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SIMULATION OF MANUFACTURING AND LOGISTICS SYSTEMS FOR THE 21TH CENTURY

Abstract

This paper deals with computer simulation of manufacturing systems. It contains the basic simulation theory and principles of a simulation project management. Furthermore the authors introduced the idea of parametric simulation model, followed by special application areas of simulation, e.g. scheduling, emulation, metamodelling. The paper discusses the possibility to utilize a cloud computing technology in simulation. The case example of the application of simulation by the optimization of real production system concludes the working part of paper. The final part summarizes benefits and recommendations.

INTRODUCTION

If today's enterprises want to stay on the market and be winners in competition they have to respond flexibly to the requirements of market environment, whether requirements for changes of production program, outputs, or loading and managing changes of the system. This relates to the detailed production planning and taking quick and correct decisions.

Currently, it is axiomatic to solve complex problems by an appropriate computer model that reflects characteristics of a real system or helps to find a solution close to optimal, or directly optimal, for existing or conceptual systems. Therefore, a computer simulation is still gaining major importance. It allows quick testing of various variants of solutions and it minimizes the risk of wrong decisions. This is reflected to considerable economic benefits.

1. SIMULATION OF MANUFACTURING SYSTEMS

Simulation is a method involving the replacement of the dynamic system by its simulation model in order to:

- obtain information how modeled system works in given circumstances,
- conduct experiments with it by the change of input parameters in order to detect how does the model behave, so how would the real system behave.

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Such model includes only those characteristics of a real system which the analyst is interested in. After evaluation of results the analyst makes conclusions about the whole real system, based on experiments with the model.

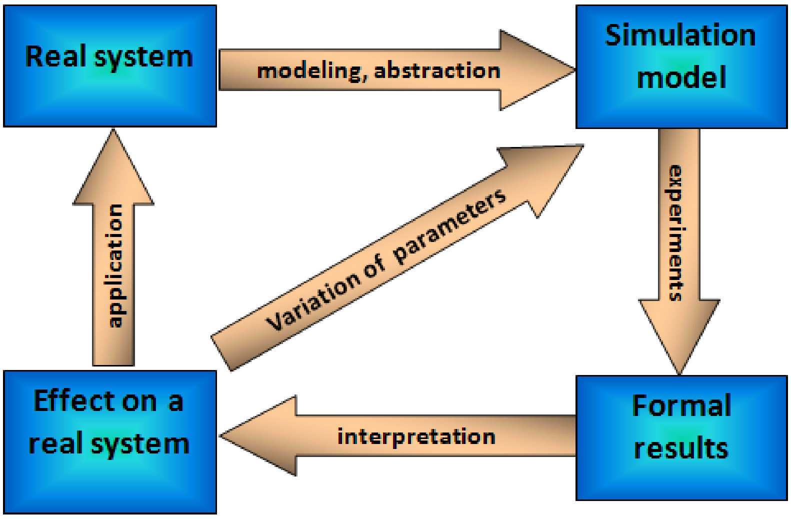

Fig. 1. The Principle of Simulation

Simulation overcomes many boundary conditions and limitations of analytical modeling procedures, and its use is justifiable especially in those cases where other solution options have failed.

1.1. Simulation Project

Simulation is not just to build a simulation model and the random “playing” with it on computer. It is needed to access the simulation as a project. Each project has to start with a thorough analysis of the problem and selecting appropriate methods and procedures for their solving. It means to determine whether and in what phase it is necessary to use simulation, or if simpler method is sufficient. This decision greatly affects the time and financial costs to fix the problem.

The simulation project includes the following general phases:

1. System analysis and problem definition, formulation of simulation's objectives. This phase includes preparation of requirements used to verify selected problems in designing and operation of manufacturing systems (e.g. dynamic permeability changes depending on range of goods changes and output changes, determination of shift influence on its flexibility and productivity, an alternative material flow in production system, tools flow and organization of tools assigning to technological workplace, identification of a narrow activities or elements of the production system, number and types of machines determination, etc.).

2. Collection and processing of process information, preparation of input data for model creating - estimates of the parameters and types of random variables distribution (Chi-square test).

3. An abstract logical model creating.

4. Construction of the model on a computer that is based on requirements formulation and on functional relationships of elements and activities of the real system.

5. Model verification and testing - verification and validation. It means to determine validity area of functional relationships (check the model from a logic view, extant of its validity, sensitivity for changes of its elements, etc.).

6. Planning and preparation of simulation experiments (pilot runs or short simulations, warm up period estimation, initial conditions determination, length of simulation run determination). Experiments should respect requirements of questions and issues set couched in the task.

7. Execution of simulation experiments with a change of factors in the model, perhaps even adjusting the model.

8. Evaluation and processing of experiments results, the final report.

1.2. Parametric Simulation Model

External information system (e.g. MS Excel) is often source of data for simulation model. It allows easy transfer and data processing, and it facilitates manipulation with data in database of the model. Parametric simulation model is a practical tool for finding problems' causes of the selected type of manufacturing systems, created for selected input variables. After modeling and entering the specific characteristics of production system (such a service time for each workstation, the way of parts arrival to the workstation, the transportation size, the way of manufacturing system control, etc.) can the process be simulated with sufficient precision. The analyst can also directly see critical points of production process and simulate various possibilities for their removal.

The obtained results, in the form of tables or graphs, are after execution of simulation experiments automatically transferred to external information system and on their base optimization of real system can be done. All this can be carried out without detailed knowledge of modeling and simulation methods and without deep knowledge about simulation software.

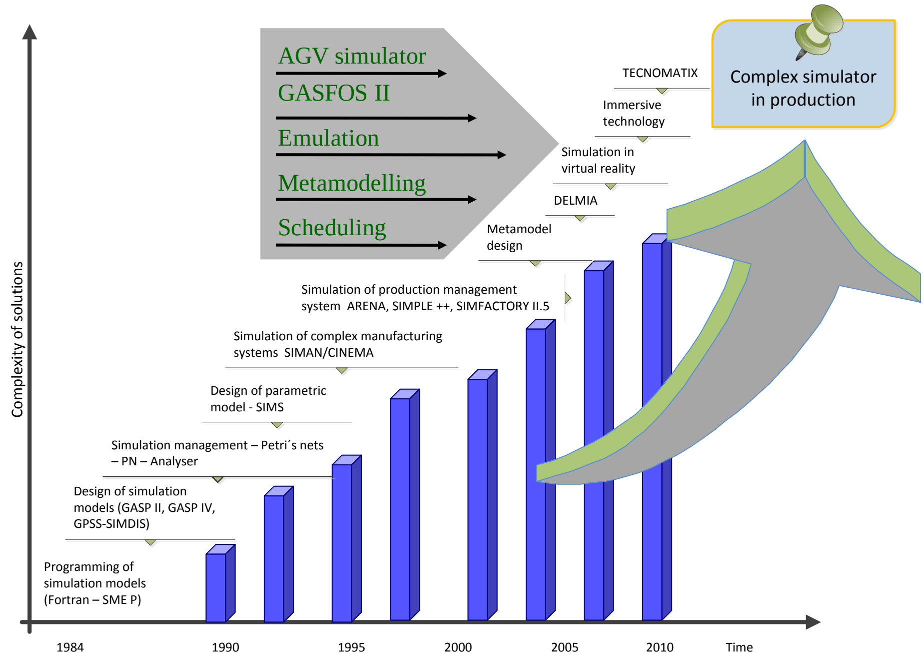

Fig. 2. Complex Simulator in Production

The current research intention of The University of Zilina in cooperation with the Central European Institute of Technology (CEIT) is to develop a complex simulator of production system, which will include progressive tools described below. The development of simulation tools at the University of Zilina dates back to 1984, when simulation models were programmed. Later it was a design of simulation model with the use of Petri´s nets, simulation of complex manufacturing and production management. Nowadays top commercially available simulation software systems are in use and the main effort is focused in development of supportive modules like: AGV simulator, optimization module GASFOS II, emulation, metamodelling and scheduling. The result is a complex simulator that is easily useable and implementable in a wide range of applications.

