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Ensuring dependability of unique highly vital systems

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Abstract. Aim. *Dependability of products is usually researched with no regard to its genesis, while the causes of undependability are conventionally regarded as generalizing stochastic relationships that take into consideration "the result of interaction of a number of factors: the environment, system properties, process-specific, operational and other requirements." Consequently, the evaluation of dependability indicators is based on the assumption that by the beginning of operation the product is in working order. Respectively, the relations between the dependability and the time are considered only for the product operation period. The best known dependability-to-time relation is the empirical failure function, the so-called U-shaped dependability curve, which no one yet was able to describe with simple mathematical formulas usable in engineering calculations. The presence of the first "hump" in the U-shaped curve is associated with the manifestation of design errors, manufacturing defects or incorrect assembly of products, yet the specific causes of this "hump's" existence are not clarified in publications. The definition of the term "operability" does not rule out, and in practice there are often cases when design and development activities do not cover all the parameters that characterize the product's ability to perform the specified functions or when some of the documented requirements are not coordinated with the values of functional parameters, while during manufacture the values of such parameters may exceed the specified limits. As the result, a seemingly operable structure that passes experimental development may not be fit in terms of specified dependability indicators.* **Methods.** *The dependability properties of any product are specified long before the operation and can only fully manifest themselves after its beginning. The paper shows a graph that reflects the conditional probability of fault-free operation per lifecycle stages of products long before the beginning of operation. The dependability of unique highly vital systems (UHVS) may be ensured from the very early lifecycle stages based on consecutive execution of certain design, process engineering and manufacturing procedures, as well as application of engineering analysis of dependability.* **Results.** *The paper examines the role and significance of each lifecycle stage in ensuring UHVS dependability. The procedures of the engineering method of ensuring dependability are listed, the principles of UHVS design principles are set forth. Basic tools for increasing dependability and its evaluation principles are shown.* **Conclusions.** *The paper shows the possibility of ensuring the dependability of UHVSs using engineering procedures implemented at each lifecycle stage before the beginning of operation. Such procedures would enable an adequate level of design, development, preproduction, manufacture, as well as the development of a UHVS dependability evaluation method based on a single theoretical and methodological basis.*

Keywords: *unique highly vital system, ensuring dependability, dependability analysis, dependability evaluation, lifecycle stages, design, development.*

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Introduction

Dependability of products is usually researched with no regard to its genesis, while the causes of undependability are conventionally regarded as generalizing stochastic relationships that take into consideration *"the result of interaction of a number of factors: the environment, system properties, process-specific, operational and other requirements."* [1] Consequently, the evaluation of dependability indicators is based on the assumption that by the beginning of operation (moment when operation time calculation begins) the product is in working order [2] and if t is the total operation time, while τ is the product's operation time to first failure, then the probability of no-failure (PNF) over time t is defined as follows:

$$P(t)=P(\tau>t). \quad (1)$$

Respectively, the relations between the dependability and time are considered only for the product operation period. The best known dependability-to-time relation is the empirical failure function, the so-called *U*-shaped dependability curve [3], which no one yet was able to describe with simple mathematical formulas usable in engineering calculations. The presence of the first "hump" in the *U*-shaped curve is associated with the manifestation of design errors, manufacturing defects or incorrect assembly of products, yet the specific causes of this "hump's" existence are not clarified in publications [4].

In this context it is appropriate to recall a quizzical remark that I.A. Ushakov makes in his informal history of the dependability theory: "Dependability is calculated by people who cannot achieve it [5]." Indeed, in terms of theory the dependability of any complex technical system is a multidimensional problem, the definition and solution of which requires taking into consideration a multitude of interdependent parameters, stochastic in their nature, which is practically impossible to implement. At the same time, engineers have learned to practically achieve a more or less acceptable level of reliability of complex technology by using qualitative dependability criteria [6]. For instance, the designers of deployable structures of spacecraft know well that the product that is being designed, firstly, must be solid not to break before or during the loading, secondly, it must be operable so that the design allows deploying after flight loads, and thirdly, dependable in order to ensure stability of deployment time and again in given modes and conditions of operation.

