UDC 389:14:621.317:354
DOI: 10.15587/1729-4061.2021.231225

MODELING OF THE PROCESS APPROACH TO THE LIFE CYCLE OF MEASURING INSTRUMENTS

Oleh Velychko
Corresponding author
Doctor of Technical Sciences, Professor, Director
Scientific and Production Institute
of Electromagnetic Measurements
State Enterprise "All-Ukrainian State Scientific and Production Centre for Standardization, Metrology, Certification and Protection of Consumer"
(SE "Ukrmetrteststandard")
Metrologichna str., 4, Kyiv, Ukraine, 03143
E-mail: velychko@hotmail.com

Oleh Hrabovskyi
PhD, Associate Professor,
Dean Faculty of Metrology, Automation and Electronics*

Tetyana Gordiyenko
Doctor of Technical Sciences, Professor,
Head of Department
Department of Standardization, Conformity Assessment and Educational Measurements*

Serhii Volkov
Doctor of Technical Sciences, Associate Professor,
Head of Department
Department of Automated Systems and Information and Measurement Technologies*
*State University of Intellectual Technologies and Communications
Kovalska str., 1, Odessa, Ukraine, 65029

The problem of increasing the reliability and competitiveness of products in all sectors of the national economy can be solved only on the basis of obtaining complete and reliable measurement information. This is facilitated by modern measuring instruments (MI), which are complex hardware and software systems. The relevance of the study is due to the fact that modern MI need an effective assessment of their quality at all stages of the life cycle (LC). This requires the development of appropriate assessment methods both at the stage of production and operation of MI.

The expediency of using the process approach to MI LC stages and its advantages over the functional approach were proved. The process approach allows more effective assessment of MI quality indicators at different LC stages and is compatible with the construction of modern quality management systems.

Mathematical modeling was carried out, a set process model of the MI LC was developed and its representation as a process V-model was carried out. This allows studying the interaction of processes of all MI LC stages and performing process quality management at all MI LC stages.

Mathematical modeling was carried out, a set process model of evaluation of quality indicators of MI LC stages was developed and its representation as a process V-model was carried out. This allows evaluating quality indicators of the MI and its components throughout the MI LC.

Recommendations for the use of international standards were formulated, in particular for project management planning, measurement processes, system requirements throughout the MI LC, risk analysis and management at the LC stages. This should help increase efficiency in achieving the planned results at all stages of the MI LC

Keywords: process approach, life cycle, quality system, measuring instrument, set model

Received date: 10.04.2021
Accepted date: 20.05.2021
Published date: 30.06.2021

***How to Cite**: Velychko, O., Hrabovskyi, O., Gordiyenko, T., Volkov, S. (2021). Modeling of the process approach to the life cycle of measuring instruments. Eastern-European Journal of Enterprise Technologies, 3 (9 (111)), 84–93. doi: https://doi.org/10.15587/1729-4061.2021.231225*

1. Introduction

Product lifecycle (LC) is a set of interconnected processes of sequential change of product status from the beginning of the study and justification of development to the termination of product operation. The complete product LC is divided into a number of stages, each being characterized by the specifics of work and final results. In general, these stages include: research, design and development; manufacturing; turnover; consumption (operation) and disposal of products. Each of these stages contains a number of elements that have their own specifics. For example, such an important stage as product manufacturing begins with technological preparation of production and logistics and ends with acceptance control and testing of finished products [1–4].

The model of a typical system LC was recommended in the first version of the international standard ISO/IEC/IEEE 15288 and included the following successive stages: design; development; manufacturing; operation/maintenance; decommissioning (disposal). In subsequent versions of this standard [5], the typical model was removed, but the typical LC stages remained with reference to the international standard ISO 24748-1 [6]. It was noted that the standard does not attribute the use of any model of the system LC, but only defines a set of life cycle processes. ISO 24748-2 [7] provides guidance on ISO/IEC/IEEE 15288 application.

Copyright © 2021, Authors. This is an open access article under the Creative Commons CC BY license

In accordance with the international standard ISO 24774 [8], the adopted model of the system LC should provide a formal description of the evolution of an artificial object as development in time from one stage to another. The transition between stages should be carried out at checkpoints on the basis of accepted procedures and decision-making criteria. Such a model should ensure the implementation and management of the system LC, i. e. planning and synchronization of different system states. Creating a system and managing its development are carried out within one or more projects – efforts with specific start and end dates in accordance with the specified requirements and resources [5]. When executed, the project is divided into stages, each of which may contain one or more stages or parts as a set of processes of the system LC.

The process approach to the effective conduct of work is based on the well-known Shewhart-Deming cycle. According to this model, the process of continuous product quality management is cyclical and includes, as noted earlier, planning (Plan – P), implementation (Do – D), checking (Check – C), action (Action – A), that is, the so-called PDCA cycle.

In this cycle, the stages of product quality management have the following four main steps:

– development of a plan of changes aimed at improving product quality;

– product creation/improvement, laboratory testing and marketing on a small scale;

– checking the effectiveness of what has been done, studying the results, comparing the planned results with the actual ones;

– adaptation and implementation of tested changes, as well as rejection of changes that have not been tested.

The last step leads to a new first step, and the cycle starts again.

The process approach as a PDCA cycle is used in modern quality management systems (QMS) of enterprises and organizations in accordance with the requirements of international standards ISO 9000 series. The principle of the process approach in the system is one of the main tools for creating QMS. The concept of the process approach, established in the ISO 9000 series standards, does not have clear recommendations for application in the organization. The ISO 9000 standard [9] considers the process as a set of interconnected or interacting stages of work. There is no standard list of processes, so their composition and structure are chosen based on production specifics. According to the ISO 9001 standard [10], processes are classified into two categories: main processes or product LC processes and auxiliary processes. The main processes are directly aimed at creating products, and auxiliary processes combine support and management processes. The results of the main processes directly affect the quality of the final product.

Current legislation on metrology and metrological activities of advanced countries of the world provides for conformity assessment of measuring instruments (MI). Directive 2014/32/EC [11] regulates essential requirements for MI and procedures for MI conformity assessment. The Directive also sets requirements for MI manufacturers, designated bodies for conformity assessment and state market surveillance and control of MI. Conformity assessment of MI under the requirements of this Directive shall be carried out by specially established modules or combinations thereof. Traditional MI tests to verify the MI type are now only the initial stage of conformity assessment (module B).

The introduction of MI on the market became impossible without additional stages of MI conformity assessment. One of these steps is to determine the conformity of the type (after completion of module B) based on the results of checking each sample of MI (module F). Another step may be to ensure the quality of the MI production process (module D) for those MI for which module B has been completed. Another possible step in assessing MI conformity may be conformity based on full quality assurance (module H). The last stage also requires the use of an approved QMS for MI design. When determining conformity of the MI to all the requirements of the Directive, a conformity mark and additional metrological marks are applied to the MI.