2. PROGRESSIVE APPROACHES IN SIMULATION OF MANUFACTURING SYSTEMS

1.3. Scheduling and Simulation

The production process of manufacturing enterprises has always been a key factor for overall business success. Production scheduling problems are facing thousands of companies all over the world that are engaged in the production of material goods. Therefore, the solution of production scheduling problems effectively and efficiently has attracted the interest of many experts and researchers from both fields of production control and combinatorial optimization.

The scheduling can be described as the allocation of available resources over time to meet the performance criteria defined in a domain. Typically, a scheduling handles a set of jobs to be completed, whereas each job consists of a set of operations. Each operation is performed by specific resources such as machines and operators. In terms of scheduling theory, most of scheduling problems are in the class of NP (non-deterministic polynomial-time) hard (Pinedo, 2002).

Scheduling using Simulation and Evolutionary Methods (SSEM) consists of three modules, which are necessary for generating, evaluating and optimizing production schedule. The first module was developed for generating a schedule respectively scheduling using priority rules. The second module was designed to evaluate production schedule with support of a parametric simulation model and the third module executes the implementation of evolutionary optimization methods to get better solutions.

The conceptual system architecture of the SSEM is represented in Figure 3, which shows its three main modules. The flow of information among given modules is represented by the directed arrows. The input data can be provided from the production database systems such as Enterprise Resource Planning (ERP) system or Manufacturing Enterprise System (MES). The obtained output is the schedule optimized according to the selected criterion value (for example minimization of makespan).

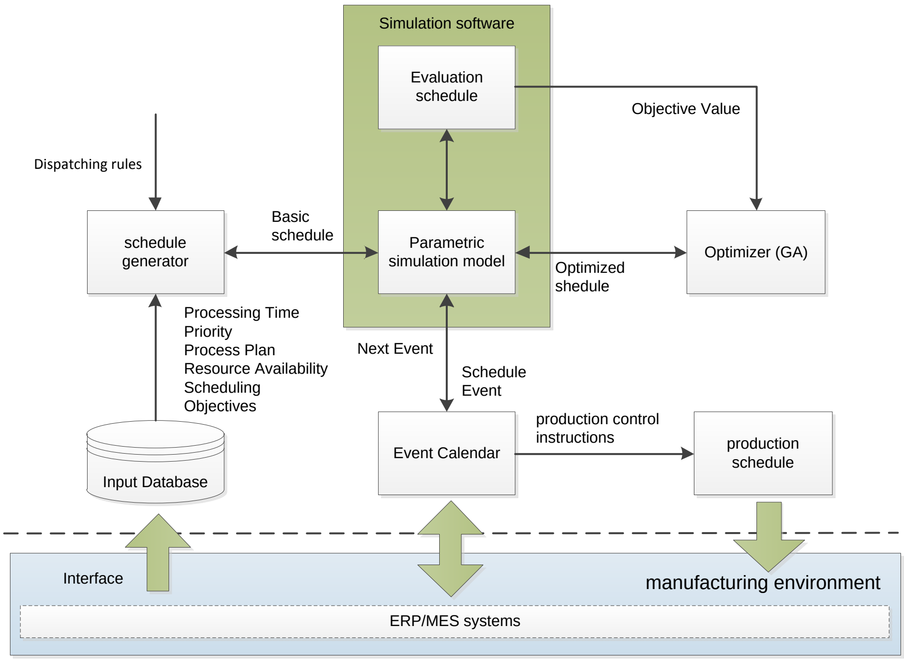

Fig. 3. Conceptual SSEM Architecture

A more detailed description of individual modules can be found in (Figa, 2011), which describes the various modules necessary to generate, to evaluate and to optimize the production schedule. Proposed methodology can be used as the practical tool for manager in a practice for a quick identification of bottlenecks in the generated schedule to minimize production costs.

1.4. Emulation

Apart from production planning management, production management requires current information about real manufacturing process (feedback from the manufacturing process) in a real time. The systems collecting data from a manufacturing process inform about the current states of production facilities. They also provide an opportunity to intervene in production process and affect it, to change real system's settings on computer.

The emulation means connecting a real system with its parametric simulation model and loading the data directly from a real system into a model database (possible by using sensors connected via a control unit in computer). In addition to simplify data handling this system allows to change settings of a real system (a vector of input factors) on computer using excel interface which eliminates need for knowledge of simulation program. Fundamental of emulation is that the simulation model is a substitute of real, missing module, respectively elements of comprehensive simulation model are gradually replaced by real devices.

The main advantage of this purpose is rapid determination of the effect of changes in guiding principles of production on a virtual model, which is in direct connection to the real production system. Emulation environment can monitor production respectively logistic system, evaluate collected data in a real time, update the model on the base of data from a real system, and execute experiments on accurate, updated and verified simulation model.

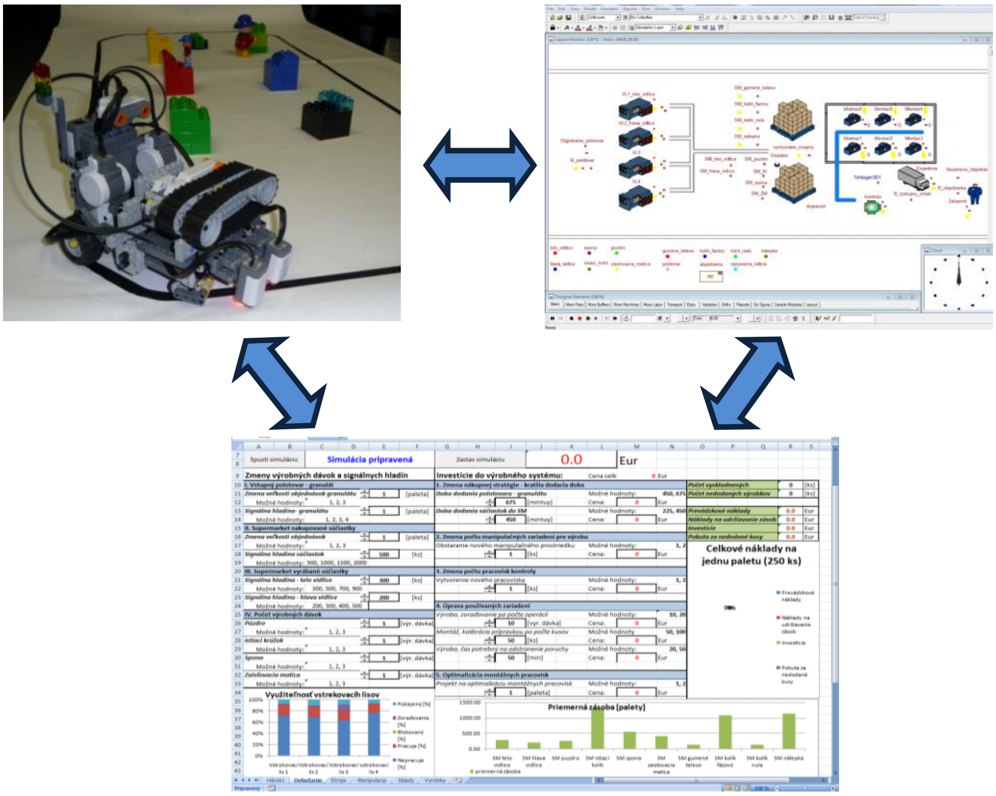

Fig. 4. Real System - Simulation Model - MS Excel Interface (Palajová, 2011)

1.5. Simulation Metamodelling

Simulation runs are usually computationally difficult and it is not unusual for complex simulation models that they last for hours. For practical applications of simulation optimization it is important that the optimization process is constrained within reasonable time limits and the efficiency of the optimization process is crucial. One of the possible ways how to enhance effectiveness of simulation optimization and reduce the requirements of time-consuming simulation is to use computationally cheap metamodels (Persson, 2010). Simulation metamodel (Barton, 1992) is a model of simulation model and it explains the fundamental nature of the system's input-output relationships through simple mathematical functions:

$$Y = \underbrace{f(X,\beta)}_{\eta} + \varepsilon \qquad (1)$$

$Y = f(X, \beta)$ - regression function,
Y – dependent variable,
X – vector of values of input factors,
ε - vector of random numbers.

