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The Concept of Functional Virtual Prototype in the Design of Excavator Cutting Teeth

RESEARCH

Cutting teeth for continuous excavator is an element of bucket assembly which has a dual function in the process of excavation, that is destruction of soil (media) and its excavation. Since most excavator processes depend on the processes in the cutting zone, it is necessary to pay particular attention to the cutting teeth design and testing of completed prototypes in working conditions. Prototype testing might be a problem, regarding distinctive excavator design,working conditions and work technology. This paper presents an alternative method for resolving these problems by utilization of simulations and simulation models through development of functional virtual prototype. Further more, it presents an example of the development of the basic model of functional dependence of cutting teeth wear and appropriate load. Development objective of such and similar models is their implementation into the virtual prototype.

Keywords: *cutting teeth, design, virtual prototype, rotor excavator*

1. INTRODUCTION

In order to present a high-quality, low-cost product to the market in a very short time, it is necessary to shorten the time for development and innovation of the product, reduce design and production costs, and provide high quality of the product as well. Considering the fact that much has been already done in the field of the production optimization, it is necessary to search after new reserves for attaining stated goals in the first phases of the development, particularly during the design process of the product, but also during the production and examination of the prototype.

Modern approaches in the product design as well as methods used to this effect imply interdisciplinary bases of knowledge and constant communication among them.

All previously mentioned refer to several significant and unique requests that are imposed by the design process[5]. Design solutions also have to satisfy complex production requirements as well as the requirements concerning the assembly work. Design engineers must take into consideration a number of aspects reffering to fixture, maintenance, storage, lifetime, reliability, safety, recycling etc. The product has to be designed in such way so as to make a profit and satisfy the requirements both of the users and the market, in other words, design engineers have to be aware of the user's expectations about the product. Finally, it is necessary to take into account the fact that both processes within which the product and its parts are being produced and the conditions under which they are used are changeable. Considering the changeable nature of production and exploitation conditions, the requirement reffering to the product robustness (strength, resistance etc.) is an essential design requirement.

Production design, from simple to the most complex forms, with fulfilment of previously stated requirements, is a very difficult, demanding and complex task.

It is, therefore, of great importance to find creative and efficient solutions to the problems that might occur during the processes of production and exploitation. It is particularly important in early phase of design when ideas are generated and decisions which determine the nature and characteristics of the product are made.

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2. INTEGRATED DESIGN APPROACH

The aim of integrated approach is to shorten the development time and additionaly improve the product in this phase [6]. Realization of integrated approach can be observed through simultaneous and virtual concept. Simultaneous concept is based on need for close communication between design and technology. The point is that the product and technology development are simultaneous. Decisions concerning the design process are made on the basis of technology development and vice versa. In such a way the time for development is shortened and possible misunderstandings concerning the realization of proposed solutions are avoided. Virtual concept is based on the unification of the product development in space and time. It is models, modeling and simulation that represents the basics of the concept. The models are used to simulate the product, its properties, the production and the process of exploitation as well. The aim is unification of the simulation and its simultaneous realization from several different aspects depending on the current subject of consideration.

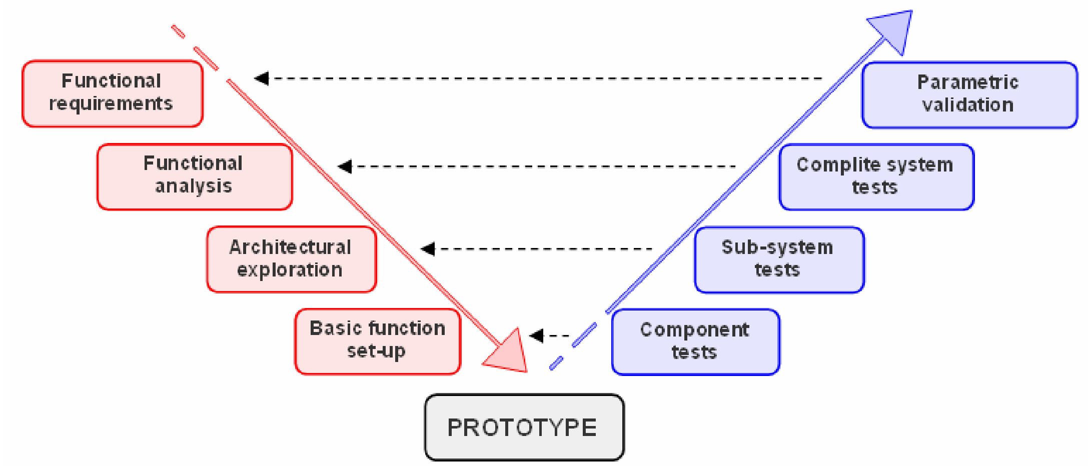

Figure 1. Classical V approach to design with the physical prototypes [1]