As it is known, the state of operability *is a state of an object under which the values of all parameters that characterize the ability to perform the specified function comply with the requirements of regulatory technical and/or design documentation* [7]. Obviously, the definition of the term "operability" does not rule out cases, and in practice there are often cases when design and development activities do not cover all the parameters that characterize the product's ability to perform the specified functions or when some of the documented requirements are not coordinated with the values of functional parameters, while during manufacture the values of such parameters may exceed the specified limits. As the result, a seemingly operable structure that passes experimental development may not be fit in terms of specified dependability indicators. A prime example is the repetitive non-deployment of solar array panels of the Soyuz TMA-14M (in 2014) and Soyuz TMA-17M (in 2015) spacecraft due to jammed array mounting elements.

The role of the lifecycle stages preceding the operation in ensuring dependability of unique highly vital systems

In [8-10] the authors show the impossibility of developing UHVSs from the perspective of ensuring specified dependability with no account for the principles of its genesis. The dependability properties of any product are specified long before the operation and can only fully manifest themselves after its beginning.

As it is known from practice while in the state of expectation of operation any objects bear the risk γ of failures due to design, process engineering and manufacturing errors that may reach 80 % [10-11]. Up to 80 to 85 % of costs in the machine building industry is defined by the design solutions that are created in the process of technology design and development [12].

In [10] the impact of design and process preproduction on the dependability is examined and it is suggested to evaluate UHVS PNF (1) as follows:

$$P(t)=(1-\gamma)\cdot P(\tau>t). \quad (2)$$

Formula (2) is to focus the developer's attention on the initial lifecycle (LC) stages, i.e. the design and development that are the only stages at which it is possible to take such design solutions that will ensure maximum dependability of the future product. At further LC stages of the product such opportunities do not present themselves, not to mention that *"it is impossible to improve technology dependability in the course of operation"*[6].

In one of the oldest Russian standards – GOST 2.103 – the stages of design documentation (DD) release are divided into the development of detailed design documentation (DDD) and working design documentation (WDD). The DDD stage in turn consists of three stages, i.e. technical proposal, draft design and engineering design. Each stage of design and development performs strictly defined tasks and has a quite specific significance that is implied by the definitions sets forth in the respective engineering regulations:

1) Design is *the process of description required for the creation in given conditions of a not yet existing object based on the initial description of such object and/or the algorithm of its operation or the algorithm of transformation (in some cases repeated) of the initial description, optimization of the specified characteristics of the object and the algorithm of its operation or the process algorithm, elimination of errors in the initial description and consecutive presentation (if required) of descriptions in various languages*. [13].

The design stage corresponds with the development of the technical proposal and/or draft design and its deliverable is the DDD of the technical proposal as per GOST 2.118 and/or draft design as per GOST 2.119.

2) Development is *the stage of design preproduction performed using a CAD system during which a detailed 3D model of the product is developed, along with 3D models of units, assemblies and primary (basic) parts, that are used in the preparation of 2D projections (drawings), improved design calculations and modelling. The deliverables are completed as information objects that are placed in the integrated information environment. As per GOST 2.120 this stage and its deliverable are called engineering design* [14].

