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Quality testing model for unit prototype technological devices

Key words

Prototype testing, structural decomposition, process decomposition.

Słowa kluczowe

Badania prototypu, dekompozycja strukturalna, dekompozycja procesowa.

Summary

The article presents the model of testing individually manufactured unique prototype technical devices. Furthermore, problems occurring in such prototype testing are identified, and, on this basis, the assumptions of the model for quality tests of prototype technical solutions are made. Essential components of the model, including structural and process decomposition procedures, are discussed. Moreover, potential applications of the model are analysed and indicated. Results of the model verification are presented using the example of selected, technologically advanced prototype devices.

Introduction

Identification and verification of functional and operating properties of prototype solutions are one of the pivotal stages determining the final quality of

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designed devices, particularly those of an unique, individual character [1]. Quality tests for such solutions allow the control the conformity of obtained parameters and properties with the design assumptions. Additionally, they enable the identification of "weakest links" of the developed solution and determine methods and technical means to be used in the process of their elimination. Such tests also help the authors of the solution decide whether the prototype complies with the directives and requirements of international, national and sectoral norms or whether it can stimulate standardisation undertakings, norm modifications or new quality, safety, environmental impact and compatibility directives to be drawn up [11]. Properly planned quality tests for prototype solutions usually result in a shorter time of their implementation in industrial practice and reduce the costs of its launching [10]. Quality tests improve knowledge in the field of structural and functional elements as well as elements and components used to construct the prototype solution. These tests have an important input into procedural knowledge concerning particular types of groups of prototype solutions, which is especially important in the aspect of sustainable development, since prototype tests are an important element of LCA methods.

Conditions presented indicate that this matter is particularly important for scientific institutions, R&D institutes and those enterprises that are directly involved in the development and manufacturing of individual units of prototype technological devices [2, 3]. This type of applications should meet the technical, operating, ergonomic, economic, and human engineering requirements assumed in the design process as well as be adjusted to the requirements of sustainable economic development [4, 5]. Thus, the scope and the methods of quality testing for prototype technological devices should be selected with great deliberation and precision so as to provide information about its functional properties and the potential behaviour of the devices in the actual operating environment [2, 7, 8].

The holistic approach towards this matter, based on the authors' practical experience gained in design, manufacture and implementation processes of several dozen of prototype solutions [12, 13, 14], determined the genesis of activities aimed at the development of the model of quality testing for prototype unit technological devices, technologically advanced unique test and research apparatus in particular.

Problems associated with quality tests for prototype solutions

Practical problems to be solved in the process of the planning of experiments connected with quality tests for innovative prototype solutions were identified on the basis of several dozen of selected unit devices developed and produced at the Institute for Sustainable Technologies – National Research Institute in Radom [15], presented in detail in the electronic catalogue of innovative solutions attached to this publication.

These solutions are characterised by technical parameters, functionality, and purpose allowing them to be classified into the group of unique, niche prototype solutions conforming to the technical level of highest global standards. The solutions are composed of specialised mechanical, electronic, optical, computer, control and measurement units integrated with one another. Original components, that is mechanical structures, electronic and optical elements, and units were used in their structure. Control-measurement units, actuators and effectors, as well as IT procedures were used in their construction. The unique structure and purpose of the developed prototype solutions enforced unconventional quality tests to be conducted. Without the methodologically justified selection of test and verification methods particularly concerning original components of the prototype solution, the tests do not guarantee proper verification of the predefined functional and operating properties to be obtained, and, in consequence, fail to ensure that the device will work in real operating conditions without any faults. The results of the lack of the methodologically justified selection of verification procedures are presented on the basis of the chamber for thermo-mechanical properties of ceramic and composite energy insulators testing (Fig. 1).