It is physical prototype production and testing that is a bottleneck in almost every design process of a new constituent element of an continuous excavator or in reconstruction of the existing ones. The question concerning this issue has been raised. Continuous excavators are recognized as one segment of the continuous excavation process and the process of coal transport. Since the process is continuous, if any element of the system does not work, the entire line is out of order. Considering the fact that such systems are expected to work continually, disregard for planned stoppages and overhauls, any other stoppage would generate serious problems in terms of the satisfaction of the set requirements and it would also reflect on economic costs [9]. In addition, working conditions are quite unfavourable and there is a danger concerning large dimensions of rotor excavator components, a danger regarding work performance and technology as well as current condition of the machine and her impact on prototype behaviour (e.g. prototype can be valid, however, due to relatively bad condition of the assembly or subassembly, it is not possible to get valid results). We have to take into account the quality and assembly work of the completed prototype as well as the impact that the prototype breakdown has on another machine elements (e.g. concurrent fracture of several cutting teeth can cause bucket damage). On the other hand, prototypes are principal instances as they have a key role in the final confirmation of the default solution.

Concerning the above mentioned issues, it is of an immense importance to find an alternative approach to assembly work which would imply assembling of the physical prototype only when all possible previous adjustments are made and afterwards tested and when all other possibilities are exhausted. A possible alternative lies in the development and application of the virtual prototype. Nowadays, virtual prototypes are used for better perception of future product appearance even at the early stage of development as well as for simulation and testing of the product characteristics before the production of physical prototype. Thus, it is possible to achieve major economies in, or even to eliminate, costs and time needed for production and modification of physical prototypes. Apart from visual representation of the product, virtual prototype has the task of description and simulation of the product physical performance ([4], [5]). As distinguished from the physical prototypes, virtual prototypes make use of modern computer science, so the focus of design process shifts from physical to virtual environment, which represents a significant advantage in resolving problems concerning strip mining excavators.

3. FUNCTIONAL VIRTUAL PROTOTYPE

The design process, known as process V (Figure 1.), consists of two clearly defined phases. The first phase includes the top-down analysis that leads to a gradual and hierarchical definition of the system functions and its components to the lowest level, i.e. the level of the basic physical examination. The second phase includes systematically repeated serial of corrected prototype tests up to a point when the complete validation of the system has been realized.

Classical CA-x approach covers computer supported technologies aimed at the generation of product model, the analysis of its condition and definition of necessary technological processing parameters. Such approach is also known as "art to part". Solutions attained in such a way satisfy requirements for solving the problem in the cases of less complex systems (products and processes) design. The notion of complexity is not related to the number and complexity of the components, but to the possibility and appropriate account of inner and outer interactions in the system. By generating the complex systems, whereat the elements are connected through basic metaphysical manifestations on the lowest level, early defect identification becomes practically impossible, therefore the success of the "first" design is hard to achieve. On the other hand, the later we perceive the problems during testing, the higher costs of correcting them are required (for example, perceiving errors in linking components of the cutting tooth is more convenient than perceiving problems in versification of the adopted concept of the cutting tooth). Furthermore, it should be pointed out that the problem of building optimal system on the whole cannot be solved by optimal design of certain components of the system.

Therefore it is necessary to define new horizons in the field of the existing technologies and step towards new ones. It is feasible to be done by development of new devices as well as integration and modification of the existing technologies, such as CAD/CAM/CAE, so that the subject of their examination might be extended to a complex system.

