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Improving the Systems for Increasing the Manufacturability of Products Under the Conditions of Industry 4.0

Aleksandr A. Gusakov
Department of management
Peoples' Friendship University of Russia (RUDN University)
Moscow, Russia
gusakov-aa@rudn.ru

Michael S. Savchenko
Concern Radio-Electronic Technologies
Moscow, Russia
savchenkomik@yandex.ru

***Abstract* — Improving the manufacturability of a product is an important part of the process of designing a new product and preparing its production. For manufacturability testing it is currently recommended to take account of a wide range of factors related to the entire product life cycle. The analysis of technologies and tools to be used to improve the manufacturability of products under the conditions of the 4th industrial revolution has been carried out. Our analysis has revealed the advantages, difficulties and risks of introducing new systems for improving manufacturability using the example of a design organization and manufacturing enterprises in the production of electric machines for civil aviation. We have formulated proposals for organizing the process of digital transformation of the analyzed organizations in order to implement the process of "technological designing" of products using Industry 4.0 technologies.**

Keywords: design for manufacturability, digital transformation, implementation of Industry 4.0, smart factory

I. Introduction

The importance of ensuring the design for manufacturability (DFM) of a new product is determined primarily by the fact that 80% of the cost of the product is determined by decisions made during the development of the product's concept and design [1]. Along with the reduction of costs during the production process, the following are the usually specified positive aspects of DFM: a shortened production cycle, an increased level of trust between designers, technologists and manufacturers; a positive impact on quality assurance process [2]. High-quality testing of the product design for manufacturability and technological design of the product leads to reducing the terms of launching the product into production as well as solving the most important task of maximizing the use of existing technological processes, existing equipment, jigs, fixtures and tools, and established industrial cooperation in the production of a new product.

On a simple level, carrying out the process of testing a new product for manufacturability means that the design will be more suitable for its production [3]. In a broader sense, DFM can mean creating a product design that will meet the market requirements more closely, enhance manufacturing learning and increase the productivity of the manufacturer [3]. The designer should aim to optimize the conformity of the product design to the production system. The company's production system includes suppliers, material processing systems, production processes, employee skills and distribution systems [4].

There are two traditionally distinguished methodologies: design for manufacturing (DFM) and design for assembly (DFA). DFM includes the selection of cost-effective raw materials and recommendations for minimizing the complexity of production operations at the product design stage in order to shorten the overall production cycle and reduce the cost of product components. Similarly, DFA covers the analysis of assembly processes in order to reduce the product's assembly time, cost and complexity, minimizing the number of individual parts, assembly steps and the ability to change the assembly quality [5].

Various design techniques aimed at improving the manufacturability of a new product are known under various names, such as simultaneous engineering (SE), concurrent engineering (CE), engineering for excellence (EFE), concurrent product and process design (CPPD), design for production (DFP), producibility engineering (PE), and system engineering [6]. In order to increase the company's competitiveness during the creation a new product, one should take account of both internal factors associated with the product's manufacturing conditions and external factors of the enterprise. This is why researchers are starting to focus on design for the environment, design for recycling, design for life cycle (DFLC), etc. These studies are sometimes referred to as the so-called Design for X (DFX) [7]. In the face of development of manufacturing technologies for parts and assembly units and a broader use of 3D printing technologies, recommendations have been made on increasing manufacturability for additive technologies (Design for Additive Manufacture) [8].

This is consistent with the fact that value creation requires a new paradigm which is more than just "making things". Making things (for example, manufacturing) is often an important part, but value creation requires an integrated system that includes understanding of customer needs, research and development, design, production and delivery of products and services [9]. At the same time, the authors of DFM publications specify that the developed approaches to testing for manufacturability have their limitations and disadvantages [1]. CAD system developers are currently creating various software tools for testing new designs for

manufacturability. This, for example, includes the DFMPro module for NX CAD, SolidWorks components and others. Since these components of CAD design systems are not tied to a specific production company, they contain the most general recommendations primarily related to the shape of the parts and the materials used. In order for DFM recommendations to be more useful, they should be supplemented with recommendations and examples on the use of cutting and measuring tools, special engineering facilities, and test equipment that can be used during production, assembly, testing, and quality control. Such specific recommendations can be formulated as part of a closer interaction between designers, technologists and employees of production units of enterprises.

II. Product Manufacturability Improvement and Industry 4.0

An expanded understanding of the changing role of product design is in tune with the concept of Industry 4.0 where feedback from the market, design, and value chains play an important role. Next, we will focus on the place taken by DFM in the general concept of digital transformation of production based on the concept of Industry 4.0 and new digital technologies that can improve the efficiency of DFM.