This relationship is the regression model that expresses free (stochastic) dependence between explanatory variables X and explaining variable Y. It means that for one particular combination of values of independent variables X may depend variable Y acquire different values. It is caused by an influence of random events ε.

The metamodel creation (see Figure 5) begins with a simulation model which is preceded by defining the problem, defining the scope of input variables, the draft of the plan of experiments. After construction of a computer simulation model, his validation and verification is made, so logical structure of the model with respect to real system is proved. Then predefined number of replications for different input values is executed with the simulation model. In order to continue in metamodel development process the analyst has to be sure that data are sufficiently independent.

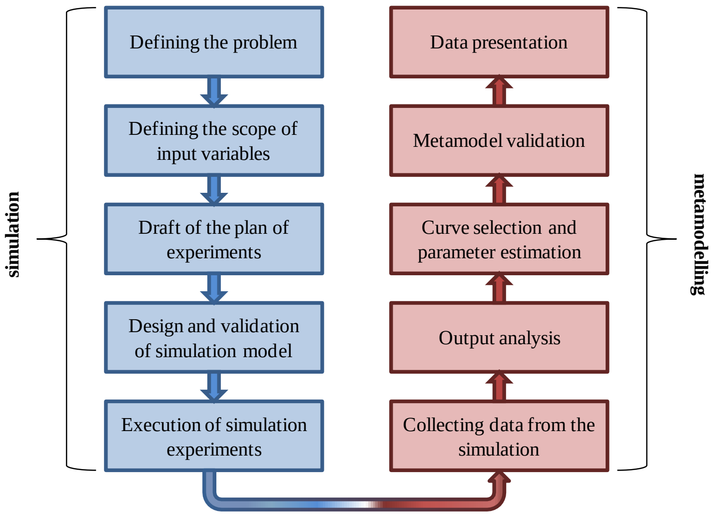

Fig. 5. Metamodel Development Process

In the next step, output data from the simulation are collected. In order to simplify the metamodel it is possible to combine some of the entries and remove those which have proved to be needless. These results are used for deriving a statistical model in the form of regression.

The heart of metamodelling is to determine a vector $\beta = (\beta_1, \beta_2, ..., \beta_p)^T$ which is a set of coefficients that determine regression function. Method of least squares is the most common method for estimation of regression functions. It is used for calculation of functions, providing its estimation is linear in parameters or it can be achieved by simple transformation. The values of the vector β are used for creating of curves that describe the metamodel. In order to check a suitability of the metamodel for intended purposes, validation of the metamodel (by comparison of metamodel with simulation output data using mathematical statistics) is done. The graphical representation of metamodel's inputs – outputs relationships provides a simple presentation of expected system behavior, often known as the approximate control.

Simulation metamodelling is an appropriate managing and optimizing tool for complex manufacturing systems. The research work (Hromada, 2004) was done at the Department of Industrial Engineering of the University of Žilina and it deals with the system analysis of input factors influence on the performance of manufacturing system. This approach uses computer simulation and metamodelling principles, and proposed methods were verified in practical conditions. Other publications focus on metamodelling as a support tool in the frame of Digital Factory (Gregor, 2008a), as a practical approach for a statistical summary of simulation results (Gregor, 2005), (Gregor, 2008b), or as a support tool for designing and testing the control principles in production (Škorík, 2010). Theoretical assumptions and developments were validated on the chosen production system. Principles of experimental concept of production management with simulation metamodelling application are shown in Figure 6.

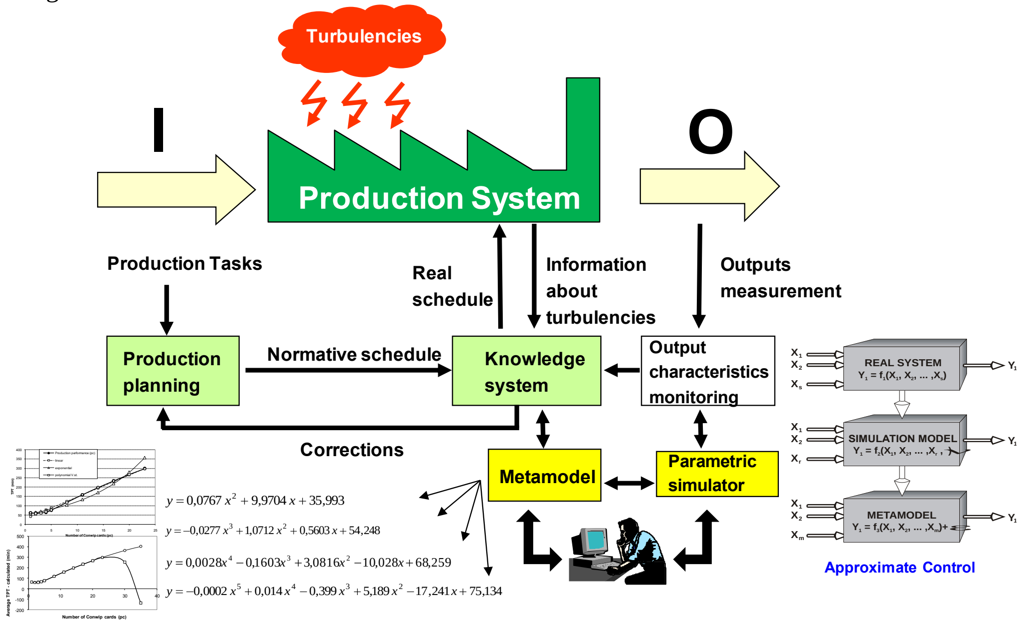

Fig. 6. Possible Configuration for Decision Support (Gregor, 2010)

1.6. Cloud Computing

One of the main problems why companies do not use simulation approaches is their high cost. One of the possible ways how to resolve this problem is to use cloud computing, a particular type of service providing called „Sofware as a Service - SaaS“. It means that software (in our case simulation software and its modules) is provided as a service. Hence the company avoids any need to own such software, whereby costs connected with the special software purchase and employees training are significantly reduced. The difference between traditional approach of software delivery and SaaS model is shown in Figures 7 and 8, respectively.

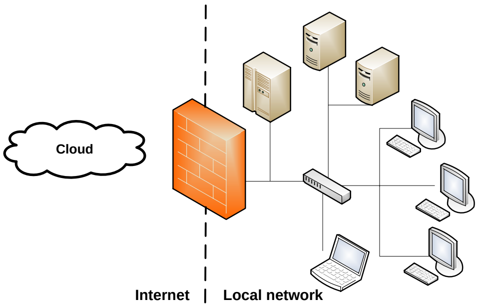

Fig. 7. Traditional Computing Model

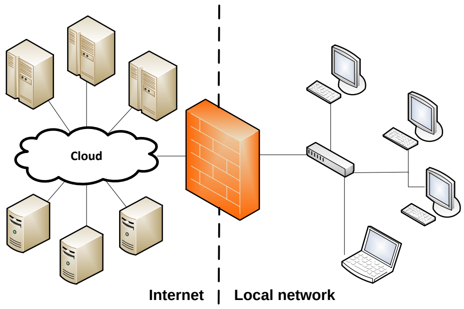

Fig. 8. SaaS Model

The traditional software requires local storage of data, whether on local disks or network resources. Servers, databases and other key elements of IT infrastructure are situated on the right side from the firewall "local network". In contrast, in the SaaS applications can be many of these resources outsourced and safely accessible via the Internet. They store clients' data into "cloud", what is a general term used for outsourced storage and computer equipment used for support of most of the web sites and applications. The principle of such approach functioning in terms of simulation exploitation shows Figure 9.