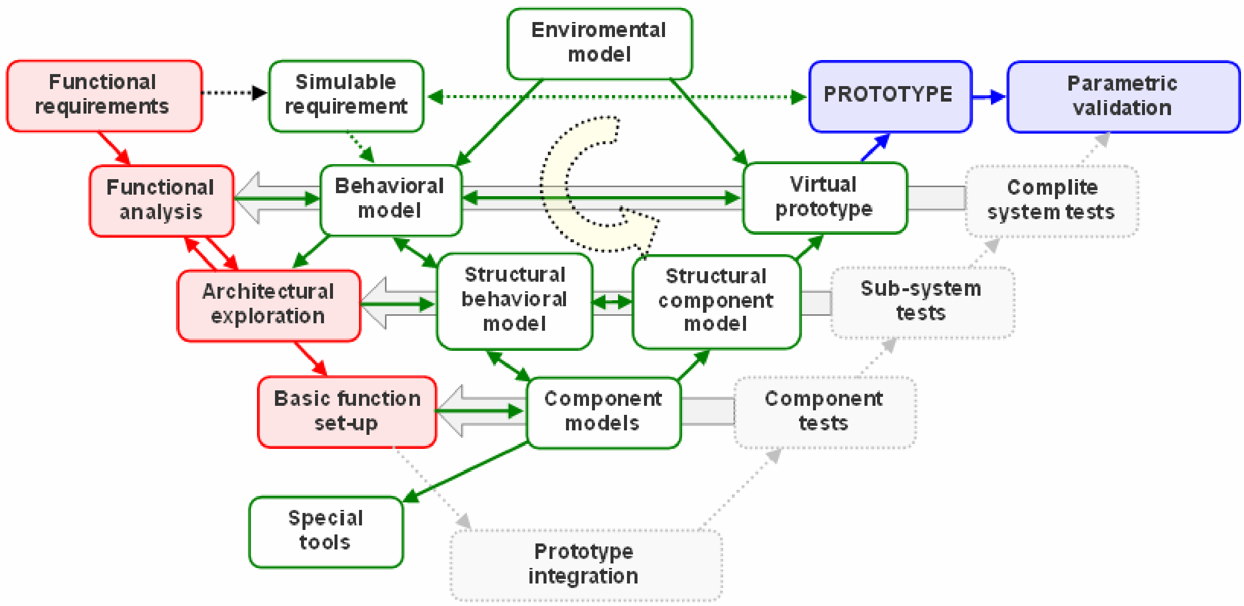

Figure 2. The diagram of the Functional Virtual Prototype concept [2]

The concept *Functional Virtual Prototype – FVP* (Figure 2.) enables perceiving not only the functions of some of its components, but also the function of the entire system and its operative performances. The approach based on FVP is a range of well-organized tasks used in the design process or the process of improving the existing system through constructing separate models that describe the system. By the analysis of the system functions and categorization performed in accordance with the specification of the realization, a complex model that provides better comprehension of its essential meaning can be built. Basically, this concept is founded on the descriptive and predicative models of the objects, parts of the systems and their environment. Thus, computer simulation and testing are placed in the foreground, whereas physical production and testing are used as utmost tools for design versification and improvement of the simulation models.

4. BASIC ELEMENTS NECESSARY FOR GENERATON OF THE VIRTUAL PROTOTYPE

The most important task of the virtual prototype is a complete conveyance of design, production, development and testing phases on a computer, which would considerably reduce the time and costs of product development. Without distinction of what type of functional virtual prototype it is about, i.e. no matter what process or system is modelled, the following phases in construction of such models can be defined [5]:

1. Production
2. Testing (testing simulations)
3. Estimation
4. Development
5. Automation

Design of the system virtual prototype (of the product, process etc.) is completed in the first phase. In this phase structure defining and disintegration into integral subsystems and components are performed. Clear correlations established between the integral components at this stage enable the development of true and complex model with possible variations. For example, geometry and mass features of separate components of the cutting elements can be attained from solid models, whereas mechanical characteristics can be achieved from component models of the definite elements or from experimental testing.

One of the significant phases includes formation of the virtual equivalent for laboratory testing and testing in the field. Within laboratory testing, the virtual prototype requires installation of the virtual test equipment for procedure reproduction and reproduction of conditions realized by the utilization of real appliances and testing machines. Thereupon, test constitution reflecting actual or needed exploitation conditions are performed.