Fig. 1. Prototype chamber for thermo-mechanical properties of energy insulators testing
Rys. 1. Prototypowa komora do badań właściwości termomechanicznych izolatorów energetycznych

System errors consisting in the too general structural decomposition were made at the time of selecting quality test methods, which resulted in the omission of some of the structural elements of the prototype, which, in practice, turned out to be necessary for the proper maintenance of the chamber. Endurance tests did not cover the full scope, which made it impossible to detect the following:

- A failure frequency that was too high of the dual temperature regulation system in the range of temperatures below –30°C;
- The lack of the operating durability of hydraulic load sets enforcing vertical stretching force in the 0–220 kN range and the horizontal bending force in the 0–20 kN range; and,
- Intervals in transmission between the computer monitoring system and the PLC controllers in measurement-control systems.

In the case of the device for the conditioning of emulsion treatment fluids (Fig. 2), in which the novel solution applying the coalescence phenomenon for the removal of external oil, the four-level sensor for the measurement of the fluid level, was the problem. Reliability and frequency of fluid level measurement plays an important role in the general functioning of the device, since it improves filtration efficiency, which in turn prolongs the operating time of the fluid and maintains the high quality of processed details. The developed prototype of the solution showed measurement errors that were too great of the fluid-level measurement sensor. The properly prepared, from the methodological point of view, plan for the experiments with the use of methods for the quality testing for structural elements and an in-depth analysis and interpretation of obtained measurement results enabled the detection of the reasons of these errors. This was the non-linearity of the characteristics of the sensor with reference to the designed measurement range, which allowed the fault to be completely eliminated. A different kind of problem occurred in the case of quality tests for the device for the control of the side surface of roller bearings (Fig. 3.) equipped with the multicamera system of automatic optical inspection.

Fig. 2. Device for the conditioning of emulsion treatment fluids
Rys. 2. Urządzenie do uzdatniania emulsyjnych cieczy obróbkowych

The device enables one to control the quality of the side surface of metallic cylindrical products by means of advanced mathematical and algorithm models of digital image analysis and processing. The results of image analysis form the basis for the qualification of goods into one of three categories: good, faulty, requiring correction. In quality tests, the verification of visual paths of the software of the frame grabber and the analysis and classification algorithms needed to be incorporated. An intermediate method was used to verify the correctness of the analysis and classification algorithms. It required factual data that is digital images containing model side-surface defects, including, *inter alia*: material loss, cracks, corrosive pits and edge defects. Acquisition and inclusion of a statistically justified number of exemplary images was important from the point of view of quality test for algorithms developed. Problems that occurred in this case concerned the models of data acquisition necessary for quality tests as well as the identification of the informational range and the structure of simulation models using data gathered.

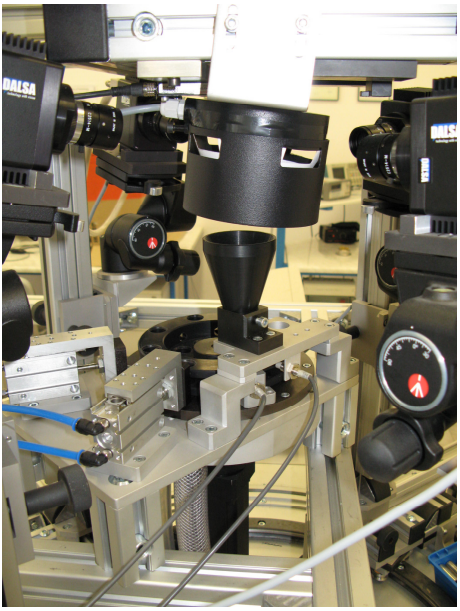

Fig. 3. Device for the control of the quality of roller bearings assembly
Rys. 3. Urządzenie do kontroli jakości montażu łożysk ocznych

Presented examples of practical problems connected with prototype tests complemented with years of experience gained from the realisation of numerous R&D tasks and constructions undertakings, enabled the development of the synthetic classification of issues occurring in quality tests for prototype unit technological devices (Fig. 4).