The existing recommendations contained in various DFM guidelines will undergo changes as the technological production basis develops and changes and the application area of technologies in Industry 4.0 expands, primarily due to IoT. This accounts for the importance of creating close informational interaction between the design and production processes. IoT technologies, various sensors, and network tools allow you to receive data on the time spent on manufacturing parts, on the readjustment of equipment, on energy consumption and other parameters directly from the equipment. The first step in the workshop is to equip all physical objects and parameters with the help of sensors, drives and programmable logic controllers (PLC). Then the data is collected via a supervisory control and data acquisition system (SCADA) for controlling the production process and diagnostics [4]. Projects for implementing the equipment condition monitoring systems based on the Internet of Things technologies have been carried out in recent years at leading Russian enterprises. Transformation of production management systems into the so-called cyber-physical systems (CPS), which are connected to a shared system through network technologies. Connectivity is an important prerequisite for the creation of such systems [10].

The most suitable solution for the interaction of information systems intended for design and production automation and distributed in space is cloud technologies [11]. Further development of existing DFM techniques and their updates in order to meet the changing technological production basis suggests the use of great amounts of information, both previously accumulated and that which can be obtained by implementing IoT for equipment operation monitoring. Processing such volumes of information and obtaining practical recommendations requires using big data technologies and analytics with the application of artificial intelligence.

Smart manufacturing includes technologies that are part of the Industry 4.0 concept along with the technologies of Smart Supply Chains, Smart Products and Smart Working. Smart manufacturing technologies can be divided into subgroups in accordance with six main objectives: vertical integration, virtualization, automation, traceability, flexibility, and energy management [4]. Virtualization is an important technology that allows us to evaluate the production capabilities and production costs for a specific design option. Therefore, in accordance with the goals of DFM implementation, the key technology approaches in modern conditions are: IoT, cloud technologies, big data, and virtualization.

One of the ways to overcome the existing limitations and shortcomings of existing systems that implement the DFM approaches, as well as to introduce new capabilities of information technologies, can be the integration of expert systems into CAD systems [7]. This will contribute to the creation of smart DFM systems. The application of systems using artificial intelligence requires designing and creating a learning process for neural networks and other elements of such systems. Quality learning requires enormous amounts of information. Proposals for integrating expert systems into design systems (CAD) were actively expressed in the 90s. However, the development level of artificial intelligence technologies did not allow implementing these proposals to the full extent. New information technologies have led to an explosive increase in the volume of data collected, which created the conditions for training various systems based on the use of artificial intelligence. The development of artificial intelligence technologies creates the conditions for the creation and development of smart DFM systems that will be constantly trained on the basis of data received from production systems.

III. Existing Problems of Introducing Modern Solutions for Ensuring the Manufacturability of Designed Products under the Conditions of Interaction between Design and Production Units

A large number of publications devoted to the concept and technologies of Industry 4.0 describe new opportunities and prospects that open up due to their implementation. At the same time, owners and managers of enterprises see the introduction of Industry 4.0 as a challenge, since it requires major changes in many management areas. Introducing new technologies always requires careful preparation of such a transition project. This is even more true for the digital transformation of most processes, as required by the new industrial revolution. Each enterprise requires an assessment of what such a digital transformation can bring, what costs are needed, how this will affect the company's business model, what risks are associated with it, etc. This leads to a demand for research and publications on organizing the introduction of Industry 4.0 technologies in the conditions of existing enterprises with regards to the enterprises' actual state of affairs [3, 10, 12, 13].

It is advisable to analyze the possibilities of improving the manufacturability testing system in the interaction of the design organization and the enterprises that produce new products. Depending on how closely the design organization and the manufacturing enterprise are connected, whether they are part of one company, various models of information

interaction between them can be implemented to create a DFM system, which will also include recommendations that will complement that which exists in the applied CAD systems. If they are part of the same company, it is advisable to create a shared information repository that will accumulate data on the time and energy spent on the production of parts and assembly units, as well as other indicators. This information repository should also contain information on the composition of the special tool and equipment and other process parameters.

The main stages of the implementation of the DFM concept based on new digital technologies will be considered through the example of a design bureau developing aircraft generators for civil aircrafts. This design bureau is a subdivision of one of the enterprises included in the holding company AO Technodinamika. Depending on how closely the design department and the production complex are connected, various schemes of information interaction between them may be offered. Since the designed electrical equipment for airplanes is produced at various manufacturing enterprises, it should be possible to create an information exchange system necessary for ensuring the process of testing new products. Information exchange can be organized through VPN channels and the creation of an exchange system using cloud technology. A survey of 92 European manufacturing companies conducted as part of a study [4] showed that cloud services were one of the most common core technologies of Industry 4.0 used by respondent companies. Interaction between AO Tekhnodinamika and component manufacturing plants is based on a model in which the holding organization is the customer and manufacturing enterprises play the role of contractors who actually manufacture products according to the documentation of their own design divisions or enterprises included in the control loop. Production enterprises differ in the level of availability of production equipment, in the degree of equipment automation, in the level of automation of planning and production management processes, and applied technological processes.

