International Journal for Quality Research 18(1) 199–208
ISSN 1800-6450

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Article info:
Received 11.02.2023.
Accepted 02.12.2023.

UDC – 622.7.092
DOI – 10.24874/IJQR18.01-13

MODERN APPROACHES TO PRODUCT QUALITY ADAPTIVE CONTROL

Abstract: *The effective development of modern high-technological manufacturing is inextricably linked with the establishment of a balance between the customers interests and the manufacturers technical capabilities. To the greatest extent, this is relevant to the development and promotion of innovative types of products at the market conditions. At the same time, there is a necessity for a prompt response of the manufacturer to incoming requests from the customer. This is not always consistent with the technological capabilities of the manufacturer or go beyond the requirements of known product standards. It means that certain two-way adaptation of the manufacturer-customer system is required. The article considers the theoretical aspects of metal products quality indices adaptive control based on the concept of operational "technological adaptation" under the conditions of multi-stage multi-variant systems. The two-level two-loop system for metal products adaptive quality control under the conditions of complex technological systems operation is presented.*

Keywords: *adaptive control, multi-stage multi-variant technological system, adaptation, quality indices, metal products.*

1. Introduction

Modern market relations are a complex set of interactions between manufacturers and customers. The timely reaction of the manufacturer to the ever-changing market conditions is the key aspect to its successful and sustainable development. One of the key factors determining the competitiveness of an enterprise is the ability of a manufacturer to maintain a balance of its own and customers interests. This can be achieved through the application of competitive advantages such as significant accumulated production experience, the introduction of new innovative technological and/or technical solutions as well as by maintaining the high quality of exclusive products. In this regard, there is a necessity to develop an effective strategy to create technological processes at a large-scale enterprise using the latest concepts of production organization. One of these concepts can be determined as the application of "technological adaptation" principles.

In conditions of mass production with wide nomenclature of products entire technological cycle for a group of identical products, and continuous capacity of the main technological equipment, it becomes necessary to find ways to predict quickly the final results of the entire technological system operation. Moreover, it is more important to realize this at the early stages of the product life cycle. This problem is especially relevant for multi-stage technological systems. Obviously, these systems have to be able to adapt quickly to

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customer requirements and market change in order to ensure the required quality level of complicated or new kinds of products and increase the effectiveness and competitiveness of their manufacturing. At the same time, the costs necessary for both “usual” operation of the technological process and the development of innovative or “exclusive” products should be minimized.

One of the tendencies in metallurgical industry is the design of such manufacturing processes which provide complex multi-operational technological impact on the processed metal products. At the same time, the product manufacturing at existing industrial conditions can be characterized as the multi-variant technological processing. Moreover, different level of efficiency and effectiveness of the entire manufacturing process can be achieved depending on the choice of the option to design the definite technological system.

At present time, concepts based on the principles of adaptive quality management are actively developed in practice of manufacturing in different countries. Adaptive algorithms for the functioning of autonomous production systems (AMS, IMS-CA) based on principles of cognitive technologies have been developed to analyze and consider the production interference (Park et al., 2011, 2012). The scientific and technical literature describes approaches that provide organization of the so-called “intelligent adaptive production”. These approaches reflect various aspects of adaptation at the industrial enterprise. For example, the principles of adaptation of decision-maker about the management of technological processes are formulated which are aimed at finding the most effective solutions (Sokol, 1994). Also mechanisms of business processes adaptive management on the level of a company are developed taking into consideration its interactions with the external environment (Kim & Pae, 2007). Approaches to the production systems adaptive control based on the operative monitoring of emerging problems and correct decision-making are also been developed (Riegler et al., 2013; Žapčević & Butala, 2013). Researches based on the methodology for solving problems of technological systems adaptation based on existing experience are also of sufficient interest (Policastro et al., 2008). This approach is based on the attempt to solve the new problem by extracting and adaptation of previously known solutions to similar existing problems. A number of other concepts of adaptive management of quality indices and manufacturing is presented in literature (Bratan et al., 2013; Dombrowski et al., 2010; Domingues et al., 2015; Dooley, 1997; Gregory et al., 2006; Hansen & Lilja, 2021; Keskin et al., 2022; Lughofer et al., 2019; McCarthy, 2003; Naumann, & Vajna, 2004; Ogland, 2008).