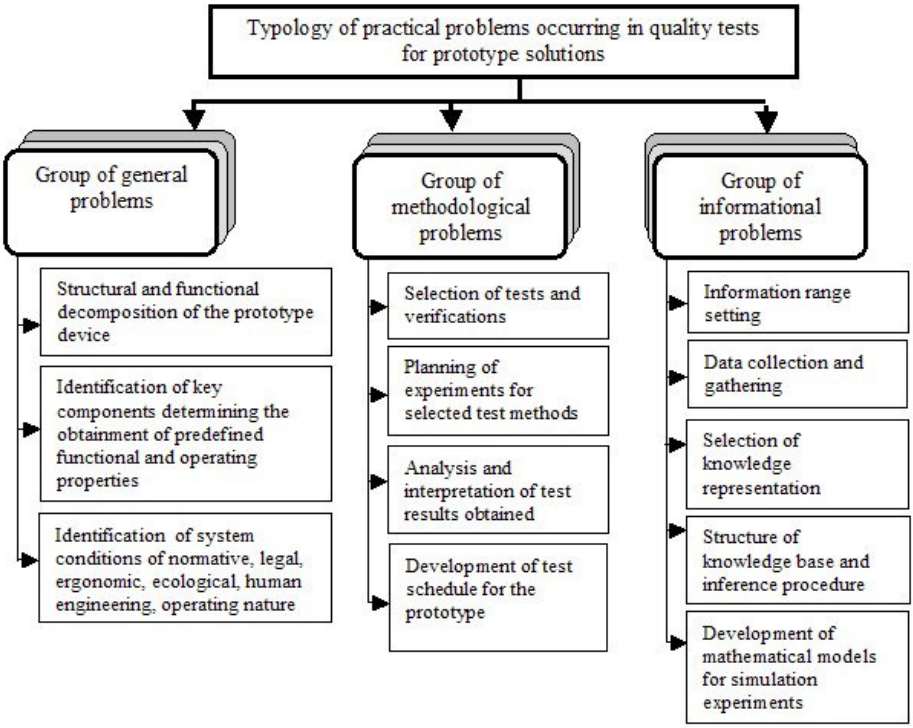

Fig. 4. Classification of practical problems taking place at the time of prototype technological device testing
Rys. 4. Klasyfikacja problemów praktycznych występujących przy badaniu prototypowych urządzeń technicznych

These problems can be classified into the following groups:

- General problems concerning, particularly, the issues of structural and process decomposition determining the selection of sets of structural elements used on different functional levels of the prototypes of the device that should be further tested in order for the verification of technical parameters of the prototype and the estimation of its reliability, durability to take place; and the type and time of tests and verifications to be determined, as well as quality analysis to be conducted in order to enable the identification of discrepancies between the obtained and the predefined operating characteristics and cause-effect relations for the occurrence of potential faults and critical defects;
- Methodological problems connected with the selection of test and verification methods, as well as experiment planning, which is particularly important since unit devices can rarely be subject to destructive testing; and,
- Informational problems concerning difficulties connected with acquisition and gathering of data necessary for the construction of simulation models and inference methods for probable operating properties of devices, a well as

information about the prototype quality tests, which is important for its modification.

The necessity to develop an original model for quality testing for prototype technological devices was also justified by the difficulties in direct application of FMEA (*Failure Mode and Effect Analysis*), FMECA (*Failure Mode, Effect and Criticality Analysis*), FTA (*Fault Tree Analysis*), PRN (*Probabilistic risk assessment*), TQM (*Total Quality Management*) methods, and RCM (*Reliability Centered Maintenance*) and CRI (*Continuous Reliability Improvement*) models, particularly in standard reliability methods and models or machine diagnostics used in statistical quality management, RCM systems and CRI procedures. Unsuccessful application of these methods stemmed particularly from the following prerequisites:

- The frequent lack of data about the reliability of components, which the prototype technological device is built from;
- The lack of the possibility to conduct the statistically justified number of tests and verifications that could provide information required to determine the probability of defect occurrence in individual structural elements and the entire device, which prevents quantitative assessment of operating durability and indicates qualitative methods, e.g. rating;
- The impossibility to use destructive tests, e.g. fatigue tests, due to the fact that usually only one copy of the prototype solution is available;
- The necessity to include such characteristics as effectiveness, functionality, safety, and ergonomics in complex quality assessment;
- The limited liability with reference to the proper functioning of the diagnostic module of the device, which also is subject to quality testing; and,
- The lack of possibility to obtain new information sources that can make the assessment of the characteristics of the prototype solution easier, because these devices are unique or niche solutions that cannot be compared with any other solutions available on the market with reference to their technical parameters and functional characteristics.

An important difference between unit and mass production is the fact that prototype solutions developed are in fact final versions presented to the end customer. These devices are manufactured individually or in short series, usually with no knowledge of the operating characteristics of each of their components, which results in the lack of the possibility to apply various statistical methods typically used in the case of verification tests for prototypes of devices manufactured serially. Contrary to mass production, in the case of tests of this type of prototypes, consideration of conditions close to manufacturing conditions is not necessary; whereas, technical and functional parameters definitely need to be preserved. Thus, taking classical requirements into consideration [9], quality tests ought to provide statistical a priori knowledge enabling prediction inference about operating properties of prototype solutions.

Assumptions for the development of the model for quality tests for unit technological devices

The presented, selected practical problems formed the basis for the formulation of guidelines for the development of the model for prototype device testing.

The following general assumptions were chosen:

- The primary objective of the model is to enable the verification of the conformity of obtained technical and functional parameters of the prototype with those predefined in the design process.
- The selection of tests and test methods should allow the following:
  - the identification of hidden material defects or faulty components, whose defects may lead to critical faults or defects of the entire prototype solution;
  - the assessment of prototype solution durability and reliability in real operating conditions; and,
  - the reduction of the number of operational and analytical procedures depending on the importance and the time available for prototype testing.
- The model is composed of three major components, that is structural decomposition, process decomposition, and procedures for the selection of test methods and verification tests, which enables the assessment of the effects and sequences of events caused by the fault identified on different levels of the hierarchic structure of the prototype solution and additionally allows one to determine the importance and the critical nature of every type of defect in relation to the general functioning of the prototype solution.
- The structural decomposition is conducted with the use of recurrent procedure enabling the representation of the structure of the prototype solution in the hierarchic tree structure, which is crucial in the case of the application of the computer system for the support of planning processes and the management of prototype tests.
- The process decomposition enables the selection of a set of processes taking place in the prototype on different levels of its functioning, playing a critical role in the functioning of the entire prototype solution.
- The only elements that are subject to tests are original components used in a given prototype. Components that do not meet the requirements of the originality criterion (e.g. commercial parts) are only assessed within the module into which they have been built.
- The model is equipped with a database, which enables the application of regularly collected information necessary for the planning and realisation of test programmes.

– The model is based on knowledge and experience acquired from previously conducted analyses and development research; it thus is equipped with the knowledge base.
– The effects of the application of the model include the confirmation of the conformity between project and predefined characteristics and the set of identified, potential defects and faults categorised according to the criteria of importance and detection.

