Computer engineering as the knowledge-intensive core of digital Production: origin and development

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Abstract. The paper considers the scientific and technical essence of forming and developing computer engineering from the very beginning of engineering analysis and design to the latest achievements in this field. In the course of their work, the authors, following the traditions of St. Petersburg Polytechnic University, rely on the development of the fundamental foundations of the natural science knowledge, which has always served as a measure of engineering development. We consider a fairly long historical period from the time of I. Newton, L. Euler and J.-L. Lagrange, who laid the foundation of engineering sciences, through the XIX and XX centuries to our time. The authors focus on the most important tools of research, for both natural phenomena and engineering calculations, - tools of mathematical analysis. Nearly in the second half of the XX century, with the advent of computers, this tool acquired the features of mathematical modeling technologies. Today this mathematical modeling is the basis for development of advanced methods of computer engineering. But this very tool is evolving at an extremely rapid pace, integrating the most advanced approaches of mathematics, physical mechanics, computer (supercomputer) technologies and information and communication resources. This development, together with a number of other computer technologies, radically changed the concept of the traditional, centuries-old production process and gave rise to the idea of the Digital industry.

1. Introduction

Computer engineering as an integral concept which integrates the whole cycle of technologies of engineering analysis and design, emerged approximately in late70s of the last century on the basis of mass adoption of computers in the industry [1], [2], [3], [4]. In this case, it is incorrect to interpret computer engineering only as a product of the actual computer technology; what is worse is that it can lead us to incorrect estimates. What do we mean by that? The answer to this question is extremely important, and it amounts to the core of this work. At the beginning of our detailed answer, we must begin with this question: what methods and techniques, has our civilization used to study and master the world around us? The textbook examples of Archimedes ' bath, Leonardo da Vinci's observations of bird flight s, and apple falling on Newton's head reveal the first method: - this is a physical experiment. But since the time of the genius of I. Newton (1643 – 1727 gg.), L. Euler (1707 – 1783 gg.) and J. L. Lagrange (1736 – 1813 gg.), the dramatic development was associated with approaches
that were attributed to the theoretical methods of studying the natural phenomena. Consequently, theoretical approaches have become increasingly important in the creation of machines, mechanisms and all sorts of systems (irrigation, defensive, etc.). The most important role was given to the natural sciences, such as mathematics, physics and mechanics—the foundations of theoretical approaches [5].

It is extremely interesting and important to pay attention to the XIX century. At its beginning, which was the last years of Lagrange's life, the classical infinitesimal analysis was mainly formed, and by the end of the century took the shape of the mathematical analysis, which is studied in modern higher school, as higher mathematics. Mathematical analysis has created a powerful foundation for almost all branches of science, which by that time accumulated and systematized knowledge. All this prepared and contributed to an unprecedented boom in inventions and developments: steam locomotive and steam ship, electricity and associated telegraph, and later telephone. Electric lighting alone was a breakthrough in the civilization development. There were completely new industries such as chemical, electrical, power generation, etc. It was the time when engine (steam engines), power engineering (steam boilers, and later steam turbines) and, finally, machine tool and mechanical engineering emerged.

It is the XIX century when, as we can consider, the modern engineering analysis and design were initiated. They are considered be the basis for engineering, which is in the focus of this paper.

Outstanding scientific achievements continuously set new and more complex tasks before engineers, who were engaged in the development of advanced systems on the basis of these achievements in transport and communications, new machinery, designs and technologies. Imagine that in the first fully-produced steam engine Thomas Newcomen (1712) between the piston and the cylinder could slip a small coin, while in the diesel engine, created by Rudolf Diesel in the late XIX century (1897) the "gap clearance" between the piston and the cylinder should be very high. In other words, requirements for accuracy for the description of physical processes continuously toughened, and consequently, the need for accuracy of calculations also grew. In our work, we try to consider what theoretical tools a human uses to study and transform Nature, creating necessary benefits for life. Moreover, we show how these tools have evolved over the centuries, primarily in terms of development of production processes, going from the simplest methods of calculation to advanced software systems of computer engineering.

