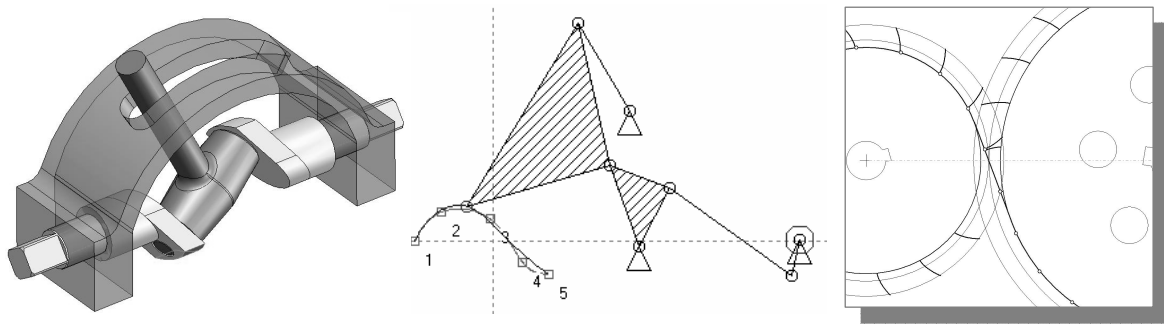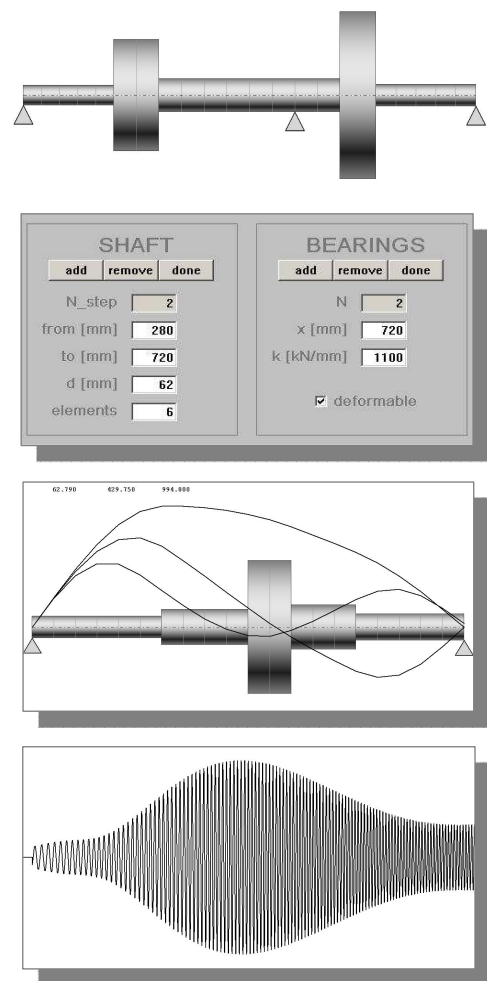
Fig. 2. Animated tools for course of Theory of Machines and Mechanisms
(*SolidWorks, Watt, ME&TMM Toolbox*)

In cases when more complicated animation governing rules than part mates are required, specific software is to be searched or developed. Tasks of this kind typically come from area of synthesis and analysis of mechanisms, where the primary rule is precise realization of functional relations of motion parameters of parts and their elements [4, 5].

1.3. Simulation

The difference between animation and simulation is in the strength of governing rules that define the sequence of frames. If only kinematics of mechanism is to be investigated, animation and simulation are the same. Adding more physical rules, typically differential equations of motion, relations of forces and deformations etc., increases adequacy of simulated and real events. Owing to effective computing algorithms and powerful solvers, mechanistic simulations have reached the level, when they can successfully replace the real-world physical prototypes in testing, expertise or similar procedures of investigation.