It is becoming clear that without the manufacturer's approved QMS, MI become uncompetitive in the market. This requires the manufacturer's efforts to create a QMS and ensure its approval by one of the designated MI conformity assessment bodies. The best option for the MI manufacturer is the approval of the QMS for the MI design stage, i. e. the QMS covers all stages of the MI LC.

The problem of increasing the reliability and competitiveness of products in all sectors of the national economy can be solved only on the basis of obtaining complete and reliable measurement information. This is facilitated by modern MI, which are complex hardware and software systems. The relevance of the study is due to the fact that modern MI need an effective assessment of their quality at all stages of the LC. This requires the development of appropriate methods both at the stage of production and operation of the MI.

2. Literature review and problem statement

There is a great variety of modern MI in terms of their purpose, scope, complexity of implementation, LC duration, etc. However, they are all complex hardware and software systems, mainly using modern software.

A number of standard schemes for organizing the stages of software design and development have been created for the software, which are examples of software LC. They are summarized in the international standard ISO/IEC/IEEE 12207 [12]. However, these schemes are designed for software LC and require additional analysis of the possibility of application to other products. ISO 24748-3 [13] provides guidance on ISO/IEC/IEEE 12207 application.

In [14], the application of the process approach in project management in one of the companies dealing with information technology issues, which are also limited to software issues, was considered. [15, 16] proposed special approaches to the stage of testing MI software as one of the stages of MI software LC, but they cannot be extended to the entire MI.

In [17], only the issues of systems engineering in the field of enterprise quality management were considered, differences and similarities of the international standards ISO/IEC 15288 and ISO 9001 were determined. In [19], the process approach in energy management was given. These approaches cannot be directly applied to MI manufacturers, as there are a number of additional issues regarding the specifics of MI testing.

In [20], the issues of applying the process V-model for project management of information systems were considered, in [21] – quality assessment of an artificial object, in [22] – software quality assessment, in [23] – development of self-organized production systems. In [24], the existing V-models with different interpretations and individual approaches in three different industries at different stages from development to general LC were analyzed. The considered V-models are based on a complex model for engineering mechatronic and cyber-physical systems, described in the Guidelines of the German Association of Engineers VDI 2206: 2004 [25]. A comparison of different interpretations of the V-model by characteristic properties for the analysis of differences was made.

Prospects for the mechatronic V-model were determined in [26–28], on the basis of which a new basic V-model was derived, explained and illustrated. Such a model can be used as a basis for building a specific industry V-model. In [29], a comparison of system design approaches based on the V-model was made. It was determined that the main advantage of the V-model with extended wings is the ability to illustrate the representation of the entire LC. Therefore, the use of a process V-model to assess the quality of a particular object is considered appropriate, but it is necessary to analyze the features of its application to assess the quality of MI.

The analysis showed the feasibility of applying the process approach at all stages of the MI LC using the process V-model.

3. The aim and objectives of the study

The aim of the study is to introduce the process approach to the management of MI LC using mathematical modeling of the MI LC as a complex system. This will make it possible to identify specific stages for the MI LC and to determine appropriate quality assessment methods for each of them.

To achieve the aim, the following objectives were set:

– to explore the possibilities and features of application of the process approach to the MI LC;

– to conduct mathematical modeling in order to determine a process model of the MI LC;

– to carry out mathematical modeling in order to determine a process model of quality indicators of MI LC stages.

4. Materials and methods of research of the process approach to life cycle management of measuring instruments

In terms of the process approach, management of certain works is considered as a continuous process, as a series of continuous interconnected actions. The essence of this approach is that work on a particular product is divided into certain processes. The whole organizational system is represented as a cycle of processes (procedures, actions). In the process approach, the four basic functions (planning, organization, motivation, and control) are presented as a cycle of interconnected objects, rather than a simple set of sequential actions as in the functional approach (Fig. 1).

The main stages of the evolution of the organizational management system of certain works from the application of the functional approach to the process approach and its implementation in the QMS are shown in Fig. 1.

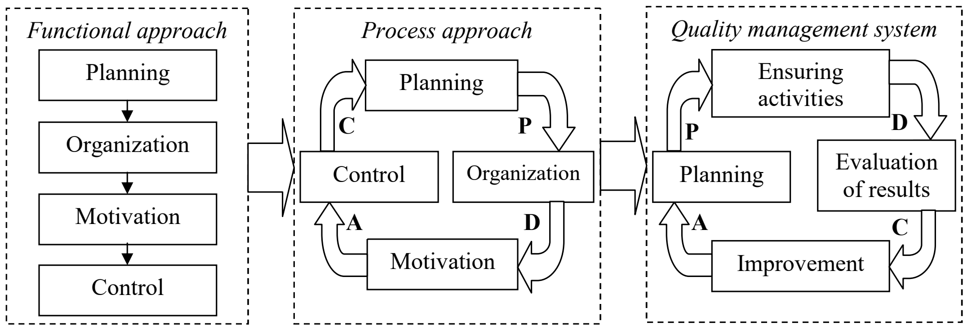

Fig. 1. Main stages of the evolution of the organizational management system

With the functional approach to work management, it is assumed that the maximum efficiency of work is achieved when each of its elements works with maximum productivity. Functional specialization, as a rule, provides high quality of individual work. However, this requires constant coordination and strict control of the activities of executors, whose goals may not coincide. In the process approach, all activities are aimed at obtaining the end result and are perceived by executors as a chain of interrelated processes that ensure the achievement of a common goal. This approach aims to identify the level of allowable (not maximum) effectiveness of a particular function to achieve the maximum set of performance as a whole.

The differences between the functional and process approaches to work management are shown in Table 1.

Typical phases (stages) of the product LC can be considered as follows:

1 – marketing, market search and research;
2 – product development and design;
3 – preparation and development of production processes;
4 – logistics;
5 – production;
6 – control and testing;
7 – packing and storage;
8 – sales and distribution;
9 – installation and commissioning;
10 – technical assistance and maintenance;
11 – after-sales service;
12 – disposal after use.

The well-known Juran quality spiral clearly reflects the process (step-by-step) approach to quality management. In this model, the transition from cyclic concepts to three-dimensional spatial models was made. They take into account the time factor and indicate that over time, repetitions of the cycle occur at another, higher level. One of the varieties of this three-dimensional spiral has the following stages for the product [30]:

1 – market research;
2 – development of the project task;
3 – design work;
4 – drawing up technical specifications;
5 – technology development and production preparation;
6 – logistics;
7 – manufacturing and staffing tools with control and measuring instruments;
8 – production;

9 – control of the production process;
10 – control of finished pro-ducts;
11 – product performance testing;
12 – sales;
13 – maintenance;
14 – market research for the next stage, etc.