2. Methods

The approach developed in the work is based on the historical analysis of the "theoretical technologies", to put it another way, the methods used by the scientific and engineering community to study nature and create mechanisms, machines, systems and technologies over the past three centuries, based on mathematical methods, with in-depth consideration of these methods in the last few decades.

Returning now to the question raised earlier about the ways of studying nature, we can say that the mathematical experiment in the scientific and engineering research gradually became as important as the physical experiment. And this was accompanied by such triumphs of science as the discovery of the planet Neptune through calculations in the middle of the XIX century, when the Englishman John Adams (1819-1892) and the Frenchman Urbain leverier (1811-1877), independently from each other in 1845-1846, predicted its existence and position in the sky; later the planet was discovered by the German astronomer Johann Halle (1812-1910) in September 1846.

But along with such outstanding achievements of science, imperfect setting an engineering problem and its incorrect solution, as well as the failure of purely empirical approaches, sometimes led to tragic consequences. This can be illustrated by the construction of complex structures, such as bridges, are subject to multiple impacts and strains. For many years, despite the great empirical experience of many engineers, the quality of bridges was low. Despite the experience and caution of the bridge builders, there were a lot of accidents and wrecks. Here is the most tragic story with a huge bridge (length 3264 m) through Taski Bay (UK), built in 1870-1878, the second half of the century. Disasters occurred twice, the first time during the construction of the bridge in 1877, when three spans fell into the water, due to the lack of stability of the spans, as the bridge was not designed to withstand strong
winds. The second disaster was terrible, and for the same reason: it was not taken into account the impact of the wind, which in a strong storm can reach a load of several hundred kilograms per square meter. December 28, 1879, in a strong wind, thirteen spans of the bridge collapsed, with the train proceeding along the bridge. The train fell into the water, there were no survivors.

3. Results

Thus, as we have seen, the priority was given to the problem of improving engineering calculations, which resulted into necessity of accurate problem setting and the use of such complex mathematical objects as partial differential equations, solution methods which were actively developed within the framework of mathematical physics at the time. As a result, at the turn of the XIX - XX centuries, the century-long integration of engineering analysis and design with methods of mathematical analysis completed, which actually marked the beginning of today's powerful development of engineering.

All further engineering development in the first half of the XX century went in two important directions. Firstly, natural science and engineering thought were aimed at improving problem statement of real engineering practice, and secondly, they were aimed at the development of computational methods for solving such problems [6], [7], [8], [9].

Both above-mentioned directions evolved very fast; and it is necessary to point out that in each of them the Russian science was the tops. Indeed, the works of Sergei Lvovich Sobolev (1908-1989) played an outstanding role in setting problems in real practice, where researchers and engineers were forced to move away from the classical "totally smooth" mathematics, while the contribution of Ivan Grigoryevich Bubnov (1872-1919) and Boris Grigoryevich Galerkin (1871-1945) was invaluable in the development of numerical methods for solving differential equation. It should be noted that I. G. Bubnov and B. G. Galerkin had been lecturers at St. Petersburg Polytechnic Institute for many years.

In addition, a lot of considered engineering and natural science problems had to be solved with numerical methods, therefore, more and more computational resources were in need. Available by the end of the first half of the XX century computing tools, in the form of various kinds of arithmometers, greatly lagged behind in their capabilities from the needs of scientific and engineering practice. A breakthrough in solving the problem of computing resources occurred with the creation of Electronic Digital Computers (ECM), the large-scaled introduction of which in scientific and industrial practice began in the mid 60s. That time can be regarded as the boom in solving problems from various branches of science and production based on the use of numerical machines, which are now called computers.

It is the period that we can consider as the starting point in the formation and development of engineering analysis and design based on the use of computers, or computer engineering. Before moving on to the analysis of the essence of the advanced computer engineering and its role and place in modern industrial chains, we need to turn to the historical retrospective of the formation and development of both this concept and the group of technologies integrated under this name. It is natural to start with the first years of the adoption of computers at industrial enterprises.