The analysis of the existed approaches shows that principles of adaptive quality management are based on the evaluation of the manufacturing system activity or on the already received actual data. It does not allow to use the operative adaptation under conditions of incompleteness of a priori information.

At present time the situation develops to the direction when quality indices of high profitable metal products, for example, metal ware products, are normalized not only and not to high extent by regulatory documents (standards) but also by additional requirements of customers. At the same time, in some cases such requirements either do not always match with norms in standards or are difficult to be achieved in the product manufacturing process or processing of the final product (for example, cold rolled strip, bent profile, coated rolled steel sheet, etc.). This is the reason to analyze efficiently the manufacturing capabilities, to find new ways to design effective technological schemes for the manufacturing of such kinds of products, and, accordingly, to develop and implement the new concepts and approaches using adaptive models of technological impact. In this regard, there is an urgent problem to create the methodology for adaptive control of metal products quality indices when complex multi-variant multi-stage technological systems are used for manufacturing.

The scientists of Nosov Magnitogorsk State Technical University (Russian Federation) within the framework of this direction have created the new scientific approach of adaptive quality management aimed at formulization of theoretical aspects and creation of various models which make it possible to implement methods of operational technological impact on the metal products quality indices during the processes of their manufacturing (Golubchik et al., 2012, 2014).

2. Methodology

Development of the concept of metal products quality indices adaptive control as applied to complex multi-stage multi-variant technological systems (MMTS) should be based on the results of theoretical research in different areas. One of them is the analysis of the existing thesaurus in the area of product quality technological and logical management which in its turn requires the development of an appropriate conceptual apparatus.

Almost all state-of the art technologies imply a technological multi-stage and/or multi-variant manufacturing process of a particular kind of product. Often, only for simplicity, such processes are reduced to the concepts of a "complex" technological system, a multi-level hierarchical system, etc. Directly the term "multi-stage" in relation to technological processes is denoted as a set of one-stage operations with rigidly fixed connections. At the same time, the manufacturing process can be organized in accordance with the principle of operations sequence, their parallelism, or other possible combinations. Another interpretation of the analyzed concept of "multi-stage technological process" is the representation of two or more technologies in the form of a single entity as their integrative combination which greatly simplifies the overall structure of the technological system. It excludes the possibility of quality indices operational management at a single stage of processing. From the point of view of the system approach, the description of a multi-stage system in the form of a set of complexes of applied resources and the links between them can be considered quite interesting. At the same time, the purpose of the operation of a such system is the parallel-sequential step-by-step transformation of certain input resources into the corresponding sets of output resources.

Similar interpretation is typical for the term "multi-variant system" which is quite actively used in decision making theory, in the economic literature, as well as in the description and construction of automatic control systems. Directly the term of "technology variant" can be interpreted as the set of operations with multi-links. At the same time, it is assumed that two multi-link technological processes can belong to different options if they differ in at least one link. Moreover, the multi-variant state of technological processes is considered to be the simultaneous existence of several technological processes that can provide a solution of the problem. In accordance with this approach, the variation of technological processing within a single operation ("link") is excluded which significantly reduces the ability to control quality indices in the selected version of the technological system.

The presented examples of existing approaches to the concept of a multi-stage or multi-variant technological system do not allow to organize effectively on-line management of the procedure to achieve a given quality level in the manufacture of a specific type of metal products and determine the strategy to design such processes especially when innovative technology is created.

Within the framework of the developed concept of quality indices "technological adaptation" the following interpretation of the term "multi-stage technological system" is proposed. The "multi-stage technological system" is a system that implements change in the initial state of a set of quality indices to the final state by repeated technological impact on a given separately taken stage of the product life cycle. At the same time, the one-stage technological system implies the single technological impact on a change in quality indices during the given stage of processing. In this case, the concepts of "operation" and "stage" become identical. Thus, in the case under consideration, the criterion for classification of technological systems into single- and multi-stage ones is the multiplicity of the technological impacts which result in any change in the state of the quality indices system of a given kind product during its manufacturing. In this case, every change of the quality index value for a single technological impact will be considered to be the separate stage of the process.