Table 1

Features of the functional and process approaches to work management

Functional approach	Process approach (quality system)
Work management activities – a simple set of assigned functions for performing work	Work management activities – a series of interrelated processes, the completion of one of which is the beginning of another
Narrow specialization in works ensures high quality of their performance, but limits the vision of executors outside this specialization	Executors perceive their work as part of the overall process and associate their contribution to the overall results obtained
Each executor is limited by his own interests and goals, which creates certain conflicts of interest and conflicts over work budgets	All executors are connected by a chain of interrelated elements, in which the result of one process is a certain resource for the next one
The goals of different executors may not coincide, which requires constant coordination and strict control over the implementation of certain stages of work	All executors are focused on the end result of the process and improving their work, as they are aware of their interdependence
Focus of work management on the structure and functions of individual works	Focus on managing each process separately and all work processes as a whole

5. Results of mathematical modeling of the measuring instrument life cycle

5. 1. Research of possibilities and features of applying the process approach to the measuring instrument life cycle

One of the most used models of the system LC is the V-model, which is an option of the cascade model of the LC, bent at the point of transition from the stages of system definition (development) to the stages of system implementation. A detailed description of the V-model is given in [20], the analysis of which allows determining the basic principles of the model:

– decomposition of LC stages into separate phases consisting of a set of LC processes;

– formation of requirements to applied processes;

– integration and assessment of system development when moving from left to right from the system development stages to the implementation stages;

– interaction between the processes of the system development and implementation stages.

The latter is ensured by the feedback between the phases of the descending and ascending sides of the letter, which makes it possible to assess the correctness of the requirements and their implementation for each of the product LC processes. This model can be detailed to a seven-level model (system, subsystem, node, element, assembly, component, part). The development of the V-model was a double V-model that allows development, maintenance, operation and upgrading, i.e. management of the LC of systems with a complex hierarchical structure [20].

A generalized V-model of product design and sales, in particular MI, is shown in Fig. 2. The stages of this model have general application for any product for the design and implementation phases.

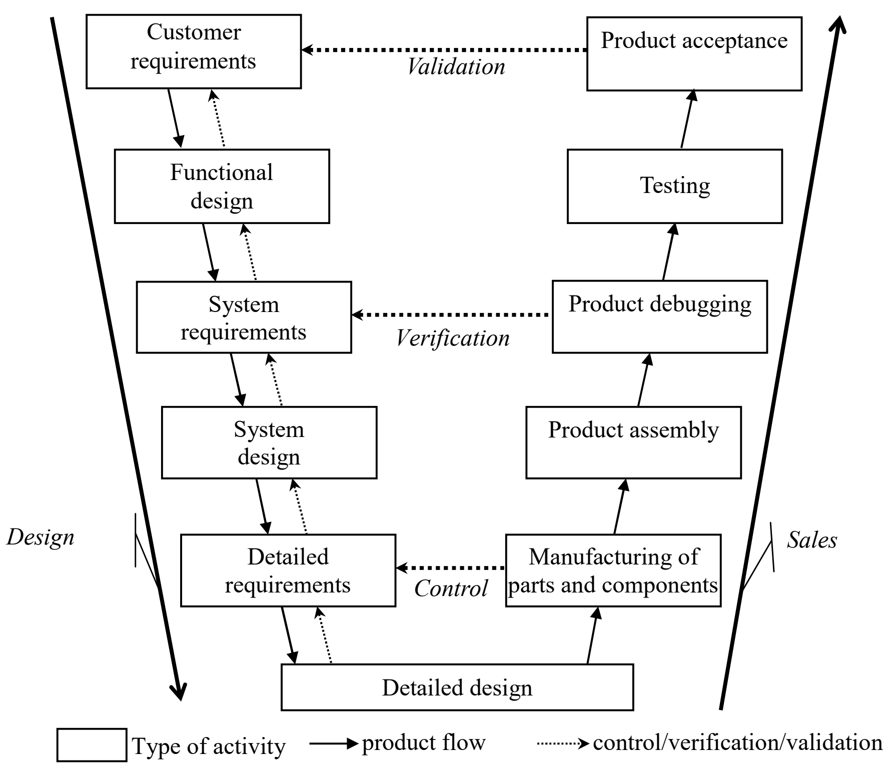

Fig. 2. Generalized V-model of product design and sales

The descending phase of the V-model concerns product design, and the ascending phase – product sales. At certain stages of the V-model, either control, or verification, or validation is carried out to ensure the assessment of the correctness of the requirements and their implementation at each stage of the product LC.

5. 2. Mathematical process model of the measuring instrument life cycle

A complex system, to which modern MI can be attributed, taking into account [31], has a hierarchical structure and can be mathematically presented in general:

$$S_{MI}=\left\{\bigcup S_{AS}\left\{\bigcup SS_{AS}\left\{\bigcup FE_{LL}\right\}\right\}\right\}, \qquad (1)$$

where S_{AS} is the set of MI hardware and software nodes $\left(\forall S_{AS}\subset S_{MI}\right)$;

SS_{AS} is the set of subsystems of MI hardware and software nodes $\left(\forall SS_{AS}\subset S_{AS}\right)$;

FE_{LL} is the set of lower-level functional elements of the corresponding subsystem $\left(\forall FE_{LL}\subset SS_{AS}\right)$.

Turning to the set of the MI LC, we obtain the following expression:

$$LC_{S_{MI}}=\left\{\bigcup LC_{S_{AS}}\left\{\bigcup LC_{SS_{AS}}\left\{\bigcup LC_{FE_{LL}}\right\}\right\}\right\}=$$

$$=\left\{\bigcup_{a=1} LC_{a}\left\{\bigcup_{b=1}^{c} LC_{ab}\left\{\bigcup_{d=1}^{e} LC_{abd}\right\}\right\}\right\}, \qquad (2)$$

where $LC_{S_{AS}}$ is the set of the LC of MI hardware and software nodes

$$\left(\forall\left(LC_{S_{AS}}:=LC_{a}\right)\subset LC_{S_{MI}}\right);$$

$LC_{SS_{AS}}$ is the set of the subsystem of the MI LC

$$\left(\forall\left(LC_{SS_{AS}}:=LC_{ab}\right)\subset LC_{S_{AS}}\right);$$

$LC_{FE_{LL}}$ is the set of lower-level elements of the MI LC

$$\left(\forall\left(LC_{FE_{LL}}:=LC_{abd}\right)\subset LC_{SS_{AS}}\right);$$

a, b, d are the indices of the system, subsystem and lower-level element, respectively.