Like conformity of animation and Kinematics, simulations are natural for Machine Dynamics course. Due to obviousness and practical significance, flexural vibrations of rotary machine's shaft were selected as a prototype for developing corresponding simulation module (currently under construction) within the *ME&TMM Toolbox*. Configuration of shaft and location of supports, as well as mechanical properties of material are interactively determined via user's data input interface (Fig. 3). Because attempt of implementation of Finite Element Method failed due to rounding errors' provoked divergence of eigenvalues and distorsion of

Fig. 3. Screenshots of the simulation module

eigenvectors, natural frequencies and mode shapes are calculated by implementation of Transfer Matrix Method (TMM) for a Lumped Mass Beam Model [6]. Chainlike topology of the shaft is reflected by the method's basic equation

$$\mathbf{v}_n = \mathbf{U}^n \mathbf{U}^{n-1} \ldots \mathbf{U}^i \ldots \mathbf{U}^2 \mathbf{U}^1 \mathbf{v}_a \,,$$

where $\mathbf{v}_a = \{\, y_a \,,\, \theta_a \,,\, M_a \,,\, Q_a \,\}^{\mathrm{T}}$, $\mathbf{v}_n = \{\, y_n \,,\, \theta_n \,,\, M_n \,,\, Q_n \,\}^{\mathrm{T}}$ are the state vectors at the end and arbitrary section of the shaft; $\mathbf{U}_i$ - 4×4 transfer matrix, accounting stiffness and inertia properties of the i-th element. Global or overall matrix binds state vectors of both ends

$$\mathbf{v}_z = \mathbf{U}\mathbf{v}_a$$

that include two zero elements each. For instance, in case of shaft with pinned ends we have

$$\begin{Bmatrix} 0 \\ 0 \end{Bmatrix} = \begin{bmatrix} u_{12}(\omega) & u_{14}(\omega) \\ u_{32}(\omega) & u_{34}(\omega) \end{bmatrix} \times \begin{Bmatrix} \theta_a \\ Q_a \end{Bmatrix}$$

and natural frequencies ω_k^2 of shaft are the roots of

$$u_{12}(\omega)u_{34}(\omega) - u_{14}(\omega)u_{32}(\omega) = 0$$

that are found by monitoring the changes of sign of expression while frequency ω is monotony increased. Subsequently mode shapes are computed by making use of basic equation and

$$\mathbf{v}_a = \{\, 0 \,,\, 1 \,,\, 0 \,,\, -u_{12}/u_{14} \,\}^{\mathrm{T}}.$$

Algorithms have been proved by analysis of uniform shaft with exactly known vibration features (Table 1).

Table 1

Natural frequencies ω_k for uniform shaft (Hz)
(Ø24×1000 mm, pinned-pinned, E = 2.1e11 Pa)

k	Theoretical	TMM	SW/Cosmos
1	48,809	48,820	48,715
2	195,236	195,249	195,129
3	439,281	439,292	-
4	780,944	780,914	-

Output section of simulation module animates modal forms of free vibration and illustrates process of passing through resonance with increasing of rotational speed of the shaft. Governing equation in this case determines the general response of a discrete linear system [7]:

$$\{y(t)\} = \sum_{k=1}^{K} \{w_k\} \int_0^t q_k(t-\tau)\, h_k(\tau)\, d\tau \,;$$

$$h_k(\tau) = \frac{1}{\omega_k \sqrt{1-\zeta_k^2}} \exp(-\zeta_k \omega_k \tau) \sin \omega_k \sqrt{1-\zeta_k^2}\, \tau \,,$$

where $\{w_k\}$– k-th vector of the normalized modal matrix $[W]$, $\{q(t)\} = [W]^{\mathrm{T}} \{\, m_i e_i \Omega^2 \sin(\Omega t + \varphi_i)\,\}$ – vector of generalized forces, induced due to unbalance of the i-th mass at rotational frequency Ω, $h_k(\tau)$ – impulsive response of viscously damped system for k-th natural frequency, ζ_k – damping factor.

Since number, location, frequency, magnitude and phase of excitation forces can be interactively adjusted, the simulation module is intended as a virtual experimentation device for corresponding laboratory works in Machine Elements and Machine Dynamics courses.

4. CALCULATIONS

"When I see, I remember. When I do, I understand [2]"

There is plenty of computer software devoted to performing mathematical calculations of different kind and comprehensiveness (*MathCAD, MatLab, Maple, Mathematica* etc.). By use of such software, the intellectual and technical tasks of studies can be separated, leaving first one for the students and automating the second. As a result, time and effort economy is obtained and study process quality is increased to principally higher level: *"...mathematical assistant software can provide an exploratory tool that both accelerates and enriches concept exploration to a degree never before possible. Mathematical assistant software permits more extensive manipulation of the model through rapid experimentation and parameter variation in order to visualize richer patterns of behavior. More complex models can be explored with mathematical assistant software that extends and deepens the connections discovered* [8]."