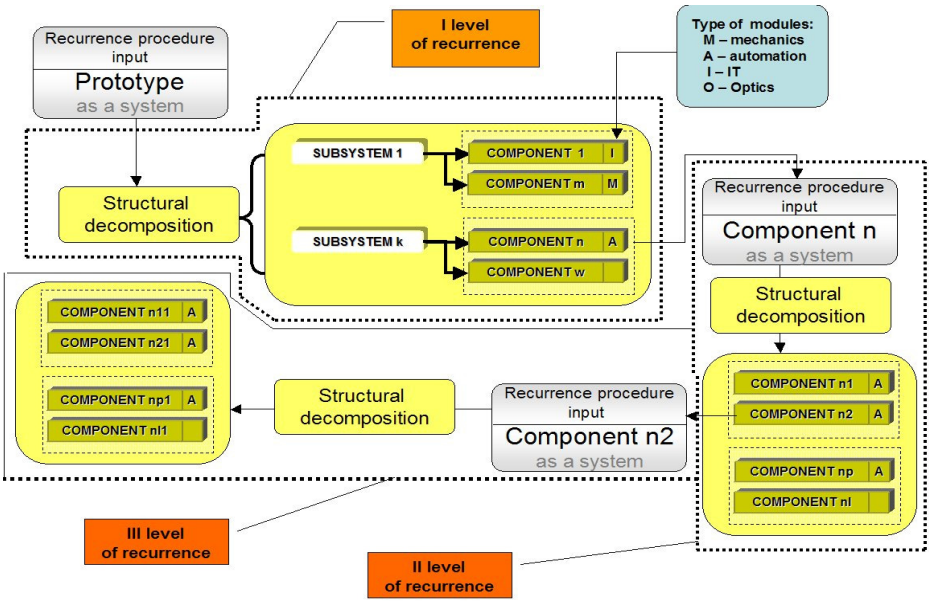

Fig. 5. Diagram of the recurrent procedure of structural and process decompositions
Rys. 5. Schemat procedury rekurencyjnej dekompozycji strukturalnej i procesowej

The presented classification of practical problems occurring in quality tests for unit prototype solutions and formulated assumptions imply the use of declarative and procedural knowledge, particularly the knowledge of the authors and the users of these solutions for the development of formal and heuristic decomposition models.

Structure of the model for quality tests for prototype unit technological devices

The essential role in the model developed (Fig. 5) is played by the recurrent procedure of structural and procedural decomposition processes. The application of this type of the solution allows the following:

– The use of unified procedure for different kinds of prototypes;
– The beginning of the decomposition process on any level (Fig. 6) – the procedure can be implemented for the entire prototype solution, its subsystem or the original component of the prototype application; and,
– The ending of the decomposition process after the identification of the set of all the components that, in the authors' or experts' opinion, should definitely be subject to testing due to the fact that they can play a critical role in the proper functioning of the entire prototype.

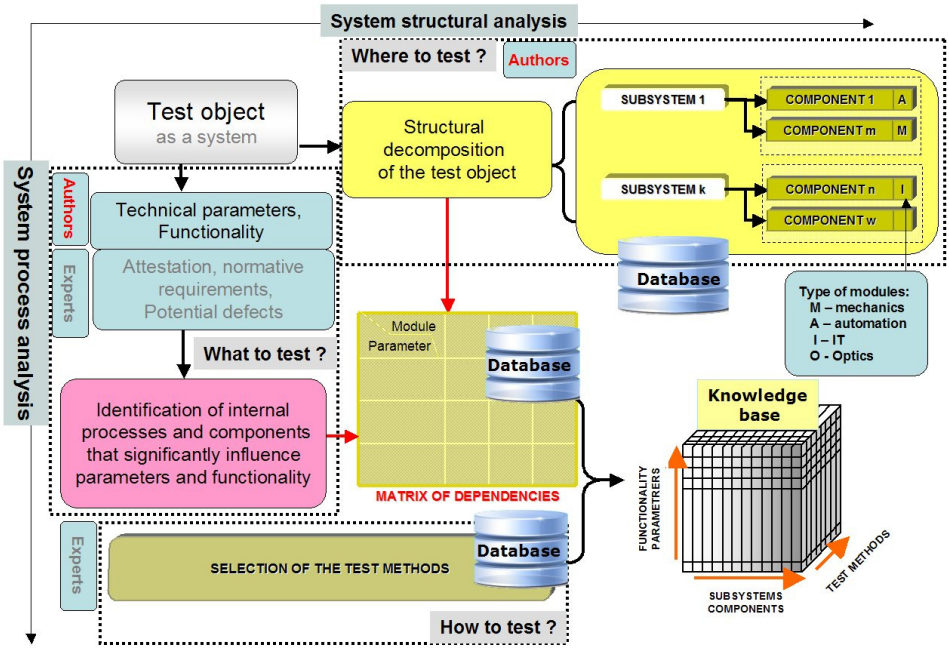

Fig. 6. Model for quality tests for prototype solutions of unique technological devices
Rys. 6. Model badania jakości rozwiązań prototypowych, unikatowych urządzeń technicznych