The MI LC of components of each hierarchical level of the system consists of separate phases, each of which is a set of MI LC processes. Expression (2) can be represented as follows:

$$LC_{S_{MI}}=\left\{\bigcup_{a=1}\left\{\bigcup_{k=1}^{\gamma} PhLC_{ak}\left\{\bigcup_{b=1}^{c}\left\{\bigcup_{l=1}^{\lambda} PhLC_{akbl}\left\{\bigcup_{d=1}^{e}\left\{\bigcup_{m=1}^{\xi} PhLC_{akbldm}\right\}\right\}\right\}\right\}\right\}\right\}, \qquad (3)$$

where $PhLC_{ak}$, $PhLC_{akbl}$, $PhLC_{akbldm}$ are the sets of MI LC phases

$$\left(\left(\forall PhLC_{akbl}\subset LC_{ak}\right),\left(\forall PhLC_{akbldm}\subset LC_{akbl}\right)\right);$$

k, l, m are the indices of the phases in the corresponding MI LC.

Each of the processes that make up the MI LC phases has its own LC LC_{Pr}. This allows allocating their LC into separate levels, the feature of which is the affiliation of its components separately to each of the phases $\left(LC_{Pr}\subset PhLC\right)$. Due to this, expression (3) can be represented as:

$$LC_{S_{MI}}=$$

$$=\left\{\bigcup_{a=1}\left\{\bigcup_{k=1}^{\gamma}\left\{\left\{\bigcup_{i=1}^{j} LC_{aki}\right\},\left\{\bigcup_{b=1}^{c}\left\{\bigcup_{l=1}^{\lambda}\left\{\begin{array}{l}\left\{\bigcup_{i=1}^{j} LC_{akbli}\right\},\\ \left\{\bigcup_{d=1}^{e}\left\{\bigcup_{m=1}^{\xi}\left\{\bigcup_{i=1}^{j} LC_{akbldmi}\right\}\right\}\right\}\end{array}\right\}\right\}\right\}\right\}\right\}\right\}=$$

$$=\left\{\bigcup_{a=1}\left\{\bigcup_{k=1}^{\gamma}\left\{\begin{array}{l}\left\{\bigcup_{i=1}^{j}\left\{\bigcup_{r=1}^{s} PrLC_{akir}\right\}\right\}=\\ =\left\{\bigcup_{b=1}^{c}\left\{\bigcup_{l=1}^{\lambda}\left\{\begin{array}{l}\left\{\bigcup_{i=1}^{j}\left\{\bigcup_{r=1}^{s} PrLC_{akblir}\right\}\right\},\\ \left\{\bigcup_{d=1}^{e}\left\{\bigcup_{m=1}^{\xi}\left\{\bigcup_{i=1}^{j}\left\{\bigcup_{r=1}^{s} PrLC_{akbldmir}\right\}\right\}\right\}\right\}\end{array}\right\}\right\}\right\}\end{array}\right\}\right\}\right\}, \qquad \mathbf{(4)}$$

where LC_{aki}, LC_{akbli}, $LC_{akbldmi}$ are the sets of the MI LC process

$$\left(\left(\forall LC_{akbli}\subset LC_{aki}\right),\left(\forall LC_{akbldmi}\subset LC_{akbli}\right)\right);$$

$PhLC_{akir}$, $PhLC_{akblir}$, $PhLC_{akbldmir}$ are the sets of the MI LC phases of the respective processes

$$\left(\left(\forall PhLC_{akbl}\subset LC_{ak}\right),\left(\forall PhLC_{akbldm}\subset LC_{akbl}\right)\right);$$

i=1, 2, ..., j are the indices of the MI LC process;

r=1, 2, ..., s are the phase indices in the MI LC process.

The decomposition of the set process model of the MI LC constructed according to expressions (2)–(4) as a V-model is shown in Fig. 3.

Particular attention in this process V-model is paid to the design (first – descending phase) and production (second – ascending phase) phases of MI. In the design phase, the MI design processes include stages 1 and 2, and the development processes include stages 3 and 4. In the production phase, the production processes include stages 6–10, quality assessment processes – stages 11 and 12.

Separately at the phase of operation and disposal of MI (third phase), the relevant processes can be considered, which include the following stages:

– sales and distribution;
– installation (if necessary) and commissioning;
– technical assistance and maintenance;
– disposal after use.

In contrast to the classical representation (Fig. 2), this V-model includes an additional operation phase, corresponding to operation stages of hierarchical levels. This modification eliminates the imperfections of the classical V-model, which ends with the system commissioning, and does not allow studying the interaction of processes of all LC stages.

Unlike other technical objects, for MI, stages 11 and 12 have their own characteristics. Thus, at stage 11, MI tests are performed to verify the type of MI with the involvement of the designated MI conformity assessment body. Part of these tests is to determine the metrological characteristics of the MI. At stage 12, the conformity of the type is determined based on the results of checking each MI sample with the involvement of the designated MI conformity assessment body. At this stage, the conformity of the MI type can also be determined within the approved QMS for the production, control of finished products and testing.