In the first years of introduction of computers in manufacturing, their use in engineering analysis and design was limited to the solution of common that do not require large resources, tasks of computational mathematics, which did not need numerous resources, such as approximate evaluation of integrals, solution of algebraic and transcendental equations, linear algebraic systems, etc. In this way, the scientific and engineering community realized the necessity of classifying standard computing tasks. Thus, researchers received the Toolkit which included packages of standard mathematical applications. The next stage was allocation for groups of specialized engineering tasks, such as mechanics of solid deformable body, fluid mechanics, heat and mass transfer, and so on. It also began to form a class of application software packages, but with more capabilities than the first purely computational packages. It was the stage where the essence of modern computer engineering began to take shape.

With the increasing power of computing systems, the level of complexity of applied engineering and natural science problems was growing rapidly, while the transition to spatial problems led to the
need to solve the problems of visualizing the results of calculations. Thereby this led to a qualitatively new approach to the research in mechanics, physics, and biology; it became possible to observe the modeled processes from the appearance of microcracks in the metal, microvortices in the fluid and "constructing molecules" with the given properties to the modeling of global atmospheric processes and tectonic faults in the earth's crust. It led to the breakthrough in engineering calculations: the calculating designer-engineer could see a picture of the developed system in action! However, the range of problems solved with the use of application software systems grew fantastically [5], [6], [7], [8], [9], [10].

Gradually a range of widely distributed software systems for solving problems of engineering analysis and design began to be adopted and shortly after this, a separate class of complexes that were focused on purely design work, i.e. to create a product or a design "as a whole", began to emerge. This class of software systems received the name of computer design systems CAD (Computer Aided Design). The approaches developed within the framework of CAD technologies did not require particularly large computing power, but contributed to the development of software tools for visualizing the results of calculations. For example, already at the turn of the century only in the construction industry for design and research used many such software CAD systems, among which, for example, were:

- AutoCAD electronic drawing Board and CAD systems,
- Autodesk Architectural Desktop - architectural design,
- Autodesk Map - building geographic information systems,
- Autodesk Land Desktop-land management and geodesy, and many others.

We have provided only the most popular software products. And the very creation and distribution of such complexes are characterized by the mass commercial character. However, a comparatively larger scale was creation and distribution of software systems for a proper engineering analysis. Moreover, such systems, absorbing all the latest achievements of computational mathematics, natural sciences and computer technology acquired the character of powerful software systems. In such complexes, a single framework of software systems can be solved in almost the whole range of engineering tasks from making requirements, and in the form, practically similar to the standard mathematics, then the engineer is given the opportunity to choose a numerical method at the last stage for the most evident visualization of calculation results. By the end of the last century, the use of such complexes covered almost all industries in highly developed economies, and acquired a mass commercial character. Formed a separate, continuously growing industry for the development of CAE (Computed Aided Engineering) - software systems for engineering analysis.

Let's exemplify this. Take the ANSYS software package designed to solve the problems of solid and deformable body mechanics, selecting its first versions and look at the scale of its use by leading us research centers and firms at the turn of the century (1998-2000). All 10 leading companies relied on its use. If we expand this list to 25, and then to 100 companies and centers, in the first case it is 75% with the growth dynamics, while in the second 70% used ANSYS also with the growth dynamics. We emphasize that this data are 20 years old!

As for the ANSYS complex itself, it has evolved from its "parent" field – solid deformable body mechanics, applied to nuclear power, into all areas of industry, gaining a strong position around the world.

It is especially important to emphasize that the software systems for many years has been developed in the direction of multidisciplinary (interdisciplinary). The latter requires clarification because of the special importance of the introduced concept. At first glance, the concept of multidisciplinarity is quite obvious, because it refers to the description of processes that allow for, for example, interaction of an elastic body with the pressure field of a moving liquid or gas, i.e. two processes are interrelated. But the deep meaning of this concept is much more significant, because the limitless development of the multidisciplinarity concept is a direct way to an extremely correct description of the real physical world. And here we must again turn to the question raised at the beginning of our work, how can we study the world around us? Nevertheless, analyzing manufacturing
processes, we must consider them as the interaction of a human and nature in the broadest sense, which requires very accurate, detailed description of the interaction processes.