Figure 6 indicates that process decomposition also plays an important role in the developed model. It enables the identification of the set of technical and functional parameters resulting from the structure and the correlation between individual subsystems and components on different levels of the complexity of the prototype application. Connecting structural decomposition with process decomposition enables the selection of criteria of decomposition ending which include the following:
– The development of the set of parameters and characteristics of key importance to the functionality of the prototype; and.
– The identification of structural elements, whose fault badly influences the functioning of the entire prototype solution.

The result of the decomposition process is composed of the matrix of identified cause-effect dependencies between structural elements on different levels of complexity and the parameters and functionalities (Fig. 7). Structural decomposition is a top-down procedure.

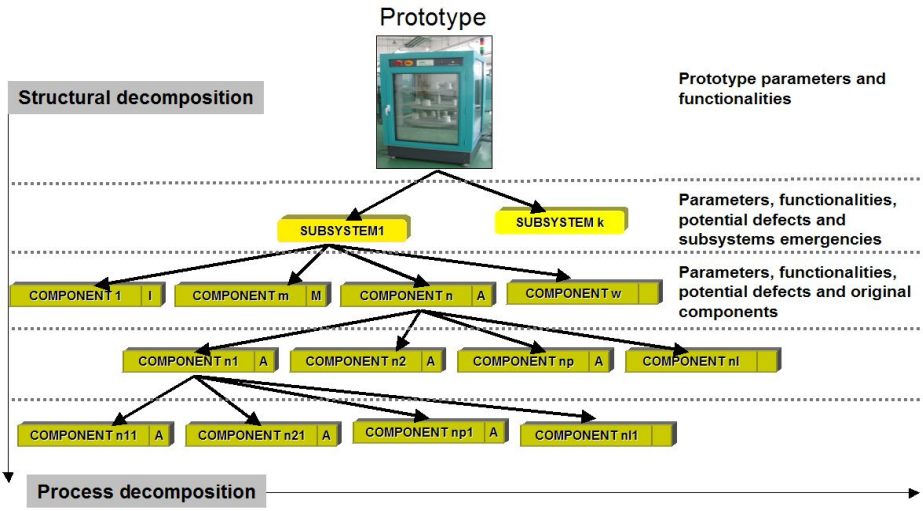

Fig. 7. Results of the recurrent procedure of the decomposition process
Rys. 7. Rezultaty procedury rekurencyjnej dekompozycji

Decomposition is a source of knowledge enabling the following:

- The identification and qualitative analysis of potential defects and the assessment of their importance for the proper functioning of the entire prototype solution and identification of probable reasons behind their occurrence;
- The determination of the cause-effect relations between the defects, their occurrence frequency and structural elements from which the prototype solution is built; and,
- The decision-making process concerning the construction of simulation models.

Once dependency matrices are developed and cause-effect relations characterised by the experts, the set of tests and probable development research is created. The assessment of time and costs necessary for individual tests allows one to identify the multidimensional matrix containing the component-parameter-test model relations. The analysis of critical paths enables the identification of the set of test procedures that are optimal in relation to safety criteria and necessary financial and time inputs ensuring the following:

- The verification of technical parameters;
- The procurement of planned functionalities;
- The diagnostics of potential “weakest links” of the prototype solution; and,

– The selection of methods and the scope of tests possible to be realised in the time given.