2.1. Arithmetic calculation

Simple, arithmetic algorithm based calculations, mostly performed by use of hand-held calculators, are typical for solving many Machine Element course standard problems [9, 10]. Calculations of this kind may be tedious due to prolonged chain of operations and need intensified attention to avoid calculation mistakes. For example, finding of appropriate bolts' size for joint with z bolts (Fig. 4) incorporates: a) determination of joint's mass center x_c, y_c , b) calculation of center to bolt distances ρ_i , c) evaluating of bolt loads q_{Fi}, q_{Mi}, Q_i, and finally d) calculation of bolt's diameter d_1 , what is algorithmized as

$$x_c = \frac{1}{z}\sum_{i=1}^{z} x_i \; ; \quad y_c = \frac{1}{z}\sum_{i=1}^{z} y_i \; ; \quad \rho_i = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} \; ; \quad \beta_i = \tan^{-1}\left(\frac{x_i - x_c}{y_i - y_c}\right); \quad i = 1,2,...,z \; ;$$

$$q_{Fi} = \frac{F}{z} \; ; \quad q_{Mi} = \frac{FL}{\sum_{j=1}^{z} \rho_j^2}\rho_i \; ; \quad Q_i = \sqrt{q_{Fi}^2 + q_{Mi}^2 + 2q_{Fi}q_{Mi}\cos(\alpha + \beta_i)} \; ; \quad d_1 = \sqrt{\frac{4Q_{\max}}{f\pi[\sigma]}}$$
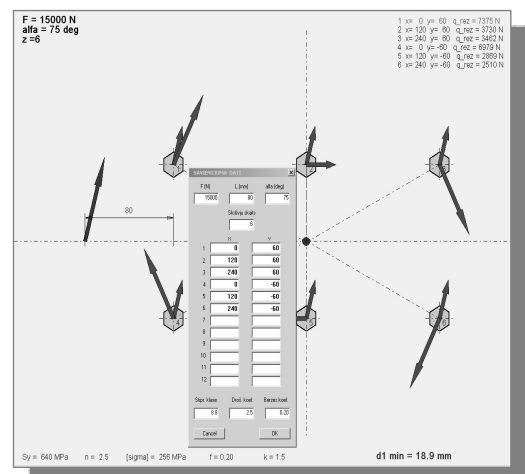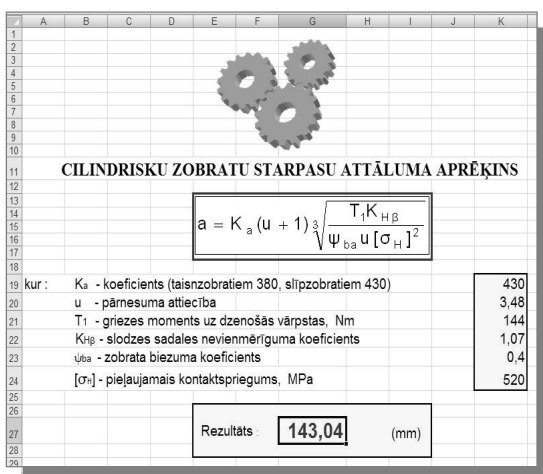

Fig. 4. Screenshots of calculation modules for Machine Elements course
(*MS Excel, ME&TMM Toolbox*)

Implementation of specialized software modules for solving of particular tasks of arithmetic calculations:

- allows clearly state and illustrate the problems, systemize input data and visualize results,
- makes calculations instantaneous, eliminates calculation errors and algorithm mistakes,
- retains full knowledge and cognition base of the problems matter and underlying theory.

If properly designed, specific software modules do not require additional time to learn how to use them. Since results depend only on values of input data and owing to calculation speed, changing parameters and trial and error approach can be effectively used for achieving satisfactory solutions.