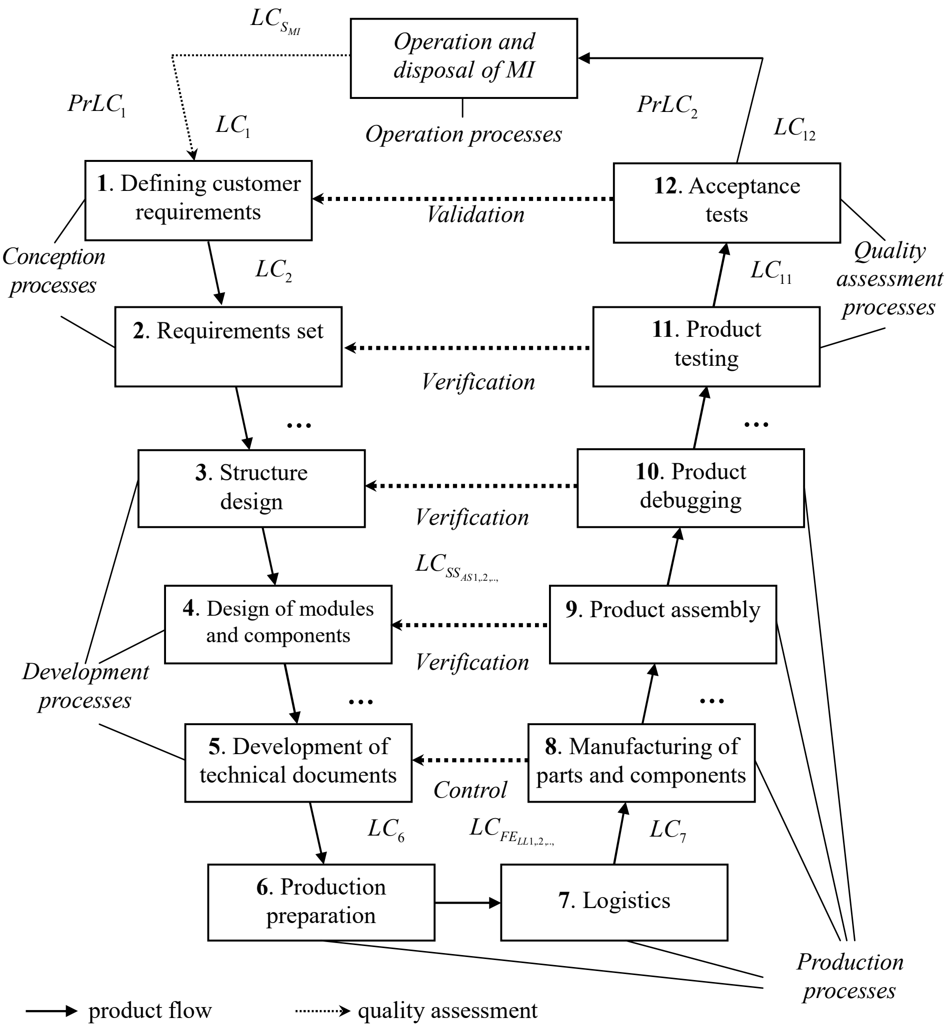

Fig. 3. Process V-model of MI LC

For the considered MI LC model, it is possible to determine additional connections between the design and production phases. This is also possible for stages 3–5 if conformity is determined on the basis of full quality assurance, provided that the QMS is also approved for MI design.

The MI operation and disposal phase is possible only if all stages of MI conformity assessment are completed. The introduction of the MI into the market is impossible without determining the MI compliance with all requirements and applying a conformity mark and additional metrological marks.

5. 3. Set process model of quality indicators of the measuring instrument life cycle stages

The ISO 9000 series standards state that if products are created using in a certain way organized production processes, the results of these processes will meet all the requirements set by the customer. That is, instead of assessing the quality of the final product, the standard implements an approach in which the processes of its creation are studied and evaluated. The quality model of technical systems, which includes both MI and software, is presented in the international standards ISO/IEC 25000 series [32–36]. This standard establishes requirements for quality management, quality models, quality measurement, quality requirements and quality assessment.

The ISO/IEC 25010 standard [32] defines two quality models: a quality model when using a human-machine system and a product quality model as a hardware-software system. The second quality model is most suitable for system-oriented MI as hardware and software systems. This model has the following characteristics: functional suitability; reliability; level of productivity; ease of use; security; compatibility; accompaniment; mobility. These characteristics include static (internal quality indicators) and dynamic (external quality indicators) properties of the system components.

Fig. 4 shows the scheme of interaction of the quality model elements at MI LC stages, taking into account the requirements of ISO/IEC 25010 [32]. In this case, in MI verification, the internal quality model (MI modules and components testing) is used, in approval – the external quality model (MI testing), in operation – the in-service quality model and the external quality model (actual operation, testing, MI calibration).

Using expressions (1)–(4) and research [37], it is possible to obtain an expression for a set of quality indicators of the MI LC:

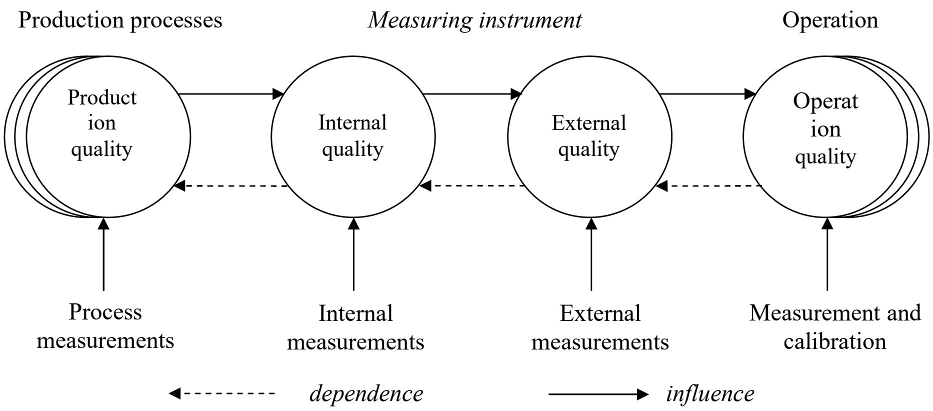

Fig. 4. Scheme of interaction of the quality model elements at MI LC stages

$$LCQ_{S_{MI}} = \left\{ \bigcup LCQ_{S_{AS}} \left\{ \begin{array}{l} \bigcup LCQ_{Pr}, \\ \left\{ \begin{array}{l} \bigcup LCQ_{SS_{AS}} \\ \left\{ \begin{array}{l} \bigcup LCQ_{Pr}, \\ \left\{ \bigcup LCQ_{FE_{LL}} \left\{ \bigcup LCQ_{PrFE} \right\} \right\} \end{array} \right\} \end{array} \right\} \end{array} \right\} \right\} = \left\{ \bigcup_{a=1} \left\{ \bigcup_{k=1}^{\gamma} \left\{ \begin{array}{l} \left\{ \bigcup_{i=1}^{j} \left\{ \bigcup_{r=1}^{s} PrLCQ_{akir} \right\} \right\}, \{VerQ_{ak}\}, \{ValQ_{ak}\}, \\ \left\{ \bigcup_{b=1}^{c} \left\{ \bigcup_{l=1}^{\lambda} \left\{ \begin{array}{l} \{VerQ_{akbl}\}, \{ValQ_{akbl}\}, \\ \left\{ \bigcup_{i=1}^{j} \left\{ \bigcup_{r=1}^{s} PrLCQ_{akblir} \right\} \right\}, \\ \left\{ \bigcup_{d=1}^{e} \left\{ \bigcup_{m=1}^{\xi} \left\{ \begin{array}{l} \{VerQ_{akbldm}\}, \\ \{ValQ_{akbldm}\}, \\ \left\{ \bigcup_{i=1}^{j} \left\{ \bigcup_{r=1}^{s} PrLCQ_{akbldmir} \right\} \right\} \end{array} \right\} \right\} \right\} \end{array} \right\} \right\} \right\} \end{array} \right\} \right\} \right\}, \quad (5)$$

where $LCQ_{S_{AS}}$, $PrLCQ$ are the sets of quality indicators of the LC of the MI hardware and software nodes and the process phase in accordance with the required indices;

$LCQ_{SS_{AS}}$, $LCQ_{FE_{LL}}$, LCQ_{PrFE} are the sets of quality indicators of the LC of the subsystem of hardware and software nodes, lower-level functional elements and processes in accordance with the required indices;

VerQ, *ValQ* is the quality of checking (verification) and the quality of approval (validation) of the phase in accordance with the required indices.