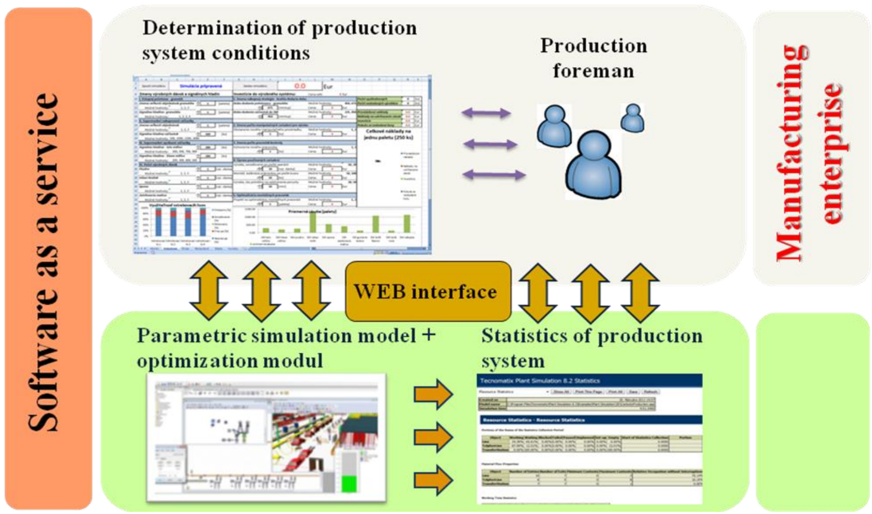

Fig. 9. The Principle of SaaS Functioning in Terms of Simulation Exploitation

Customers simply open excel interface where they set required parameters (such as production orders, availability of machines, workers, etc.) and initialized input parameters are loaded to the simulation model (located on a server in an external company) by using the Web interface. Simulation runs on this external server. After simulation the customer has available production system's statistics which he either accept or select another evaluative criterion to obtain better solution. So customer can flexibly respond to changes in the production environment and quickly incorporate them into the production.

Another advantage of this approach for users is that the responsibility for the system and potential problems are fully at the SaaS provider site.

3. CASE STUDY

Presented case study demonstrates one of the progressive approaches named "emulation" which was used in implementation of the FTS-CEIT AGV systems, developed in CEIT.

Simulation model was created on the basis of technological design of logistics system, using the autonomous conveyor system. The base of autonomous conveyor system consists of three main elements (Figure 10): FTS-CEIT AGV, dynamic conveyor and static conveyor. FTS-CEIT AGV is coupled with dynamic conveyors. Material is automatically imported from warehouse to the assembly line using dynamic conveyor. Transfer of material between dynamic conveyors and lines respectively warehouse is ensured through static conveyors, which are located in unloading and loading positions. The assembly line operator calls loaded AGV remotely as needed from waiting position.

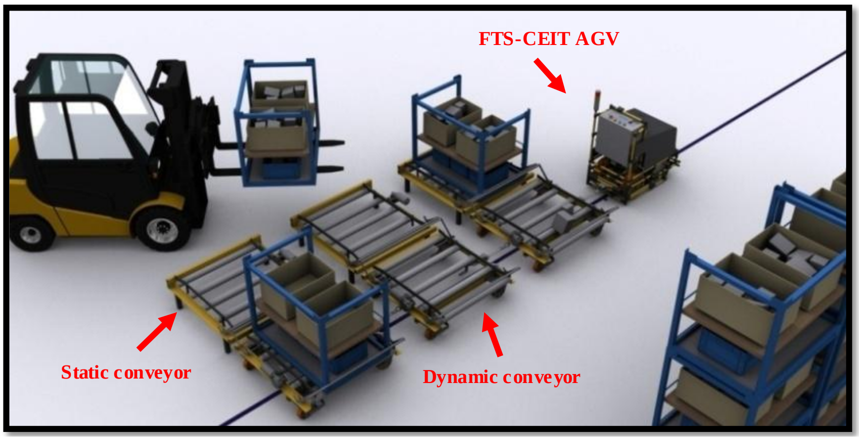

Fig. 10. Autonomous Conveyor System

The basic prerequisite for proper functionality of logistics system is the cycle of assembly line with value of 1.1 minutes. One FTS-CEIT AGV can trail 5 or 3 dynamic conveyor (depending on variant of simulation model). Each palette has 20 pieces of specific door panels. Automatic unloading/loading of dynamic conveyor takes 20 seconds and transport speed of FTS-CEIT AGV is 1 m/s for straight track, 0,2 m/s for smaller curves ,0,3 m/s for larger curves, 0,1 m/s for loading/unloading zone, traction ratio (charging time/driving time) = 1/5. The behavior of system is shown in Figure 11.

Three variants of logistic system have been designed within experiments, which can abide requirements of cycle time of assembly line. Particular variants vary by number of trucks serving logistics system and number of dynamic conveyor systems:

- *Variant 1* – one FTS-CEIT AGV and five trailed dynamic conveyors,
- *Variant 2* – two FTS-CEIT AGVs and each AGV trails five dynamic conveyors,
- *Variant 3* – two FTS-CEIT AGVs and each AGV trails three dynamic conveyors.

The FTS-CEIT AGVs supply all assembly workplaces in variants 1 and 2. The first FTS CEIT AGV supplies assembly workplace with right door panels in variant 3 and the second FTS-CEIT AGV supplies assembly workplace with left door panels.

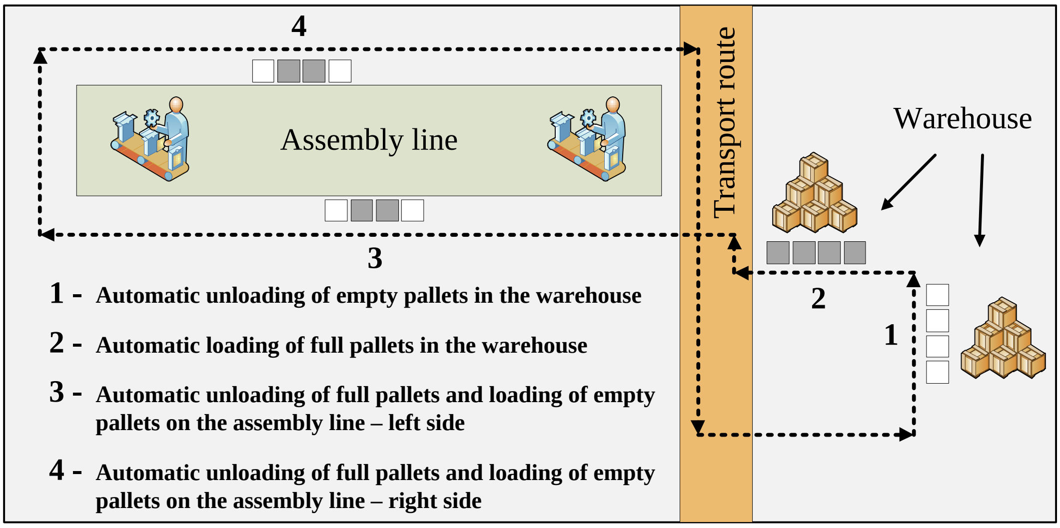

Fig. 11. Basic Principle of the Simulation Model

The following parameters have been monitored to compare usage of AGVs:

- *Idle* - the percentage time that the vehicle was idle,
- *Transfer* - the percentage time that the vehicle spent loading and unloading, including the time that the vehicle spent attempting to load or unload,
- *Loaded* - the percentage time that the vehicle was loaded with parts,
- *Stop* - the percentage time that the vehicle was stopped impact of random collision situations or was recharged,
- Waiting - the percentage time that the vehicle was waiting for call.

The following table shows statistics on the effectiveness of FTS-CEIT AGVs in different variants.