4.2. Programmed calculation

Calculations which involve large amount of data and follow comprehensive theory according to the sequence of precoded algorithms is the most typical application of programmable calculators and computers. There is no better way to get insight into some problem, as to program it. Like using mechanisms in learning of CAD software, programming of particular mechanistic problem might be a good means for understanding it. At the beginning level possibilities of suitable calculators can be exploited to develop original source code or implement some already encoded [11]. Interested and advanced students, as well as enthusiastic teachers will find challenge and satisfaction in programming more complicated problems. In a result, not only personal experience is obtained, but also effective learning aids can be developed. Fig. 5 shows the results of programmed Finite Element Method calculations, concerning analysis of thick-wall cylinders (compared with Lamé's formulas) and bending stress distribution in gear tooth, both used as visual aids in the corresponding themes of Machine Elements course.
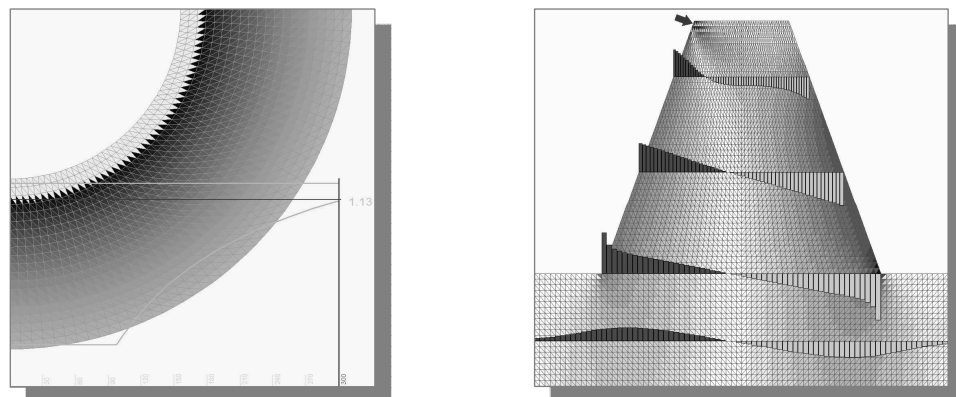

Fig. 5. Screenshots of FEA application modules for Machine Elements course

The paramount advantage of programmed calculations – wide possibilities of creating user's interfaces, varying of input data, object's parameters, boundary conditions, style of visualization etc. – makes this type of calculation the most flexible and extremely useful instrument for improvement of the teaching / learning environment.
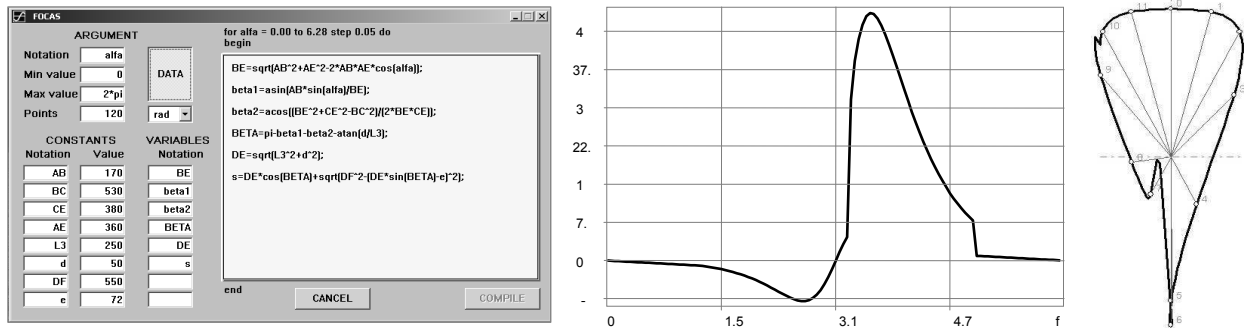
4.3. Function generating

Operation cyclicity of machines and mechanisms determines periodic nature of acting forces and motion parameters, what in case of stationary functioning regime reduces the scope of investigation of continuous processes to analysis of periodic functions, defined within one period of the sequence. For example, motion in particular case of analysis of rotary machinery is determined by Lagrange's equation in form

$$I_{\Sigma}(\varphi)\,\ddot{\varphi} + \frac{1}{2}I_{\Sigma}'(\varphi)\,\dot{\varphi}^2 = T(\varphi) - M(\varphi)\,;$$

$$\dot{\varphi} = \frac{d\varphi}{dt} = \omega\,; \quad \ddot{\varphi} = \frac{d^2\varphi}{dt^2} = \varepsilon\,; \quad I_{\Sigma}'(\varphi) = \frac{dI_{\Sigma}(\varphi)}{d\varphi}\,,$$

where periodicity of angular displacement, velocity and acceleration φ, ω, ε, i.e. parameters linked with differentiation / integration relationships, is predefined by periodic changes of mass moment of inertia $I_{\Sigma}(\varphi)$ and driving and load torques T, M. To solve problems of this type, calculation software has to satisfy the following requirements:

− interactive input of algorithms and data for function evaluation,
− realization of arithmetical calculations and calculation loops,
− presence of procedures for data transformation - differentiation / integration, Fourier transform etc.,
− visualization of results, i.e. function graphics and tables of numerical values,
− storage of results and ability of subsequent access.

Fig. 6. Screenshots of function generator input window and typical results on output

In the *ME&TMM Toolbox* package definition of the problem is realized via dialog window, containing two sections for input of data and formulas (Fig. 6). Notations of variables and constants, as well as numerical values of constants, period of function and number of discretization points are typed into corresponding edit controls. In the next step algorithms to be reiterated within *for…to* {*begin…end*} loop are typed, using previously defined tokens and common syntax of programming languages. Finally, given instructions are subsequently interpreted and in the result, graphic of the calculated function is displayed and simultaneously stored in the clipboard. Results can be saved and analyzed in the obtained form, or further modified by differentiation, integration, phase shift, Fourier transform. In the following analysis data arrays that represent formerly found functions can be called and used as input variables in calculation algorithms thus enabling possibility of chainlike arithmetic operations on functions - summation, multiplication, etc.; additionally resultant two function orbital diagrams that are important for some tasks of mechanism analysis can be created. Results of calculations can be thoroughly documented since windows metafiles with function graphic or table of numerical values can be added to the report at every step of investigation.
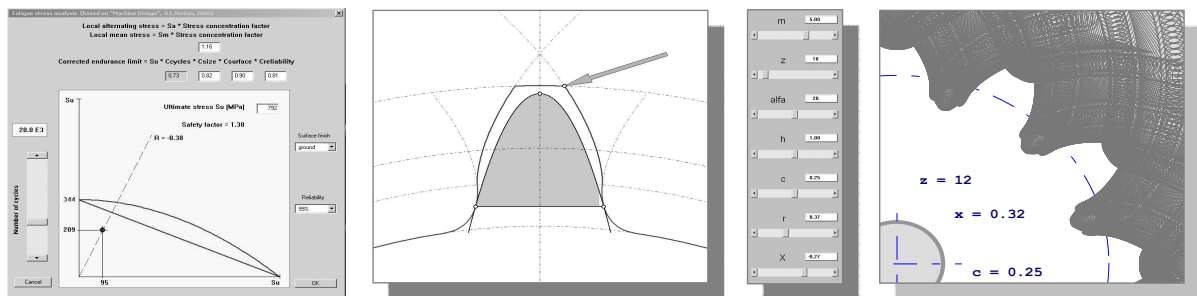
5. ANALYSIS

"The whole is more than the sum of its parts [3]"

By definition analysis is the process of breaking a complex topic into smaller parts to gain a better understanding of it [2]. Nevertheless, the cognitive value of analysis comes from summing up of the points and generalizing the statement of decisions reached. Since analysis is prerequisite for learning and understanding, actually all discussed here means can be interpreted as analysis tools, differing only by form of representation, level of informativeness and place of implementation.

"Breaking into parts" for mechanistic applications can be treated as evaluating of individual influence of each factor that concerns the problem. From such point of view scrollbars, sliders, edit controls and other Windows interface elements used to vary input data are essential instruments of analysis. Fig. 7 shows some specific *ME&TMM Toolbox* tools for analysis of machine elements [9, 10]: evaluation of safety factor (Goodman / Gerber criteria) dependently on 11 input factors, and investigation of gear-teeth geometry and strength (Lewis formula) as a function of 7 arguments.