The set representation of the process V-model of the quality indicators of the MI LC, taking into account expression (5), is as follows:

$$LCQ_{\substack{a \\ g}} = \left\{ \bigcup_{b} \left\{ \begin{array}{l} \left\{ \bigcup_{c} \left\{ \bigcup_{d} PrLCQ_{abcd} \right\} \right\}, \\ \{VerQ_{ab}, ValQ_{ab}\}, \left\{ LCQ_{\substack{ab \\ g+1}} \right\} \end{array} \right\} \right\}, \quad (6)$$

where a is the index of the system (MI) of the corresponding level in the process double V-model of quality indicators of the MI LC;

b, c, d, g are the indices of the MI LC phase, MI LC phase process, process phase, level, respectively.

Since the process level is a lower-level object, expression (6) takes the following form:

$$LCQ_{Pr} = \bigcup_{b} \{PrLCQ_b\}, \quad (7)$$

where b is the process phase index.

The set representation of the generalized process V-model of quality indicators of the MI LC with an arbitrary number of levels, taking into account expressions (5) and (6), will take the form:

$$LCQ_{S_{MI}} = \left\{ \bigcup_{\substack{a=1 \\ g=1}} \left\{ \bigcup_{b} \left\{ \begin{array}{l} \left\{ \bigcup_{c} \left\{ \bigcup_{d} PrLCQ_{abcd} \right\} \right\}, \{VerQ_{ab}, ValQ_{ab}\}, \\ \left\{ \bigcup_{\substack{a \\ g=2}} \left\{ \bigcup_{b} \left\{ \begin{array}{l} \left\{ \bigcup_{c} \left\{ \bigcup_{d} PrLCQ_{abcd} \right\} \right\}, \\ \{VerQ_{ab}, ValQ_{ab}\}, \\ \left\{ \begin{array}{l} \ldots, \\ \left\{ \bigcup_{\substack{a \\ |g|}} \left\{ \bigcup_{b} \left\{ \begin{array}{l} \left\{ \bigcup_{c} \left\{ \bigcup_{d} PrLCQ_{abcd} \right\} \right\}, \\ \{VerQ_{ab}, ValQ_{ab}\} \end{array} \right\} \right\} \right\} \end{array} \right\} \end{array} \right\} \right\} \right\} \end{array} \right\} \right\} \right\}, \quad (8)$$

The decomposition of the set process model for evaluating the quality indicators of the MI LC, constructed in accordance with expressions (5)–(8) in the form of a V-model, is shown in Fig. 5. Between the design (descending phase) and implementation (ascending phase) phases, there is an interaction in the form of appropriate control, verification and validation of the model stages. Thus, for the process at stage 8 of manufacturing parts and components of the MI implementation phase LCQ_8, their control is carried out over the developed technical documentation at stage 5 of the MI design phase ($VerQ_1$). Appropriate verification $VerQ_2$, $VerQ_3$, and $VerQ_4$ is performed for processes at stages 9 (LCQ_9) and 4 (LCQ_4), 10 (LCQ_{10}) and 3 (LCQ_3), 11 (LCQ_{11}) and 2 (LCQ_2).

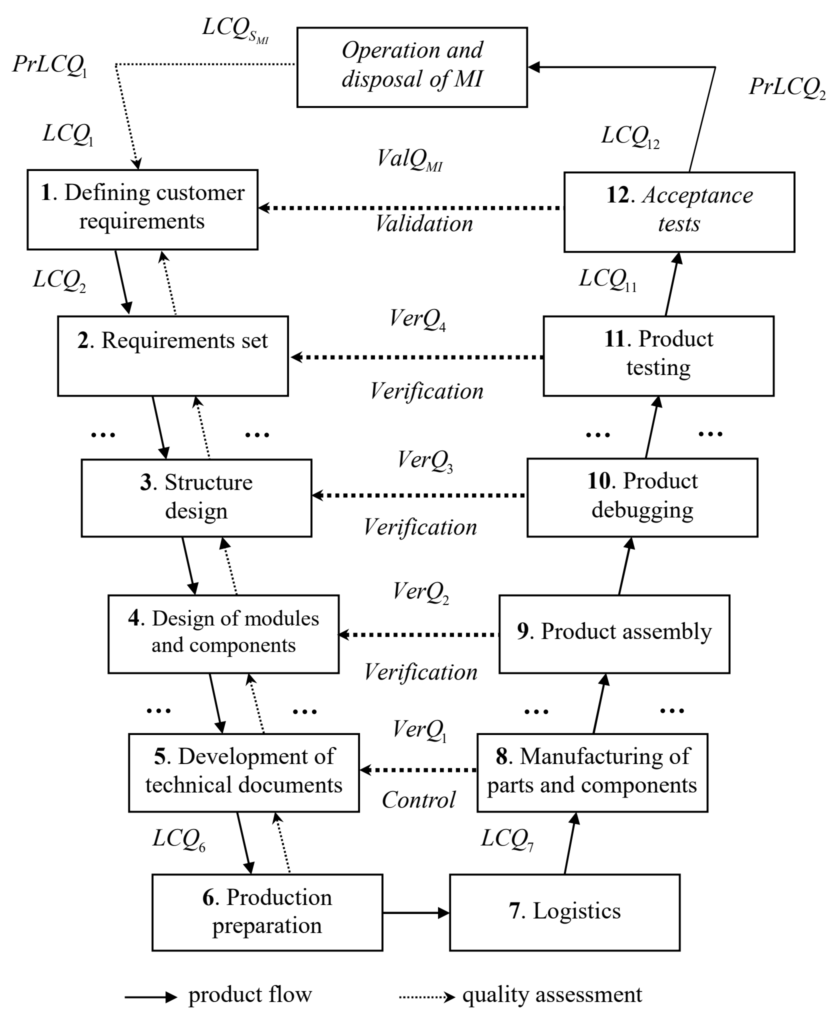

Fig. 5. Process V-model for evaluating the quality indicators of the MI LC

Relevant processes are implemented at each of the MI LC stages. At stage 12 of the implementation phase, validation of MI characteristics $ValQ_{MI}$ is carried out according to the customer's requirements, so this stage can be allocated separately for further analysis of its features. For MI, these requirements are also set separately for the software part [15, 16]. In view of this, special validation of these requirements is required, and the expression for the validation of MI characteristics will take the form:

$$ValQ_{MI} \subset ValQ_{AP} \cap ValQ_{SW}, \qquad (9)$$

where $ValQ_{AP}$, $ValQ_{SW}$ is hardware and software validation $\left(\left(\forall ValQ_{AP} \subset ValQ_{MI}\right), \left(\forall ValQ_{SW} \subset ValQ_{MI}\right)\right)$, respectively.