Tab. 1. The efficiency of FTS-CEIT AGVs

Name of parameter/ Variant	**Variant 1**	**Variant 2**		**Variant 3**	
	AGV	**AGV 1**	**AGV 2**	**AGV 1**	**AGV 2**
Idle [%]	15.38	53.40	53.34	39.09	34.21
Transfer [%]	22.29	12.27	12.29	12.37	12.18
Loaded [%]	44.45	24.47	24.49	28.86	33.96
Stop [%]	17.88	9.87	9.87	19.68	19.65
Waiting [%]	0.00	44.87	44.83	12.17	12.29

The overall efficiency of AGVs is shown in the chart below (Figure 12) and was defined as a sum of times of all activities that were directly involved in a transport of pallets of door panels (%Idle + % Transfer + % Loaded + % Stop). Also the compliance requirement for cycle time of the assembly line can be seen in the Figure 12. Based on comparison of compliance of requirement for cycle of the assembly line variant 1 is not suitable, because the time, which AGV needs to transport single circuit, is about 24 minutes and line required 22 minutes cycle time. This problem was corrected by increasing the number of FTS-CEIT AGVs (variants 2 and 3). Other variants comply with requirements of the production cycle of the system. By comparing of statistics and overall effectiveness of trucks, the best solution was variant 2. Variant 3 is suitable in terms of compliance requirement for cycle of the assembly line.

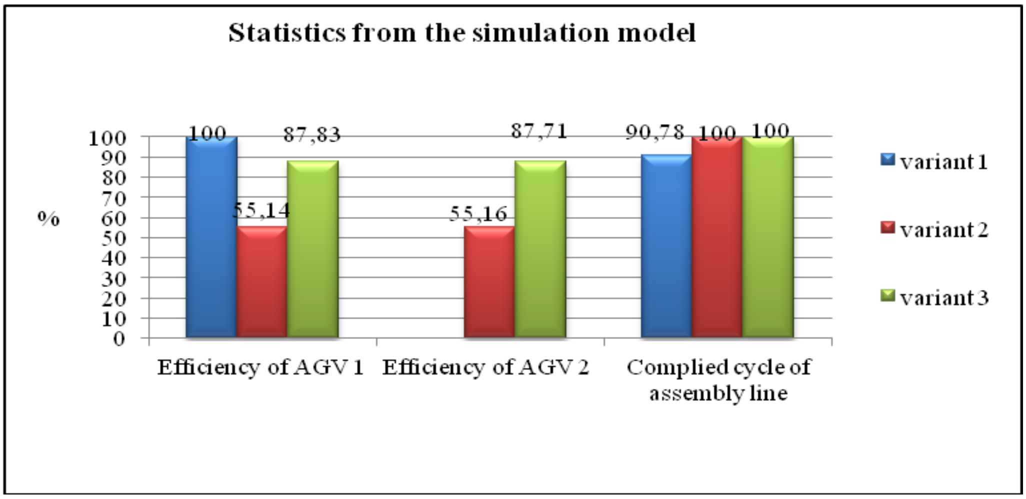

Fig. 12. Simulation Statistics

The three variants have been designed within experiments that were tested also in terms of action random collision situations:

– *Variant 1* - one FTS-CEIT AGV with efficiency of 100%, 5 dynamic conveyors needed, unrealized requirement of production cycle,
– *Variant 2* – two FTS-CEIT AGVs with average efficiency of 55,15%, 10 dynamic conveyors needed, realized requirement of production cycle,

– *Variant 3* - two FTS-CEIT AGVs with average efficiency of 87,77%, 6 dynamic conveyors need, realized requirement of production cycle.

Each designed variants needed 16 static conveyors.

The simulation and emulation offered as a part of product in implementation of logistics systems FTS-CEIT has been shown as an excellent tool. The simulation helped to find not only required number of FTS-CEIT AGVs, but also it supported the identification of system bottlenecks and thanks to that the logistical system was developed which could fit all requirements for this system in pre-implementation phase.

4. CONCLUSION

Using an appropriate combination of particular approaches designer of manufacturing systems can flexibly respond to customer's requirements and provide them a tailored service. These progressive approaches are not groundbreaking ways in the use of simulation in terms of practice; they just make availability of such solution easier. In order to make simulation part of business systems, it is necessary to develop simplified application methods (interface between user and simulation) that enable rapid use of simulation in the commercial sector, not only in terms of research. The authors vision is to afford a simulation for simple problems when they get rapidly a solution and so flexibly respond to turbulent changes. The simpler simulation for commercial sector is, the more it is in use.

The above mentioned progressive simulation approaches allow:

- to easily enter own values of elective variables (loading input data from an external source),
- to operate parametric simulation model by managers and operators in production shop,
- to test various managing and optimizing methods without deeper knowledge of modeling and simulation methods, and simulation software,
- to execute simulation runs and process optimization without possession of simulation software,
- to find the best solution of company problems in a very short time,
- to save financial resources.

The approaches described in this paper aim to the improvement of companies' interest in simulation of manufacturing and logistics systems.

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Computer aided engineering,
Object oriented programming,
Gears, gearing, gear drives

Sławomir HERMA*

DYNAMIC VISUALIZATION OF INVOLUTE CYLINDRICAL GEARINGS COMPUTATIONS, USING OBJECT ORIENTED PROGRAMMING

Abstract

The primary objective of this paper was to create a computer software supporting the calculation of geometry and strength of involute cylindrical gear elements, characterized by ease of use, intuitive graphical interface, fast data processing and the ability to present results of calculations in graphical form. The paper presents and compares some existing IT implementations available as commercial software, gives the specifications and expectations for new software based on the method of possible solutions area.

1. INTRODUCTION

The most common approach in the design of involute cylindrical gears for general use is the initial assumption of centre distance and gear ratio and then determination on this basis: operating pitch diameters, outside diameter, face width, number of teeth, pressure angle, helix angle etc.[1,2] (see Fig.1.)

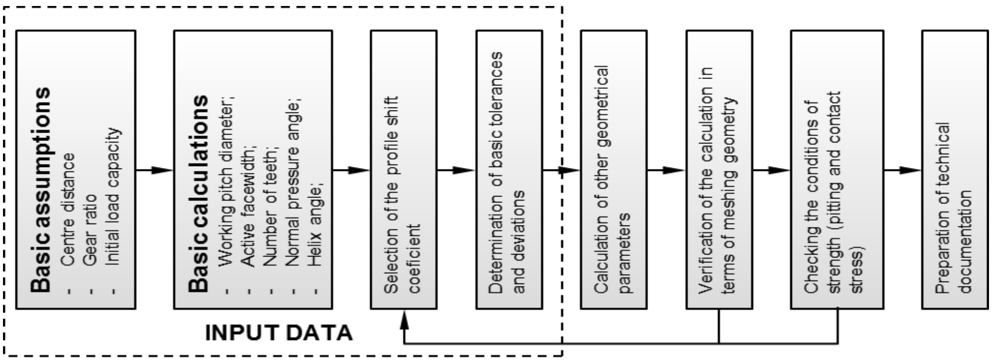

Fig.1. Standard procedure of gear designing

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Generally, there are two ways to pre-determine the basic geometric parameters. It can be assumed in advance of their value following the experience or the standards (ISO, AGMA), or to carry out a detailed procedure for the initial selection of such values, for which the high degree of probability is expected to meet the basic requirements for strength. In many cases there are used the empirical formulas.

The rest of calculations carried out according to well-defined deterministic algorithm, which leads to find a full description of the meshing. The final phase is to verify the results obtained and, if necessary, modify input parameters. Frequently this involves returning to the previous step, where the profile shift coefficients are selected (because they are the strongest influence on other parameters, which determine the geometric accuracy of meshing). Basic gear parameters are modified rarely, they are permanently fixed at the beginning of the procedure.

Strength calculations allow to validate the assumptions adopted at the beginning of the project. In case of unsatisfactory results gained from previous steps of algorithm, the procedure for calculation of geometrical parameters must be repeated (many times) for different input data combination. Also, the changes must be made in such a way as to improve the strength but not cause deterioration of geometry.