Let us consider the benefits, the possible problems and the organization of the transition to new digital technologies for both participants in such transformation. The main areas for implementing the Industry 4.0 technologies according to [13] are:

- processes and resources;
- efficient use of property;
- operations
- stocks;
- quality;
- supply and demand;
- the rate of entering the market with a new product;
- maintenance and service..

A. Benefits for the design organization

1) Virtual design and pre-manufacturing validation. The capabilities of virtual reality (VR) and augmented reality (AR) can be integrated into computer-aided design systems [12]. This will allow for a more comprehensive assessment of the design of the product before it is launched into production, as well as identifying possible features of the manufacturing process.

2) Creation of digital twins of manufacturing enterprises and divisions. An up-to-date digital model of the enterprise will allow for assessing the potential duration of the product manufacturing cycle, as well as potential costs in the form of equipment operating time. The ability to save equipment operating time can be one of the most important areas for obtaining the economic effect from the creation and implementation of such systems. If the design bureau receives up-to-date information on the parameters of the actual process of manufacturing products designed in this design bureau, this will allow solving several problems in improving the design process, including the increasing of manufacturability. In the future, big data analytics technologies can be applied to the accumulated data, which will allow revealing significant patterns and effective solutions. Firstly, up-to-date data and new technologies for processing large amounts of information form the basis for a more rational product design, its structure, layout of individual blocks and modules, selection of the shape of parts, methods of putting them together, etc. Secondly, new technologies for obtaining and processing the collected data will make it possible to give more accurate recommendations from the design organization for the technologists of the manufacturer. Since the work on creating detailed models of digital twins of manufacturing enterprises can be time-consuming and costly, it is advisable to start with those production divisions of enterprises that determine most of the costs and at the same time determine the quality of the product to a greater extent. It is advisable to use simulation modelling tools that implement such modern modeling methods as a discrete event approach, agent-based modeling, and system dynamics as tools for creating such digital enterprise models. Modeling is a powerful technique for analyzing production systems, assessing the impact of system changes and making informed decisions [14, 15].

B. Benefits of improving the DFM system for product-manufacturing engineering companies

1) Reducing energy consumption and the duration of the production cycle is of great importance for enterprises and is considered one of the main priority parameters in a good project for the introduction of new technologies. Creating an optimal design from the viewpoint of reducing the total cost of manufacturing the product without compromising performance is an important design and production challenge.

2) The possibilities of creating digital twins for the enterprise as a whole and for its individual production units will help to solve the company's own problems. Such digital twins will allow for better assessment of the possibilities of launching various products into production and potential problems in doing so by using a model. Such modeling will make it possible to assess the need for changes in the

composition of equipment, the technologies used, as well as potential costs and the duration of the production cycle.

C. Difficulties and risks of introducing new technologies

1) Difficulties and risks for the design organization. A special feature of the design bureau under consideration is the fact that not all previously completed projects and design documentation are presented in electronic form, including in the form of 3D models. In this regard, over the coming years, technical specialists will use archives of design documentation on various data storage media, both digital and paper. During the digital transformation of design and manufacturability assessment processes, knowledge and design experience accumulated by the team in previous years must not be lost in order to use the existing backlog of design and technological solutions that were embodied in previously created designs and have passed the test of time and operation in various conditions. This knowledge basis of the organization is necessary both for continuous improvement of its activities and for training newcomers in better experience. When switching to new computer-aided design systems, there is usually a problem associated with incomplete compatibility of information formats.

2) Difficulties and risks for enterprises. There is a conflict of technological paradigms at manufacturing plants that currently produce aircraft generators for civilian aircraft. One of the sides of this conflict is the need to use modern digital technologies and at the same time the existence of a large amount of outdated equipment which does not have modern digital interfaces or built-in programmable logic controllers, not to mention cyber physical systems, but is actively used in the production cycle in spite of that. Under these conditions, it is impossible to automate the reception of data from technological equipment for a complete analysis of the time, energy and other costs involved in the production of a particular product / part. This leads to the necessity of dividing the process of implementing the Industry 4.0 technology into successive stages, each of which can be a separate project [16].

3) General difficulties in introducing new digital technologies in a design organization and manufacturing enterprises.

- The necessity of creating new interfaces for Human-Machinery Interaction. Industry 4.0 will introduce entirely different ways of smart interaction between humans and the physical world [12].
- Strengthening information security. This requirement is due to the fact that the volumes of information that have a digital form and will be transmitted through different data exchange systems are increasing exponentially.
- The introduction of any information system usually leads to a double workload for employees. They must ensure the execution of existing operations, as well as test new systems under real-life conditions and verify their functionality. It is necessary to consider a system of incentives that will increase the interest of employees in introducing new solutions.