In addition to functional, resource-saving and environmental indicators common to all technical systems, purpose indicators and some functional indicators are specific to MI. MI purpose indicators include indicators related to metrological characteristics. Functional indicators for MI should be supplemented with such indicators as metrological reliability, metrological serviceability, metrological failure, calibration interval. These indicators are specific only to MI.

Unlike other technical objects, MI stages 11 and 12 also have their own characteristics. Thus, at stage 11, metrological characteristics of MI are determined. At stage 12, the determined metrological characteristics of MI are validated based on the results of verification of each MI sample with the involvement of the designated MI conformity assessment body. At this stage, the determined metrological characteristics of MI can also be validated within the approved QMS for the production, control of finished products and testing, as well as for MI design.

For a separate (additional) phase of operation and disposal of MI (Fig. 5), MI quality indicators are determined, which are also subject to evaluation. Information on quality indicators, as one of the stages of market research, obtained during the operation and disposal of MI, can be used to design new or upgrade existing MI. These indicators include such functional indicators of MI as metrological reliability, metrological serviceability, metrological failure, calibration interval.

6. Discussion of the results of building a process model of the measuring instrument life cycle

The proposed process V-models (Fig. 3) and quality indicators (Fig. 5) of the MI LC allow determining a direct connection with the process approach, which is implemented in the QMS of enterprises and organizations. Understanding and managing interconnected processes as a system (expressions (4) and (8)) help to increase efficiency in achieving planned results. For effective implementation of these models, it is necessary to use the regulated requirements of international standards, in particular the requirements for QMS. The main stages of the PDCA cycle are common to both MI LC and QMS functioning processes. Therefore, it is advisable to use specific requirements of ISO 9001 [10] for the planning (section 6 of the standard), activities – production (section 8), efficiency evaluation (section 9) and improvement (section 10) stages for MI LC processes.

The international standard ISO/IEC/IEEE 16326 [38] sets out the content of project management planning. It also provides guidance on the application of a set of design processes common to both software (ISO/IEC/IEEE 12207) and LC of the system (ISO/IEC/IEEE 15288), respectively. To effectively implement the stages of the proposed model, it is advisable to use the requirements of the international standard ISO/IEC/IEEE 15939 [39] on the measurement process. This standard provides for the development of a measurement process in accordance with the requirements of ISO/IEC/IEEE 15288 and ISO/IEC/IEEE 12207. Although this process is directly applicable to systems and software engineering and management disciplines, it can also be applied to the measurement process at different stages of the MI LC.

The international standard ISO/IEC/IEEE 29148 [40] determined processes and products related to the development of requirements for systems and software products and services throughout the LC. This standard provides guidance on the application of engineering requirements and management processes to the activities related to the requirements of ISO/IEC/IEEE 12207 and ISO/IEC/IEEE 15288. It sets out requirements that can be used alone or in addition to the existing set of LC processes according to the ISO/IEC/IEEE 12207 and ISO/IEC/IEEE 15288 standards.

To improve results in the implementation of all MI LC stages, it is advisable to consider all the most significant risks of the planned processes. The need for risk analysis is regulated by ISO 9001 [10]. The international standard ISO 31000 [41] contains principles and general guidelines for risk management and is not specific to any industry or sector of the economy. It can be applied to any type of risk and throughout the MI LC. ISO 31000 is intended to harmonize risk management processes in existing and future standards.

The international standard ISO/IEC 16085 [42] defines the process of risk management in the LC of any product. The purpose of risk management is to identify potential management and technical problems before they occur. This standard is an important tool for improving the search for and identification of potential problems that may affect the LC, as well as for improving active project management.

The formulated recommendations on the use of the requirements of international standards should help to increase efficiency in achieving the planned results at all stages of the MI LC. This applies, in particular, to project management planning, measurement processes, system requirements throughout the MI LC, risk analysis and management at the LC stages.

The presented studies are the first attempt to develop set process models of the MI LC and to evaluate quality indicators of MI LC stages. These models can also be represented by other set representations, in particular using general systems theory. The first attempt is also to present the MI LC and evaluate the quality indicators of MI LC stages in the form of a basic process V-model. Further studies of the MI LC and evaluation of quality indicators of MI LC stages can be aimed at presenting these research objects as more complex, but more advanced varieties of the V-model, in particular in the form of a double V-model.

7. Conclusions

1. The expediency of using the process approach to MI LC stages and its advantages over the functional approach were proved. The process approach allows a more effective assessment of MI quality indicators at different LC stages and is compatible with the construction of modern QMS.

2. The conducted mathematical modeling allowed developing a set process model of the MI LC, presented as a V-model. This allows studying the interaction of processes of all MI LC stages and performing process quality management at all MI LC stages. The features of the stages of product testing and MI LC acceptance tests were determined. Understanding and managing interconnected processes as a system will help increase efficiency in achieving planned results. This will also be facilitated by the use of regulated requirements of international standards, in particular with regard to system requirements throughout the MI LC, risk analysis and management at the LC stages, etc.

3. The conducted mathematical modeling allowed developing a set process model for evaluating the quality indicators of MI LC stages, presented as a V-model. This allows evaluating the quality indicators of the MI and its components throughout the MI LC. Purpose indicators and some functional indicators specific to MI were determined. It was determined that a feature of the stage of MI LC product testing is the determination of MI purpose indicators. A feature of the stage of MI LC acceptance tests is the validation of the determined MI purpose indicators.

References

1. Adizes, I. K. (2014). Managing Corporate Lifecycles. Moscow: Mann, Ivanov i Ferber, 512.
2. Sokolovskyi, S. A., Pavlov, S. P., Cherkashyna, M. V., Naumenko, M. O., Hrabovskyi, Ye. M. (2015). Upravlinnia yakistiu vyrobnytstva ta obcluhovuvannia. Kharkiv: NANHU, 264.
3. Biletskyi, E. V., Yanushkevych, D. A., Shaikhlislamov, Z. R. (2015). Upravlinnia yakistiu produktsiyi ta posluh. Kharkiv: KhTEI, 222.
4. Kalycheva, N. Ye., Bokhan, S. Ye. (2017). Napriamy zabezpechennia efektyvnoho rozvytku promyslovykh pidpryiemstv v suchasnykh umovakh. Naukovyi ohliad, 5 (37), 5–15.
5. ISO/IEC/IEEE 15288:2015. Systems and software engineering. System life cycle processes (2015). ISO, 108.
6. ISO/IEC/IEEE 24748-1:2018. Systems and software engineering. Life cycle management. Part 1: Guidelines for life cycle management (2018). ISO, 72.
7. ISO/IEC/IEEE 24748-2:2018. Systems and software engineering. Life cycle management. Part 2: Guidelines for the application of ISO/IEC/IEEE 15288 (System life cycle processes) (2018). ISO, 64.
8. ISO/IEC TR 24774:2010. Systems and software engineering. Life cycle management. Guidelines for process description (2010). ISO, 15.
9. ISO 9000:2015. Quality management systems. Fundamentals and vocabulary (2015). ISO, 51.
10. ISO 9001:2015. Quality management systems. Requirements (2015). ISO, 29.