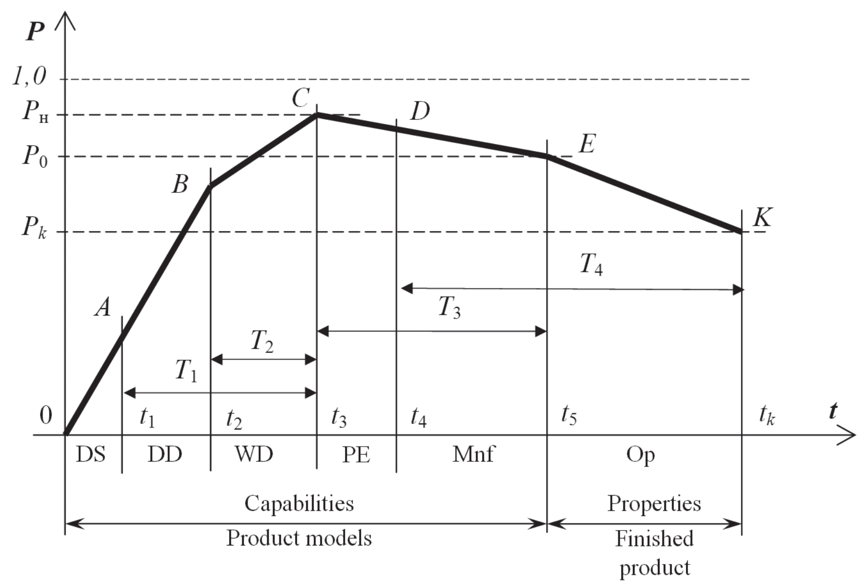
3) Development *is a stage of design preproduction performed using a CAD system, during which 3D models of all original parts and their 2d projections (drawings) are developed, specifications and bills for materials, components and standardized products are formalized, checking calculations an modelling are performed. The deliverables are completed as information objects that are placed in the integrated information environment. As per GOST 2.103 the deliverable of this stage is WDD* [14].

The modern "managerial" approach to solving industrial engineering problems is based on declarative reduction of DD development time primarily through the reduction or even omission of the DDD stage. As the results, the stages of design and development are often lumped together and are presented as *a process of design and development as a set of processes that ensure translation of requirements into specified characteristics or product, process or system specifications* [15]. The design and development process itself is divided into stages: design as *the process that translates the requirements into product characteristics set forth in the detailed design documentation* and development as *the process of development of design technical documentation for the product for subsequent preproduction and product manufacture* [16]. In some cases due to "time constraints" or sometimes due to thoughtlessness the design documentation developed in such abridged manner is handed over directly to the manufacturing facility for product manufacture while omitting the stage of process preproduction.

The potential results of such "managerial" approach in terms of achieving specified UHVS dependability can be seen in the figure that shows the conditional PNF (CPNF) per LC stages [10].

The figure reflects the general (qualitative) nature of UHVS development across LC stages subject the provisions of engineering regulations, generally accepted rules, the Common System of Design Documentation (CSDD), Common System of Process Documentation (CSPD) and quality management system (QMS), e.g. ISO 9001. The angles and shapes of the UHVS temporal variation curve in each specific case of design and development of products may somewhat differ from the shown graph, while retaining the general trend. The location of points *A*, *B*, *C*, *D* and *E* on the y axis depends on the adequate performance of the dependability procedures, which may not only largely reduce, but, in case of improper performance, significantly increase the risks γ of failures due to design, process engineering and manufacturing errors.

The figure reflects an important detail, i.e. it clearly shows the distinction between the LC stages, at which the future product exists in the form of a model and is characterized by the capability to manifest the property of dependability, and stages, at which the model materialized as finished product does manifest the property of dependability. This division allows the following:



0-t_1, release of the operational requirements and/or design specifications (DS), t_1-t_2, design and development of the product (DD), t_2-t_3, release of production drawings (WDD), t_3-t_4, manufacturing preparation (PED), t_4-t_5, product manufacture (PM), t_5-t_k, operation of finished product (OFP)

Figure 1. Graph of UHVS CPNF development across LC stages

– visualizing of hidden causes of the first “hump” in the well-known *U*-shaped curve of dependability;

– gaining the capability to compare the initial value of CPNF P_0 at the beginning of operation with the current values of CPNF in the process of UHVS development, which enables standardization of dependability per LC stages based on the specified PNF value at the end of operation P_k.

The significance of dependability procedures at lifecycle stages

The position of points *A* and *B* on the graph reflects the presence (absence) of “gross” errors due to the progress of fundamental research in the properties of structural materials, acquisition of reliable information on the external factors and loads (for point *A*), rationality of the chosen structural design solutions, observation of the design principles and rules (for point *B*) [10].