The term "multi-variant technological system" is denoted as a technical (technological) system in which the possibility to ensure the final level of quality indices is realized through the application of many options for technological impact on each of them (or a group of quality indices as an entity) at every stage of the product life cycle. Thus, the term "variant" is interpreted as a cumulative technological impact which provides step-by-step change of the quality indices (and/or system of quality indices) of the product leading to the obtaining its normalized final values.

The concept of "technological adaptation" of quality indices in relation to the systems under consideration (MMTS) is intended to mean a process of purposeful change of the technological system in accordance with certain criteria to adapt its structure and functions to environmental conditions that ensure the achievement of the system's goals: the appropriate level of quality indices, customer expectations, harmonization of the regulatory documents, etc. (Figure 1).

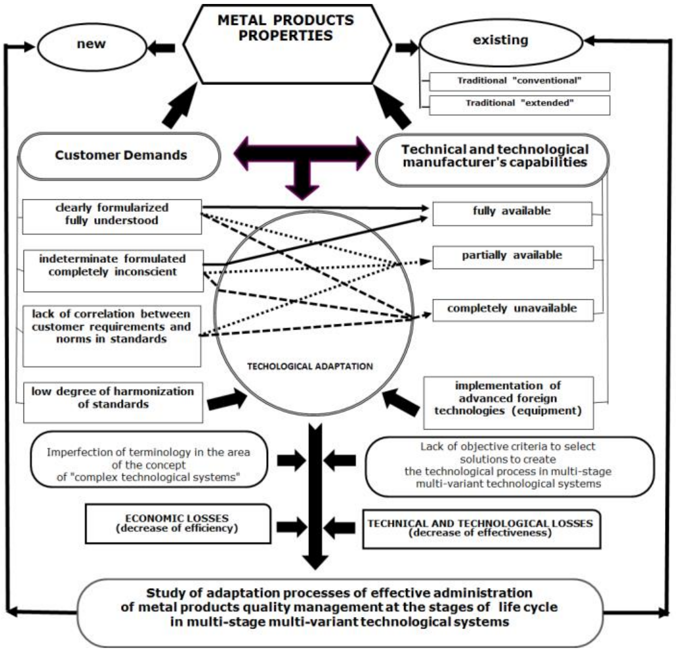

Figure 1. Concept of "technological adaptation" of quality indices

Very often in relations “customer-manufacturer” the situation occurs when technical and technological possibilities of manufacturer do not match customer demands. The possible reason of such situation is that customer demands are not always clearly understood and/or clearly formulated. Sometimes customer expresses only a desirable level of properties (quality indices) of the product or the range of such properties. Besides customer demands and quality indices which are regulated in standards do not correlate well.

Traditionally the activity of any metallurgical enterprise with customers at the stage of accepting (analyzing) the order to produce any kind of metal product includes the rapid assessment of technical and technological capabilities of the enterprise to ensure that all customer requirements for quality level can be satisfied. At the same time, quite often, in the case of absence of the possibility to fulfill (or even if there are any doubts about the possibility to fulfill) the customer requirements for a single quality index the incoming request is rejected without analyzing the resources of the enterprise to accept these requirements in future. The ideal variant of the manufacturer-customer interaction is the situation when the enterprise can accept almost all received customer orders or at least most of them.

To implement this concept of cooperation with customer on the basis of the conceptual apparatus described above in terms of MMTS as well as taking into consideration the basic fundamental postulates of theory of systems the two-level two-loop system of adaptive quality management (SAQM) for metal products under the conditions of MMTS was carried out in Nosov Magnitogorsk State Technical University. This system makes it possible to take into account and exploit existing resources of the manufacturer (Figure 2).

