An integrated model for designing of technical systems: another step to coherence between theory and practice

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Abstract - A number of authors recommend selecting the systems design methods to be used depending on the practical tasks to be solved. At the same time, results of studies aiming at clarifying and systematizing practical tasks are very rare. In the frames of the research performed, it was revealed that in the companies four major tasks use to be solved - adapting an existing solution to work in new conditions, refining an existing solution, combining it with previously developed elements and creating a new solution. Resultantly, in the research an integrated model for design of technical systems was proposed. This model was obtained by combining (overlaying) the methods for solving the four main tasks defined and subsequently the content of the different stages in the proposed model was clarified.

1. Introduction

In the second half of the last and the beginning of this century, scientific publications emerged that outlined the theoretical foundations of modern science for development of technical systems. A number of authors, summarizing the experience gained so far and adding their own personal contribution, presented completed studies that are justifiably considered fundamental from a methodological point of view (Birkhofer ed., 2011; Cross,2004; Hubka,2004; Hubka and Eder, 1992; Hubka and Eder, 1996; Koller, 1985; Pahl and Beitz, 1977; Pahl et al.,2007; Roth, 1982 and Ullman, 2010). The scientific results found their place in the training of students and generations of engineers gained methodological knowledge about the design work content and the tools available for implementation in the different stages of development of the new technical systems.’

Despite the results achieved and the students’ training completed, it has been found that methods of systematic product development are used with limits in practice (Birkhofer ed., 2011; Lopez-Mesa and Thompson, 2002). The cited authors explain this phenomenon as follows:

- There is not enough time to embed the new methods into practice;
- Misuse of various methods leads to disappointing results;
- Some methods are used according to their popularity, not depending on the task to be solved;
- Most of the methods are supported in the theoretical sources by inappropriate examples;
- The number of scientific publications is increasing in an avalanche and most of them claim that the published methods are universal;
- There is a discrepancy between the methods offered and the needs of practice.

In his analysis of problems in transferring design methods into practice, K. Wallace notes that “no-one's territory” has been formed between theory and practice (Birkhofer ed., 2011). The author cites the results of years long research done by a group, led by Prof. H. Birkhofer, according to which, in order to adopt a theoretical method from the practice, it is necessary to fulfil the following conditions - the method must be simple, adaptable, well-publicized, and the necessary training for its use must be carried out. In this context, K. Wallace proposes to be created interdisciplinary groups of specialists who would turn theoretical knowledge into reliable and simple tools for solving practical problems. According to
other researchers, methods of systems development should be systematized into computer-based catalogues to assist practitioners in selecting the appropriate method for solving any particular, practical problem (Birkhofer ed., 2011; Lopez-Mesa and Thompson, 2003).

In the presented material, an attempt has been made to clarify and systematize the main tasks being solved at the companies, and on this basis, an integrated model for development of technical systems has been proposed.

2. Analysis of existing studies

Results of studies, aiming at clarifying and systematizing the problems to be solved in the practice, are relatively rare in the technical literature. When creating his theory for solving inventive problems (TRIZ), G. Altshuller assumes that practical problems have five levels of complexity (Altshuller, 1998). The first level refers to tasks solved by using existing solutions. As the level of complexity increases, one moves on to the tasks of refining known solutions, combining pre-existing solution fragments, or creating a new technical solution. The fifth level refers to the tasks in which, based on the new technical solution, a new technical system is to be developed. The tasks solved in the practice at the companies, according to the analysis done by K. Roth's, can be attributed to one of the following five types of design - technological, subjective, functionally specific, functionally abstract and original design (Roth, 1982).

The author proposes a flexible work plan where, depending on the complexity of the task, the solution can start from a different level.

According to V. Hubka and W. Eder, one of the following four major tasks is to be solved in the development process - creating a new solution, refining an existing solution, adapting a known solution to new conditions, or creating a modified series of technical systems (Hubka and Eder, 1996). In their analysis on the different types of design and the different tasks of the design engineers in the process, G. Pahl and W. Beitz define three types of design - variant, adaptive and new (Pahl and Beitz, 1977). Routine, creative and innovative product development are the essence of J. Gero's design method using design prototypes (Gero, 1990). Design prototypes defined by the author are models (schemes) for solving the types of design tasks to which each new problem should relate. In the proposed general design theory (Yoshikawa, 1981) and later in the extended general design theory (Tomyama and Yoshikawa, 1987), H. Yoshikawa and T. Tomiyama examine the design process in the context of the axiomatic set theory. T. Tomyama proposes that if, at the beginning of the process, there is no suitable existing solution, then one of the following three options can be used - to refine an existing solution, to combine pre-existing elements or to create a new solution (Tomyama et al., 2009).