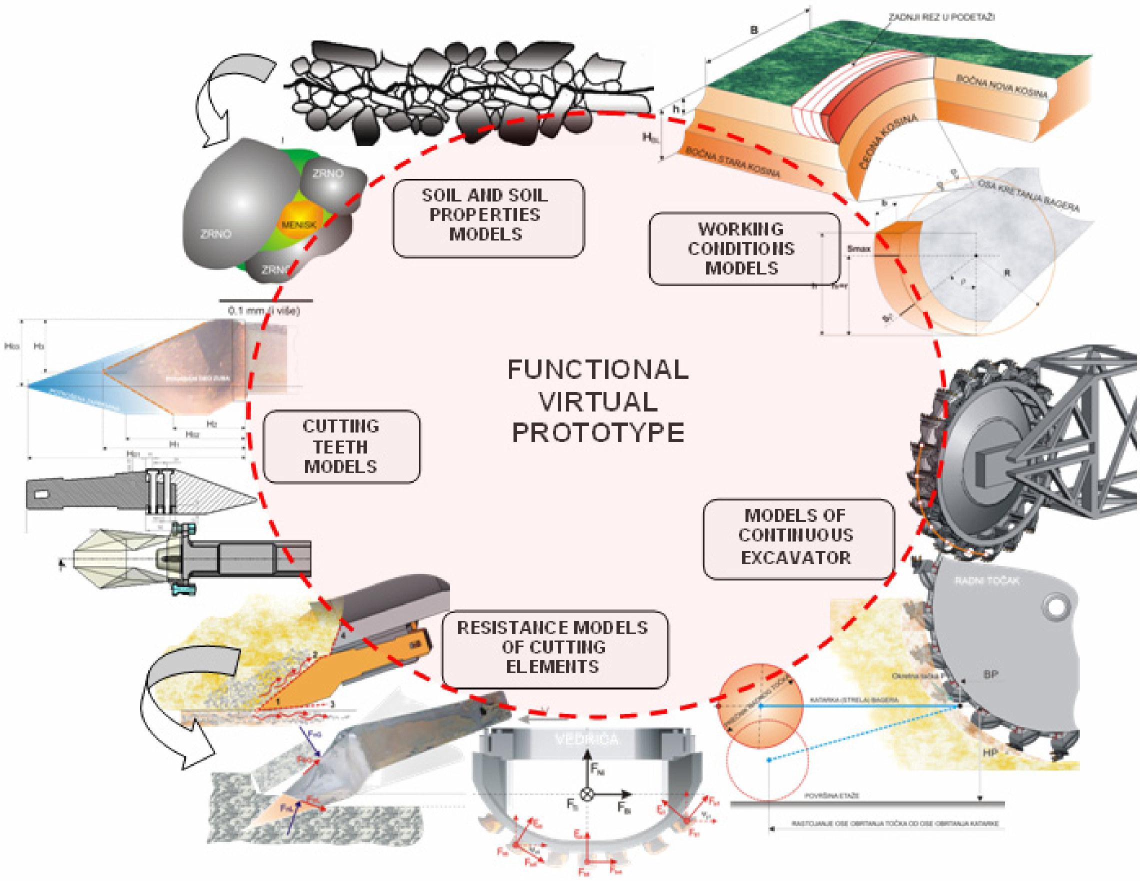

Figure 3. Synoptic diagram of the FVP for bucket wheel excavators

At the next stage model estimation is performed, i.e. virtual and physical model are tested in the identical manner, and afterwards comparison and deduction are performed. By additional adjustment of the virtual test we achieve a reliable model for further testing.

In the process of the virtual prototype utilization, its development and improvement are carried out, within which simpler initial virtual prototypes are composed into complex functional virtual prototypes. Thus, modular solutions that can significantly expand activity field of the basic virtual prototype are obtained, whereat further adjustments refer only to some newly-added segments (e.g. in the process of bucket testing whereat not only cutting teeth but special blades in a form of a knife are added as well. Concerning this, VM teeth buckets can be used with an addition of new modules that are later adjusted). Improvement is always carried out in two directions, in the direction of improvement of the model accuracy and constancy, and in the direction of improvement of the product design.

The final phase of the design is process automation of the virtual prototype construction. It is only when enough "knowledge" and "experience" in existing models are generated, that we can approach this phase. Current generation of new similar constructions is achieved by the automation in a short time. Thus the structure and most components are "lent", whereas adjustments refer only to those segments that have difference for new and existing design. The utilization of FVP can be automated only when one completed, through many cycles estimated model of the virtual prototype exists and when it is tuned through the change of its characteristic parameters.