In case of absence of “gross” errors in the design the position of point *B* on the y axis may be close to 1, but not reach it due to two groups of causes. One of the groups of causes is associated with the project activities integration process that may last throughout the design stage and usually causes insufficient elaboration of the scope and content of requirements for product manufacture that are supposed to ensure specified dependability [9]. The second group of causes is set forth in [12]. It consists in various inevitable “small” errors due to the imperfection of the design methods, non-observance of regulatory technical documentation, insufficient qualification of the designers, their psycho-physiological properties, i.e. lack of attention, working speed, overall tiredness, etc.

Underestimation or disregard for the design stage significantly increase the risk of failing to achieve specified dependability indicators. If the above “minor details” are not properly dealt with during the design stage, the position of point *C* on the y axis may remain unchanged or be even lower that the position of point *B*. The aim of the WDD stage is to improve UHVS dependability by correcting the design errors and establishing required and sufficient requirements for manufacture. The position of point *C* on the graph reflects the maximum possible level of dependability P_d for this design that at subsequent LC stages can only decrease.

The position of points *D* and *E* is defined by the probability of errors of process preproduction and product manufacture. QMS is very important in this context as it is supposed to improve the production practices while reducing to an acceptable level the probability of production error. It is important to realize that the QMS in place at a manufacturing facility does not directly reflect on the quality and dependability of the finished product itself, as it is in practice a declaration of the fact that the enterprise is capable of releasing products of sufficient quality. Without proper design and process engineering support the QMS itself is incapable of solving the dependability problem, yet without proper QMS it is impossible to ensure dependability.

The position of point *K* is defined by the probability of errors of product operation. As in accordance with GOST 2.102 operational documentation is part of the DD the above errors are defined, on the one hand, by the establishment of clear requirements for observance of operating procedures, and, on the other hand, their proper observance.

In theory, for UHVS the position of points *C*, *D*, *E* and *K* on the y axis may reach its maximum possible values close to 1 upon condition of sufficient development and implementation of design and process engineering methods of dependability analysis and assurance [9]. The significance of activity per LC stages according to the figure is as follows:

– graph section 0-*A*-*B* is the elimination of “gross” design errors;

– graph section *B*-*C* is the correction of “small” design errors;

– graph section *C*-*D* is the elimination of errors of process preproduction;

– graph section *D*-*E* is the prevention of manufacturing defects;

– graph section *E*-*K* is the elimination of errors in operation;

Basic dependability method

The idea of design and process engineering support of dependability consists, on the one hand, in the implementation of procedures aimed at establishing required and sufficient DD requirement and ensuring the compliance with those requirements in manufacture. On the other hand, it consists in providing formalized confirmation of compliance with all design, process engineering and manufacturing procedures by means of associated analyses. The dependability analyses are considered the most important and integral part of the UHVS dependability methodology.

The design and process engineering analyses and dependability procedures are based on the common foundation, i.e. status and quality of the prepared DD and process engineering documentation (PED) and common principles of procedure performance based on the logical formula: done→to be confirmed, what’s done→to be documented. The common foundation of design and process engineering analysis and dependability methods allows developing a methodology that can be used for three purposes, i.e. as a roadmap of design and development, a tool for verification of design and development and as a peer review tool. Thus, by using the design and process engineering methods of analysis and dependability the efficiency of the development process can be improved through division of powers and elimination of conflicts of interest between the developer who constantly thinks how the system will work and the dependability expert, a critical inspector of sorts, who must think how the system will fail to work [9].

It is important to note that design and process engineering dependability analysis (DPEDA) aims to research human decisions and errors (by designers, process engineers, production engineers) throughout consecutive LC stages, the FMEA method widely used in the West and its Russian counterpart, AVPKO, are designed to research product properties and processes. Unlike FMEA the association of the results of human activities with the end of each LC stage allows integrating DPEDA methods and the *Stage-Gate*-based design for reliability (DFR) methods [17].

From the point of view of dependability procedures the design and process engineering methods must be used alongside the QMS requirements fulfilment. In the verification of dependability requirements DPEDA must be used with other analysis methods in a strict order: functional analysis (FA), worst case analysis (WCA), DPEDA itself and dependability analysis (estimation) (DA) [9] as the results of each previous analyses serve as the source of data for the subsequent analysis.