IV. Organizing of the Process of Introducing a New Digital System for Improving Manufacturability in the Design of Aircraft Generators

Organizing the implementation Industry 4.0 technologies depends to a large extent both on the current state of the design organization and machine-building enterprises, and on their capabilities. In this case, by capabilities we mean both financial means for the acquisition and modernization of equipment and design systems, and the understanding of the necessity of going for such radical reforms of production and management processes by organizations' owners and management. The choice of the area of development and production of electric machines for civil aviation as the receiving end for implementing modern manufacturability improvement systems is associated with a fairly wide range of manufactured products with limited serial production and the need to combine the simultaneous mass production of previously mastered products with launching the production of new products determining the appearance of modern aircrafts.

To organize the process of digital transformation of enterprises in Germany, the VDMA Industrie 4.0 Implementation Guideline [17] was developed. This guide was created in partnership with several organizations: VDMA Industry 4.0 Forum, Department of Computer Integrated Design (DiK) of Technical University Darmstadt, wbk Institute of Production Science of Karlsruhe Institute of Technology. The authors note that the need to create such a guide is related to the fact that German engineering is notable for a wide variety of operating companies both in size and in their production capabilities. The purpose of the guide is to formulate recommendations for companies on organizing their own implementation projects, creating their own Industry 4.0 business models, as well as phased roadmaps for implementing these business models. The guide consists of five sections: preparation, analysis and creativity phase, assessment and implementation of developed business models. The organizational basis of the digital transformation process is the creation of an own design workshop within the organization that implements Industry 4.0 technologies. The practical value of the guide was tested in the implementation of pilot solutions in several German machine-building companies. Since the machine-building industry of Russia as a whole, as well as the enterprises and the design organization under our consideration, also differ greatly in their technological level and size, it is advisable to use this guide to manage the process of introducing new approaches for DFM.

In order to apply the VDMA Industry 4.0 Implementation Guideline for improving the interaction between the design organization and the manufacturing enterprises producing aircraft generators for civilian aircraft, the management of these organizations should create interdisciplinary teams, which must include representatives of both design bureaus and engineering enterprises. The following issues can be considered and solutions can be found within such interdisciplinary working groups:

- assessing the effect from introducing new DFM systems based on Industry 4.0 technologies and defining the main stages of this process. The effect should be assessed both for individual participants and in terms of how this will affect joint projects;
- providing data collection and analysis of infrastructure problems of the production, identifying production bottlenecks in order to ensure the loading pace regularity and cost optimization;
- an overall reduction of development and production costs, including the time spent on production preparation;
- using design to ensure manufacturability throughout the entire product life cycle, including maintenance, repairs and disposal;
- the possibility of applying value engineering or its modifications for evaluating individual projects in implementing Industry 4.0 technologies;
- the support of the new DFM system implementation process by specialists – materials scientists, patent experts, metrologists;
- analyzing the paper archives of drawings to ensure the possibility of efficient use of proven and well-proven solutions; that is, integrating 3-D models and design and technology solutions formalized on paper into modern CAD systems, including the creation of a resource guide (data bank) of such solutions by subsections (body, active part of an electric machine, cooling system, etc.) for use in the designer's work;
- improving the development quality of new products by redistributing the time for solution development, for the search and adaptation of previously created designs and technologies along with obtaining the time resource for truly new developments;
- combining the design of new products with the process design of existing ones; with this approach, representatives of the manufacturer who know the real level of technologies, ways and resources for their development actively participate in product development;
- advanced training methods and programs for the personnel of the design organization and manufacturing enterprises for ensuring the work on the implementation of new solutions.

V. Conclusion

We have reviewed the development of the concept of improving the manufacturability of the product design and identified the modern digital technologies that can be used for developing these concepts. The problems associated with the implementation of the Industry 4.0 platform in the manufacturing complex related to the development and production of electric machines for civil aviation were identified and analyzed. It is demonstrated that in the face of actual production and economic activity, with the approaches suggested by Industry 4.0, a number of difficulties associated with established business processes of product development and production arise at the implementation stage. These problems that impede the immediate implementation of Industry 4.0 are rooted in organizational, technical, and infrastructural factors, namely:

- the inconsistency of information and the need for its search, synthesis and digitalization for effective use in development and production;
- ensuring close interaction between design and production units (enterprises) using a shared information space;
- implementing the "process design" approach for products by including technologists in the development team in order to build the solutions that allow for production preparation with the maximum use of existing equipment, jigs, fixtures and tools, test benches, tools and processes into the product design at the development stage;
- enhancing staff competencies through the continuity of design and technology solutions.

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