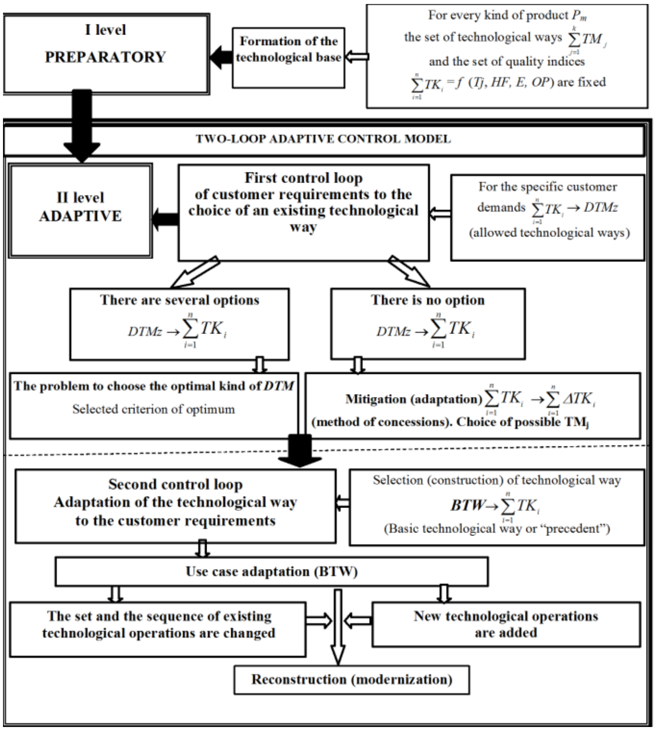

Figure 2. Two-level two-loop system of adaptive quality control system of adaptive quality management of metal products in MMTS

It should be emphasized that application of this model is reasonable and necessary in cases where either there is no technical and technological full-scale possibility to manufacture any product or it is impossible to ensure fulfillment all customer requirements to achieve the required quality level (see Figure 1), in other words when “technological adaptation” of quality indices is necessary.

3. Results and Discussion

The developed SAQM of metal products includes two levels.

The first level of management, which is denoted as *preparatory*, involves the formation and accumulation of technological database of all possible (probable or matured) technological ways of manufacturing ($\sum_{j=1}^{k} TM_j$) in the frame of the enterprise for every kind of product P_m with fixing the achieved level of quality indices ($\sum_{i=1}^{n} TK_i$) or their variability range depending on the following parameters: variant of the technological scheme for manufacturing (*Tj*); human factor (*HF*), for example, the level of personnel qualification; economic expenditures for the technological process (*E*), for example, quantity of the required products, material consumption rates, necessity of tools and equipment, etc.; organizational schemes of production (*OP*), and other aspects included in this MMTS.

The presence of this level in the system is mandatory because of several factors. First of all, efficiency of decision-making about the possibility to fulfill an order depends on its content. The second factor is that potential restrictions imposed by the technological system can be identified on this level, for example, the ranges of properties variations.

Thirdly, activity of the decision-maker about the organization of the technological process is greatly simplified. So in general case it can be assumed that the decision-maker may not have the appropriate skills in all aspects of the planned manufacturing process to fulfill the specific order received in terms of ensuring normalized quality indices.

In the case when no one of the options availlable in the technological base can be used for the manufacturing of metal products with the required level of quality indices for any reason then a transition is made to the second level of SAQM. This level is denoted as *adaptive* on which the two-loop model of adaptive control of quality indices is implemented in MMTS.

In this case the first control loop is “Adaptation of customer requirements to the choice of an existing technological way”. For the specific customer (or customer group) the set of quality indices normalized by the customer is determined and established ($\sum_{i=1}^{n} TK_i$, where *n* is the quantity of quality indices) indices) and the set of probable acceptable technological ways (*DTMz*) are evaluated. In the case when the acceptable technological way is chosen the achievement of the required metal product quality level can be achieved. At the same time every *DTMz* which includes a set of certain stages of processing on the technological equipment available at the enterprise can be considered to be the singular version of the MMTS.