The matrix of dependencies is a formal presentation of the effects of activities connected with the selection of technical and functional parameters subject to verification, and the identification of faults, defects and emergencies. The matrix can be expanded by cause-effect diagrams enabling holistic analysis of cause effect chains *(defect – results of it occurrence)*. The results of the analyses are used, *inter alia*, in the following:

– The calculation of the priority number or critical character number of known FMEA or FMACA methods that are the measurements of the quality of the prototype technological solution;
– The identification of the components for which experimental or simulation tests should be conducted in order to obtain information about their reliability and durability;
– The selection of components for which tests and verifications need to be done;
– The procurement of data about the components of the technological device, particularly information required for risk assessment and defect occurrence frequency issues;
– The determination of test methods to be applied in the case of the entire device testing in order to confirm its technical and functional parameters; and,
– The gathering of data necessary for inference about operating properties of the device in real operating conditions.

A set of measurement techniques is ascribed to each of the methods. It includes tests, research apparatus, and measurement methods. The point assessment of the usefulness of a given method is conducted by the experts.

Temporary conditions for the application of the developed model are presented in Fig. 8.

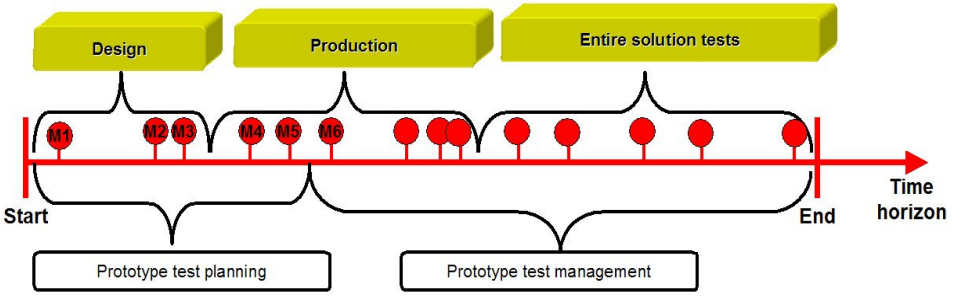

Fig. 8. Draft of dependencies in the life cycle of the prototype solution and operational procedures of the model for its assessment

Rys. 8. Schemat współzależności cyklu życia rozwiązania prototypowego i procedur operacyjnych modelu jego oceny

The model can be applied at the very stage of prototype solution design for test plans, as well as on the level of original component manufacture. Possibilities of its application in tests planning and tests management are presented based on the chamber for concrete carbonisation.

Case study – quality tests for the chamber for concrete carbonisation

Chambers for concrete carbonisation (Fig. 9) are used in attestation tests for processes of CO_2 calcium hydroxide reaction. What decides the innovativeness of the chamber is the application of the module for CO_2 condensation testing. A crucial element of the module is the original, operational structure enabling precise, long lasting gas dosage. Application of Peltier links in the systems for temperature reduction and atmosphere drying is also a unique solution. Water that is released at the time of concrete carbonisation is automatically removed from the chamber by means of an original application for the control module with the use of PLC controller. The matrix of dependencies between the aforementioned solutions and the functionality and technical parameters of the chamber obtained at the time of structural and process (functional) decomposition is presented in Fig. 10.

Fig. 9. Chamber for concrete carbonisation tests
Rys. 9. Komora do badań karbonatyzacji betonu

Analysis of data included in the matrix allowed one to indicate that CO_2 concentration and temperature measurement systems needed to be tested together with the subsystem for water removal. Applying expert knowledge, the set of test methods possible to be used in these cases was developed (Fig. 11).