In the course of the evolution, a number of outstanding scientists presented some conceptual understanding of the approach to the study of the world around us, which we name as theoretical. The most complete and accurate description of such approaches was creation of the concept of mathematical modeling put forward by the Russian mathematician Alexander Andreevich Samarsky (1919-2008). [8], [9], [10], [11]. The essence of the conceptual approach A. A. Samarsky is that all natural phenomena, the life of society and the sphere of industrial production are considered through the prism of quantitative relations. It does not matter what these relations, differential or algebraic equations, integral equations or some inequalities are. It is fundamentally essential that these relations correctly describe the process under study, and that the mathematical model of a phenomenon, mechanism or system is adequate to reality. And this is only part, though a very important part of the concept of mathematical modeling. The concept also involves development of a numerical method to solve our model problem, "transfer", built in the framework of the algorithm method, to a computer, that is, the programming procedure and the analysis of the results. But apart from this, the approach of A. A. Samarsky also involves consideration of purely mathematical issues, such as correctness of formulating a mathematical problem, and a constructed numerical procedure. It should be noted that the last questions, as a rule, remain neglected by those who are engaged in subject tasks, in our case, the engineering community. All this is not always groundless.

Thus, we see that the previously considered software systems for the both engineering and natural science analysis mostly represent direct embodiment of the ideas of the mathematical modeling. Indeed, they contain all the major stages of the concept, i.e. the problem, the choice of a particular technology for task algorithmization, for example, transition from continuous to discrete models, the same choice of numerical solution procedures obtained in our example of discrete models and, finally, the visual result.

Now we have come close to specifying the essence of our work, namely, to considering what factors give us the basis to assert that computer engineering is the knowledge-intensive core of digital production. And here we have to turn to the structure or to the main components of digital production [6], [8], [9], [10], [12]. It should be noted that these main components were formed several decades ago, and they rooted in the ideology of production computerization, resulting from the approach of CALS – technologies (Continuous Acquisition and Lifecycle Support - continuous information support the supply and life cycle of the product) Afterwards, the term CALS was rejected and later it is dominated by the notion of PLM environment (Project Lifecycle Management, PLM technologies to manage the life cycle of the product). [6], [8], [9], [10], [12]. Over many years of the development of information and communication technologies, and computer technologies in the field of production, the essence and content of the main blocks of CALS technologies has changed slightly, whereas the forms of their application have undergone major changes and numerous works are devoted to this[6], [8], [9], [10], [12]. Here are the main blocks of this application:

ERP-technologies (Enterprise Resource Planning) of enterprise management and resource planning, designed to solve the entire range of organizational and technical production problems;

PDM-technologies (Product Data Management) of production data management are closely related to the following triad of CAD/CAE/CAM technologies (Computer Aided Design/Engineering/Manufacturing), providing its direct implementation in the production process;

ILS-technology (Integrated Logistic Support) integrated logistics support provides information support of the product in operating conditions, management of spare parts flows, repair and maintenance of products in operation.

The framework of the ERP, PDM and ILS technologies, comprises all main interests of economic science, production management, resource management, problems of standardization and unification, etc. Now we should turn to the mathematical subjects which are based on computerized production units. A careful analysis shows that the dominant mathematical technologies are elements of discrete system control theory, which goes back to the methods of solving linear programming problems,
mathematical programming, mathematical statistics, and some others. The emergence of the Internet of things in recent years, in relation to the problems of the industry, has not expanded the list of mathematical technologies used in the considered blocks.