Procedures of the engineering method of ensuring dependability

The design and process engineering support of dependability includes 4 procedures shown in the figure:

1) Procedure T_1 is to substantiate the finding within the set limits the values of parameters and indicators that characterize the ability to perform the required functions in specified modes and conditions of operation. The procedure is based on engineering calculations performed according to the most appropriate methods (strength and stiffness analysis, thermal analysis, dimension chain analysis, etc.) by any appropriate means: deterministic, semi-probabilistic or probabilistic method [18]. The duration of procedure T_1 includes the time of DDD and WDD development. The calculations are performed iteratively with the elaboration and detailing of the design, e.g. from analytical estimation of strength using beam idealization to numerical evaluation of full-size *3D* models with the finite elements method. This procedure as part of strength analysis of fixed (non-reconfigurable) structures is considered to be dependability calculation if it is performed using semi-probabilistic or probabilistic methods;

2) Procedure T_2 is used to establish DD requirements of which the fulfilment during manufacture ensures unconditional identification of the values of indicators and parameters with the specified tolerances. As the result of procedure T_2 performance each parameter (indicator) in DD must correspond with specified requirements in graphic or text form which eventually will ensure unconditional performance by the product of its functions;

3) Procedure T_3 serves to ensure guaranteed fulfilment of DD requirements at the stage of process preproduction and product manufacture. The function of this procedure is to eliminate any distortions and interpretations by process engineers and production engineers of dependability requirements stipulated in DD and to confirm the fact that the design, process engineering and metrological methods of manufacture, assembly, and supervision are based on single principles;

4) Procedure T_4 serves to ensure supervision of DD requirements fulfilment by the supervisory services at the manufacturing facility.

All 4 procedures are considered as a single and indivisible set of processes that ensure the fulfilment of specified dependability requirements. If for some reason PED is not prepared, the process engineering component of DPEDA may not be performed up to the moment of PED development. Then all conclusions regarding the product dependability are based on the assumptions that the manufacturing environment allows manufacturing the product in strict compliance with DD, i.e. errors of process engineering and manufacture are impossible. In this case formula (2) transforms as follows:

$$P(t)=P(A|B)\cdot P(\tau>t), \quad (3)$$

where A is an event that characterizes the readiness of the product to operate without failure allowing for the risk of malfunction due to design errors; B is the event that characterizes the readiness of the product to operate without failure allowing for the risk of malfunction due to process engineering and manufacturing errors.

Formulas (2) and (3) are connected with this formula:

$$P(A|B)>1-\gamma,$$

i.e. the dependability estimation based on the DD analysis alone will always be exaggerated.

Unique highly vital systems design principles

Design is considered as a sum of two equally significant processes that are implemented from the perspective of single principles of implementation of the procedures T_1 and T_2: visualization of the future product in the form of drawings (2*D* projections) or 3*D* models and parametric modelling (digitization) of the structure.

Structure digitization consists in the generation of column vectors of parameters (indicators) X and tolerances ΔX:

$$X=(X_1\ldots X_n)^{\mathrm{T}}, \quad (4)$$

$$\Delta X=(\Delta X_1\ldots\Delta X_n)^{\mathrm{T}}, \quad (5)$$

that quantify the properties of the future products that ensure their operability. The procedure of substantiation of parameters (indicators) T_1 comes down to the confirmation of the fact that all parameters and indicators X (4) (area of conditions E) are within the specified tolerances ΔX (5) (area of operability G):

$$\mathrm{E}\subset\mathrm{G},$$

here $G=\{X_i(t)|X_{\min(i)}\leq X_i(t)\leq X_{\max(i)}\}$.

Thus, the parametric modelling is a key component of design. On the one hand, it allows optimizing the designs and avoiding fundamental design errors, and on the other hand the generation of column vectors of parameters (indicators) (4) can support the generation of the check list for criterial supervision of the requirement and sufficiency of the requirements stipulated in DD (implementation of procedure T_2). In this case all calculations as part of substantiation of parameters (procedure T_1) that are associated with design and development process are implemented in order to confirm the DD requirements, with the total number of such calculations being defined by the list of the requirements.