11. Directive 2014/32/EU of the European Parliament and of the Council on the harmonisation of the laws of the Member States relating to the making available on the market of measuring instruments (recast). Official Journal of the European Union (2014). L96/149. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0032
12. ISO/IEC/IEEE 12207:2017. Systems and software engineering. Software life cycle processes (2017). ISO, 145.
13. ISO/IEC/IEEE 24748-3:2020. Systems and software engineering. Life cycle management. Part 3: Guidelines for the application of ISO/IEC/IEEE 12207 (software life cycle processes) (2020). ISO, 66.
14. Lisovodskaya, K., Shadrin, A. (2019). Protsessniy podhod v menedzhmente proektov Agile-kompanii. Standarty i kachestvo, 9, 76–80.
15. Velychko, O., Gordiyenko, T., Hrabovskyi, O. (2018). Testing of measurement instrument software on the national level. Eastern-European Journal of Enterprise Technologies, 2 (9 (92)), 13–20. doi: https://doi.org/10.15587/1729-4061.2018.125994
16. Velychko, O., Gaman, V., Gordiyenko, T., Hrabovskyi, O. (2019). Testing of measurement instrument software with the purpose of conformity assessment. Eastern-European Journal of Enterprise Technologies, 1 (9 (97)), 19–26. doi: https://doi.org/10.15587/1729-4061.2019.154352
17. Shadrin, A. D. (2016). Sistemnaya inzheneriya v menedzhmente kachestva predpriyatiya. Standarty i kachestvo, 1, 58–61.
18. Borysova, L. E. (2015). Process – functional approach in system management of modern telecommunication company. Naukovyi visnyk Khersonskoho derzhavnoho universytetu. Ser.: Ekonomichni nauky, 11 (2), 55–59.
19. Novikova, O., Shadrin, A. (2014). Protsessniy podhod v energeticheskom menedzhmente. Standarty i kachestvo, 8, 70–73.
20. Kalmykov, A. V. (2012). Upravlenie proektami informatsionnyh sistem na osnove dual-V modeli. Radioelektronni i kompiuterni systemy, 4, 193–200.
21. Volkov, S. L., Kyselova, O. I. (2017). Dual-v protsesna model yakosti shtuchnoho obiektu. Metrolohiya ta prylady, 6, 62–65.
22. Velychko, O. M., Hrabovskiy, O. V., Gordiyenko, T. B. (2019). Features of application of V-model in development and estimation of measuring instruments software. Collection of scientific works of the Odesa State Academy of Technical Regulation and Quality, 1 (14), 6–11. doi: https://doi.org/10.32684/2412-5288-2019-1-14-6-11
23. Graessler, I., Hentze, J., Poehler, A. (2019). Self-organizing production systems: Implications for product design. Procedia CIRP, 79, 546–550. doi: https://doi.org/10.1016/j.procir.2019.02.092
24. Graessler, I., Hentze, J., Bruckmann, T. (2018). V-models for interdisciplinary systems engineering. Proceedings of the DESIGN 2018 15th International Design Conference. doi: https://doi.org/10.21278/idc.2018.0333
25. VDI 2206:2004. Design methodology for mechatronic systems. Guideline. The Association of German Engineers (VDI), Düsseldorf, 2004. 118 p.
26. Gräßler, I., Hentze, J., Yang, X. (2016). Eleven Potentials for Mechatronic V-Model. Proceedings of the 6th International Conference on Production Engineering and Management, 257–268.
27. Graessler, I. (2017). A new V-Model for interdisciplinary product engineering. 59th Ilmenau Scientific Colloquiu. Technische Universität Ilmenau.
28. Graessler, I., Dattner, M., Bothen, M. (2018). Main Feature List as core success criteria of organizing Requirements Elicitation. R&D Management Conference 2018 "R&Designing Innovation: Transformational Challenges for Organizations and Society", 16. doi: https://doi.org/10.31224/osf.io/grfcn
29. Gräßler, I., Hentze, J. (2015). A V-model based comparison of Systems Engineering approaches. Proceedings of ECEC 2015/ the 22nd European Concurrent Engineering Conference. Lisbon.
30. Stephens, K. S. (Eds.) (2004). Juran, Quality, and a Century of Improvement: The Best on Quality Book Series of the International Academy for Quality. Vol. 15. ASQ Quality Press, 304.
31. Volkov, S. L., Vavilov, E. V., Kolomiets, S. V. (2017). System model of process of the life cycle of artificial systems. Collection of scientific works of the Odesa State Academy of Technical Regulation and Quality, 1 (10), 84–87. doi: https://doi.org/10.32684/2412-5288-2017-1-10-84-87
32. ISO/IEC 25010:2011. Systems and software engineering. Systems and software Quality Requirements and Evaluation (SQuaRE) – System and software quality models (2011). ISO, 34.
33. ISO/IEC 25012:2008. Software engineering. Software product Quality Requirements and Evaluation (SQuaRE). Data quality model (2008). ISO, 13.
34. ISO/IEC 25020:2019. Systems and software engineering. Systems and software Quality Requirements and Evaluation (SQuaRE). Quality measurement framework (2019). ISO, 27.
35. ISO/IEC 25021:2012. Systems and software engineering. Systems and software Quality Requirements and Evaluation (SQuaRE). Quality measure elements (2012). ISO, 37.
36. ISO/IEC 25030:2019. Systems and software engineering. Systems and software quality requirements and evaluation (SQuaRE). Quality requirements framework (2019). ISO, 46.
37. Skopa, A., Volkov, S., Grabowski, O. (2013). Quality indicators and life cycles of protected information-measuring systems. Visnyk Skhidnoukrainskoho natsionalnoho universytetu imeni Volodymyra Dalia, 15 (1), 192–198.
38. ISO/IEC/IEEE 16326:2019. Systems and software engineering. Life cycle processes. Project management (2019). ISO, 29.
39. ISO/IEC/IEEE 15939:2017. Systems and software engineering. Measurement process (2017). ISO, 39.
40. ISO/IEC/IEEE 29148:2018. Systems and software engineering. Life cycle processes. Requirements engineering (2018). ISO, 92.
41. ISO 31000:2018. Risk management. Guidelines (2018). ISO, 16.
42. ISO/IEC/IEEE 16085:2021. Systems and software engineering. Life cycle processes. Risk management (2021). ISO, 47.