Let us now turn to the CAD and CAE technologies discussed above, which are interrelated technologies in many tasks they complement each other. CAD-technology, as a rule, serves as some basis for the design development as a whole, as a set of assembled parts, on the basis of which the next stages of engineering calculations are carried out. That exemplifies CAE – technology. If the calculation results of such a design do not satisfy us, we again turn to its design, returning to CAD – tools. And now suppose that the results satisfied us, then we have to transfer the data directly to the production, that is, CAM – environments (Manufacturing), where they are used for CNC machines or in the advanced manufacturing technologies, such as additive technologies. Thus, we see that in the above – mentioned chain, which is the triad of CAD/CAE/CAM technologies, the historically traditional, consistent approach to product development is replaced by an integrated approach. This approach is based on the idea of time-combined computer-aided product design (CAD), execution of engineering calculation system (CAE) and transfer of results directly to production (CAM). This allows using the digital design data from the earliest stages of the idea, engineering analysis and design, in parallel and simultaneously by different teams of specialists. It is obvious that this approach allows you to repeatedly reduce the time of engineering analysis and design and reduce its cost, in comparison with the traditional classical approach, which has been developed in the middle of the XIX century. Moreover, this approach allows us to use effective optimization methods of [20] structures as a whole, and their individual elements. Firstly, modern technologies make it possible to create the most "exotic" products, manufacturing of which is impossible within the framework of traditional approaches and technologies; and secondly, the idea of parallel design with a possible multiple return to the original design parameters at new levels allows you to create a product with optimal properties.

In general, implementation of the triad of CAD/CAE/CAM technologies allows obtaining a visible economic effect. Analyzing scientific and technical merits of the triad of technologies, we should certainly highlight the CAE technologies of engineering analysis, as the most effective science-intensive tool.

4. Conclusion

Before turning to the analysis of why computer engineering is the core of digital production, we will focus on clarifying the key concepts used - on the concept of the "Digital economy "and the less commonly used concept of the "Digital industry". To date, there has not been a generally accepted definition or even a common understanding of what constitutes the "Digital economy". The concept of the digital economy is regarded from different points of view [12], [13], [14], [15], [16], [17], [18], [19], of which two approaches are dominant. At the heart of the first some "technological" view of the type of economy, the second involves allocation system of socio-economic and organizational and technical relations. However, in the first case, the emphasis is made on the use of the entire range of digital technologies in all spheres of human activity. In the second case, the emphasis is made on distributed interaction and the use of digital technologies by economic agents. Therefore, the key to the definition of the "Digital economy" is processes of knowledge generation and exchange of resources based on the widespread use of computer and information and communication technologies, which also implies the creative potential of people involved in these processes.

This approach allows us to define the "Digital economy" as a "limit" state of the socio – economic system with a total intellectual approach to solving the problems of social, socio-economic relations on the basis of full-scale application of digital (computer) technologies. Thus, it is the society with the highest and ubiquitous level of using intelligent computer and information and communication technologies. Such a broad understanding of the "Digital economy" allows us to remove from it the segment of the "Digital industry" - everything that is connected in the society with the production processes. That is, the "Digital industry" - public production where the entire set of technologies based on computer, information and communication resources (processes in individual enterprises, group
enterprises, in the industry and the economy as a whole, all workflows and their complexes), realized by the above-mentioned technologies.

In addition, we see that computer engineering, in the format of CAE-technologies, in all its components, is based solely on the advanced achievements of the modern natural science knowledge, primarily in physics, mechanics and mathematics. Due to this, the impact and the role of the advanced fundamental knowledge, in comparison with other segments of computerized production technologies, is significantly higher.

5. Directions for further research

Today, the essence of the entire range of production technologies is an effective interaction between a human and nature, which implies the least anthropogenic impact on nature with maximum efficiency from production processes and minimum energy consumption during these processes. And a quantitative description of all aspects of this interaction, all its details requires deep study.

From the above-stated, it is clear that CAE-technology is the most science-intensive segment of the triad of CAD/CAE/CAM technologies, as in other things, and this triad itself there is the science-intensive core of digital production, since they implement directly fundamental the natural science knowledge in the form of computer technology. Their role and influence on the engineering analysis is steadily increasing and they absorb all the advanced achievements of physical mechanics from the mechanics of turbulence in liquids and gases [20], [21], or elastic, to the mechanics of viscoelastic or viscoplastic body [22]. And, naturally, the increasingly complex engineering problems require ultra-high computing resources, i.e. supercomputers, where it is impossible to do without the use of parallel computing technologies [23], and the use of supercomputers in production should receive special consideration.

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