These requirements are difficult to achieve when gear designing is carried out in accordance with the traditional approach. A slightly different way to solve the problem, was proposed in [3,4], where the method of "possible solutions area" has been applied. It uses graphs of geometric and strength parameters as a function of profile shift coefficients. This allows the simultaneous analysis of various parameters on a common graph. (see Fig. 2.)

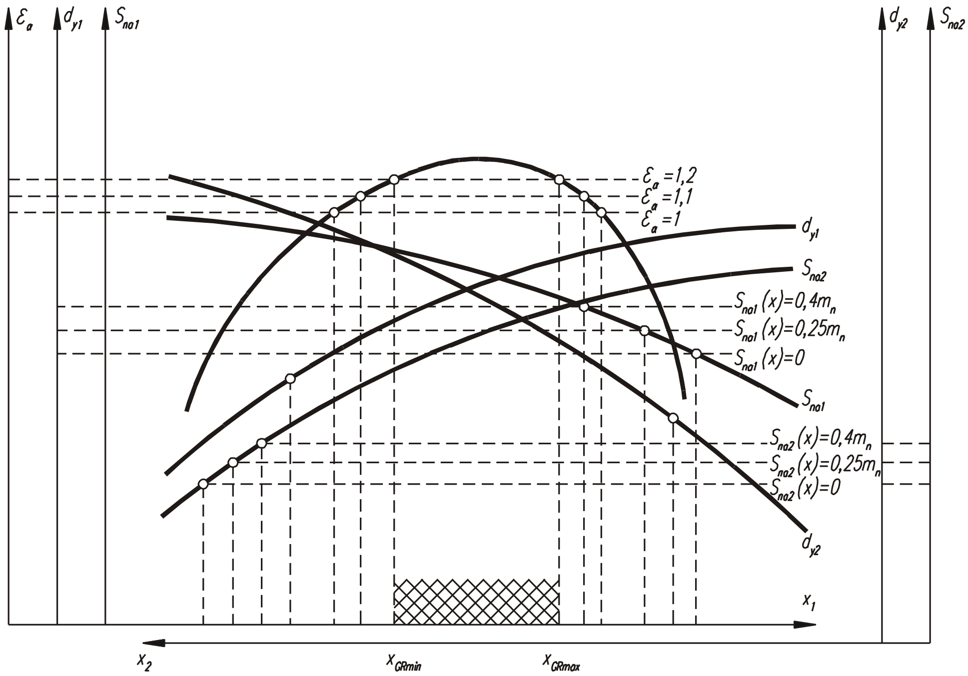

Fig.2. The area of possible solutions for a single mesh, according to the following constraints:

$$x_{n1} \geq x_{gr1},\quad x_{n2} \geq x_{gr2},\quad x_{n1} + x_{n2} = 0,\quad s_{na1} \geq 0,\quad s_{na2} \geq 0,\quad \varepsilon_{\alpha} \geq 1,\quad d_{y1}, d_{y2} \geq 0$$

Because the analysis takes place as a function of both cooperating teeth, it can be carried out taking into account the correction "P-0" ($x_{n1} + x_{n2} = 0$) and "P" ($x_{n1} + x_{n2} = const$). Presenting the selected gear parameters in a common coordinate system and taking into account all known constraints, it is possible the gradual narrowing of the areas of possible solutions to obtain a range of the arguments (x_{n1} and x_{n2}), for which there exists a feasible solution. The last step concerns the choice of values of decision variables such that the adopted optimization criteria are satisfied as well.

2. COMPUTER AIDED GEAR DESING

There are a large number of software for the design of gears. They differ within the scope of the features offered. Many of them have a high degree of specialization as they often are created for specific companies [5].

GearDesignPro from Dontyne Systems, is a program for design of external spur gears with straight and helical teeth. It combines basic and advanced options for transmission analysis:

- geometry manager with four modes,
- calculation of surface durability and tooth bending strength,
- flash temperature calculation,
- ability to define a range of input variables (module, number of teeth, normal pressure angle, helix angle gear ratio etc.), calculating all the possible gear for these ranges;
- optimization of centre distance,
- taking account of tolerance according to ISO 1328,
- 2D and 3D visualization of gear teeth, automatically updated when changing the geometrical parameters.

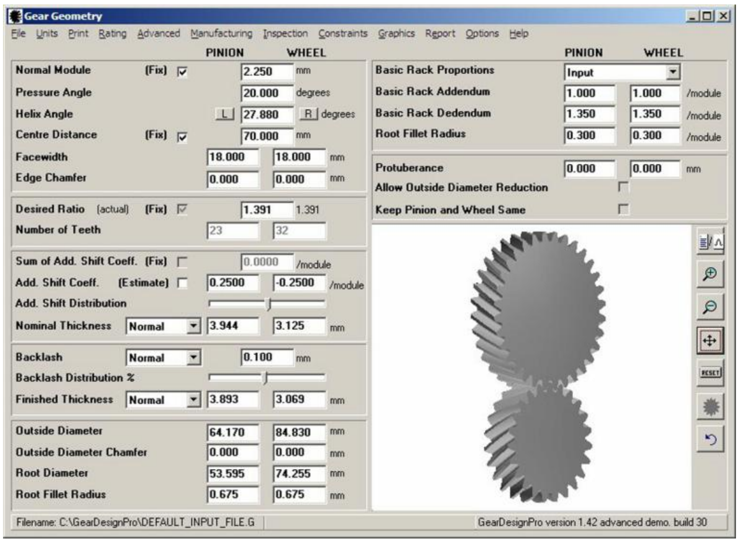

Fig.3. View of the calculation window – GearDesignPro [5]

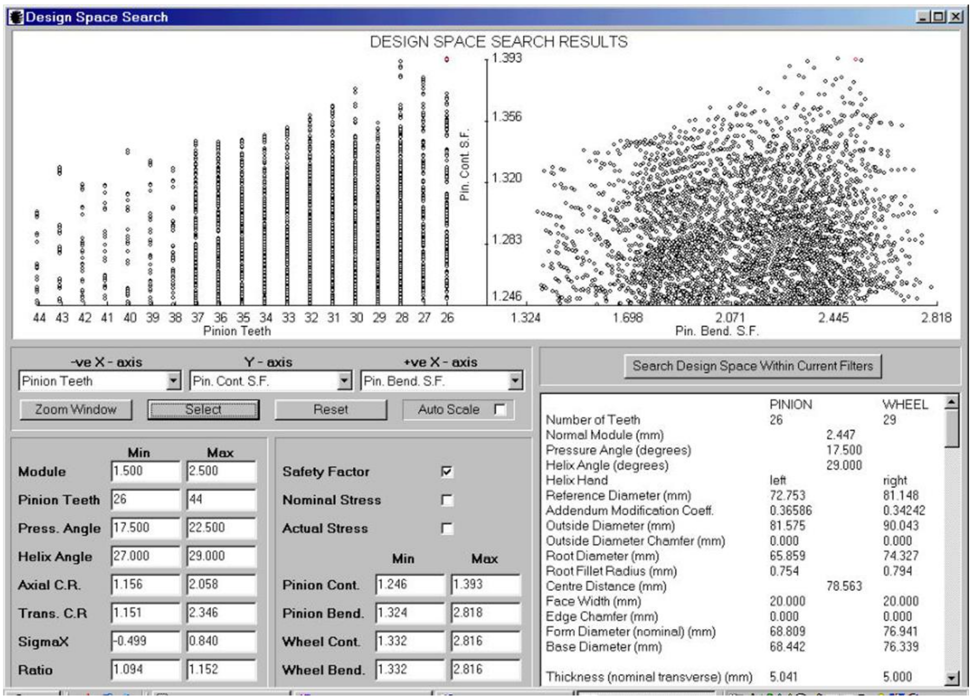

Fig.4. Searching the solution space – GearDesignPro [5]

One of the functions of the program is searching the ranges of input data and generating all possible solutions to the gear train. This allows to choose the optimum solution. However, the graphic presentation of a set of possible solutions is very difficult to read and does not perform any useful role other than aesthetic. The range of input variables is fixed rigidly. There is the possibility of a dynamic manipulation of either the input variables. The procedure for calculating all the possible gear for the given ranges may take several minutes.