Like flexibility of input data alteration, the implementation of analysis tools is also susceptible of adaptation. While the function generating and analysis tool (chapter 2.3), for example, is a typical courseware for students' use, the other *ME&TMM Toolbox* modules, which were developed as visual aids for lecture courses and demonstrated on screen as illustrations of corresponding problems

Fig. 7. Tools for analysis of machine part endurance, gear-teeth geometry and strength

can be used in different ways. Positive feedback, interest of students and practical considerations led to a self-dependent use of some tools for laboratory exercises. For example, software module for virtual forming of gear-teeth successfully replaced an obsolete, manually operated physical appliance with a set of replaceable cutting racks, CAD created 3D models of mechanisms are used for analysis of links, joints and degrees of freedom, whereas the shaft vibration simulation module is intended entirely as a virtual laboratory device, because the corresponding physical equipment is outdated and has less experimentation possibilities.

Practical experience shows that didactically and methodically optimal is the combined use of analysis e-tools and traditional teaching / learning approach. For instance, students having assigned tasks in Machine Element course to design bolted or welded connection, what usually is solved by subsequent iterations, firstly perform full calculation by hand, thus showing his / her proficiency in theory and ability to apply it, and secondly, iterate the calculations by use of specialized arithmetical calculation module (chapter 2.1) until needed result is obtained. In general, achieving the right balance of both methods depends on particular application and is one of the basic methodological tasks of educators.

6. ASSESSMENT

*"It is the quality rather than the quantity that matters [4]"*

Assessment of knowledge at all levels of education is a sophisticated process of obtaining and evaluating of information that includes the following:
– creating and distributing the assessment tasks,
– conducting the assessment procedure,
– evaluation and marking submissions.
Like everything in the Computer Age, also assessment procedures have undergone attempts to automate them. Mostly technical tasks of the problem, for example, management of the assessment process [12] are computerized. Automation of the intellectual part, i.e. evaluation of gathered information is much more problematic. Relatively simply it can be done only if the assessment task is

formed as a set of multiple choice preprogrammed or randomly selectable questions [13, 14]. Actually, this is a modernization of early programmed learning technique, realized by different physical means. Implementation of calculation module, featured with data and algorithm input capability (chapter 2.3), allows developing of an intelligent learning and assessment software in accordance with the block-chart in Fig. 8:

1) The task and input data are visualized on screen (e.g. bolted connection – Fig. 4) and the first step of calculation is formulated (e.g. "Find the center of group"). Student is free to select notations of variables and algorithms, which are fixed in the computer's memory along with the corresponding numerical values.

2) Parallel calculation results, obtained on the basis of common input data by student's and computer's algorithms are compared, if necessary, taking into account the equivocal nature of data.

3) Compliance of the results leads to formulation of the next problem (e.g. "Calculate the distance from center to the 3rd bolt". If the result is correct, other distances as well as some less significant parameters can be calculated automatically).

4) In case of disagreeing results additional specifying question can be asked, calculations repeated or terminated.
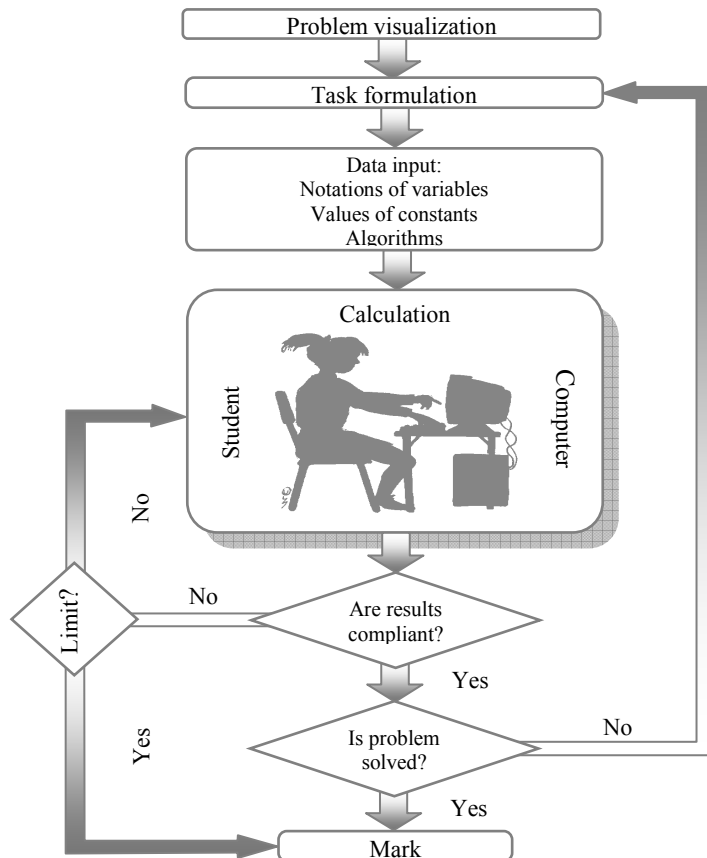
Fig. 8. Block-chart of the assessment procedure

Scenario of assessment procedure, weighting and account of mistakes, adequacy of marking – these of course are general problems to be solved for this approach.