The scientific publications contain research results clarifying specific issues of the product development process such as: different features of the product design in small and medium-sized enterprises; the impact of production volume and complexity of the designed technical system on the activities performed by the design engineers throughout the life cycle of the technical system, etc. (Ernzer and Birkhofer, 2002; Kristina, 2005; Lopez-Mesa et al., 2002; Löfqvist, 2009).

3. An integrated model for developing technical systems based on company practice

Based on the analysis of the research published and the direct observation of the processes from the practice, it can be concluded that in the companies the following four main tasks are solved - adaptation of an existing solution to work in new conditions, refinement of an existing solution, combining pre-developed elementary solutions and creating a new solution. The empirical information used for the purposes of the current research was collected by observing and analysing the development process at two companies TISEM-Ltd and METAREM-Ltd. As a result of the investigation, an integrated model for development of technical systems was proposed. The model was obtained by combining (overlaying) the methods for solving the four main tasks defined (Figure 1). The model is part of previously done studies on the downward hierarchical link between the life cycle of the technical system and the stages in it such as developing the product to be produced; developing the production (Angelov et al., 2013). From this perspective, the model has a separate entrance (input) and exit (output), which is becoming input to the next stage developing the production (Angelov, 2012). In accordance with the model
presented in Fig. 1, the design process begins by clarifying and defining the problem. There is no consensus in the research literature on the content of this stage. Proposals range from a general presentation of the problem to a list of requirements and constraints, according to which the solution should be sought.

An objective basis for clarifying and defining the task can be obtained if a technical system is considered as an element of a higher-level system for the conversion of matter, energy and information (Angelov and Haralanova, 2012). Within this system, the technical system interacts with humans, with the object under change and with the environment. Through this interaction, the main function (purpose) of the technical system is realized – the TS is the means by which the desired change of the properties of the object is accomplished. The pre-planned change of the properties of the object is realized by technology (recipe, algorithm), which remains unchanged throughout the whole process or changes depending on the intermediate results obtained. It is clear that clarifying and defining the problem at this level requires systematizing the available information about:

- the object under change and its states - initial, intermediate and final;
- the technology, which prescribes how the properties of the object are modified during the interaction between the technical system and the object;
- the interaction between the technical system and the human;
- the interaction between the technical system and the environment.

Thus, the first stage regulates only the functional connection between the technical system developed and the elements of the system for the conversion of matter, energy and information, and does not set any restrictions on the design engineers in the execution of the next stages of development process.

Conducting feasibility studies is another important prerequisite for successful completion of the task. They reduce the cost and time of design and guarantee the up-to-date level of the technical system developed. The purpose of the feasibility studies is to analyse existing solutions or theoretical research results regarding the structure and processes in the systems of the three hierarchical levels as follows: the system for the transformation of matter, energy and information on the first (highest) level; the technical system designed - on the second level; the executing organs of the TS (subsystems) on the third level (Angelov, 2012). Based on the feasibility studies, the following two questions should be answered:

- which are the requirements and constraints, defining the space of possible design solutions;
- which of the following four alternative strategies should be applied for solving the problem - adapting and implementing an existing solution into new conditions, refining an existing solution, combining partial solution elements, or creating a new solution.

The requirements and constraints shall be systematized in the specification. The content and the mode of formulating the specification are most often regulated within the company. In the practice, there are examples of standardization of this document on a national level. The particular importance of the specification is determined by the fact that at a later stage it is used for evaluating the quality of the design. For this purpose, a prototype is made and tested following the design. The test results are weighed against the requirements and limitations in the specification and on this basis, a decision is made on the further development (Angelov, 2012). In the first three stages of the proposed integrated model, the content and volume of work depend mainly on the strategy chosen for solving the problem. However, there is an overlap of activities, which is a sufficient reason for their combined presentation in Figure 1.