5. WEAR MODEL OF CUTTING TEETH

The following text presents an example of a model defining that connects cutting elements load with the extent of their wear. When we talk about a part of the cutting tooth wear and their influence on the process of cutting soil, we talk about the enormous consumption of materials in two characteristic places. The first one is the tooth-face wear, which is a consequence of excavated material influence. The second is the dorsal surface wear, which is a consequence of the interaction between back part of the tooth and the forehead of the excavated material block. In general, the worn wedge-shaped tool with finished width, as shown in the Figure 4., can be approximately assumed.

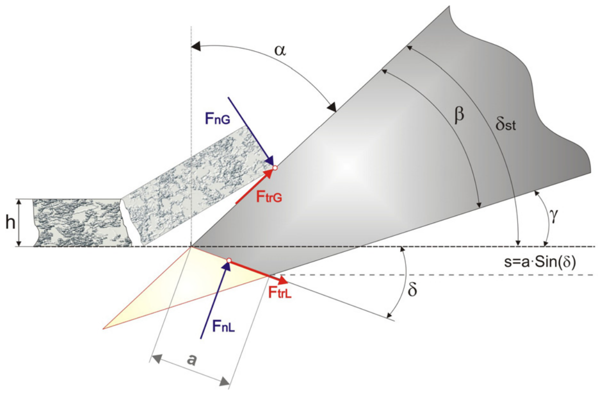

Figure 4. Wear model of the cutting teeth

The Figure 4., presents the following variables: α - cutting angle, β - wedge angle, γ - relief angle, δ - angle of tooth wear, $\delta_{st}=\beta+\gamma$, F_{trL}- frictional force (resistance) on the dorsal surface of the tooth, F_{nL}- a normal component of the frictional force on the dorsal surface of the tooth, F_{trG} – frictional force (resistance) on the tooth-face, F_{nG}- a normal component of the frictional force on the tooth-face, a – wear length, s – thrust length. The forces defined by this model are valid only with the following hypothesis:

a) The force function F_{nG} is a feature of the excavated material and it is proportional to the tooth-face ($A_G=b{\cdot}h$): $F_{nG} = b \cdot h \cdot k_B$, whereat: b – is the width of the cutting blade, k_B – is the specific resistance to chip productions [kN/m^2], h – is the thickness of the chip .

b) On the basis of the wedge effect and previously generated crack that is typical for brittle breaking with a small deformation of the soil (the initial destruction phase has been completed), the direction of the force effect F_{nG} lies close to the perpendicular to the motion path (Figure 4.).

c) Either elastic or plastic deformation of the excavated material occurring on the backside of the wear surface, brings about the force F_{nL}, a characteristic of the material itself, represented as the function of the penetrative depth s: $F_{nL} = b \cdot a \cdot s \cdot k_v$, whereat b – is the width of the cutting blade, k_v – is the specific resistance of the wear surface. [kN/m^3]

d) Direction of force F_{nL} lies perpendicularly to the wear surface or it is inclined at an angle in regard to the perpendicular (in this case the force on the top of the tooth is taken into consideration).

e) The wear specific resistances are values that should be determined and they present the function of the excavated material characteristic.

f) The presented tooth model should be observed in the plane that has been inclined at some angle (ε) in relation to the movement direction. Owing to the angle, the frictional forces would not lie in the plane of the wedge. Consequently, this angle is a result of the teeth arrangement in the bucket and current position of the examined tooth in the movement trajectory (sequence rotation of the working wheel and swerving the arrow excavator).

By observing the previous figure, it is possible to provide an analysis of the forces. Examination of the model in the plane is enabled by the decomposition of the acting forces into adequate components (Figure 5.).

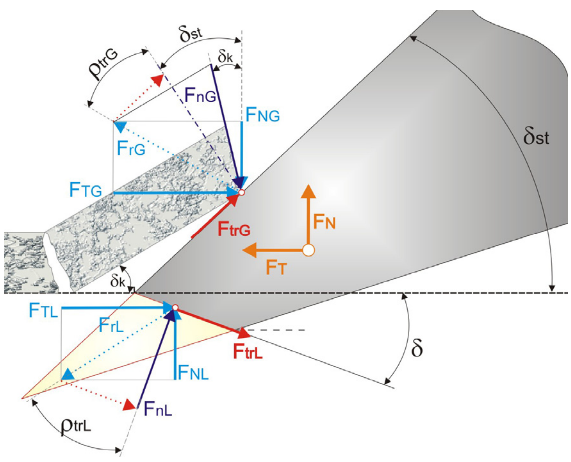

Figure 5. Example of decomposition of the acting forces

The represented model takes into consideration functions of the average values. Basically, the function differs from the model of soil failure, nevertheless it is applicable in this place due to examination of the conditions describing the process in the "middle", not to the examination of the current conditions.