HyGears from Involute Simulation Software is a program that was created to help designers of helical, spur, worm, hypoid and bevel gears to shorten production time and improve the quality of their products. The software has a graphical user interface that simplifies many operations and allows to better understand the results. Many models are presented in three dimensions. The program also allows simulation of machining processes.

The program gives the opportunity to analyze the models created in 3D and finite element modeling for comparative measurements using a coordinate machines. In the selection of geometric parameters, the program allows the calculation of output for given input values from the database and use ready-made definitions of geometry. The results are displayed in summary form, along with the settings on the machine which is designed for gear manufacturing. The program has a very rich capabilities on gears and machining processes visualization, also in the form of animation. However, much of these features is more aesthetic in nature. The program does not allow to define ranges of input variables, they are entered as a single input. The program also returns only one value for each output parameter, and does not allow a ranges.

GearCAD from GearSoft Design Company is a software designed to calculate the geometry of involute gears and design of internal, external and planetary gears. Design process occurs in several steps. The program calculates all dimensions and parameters needed to design, manufacture and measurement for the selected gear tooth shape.

3. BASIC ASSUMPTIONS FOR THE NEW SOFTWARE

Key features and requirements for new application, are as follows:

- System architecture:
  - the use of object oriented programming;
  - placing the class definitions in a separate module to ensure their independence from the graphical interface and easy implementation in any other application without modifying the source code;
  - using such programming methods to allow future modifications and implementation of new features;
- Features offered:
  - implementation of a single tooth geometry calculations,
  - implementation of a meshing gears geometry calculations,
  - implementation of strength calculations (surface durability and tooth bending strength),
  - use of the possible solution area method, which allows to present the output data as a function of profile shift coefficient – on one common graph;
  - possibility of presenting all calculations results in both graphical and numerical form;
  - the ability to define which constraints and criteria are to be included, to allow comparison of simulation results with and without restrictions;
  - the ability to control the visibility of the individual graphs, increasing the readability of the chart;
  - the ability to read the cursor position on the chart and to present of output data in numerical form, corresponding to the selected point on the graph;
  - the ability to visualize the gearing in AutoCad;
  - the ability to generate reports and print simulation charts;
- Performance:
  - application of object-oriented programming has lead to vary fast operation of the program;
  - the structure of the procedures is to enable minimization of computational complexity of algorithms;
  - execution of strength calculations during gear simulation should be optional;
  - the program should allow the definition of accuracy for creating charts and areas of possible solutions;
  - the structure of the program should also provide fast response for slower computers;
- Dynamics:
  - the high level of application performance should enhance the dynamics of the gear design process;

    - the possibility to dynamically change the decision-making input parameters, should allow a real-time analysis of all the characteristics of the simulation graph and any changes in area of possible solutions;
- GUI (Graphical User Interface):
    - provide the ability to easily navigate the program without the need to cyclic switching between different views;
    - provide the ability to use the application at different screen resolutions;
    - provide the ability to control many chart options to personalization and customization of GUI.

4. DATA STRUCTURES AND ALGORITHMS

The program defines two classes: *TTeeth* – representing a single tooth, and *TGearing* – representing the meshing gears. Their mutual relationship is not in the traditional way. *TGearing* is not a descendant class of *TTeeth* and does not inherit directly the fields and methods. Both classes inherit directly from *TObject*, however *TGearing* includes some fields of *TTeeth*. This arrangement is known as friend classes (see Fig.5.)

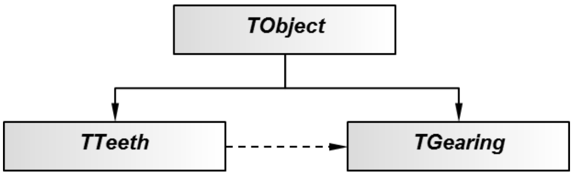

Fig.5. The hierarchy of classes in the program

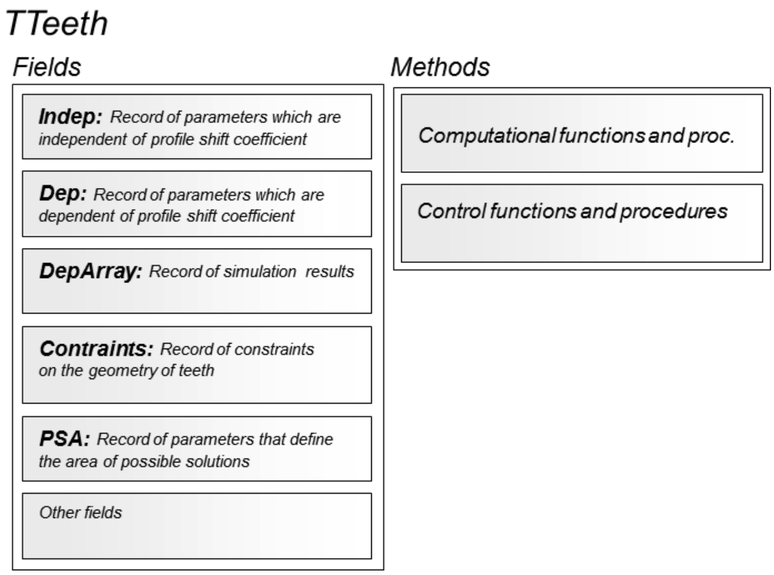

Fig.6. General structure of class *TGearing*

The *Indep* record contains a set of geometric parameters, independent of the profile shift coefficient:

- given by the user,
- calculated during the computations,
- used in the meshing analysis and used by the methods defined in class *TGearing*,
- used in the strength analysis.

```
TTeeth = class (TObject)
 Indep:record
  //{*} - parameters given by the user
  //other parameters are calculated during the computation
  {*}mN     ,{*}alphaN ,{*}beta   ,{*}z      ,InvAlphaN ,
  {*}yN     ,{*}jN     ,xGR       ,mT        ,{*}xNMin  ,
  {*}xNMax  ,{*}xNStep ,alphaT    ,InvAlphaT ,{*}kA     ,
  betaB     ,d         ,dB        ,pT        ,pET       ,
  zZ        ,zGR       ,
  //Parameters of a single toothed element, used in the
  //meshing analysis - independent of xn
  {*}b      ,{*}c      ,dW        ,zp        ,alphaTW12 ,
  invalphaTW12         ,alphaNW  ,invalphaNW ,
  // Parameters of a single toothed element, used in the
  //strength analysis - independent of xn
  {*}e      ,{*}ni     ,{*}fTMax  ,fT        ,{*}rZ      ,
  {*}hFP    ,{*}roFP   ,dBN       ,dN        ,zN         ,
  h         ,ePO       :Real
  end;
```

The structure of *Dep* record is analogous, but contains the set of parameters dependent of the profile shift coefficient.

DepArray is an array of records containing the results of the simulation process. It includes a set of parameters obtained from the iterative procedure needed to generate simulation graphs.

Constraints – is an record containing logical variables, indicating the geometrical restrictions, included in the analysis of the single toothed element.

PSA – is an record containing two parameters *xNMin* and *xNMax*, determining the area of possible solutions for a single toothed element.

Computational functions and procedures are used to calculate all the output parameters, included in the simulation of a single toothed element.

A set of main control functions and procedures include:

- *CheckInputData* – validation of input data entered by the user,
- *CheckConstraints* – checking the constraints, selected by the user,
- *GetIterations* – calculation the number of required iterations needed to generate a simulation graph,
- *GetPSA* – executing a simulation process for a single toothed element and calculation of possible solutions area (the range of shift profile coefficients).

The second major class, defined in the program – *TGearing* – has two additional fields: *TPinion* and *TWheel* of type *TTeeth.* This allow use all fields and methods defined in the

TTeeth class, by *TGearing* class and thereby create associations between various toothed components, forming the different gears.

However, the most important determinant of overall system performance is the structure of functions and procedures used in the calculations (see Fig. 7).