Subsystem/Component	Parameter	CO_2 condensation	Temperature	Temperature change dynamics	Temperature spread in the chamber	Assurance of the tightness of outflow system	Water outflow efficiency
CO_2 condensation stabilization subsystem	System (object) for CO_2 condensation measurement	X					
	System (object) for CO_2 dosage	X					
Cooling subsystem	Temperature measurement system		X				
	Peltier links regulation system			X	X		
Water removal subsystem	Construction system					X	X
	Control					X	X

Fig. 10. Matrix of dependencies between subsystems and objects and parameters and functionalities

Rys. 10. Macierz zależności pomiędzy podsystemami i obiektami a parametrami i funkcjonalnościami

Test method identifier	Name	Assumed test time/number of tests
MB_1	Venting valve opening/closing monitoring	30min/2 tests
MB_2	Gas consumption control at the attempt to fill the chamber in with air or CO_2 at increased pressure	30min/2 tests
MB_3	CO_2 condensation monitoring at the top and bottom of the chamber	200 h in the cycle 59 min work/1min interval
MB_4	Temperature measurement in the cooling cycle in 6 points in chamber space	6h/1 test 6 tests
MB_5	Measurement of the dynamics of temperature changes at Peltier links switched off	6h/1 test 6 tests
MB_6	Faulty functioning of temperature sensor simulation	6h/1 test 6 tests
MB_7	Control of the installation for water outflow from the bottom of the chamber at artificial, low spraying	6h/1 test
MB_8	CO_2 condensation monitoring at the top and bottom of the chamber	200 h in the cycle 59 min work/1min interval
MB_9	Tests for order transmission to PLC controller	>25ms/100
MB_10	Tests for data receiving from PLC controller	>25ms/100
MB_11	Transmission interval tests	several hours/10
MB_12	Buffer overfilling tests	ms/100
MB_13	Writing to file tests	<2s/25
MB_14	Reading from file tests	<2s/25
MB_15	Report printing tests	<10s/30
MB_16	System clocks synchronisation tests	>10s/25
MB_17	Colour models conversion tests	<10s/100
MB_18	Graphics conversion tests for digital images	<10s/100

Fig. 11. Set of test methods and tests that need to be done for a prototype chamber for concrete carbonisation

Rys. 11. Zbiór metod badań i testów, jakie należy wykonać dla prototypowej komory do karbonatyzacji betonu

Based on the matrix of dependencies and the set of test methods, the multidimensional matrix of *structural element – test method* type is composed. The matrix contains input data for the determination of critical paths and the minimum set of test procedures necessary for the verification of a test process for the prototype solution. It also enables the identification of tests that can be realised in parallel and enables the assessment of time necessary for the creation of a required test set.

Summary

The developed model can be used for prototype solutions with varied technological advancement.

The model enables the time and the costs of tests verifying the quality of the solution to be optimised.

The test method, realised with the use of the develop model, is far less time consuming and much more efficient than the procedures used in QFD, FMEA, FMECA, FTA, PRN or RCM methods.

The model can be used even at the design and production stage in order to plan and manage the test processes.

The developed model of structural and process decomposition enables basic parameters and functions to be assigned to the highlighted structural elements and operational processes, which makes the identification of the causes of potential faults easier. Additionally, it shows great effectiveness in quality tests for compound, unique prototype technological solutions. The decomposition also enables the identification of these structural elements of the prototype solution that are the most probable areas of fault occurrence as well as the identification of areas of crucial importance from the point of view of predefined technical and functional parameters.

Prototype tests conducted with the use of the model developed result in the high probability of the proper functioning of the tested object at the time of its excessive operation.

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Model badania jakości rozwiązań prototypowych jednostkowych urządzeń technicznych

S t r e s z c z e n i e

W artykule przedstawiono model badania prototypowych urządzeń technicznych wytwarzanych jednostkowo. Zidentyfikowano praktyczne problemy występujące w badaniach takich prototypów. Na tej podstawie sformułowano założenia do budowy modelu badań jakości rozwiązań prototypowych. Zaprezentowano kluczowe komponenty modelu, w tym procedury dekompozycji strukturalnej i procesowej. Przeanalizowano możliwości zastosowań modelu. Weryfikację modelu przedstawiono na wybranych, zaawansowanych technicznie prototypowych, jednostkowych urządzeniach technicznych.