The main difference between the four main tasks defined is the selection or synthesis of a technical solution. If there is a suitable existing solution, the task is to adapt this solution to the new conditions. In this case, the technical solution is preserved or it is only slightly modified. The technical solution changes more if there is an existing solution that needs to be refined. Although there is a perception that refinements solve relatively simpler tasks, changes can cover the entire development process. For example, if the technology in the system for conversion of matter, energy and information is improved, changes at the functional level will follow, and as a consequence, the technical solution will change.
The problem is solved similarly, while combining existing partial solutions. In this case, additional specific tasks arise, such as evaluating alternatives, evaluating the functional and structural compatibility between the elements combined, or the need to include additional matching or joining elements.

![Diagram](image)

**Figure 1. Integrated model for the practical methods of developing technical systems**

The step of synthesizing a technical solution is developed to full extend only when a new solution is created. After determining the initial, intermediate and final states of the object under change, the technology in the system for transformation of matter, energy and information is compiled (Angelov and Haralanova, 2012). Then the technology is presented as a collection of sequential or parallel elementary operations. Operations, in their turn, are presented as physical processes. For the execution of those processes, appropriate physical structures (executive organs) are sought. The compilation of the executive organs (sub-systems) results in a new technical solution.

By selecting or synthesizing a technical proposal, the first design phase - the functional phase - is completed (Figure 1). The development of the technical solution to the level of a detailed execution plan and on this basis, development of complete technical documentation are carried out in the second phase of the product development - the subject phase. The activities of the second phase, regardless of the
chosen strategy for solving the problem, can also be unified - the process of developing returns to the basic algorithm (Figure 1).

In the practice it can be seen that despite the overlapping of the steps and the repeated return to the technical solution and the requirements and limitations of the specification, the following three stages can be distinguished in the second phase - development of a conceptual design, development of an execution plan and development of technical documentation. Separation of the second phase into three separate stages creates an opportunity for better planning and management of the process and for carrying out intermediate control at the end of each stage.

By developing a conceptual solution, a step is made from the functional phase to the objective design phase. The technical solution is developed to the level of an overall preliminary project. For this purpose, sub-systems for interaction with humans and the environment are added to the conceptual solution. Then, the interaction between the subsystems, the interfaces and their relative positioning within the technical system are clarified. The structure and internal processes within the individual subsystems are also clarified to the necessary extent. The proposed solution is appropriately visualized and the fulfilment of the requirements and limitations specified in the specification are evaluated.

In the next stage, the preliminary design is developed to the level of a detailed execution plan. Based on the clarified interactions and the mutual arrangement between the executive organs, the parallel design of the components at the different hierarchical levels of the new technical system is carried out. At the core of this complex process is the structural and functional dependence between the components at the different levels. The development of a complete working project is achieved after repeated solving of strength-dimensioning problems and development of structural and functional linkages between the individual components. The working project shall be submitted in accordance with the principles of the technical documentation. The execution of the project shall be evaluated taking in consideration the fulfilment of the requirements and limitations set out in the technical assignment.

The development of the new technical system ends with the development of complete technical documentation. The components of the different levels are presented graphically following the rules of 2D technical documentation or module based documentation. The next stage after the development of a new technical system is the stage of developing the production process. The technical documentation must contain the information needed to organize the production, in accordance with the applicable company and national standards. An important condition for the smooth transition between development of a new technical system and production planning is the compliance of the working documentation with the planned production volume and technological capabilities of the manufacturing company.

4. Conclusion
As a result of the analysis of the recent scientific publications in the area and the direct observation of the processes at the companies, it was found that in the practice the following four main tasks are solved: adaptation of an existing solution for application in new conditions; refinement of an existing solution; combining existing sub-solutions and creating a new solution.

Based on these findings, an integrated model for designing a technical systems has been proposed. It is obtained by combining (overlaying) the methods for solving the four main tasks defined. The design of a new technical system is considered to be an integral part of the first stage of the technical system's life cycle - production planning. During this stage, the design and development of a new technical system is accomplished and the production plan and technological support of the production are carried out. The analysis of the processes in their interconnection makes it possible to accomplish the "whole picture" of the production set out and to make the content of this process an element of the training of the engineering design students.

The content of the developed model, its correspondence to the development process in the companies and the availability of tools for implementation at each stage of the model have been discussed repeatedly with specialists from universities and companies in Bulgaria and Sweden. The main results of the study are used in the educational process in the field of technical design and development, with
students from the University of Ruse "Angel Kanchev" (Bulgaria) and Linnaeus University, Växjö (Sweden).

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