If there are several options which conform to the condition $DTMz \rightarrow \sum_{i=1}^{n} TK_i$ then the criterion of optimum will be chosen (determined) and the problem to find the optimal *DTMz* will be solved by known methods of optimization. If there is no the possibility to determine (compare) at least one variant of *DTMz* in the studied SAQM the adaptation mechanism will be activated on the first level which foresees the correction of quality indices ($\sum_{i=1}^{n} TK_i$). At the same time the implementation of adaptive quality management at this stage provides the possibility to mitigate part of the customer requirements of quality indices, for example, by changing the boundaries of variation of a single quality index (or all of them) or ascribing the normalized values of indices to the status of optional, etc. In other words, the manufacturer adapts the customer to the available technology and "asks" him to soften the requirements for the boundaries of quality indices. After that the set of new level quality indices ($\sum_{i=1}^{n} \Delta TK_i$) adjusted and coordinated with the customer is promptly defined. In this way using method of concessions from the side of customer quality indices are adapted to the closest *DTMz* or available on the technological base *TMj* taking into consideration the condition $DTMz(TMj)) \rightarrow \sum_{i=1}^{n} \Delta TK_i$.

In case of impossibility of "mitigation" or unwillingness of the customer to make concessions to the manufacturer the transition to the second loop of adaptive control of the considered SAQM is carried out. This loop is denoted as "Adaptation of the technological way to the customer requirements". From the available technological base of the manufacturer the technological way *TMj* is selected or determined by *DTMz*. This technological way can provide such level of quality which is approved by the customer or matches well with his demands. This *TMj (DTMz*) receives the status of the basis technological way (*BTW*) (or "precedent"). Thus on the second control loop of the SAQM the *BTW* as the precedent is adapted to the final customer requirements. At the same time every stage of the technological impact is harmonized to ensure the highest possible quality level in general or to achieve one of the quality indices which is the most significant for the customer (other indices are "accomodated"). Moreover, it is possible to change the "traditional" set of technological operations as well as their sequence which are presented in the "basic version" of the technological way of manufacturing. In addition, the appearance of new operations that do not exist in the precedent is possible. This also concerns to the existing equipment resulting in reconstruction or modernization of several technological operations and even the whole technological process.

In the case of the absolute impossibility to manufacture metal products with the requested quality level (taking into consideration application of all adaptive mechanisms covered by SAQM) the customer gets recommendations (explanations) about the maximum level of the quality indices which it is possible to achieve in the conditions of this industrial enterprise. It should be emphasized that this element of cooperation with the customer is mandatory as one of the most important in adaptive quality management at the enterprise. It is often unreasonable ignored despite the fact that there are situations when, for example, in the conditions of a large metallurgical enterprise the advanced technology for manufacturing a new innovative kind of metal product with unique set of high-level properties has been adopted or it is possible to adopt. At the same time, a customer who applies to this enterprise an order for the same kind of product but with an increased level of properties as compared with to the possible one, does not always realize the over-engineering, necessity, and justification to get the desired range of the final metal product parameters. In this case, it becomes acceptable to apply the principles of adaptation of the customer to the possibilities of the manufacturer.

4. Conclusions

In order to develop rational mechanisms for technological adaptation of the system to the customer requirements it is necessary to take into consideration factors which affect on the manufacturing process. At the same time unaccounted technological solutions but which have the significant impact on the formation of the required quality level can significantly reduce the efficiency of the system. In order to avoid such situation possible options of technological impact on the system were taken into account when the algorithm for the process of technological adaptation was created. The verification of the selected options can be carried out by means of mathematical modeling based on the equations of correlation and regression analysis.

If the adaptive control of the entire multi-stage multi-variant technological system is implemented but the target level of quality is not reached then the transition to the customer adaptation procedure will be applied.

The peculiarity of the developed approach is the enterprise attempt to analyze its resources and exploit the most of its technological reserves which, as practice shows, are not always used effectively. This can be also realized in the case when the possibility to manufacture the innovative metal products initially seems not feasible.

The presented approach based on the concept of adaptive quality management makes it possible to design and research the highly efficient technological processes for manufacturing innovative kinds of metal products and identify the reserves of industrial enterprises to strengthen their competitive advantages in modern metal product market conditions.

Acknowledgment: The research was carried out under contract No. 13.2251.21.0107 (№ SIIS "Electronic budget" 075-15-2021-1031) on the topic “Investigation on 3D-printing of Advanced High Strength Steels with TRIP effect for realization of self-adapting aerospace structural elements”, funded by the Ministry of Science and Education of the Russian Federation within the joint program for science and technology cooperation and implementation of joint call for Russian-Italian projects for 2021-2023.

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