7. SUMMARY

Powerful Computer Aided Design and Finite Element Analysis software, as well as comprehensive mathematical, graphical and word processing packages, have armed industry's mechanical engineers and their growing colleagues – students – with tools, featuring possibilities never before possible.

Duty of education is to achieve that these tools are used in full strength, what cannot be realized in another way as by computerizing the learning / teaching environment. One more noteworthy reason for computerization comes from necessity to assure natural and habitual for nowadays' generation conditions of doing things.

Selection and implementation of particular software depends on a mixture of many conditions – material, organizational, intellectual. This article is focused mainly on authors' experience in development and use of special, oriented to particular objects or problems, software modules, created under circumstances with limited accessibility of physical teaching / learning aids, software packages and computer skills (both students' and teachers'). "*What makes teachers use technology in the classroom?*"- there are 88 possible answers to this question in investigation [15]. In our opinion top-five are:

- Technology helps students more easily understand the subject contents.
- It can replace actual experiences with virtual ones.
- Although initial construction is difficult, once prepared, it can be used repeatedly.
- It stimulates learner's motivation or interest.
- It increases interactions among teachers and students.
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In conclusion, we would like to express our firm belief that there is not a question *to be, or not to be* the computer technology in education. The only questions we have to answer are *what, how, where,* and this article sketches corresponding answers in our interpretation.

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CITATIONS

[1] Proverb.
[2] Calvin Coolidge, the 30th President of the United States.
[3] Aristotle.
[4] Lucius Annaeus Seneca.

Upītis, G., Rudņevs, J., Mazais, J. Datortehnoloģijas mašīnzinību studijās: kas, kā, kur?
Rakstā aplūkotas datortehnoloģiju sniegtās iespējas inženierstudiju kvalitātes un efektivitātes uzlabošanai. Ilustrēti un analizēti komerciālu un oriģinālu datorprogrammu pielietojumi mehānikas profila pamatpriekšmetos - mašīnu un mehānismu teorija, mašīnu elementi u.c. Atsevišķas raksta sadaļas veltītas tehnisku uzdevumu vizualizācijai, aprēķinu veikšanai, analīzei, kā arī zināšanu datorizētu novērtējuma sistēmu izveidei. Aplūkots datortehnoloģiju pielietojums auditoriju nodarbībās, virtuālos laboratorijas darbos un patstāvīgu studiju darbu veikšanā.

Upitis, G., Rudnevs, J., Mazais, J. Computer Technologies in Studies of Mechanical Engineering: What, How, Where?
Article deals with possibilities of enhancing quality and effectiveness of engineering studies by means of computer technologies. Applications of commercial and original computer software to core courses of studies in mechanical engineering, such as Theory of Machines and Mechanisms, Machine Elements etc., are illustrated and analyzed. Separate chapters of the article are devoted to visualization of technical tasks, calculation, analysis, as well as to development of computerized system for knowledge assessment. Implementation of computer technologies into class, virtual laboratory and home works is discussed.

Упитис, Г., Руднев, Я., Мазайс, Я. Компьютерные технологии в учебном процессе машиностроителей: что, как, где?
В статье обсуждаются возможности повышения эффективности и качества учебного процесса студентов машиностроительных специальностей с применением компьютерных технологий. Иллюстрируется и анализируется применение коммерческих и оригинальных компьютерных программ в базовых курсах механического профиля – теория механизмов и машин, детали машин и др. Отдельные подразделы статьи посвящены вопросам визуализации технических задач, проведения расчетов, анализа и создания компьютеризованной системы проверки знаний. Рассматривается применение компьютерных технологий в аудиторных занятиях, виртуальных лабораторных и самостоятельных учебных работах.