Observing the plane model, determined by directions of the tangential and perpendicular force, in relation to the forces defining within rotor excavator, according to the Figure 5., the following expressions can be defined:

$$F_{trL} = \mu_L \cdot F_{nL}$$

$$F_{trG} = \mu_G \cdot F_{nG}$$

$$\vec{F}_{rL} = \vec{F}_{trL} + \vec{F}_{nL} = \vec{F}_{TL} + \vec{F}_{NL}$$

$$\vec{F}_{rG} = \vec{F}_{trG} + \vec{F}_{nG} = \vec{F}_{TG} + \vec{F}_{NG}$$

When we look at Figure 5., and results obtained from the research [7], it is evident that the normal force F_N must represent sum of two forces, and these are a force exerted from chip generates above tooth-face and the other exerted from wear surface effect on relief tooth surface, which acts even in the case of „sharp" teeth due to blade radius and excavated material structure. This „additional" force and force of friction caused by it are not proportional to the dimensions of chips but to wear surface. Wear angle δ can be considered constant for one cycle of the teeth wear. The size of this angle depends on: design parameters of the teeth, type of excavated material, excavator work technology, bucket characteristics regarding assembly work etc.

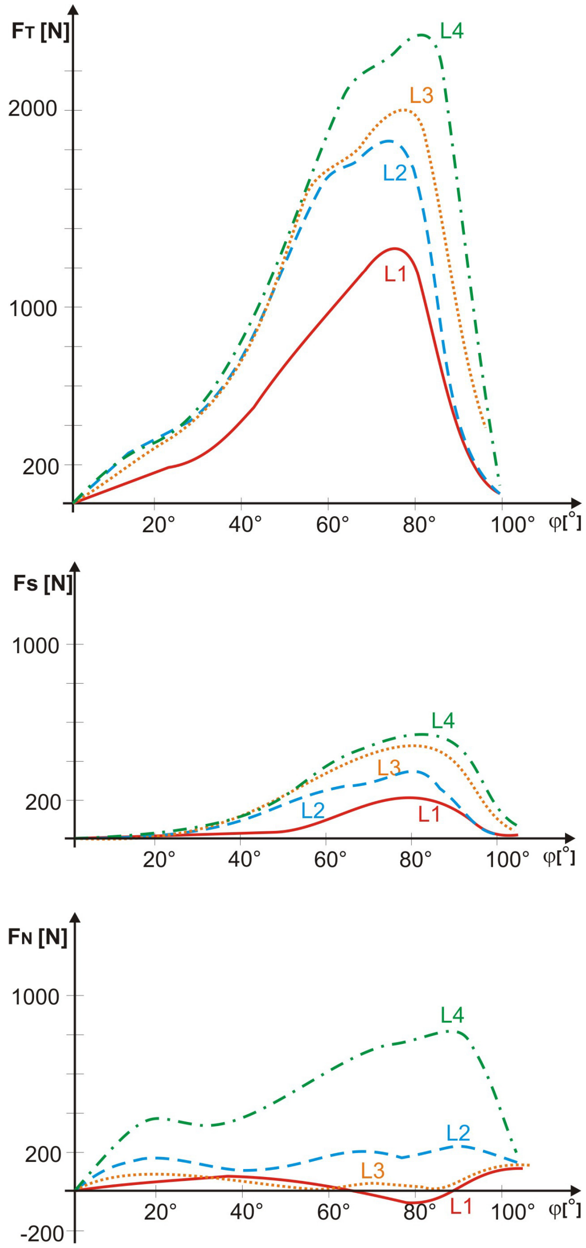

Figure 6. Measured force load for a single tooth (laboratory model)

In accordance with previously shown equations, we can notice the mutual dependence of the size of the wear surface and a component which increases the total excavation resistance. Diagrams (Figure 6.) show the results of realized measurings that testify previous statement. All three components of excavation resistance are measured within laboratory testing. With regard to the subject of this paper, it is more important to examine trends and relative ratio of the obtained results than apsolute value of the obtained resistances. The conclusion that may be drawn is that the increase of wear surface leads to the increase of total required cutting force, for it is necessary to increase the cutting force whereas the soil stress failure remains unaltered.