Basic dependability improvement tools

The graph in the figure allows visualizing the tools used in design and development activities.

At the LC stage 0-t_1 (graph section 0-*A*) the primary operational requirements of the future product are specified. The achievement of the characteristics is defined by the most general strategic principles as fundamental truths that allow generating design solutions for the development of future products. Rational operating principles of the future product are the guarantee of its dependability. The number of the principles is not large. They aim to solve target tasks and reflect the general rules for achieving that.

At the LC stage t_1-t_2 (graph section *A-B*) with the integration of project activities the chosen principles of product creation must be implemented in the form of design and development solutions by means of the design rules [10]. The rules are based on the principles and defined by them. The number of rules may be considerable, they are aimed at solving specific tasks and reflect certain trends in the causal relationships.

The principles reflect the nature of a phenomenon, while the rules pertain to its individual aspects. Design principles and rules are universal for a certain type of products, therefore they can be reduced to a standardized set of design rules.

Dependability is ensured by fulfilling the requirements as a realized need to comply with the conditions that must be observed. Such requirements must be mandatorily specified at the LC stage t_2-t_3 (graph section *B-C*) and explicitly set forth in DD. The number of requirements is always larger than that of the used principles and rules as they are individual for each product in development and are used for elaboration of the adopted design solutions.

The principles and rules, if duly formalized, can be used for making check lists used in product design. While specifying DD requirements it is required to use digitization of the structure that will later be the basis for the preparation of the check list that in turn will support criterial evaluation of the completeness of the specified requirements during the development stage.

Principles of dependability evaluation

As dependability is a property, its measure is a qualitative characteristic. A requirement in DD is the expectation that a product, after its manufacture, will achieve such properties that unconditionally ensure the performance of the required functions under given conditions and modes of operation. The desired properties can always be identified by means of system analysis. If during the FA all modes and conditions of operation are identified, and the WCA identifies the worst combination of relative positions, mutual actions and interactions of critical elements, then during the design and production engineering dependability analysis there is always the chance of identifying such properties of critical elements that are required for achieving the set goals. That is possible due the antithesis method [10] when in given modes and conditions of operation under the worst possible combination of factors the causes of failures are identified, while the desired property is identified as the result of construction of logical formulas of type *"in order to eliminate the cause of failure in the form of .../ it is required that (a) critical element has a property of..."*. Next, each property is expressed quantitatively in the form of parameters (indicators) and their allowed values. Each of such properties is characterized with the probability of events that consist in finding the associated parameter (indicator) within the specified margins. In case of sequential occurrence of *i* events the overall evaluation of the product's PNF $P(t)$ as the result of the procedure T_1 equals to:

$$P(t)=\prod_{i=1}^{n} P_i(t), \qquad (6)$$

here

$$P_i(t)=P\left[X_{\min(i)} \le X_i(\tau) \le X_{\max(i)};\ 0 \le \tau \le t\right].$$

Formula (6) without regard to procedures T_2-T_4 yields an exaggerated result, because non-fulfilment or improper fulfilment of any of the design or process engineering procedures reduces the dependability. Therefore the DA is performed based on the results of the procedures T_1-T_4 and the current status of DD and MP. In case of non-fulfilment or improper fulfilment of any of the dependability procedures per any parameter or indicator, the formula (6) must include decreasing adjusting coefficients k_i that are defined, for instance, using the method of failure criticality rating as per GOST 27.310. As the result:

$$P(t) = \prod_{i=1}^{n} k_i P_i(t).$$

Conclusion

The paper shows the possibility of ensuring the dependability of UHVSs using engineering procedures implemented at each lifecycle stage before the beginning of operation. Such procedures would enable an adequate level of design, development, preproduction, manufacture, as well as the development of a UHVS dependability evaluation method based on a single theoretical and methodological basis.

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