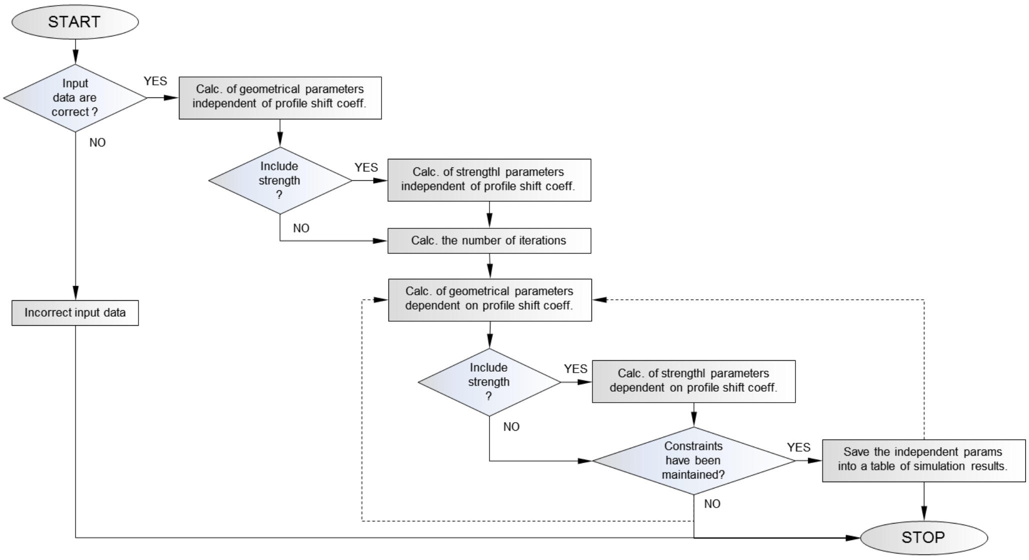

Fig.7. General structure of the main function *GetPSA*

Most of the functions calculating the parameters independent or dependent on profil shift coefficient, have the same internal structure (see Fig. 8).

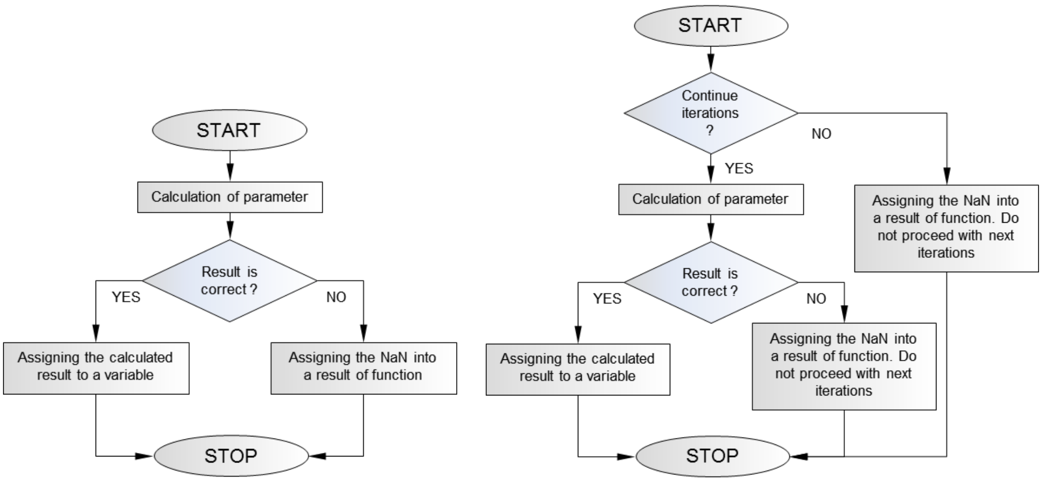

Fig.8. General structure of the functions calculating parameters independent and dependent on profile shift coefficient.

With such a structure of calculation procedures and functions, it is possible to obtain an effect similar to real-time systems. In fact, any change in any input parameter value, causes an almost immediate re-calculation of all data needed to generate the simulation graph.

5. USER INTERFACE DESIGN

The whole application has been designed and developed in the Delphi programming environment. To design the graphical user interface were used a set of components, included in the predefined VCL library. A major role in the GUI structure plays the simulation graph, implemented through *TChart* component. (see Fig. 10.)

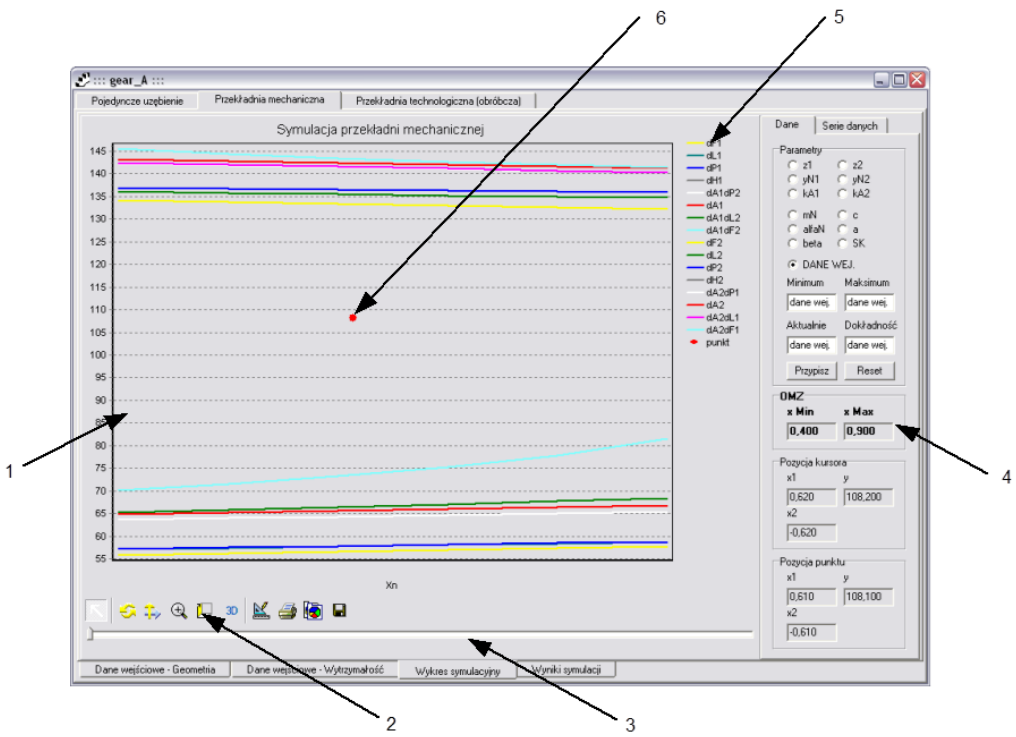

Fig.9. Implementation of gear simulation chart in the application window; (1 – the chart area, 2 – chart options, 3 – a slider used to dynamically change the values of selected parameters, 4 – simulation control panel, 5 – chart legend, 6 – gear parameters reading point)

After entering the input data and generating the gear simulation chart, the user can proceed to the analysis of meshing and search the area of possible solutions. Modify the values of any of the input parameters will re-create the chart. Increase (or decrease) the search area of solutions is possible using the control panel, choice and attempts to modify the values of one or more input parameters. The response of the system to any change made is executed immediately and every time it is possible to read and save all calculated parameters.

6. CONCLUSIONS

The possibility of visualizing the characteristics of selected gear parameters and consideration of all known constraints (geometry, strength, exploitation) allows for a gradual narrowing the common area of possible solutions and consequently obtaining the interval of the arguments, for which a solution of meshing really exists.

The last stage of the design process is to identify such values of decision variables, for which the adopted criteria of optimization will be met most satisfactorily.

The combination of graphical and analytical methods for determining areas of possible solutions, and practical application of the program described, also provides the following benefits:

- the possibility to simplify and accelerate the production process through the unification of product range.
- the gear design process automation with the use of computer algorithms,
- reduce the time and costs of technical production preparation stage

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