Table 1. Measured values for previous diagrams

L_1	δ_{st}=35°	δ=0°	a=0 *mm*
L_2	δ_{st}=35°	δ=5°	a=7 *mm*
L_3	δ_{st}=55°	δ=0°	a=0 *mm*
L_4	δ_{st}=55°	δ=5°	a=8.5 *mm*

The model shown on Figures 4.,5., represent a base for connecting cutting teeth load with parameters of its wear. In such a way, variations and possible appearances of wear surface and its dimensions would represent the input, and the output would be the load of cutting elements and other elements of the rotor excavator system. The aim of the development of such and similar models is their implementation in functional virtual prototype. The next figure shows a model which offers a parametric definition of the cutting teeth wear [8].

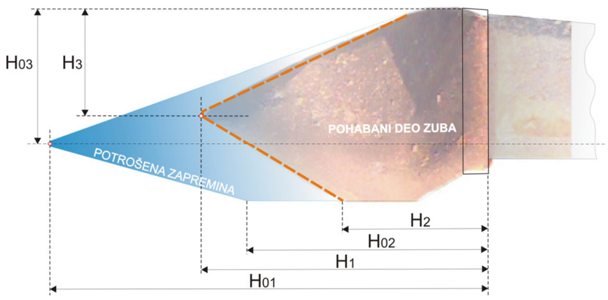

Figure 7. Example of parametric values for cutting teeth wear

6. CONCLUSION

The paper presents the application of the concept of functional virtual prototype in the development of cutting teeth for the continuous excavator. Initial model is singled out and described as an example. It is this model that establishes connection between the load and the degree and form of cutting tooth wear. It represents only one segment that is to be used for complex virtual prototype generating.

Such approach in the development of a new generation of teeth used for continuous excavators would bring about the following positive effects:

- Risk minimization concerning the failure of the teeth conception and its final design
- Time required for the prototype development and testing would be shortened
- The number of repetitive steps within and better organization of design and testing processes
- Improved reliability of design process
- Testing of similar structures would also be possible to carry out repeatedly and there would be a possibility for other excavator components to be tested

REFERENCES

[1] Herve, Y., Desgreys, P., *Functional virtual prototyping design flow and VHDL-AMS*, Forum on specification & Design Languages (FDL'06), Darmstadt (Germany), September 19-22, pp. 69-76, 2006

[2] Legendre, A., Herve, Y., *Functional Virtual Prototyping Applied to Medical Devices Development*, Systems VIP, Strasbourg, 2008.

[3] Ryan, R., *Digital testing in the context of digital engineering - Functional Virtual Prototyping*, Mechanical Dynamics, Inc., Michigan, USA, 1999.

[4] Mandić, V., *Virtuelni inženjering*, Mašinski fakultet, Kragujevac, 2007

[5] Kolarević, M., *Brzi razvoj proizvoda*, Beograd, Zadužbina Andrejević, 2004.

[6] Ognjanović, M., *Konstruisanje mašina*, Mašinski fakultet, Beograd, 2003.

[7] Hitzschke, K., Jacob, K., *Experimentelle Analyse der Belastung des Schaufelrades durch den Grabvorgang*, Teil 1,2, Hebezeuge und Fördermittel 24, Berlin, 1984.

[8] Popović, M., Jugović, Z., Slavković, R., *Integrisani pristup konstruisanja habajućih reznih elemenata kod rotornih bagera*, Serbiatrib'07, Kragujevac, 2007

[9] Popović, M., *Istraživanje i razvoj dvodelne konstrukcije zuba kod rotornih bagera*, Magistarski rad, Tehnički fakultet, Čačak, 2007.

[10] Franek, F., Vorlaufer, G., Edelbauer, W., Bukovnik, S., *Simulation of Tribo systems and Tribometrology,* Tribology in industry, Vol.29, No.1&2,2007.

[11] Ivković, B., *Tribološke površine u tribo-mehaničkim sistemima*, Tribology in industry, Vol.21, No.2, 1999.