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THE SYNTHESIS OF MODEL-BASED SYSTEMS ENGINEERING APPROACHES AND TOOLS INTO A METHODOLOGICAL TOOLKIT FOR THE DEVELOPMENT OF TECHNICAL SYSTEMS: THEORY, ITS VERIFICATION AND VALIDATION

Abstract: *It is required to shift from separate life cycle (LC) stages to a single project implemented in the model-based systems engineering (MBSE) paradigm. However, MBSE software (SW) tools based on Systems Modeling Language (SysML) are complex and expensive. The paper raises the question, "Is it possible to make available MBSE SW and methodological tools (SMT) to a wide audience of users?" To address this question the following MBSE tools were considered: SysML, Quality Function Deployment (QFD) and House of Quality (HoQ). Their drawbacks were identified and solutions were proposed. All solutions were synthesized into a single methodological toolkit that allows in the automated way to create and update SysML requirement diagrams. Its implementation improves the quality of current projects by up to 10%, speeds up the planning process of analog projects by 60% and allows to implement projects in the MBSE paradigm wherever costly SysML SW tools are not available.*

Keywords: *Systems Engineering; MBSE; Methodological Toolkit; SysML; QFD; HoQ; Software; Design; Development; Space*

1. Introduction

The increasing systems' complexity leads to stricter requirements and to an increase in the volume of developed reporting and technical documents. Within the document-based paradigm, it leads to a high risk to make discrepancies and errors. This problem in its turn leads to results non-compliance with all requirements. From the systems engineering (SE) point of view, achieving quality by changing the product at last LC stages is very dangerous because in this case time and cost of design and development (D&D) increase (Romanov, 2015). To solve these problems, it is necessary to move from separate product life cycle (PLC) stages to a single project implemented in a new systems design paradigm based on MBSE (Romanov, 2017).

The existing SysML-based MBSE SW and methodological tools (SMT) are expensive and complex. Therefore, an important question is formulated as follows: "Is it possible to reduce the costs and to simplify the usage of MBSE (SysML) SMT by means available to a wide audience of users?"

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To answer this question, the following MBSE tools were considered: QFD, HoQ, SysML. QFD and HoQ are meant to determine “What” and “How” (with which priority) must be performed during PLC stages. SysML is designed to increase the efficiency of communication of a large amount of information about a system and to improve the management of requirements, functions and physical characteristics. In 2018, at the first Stanford University conference on SysML, it was stated that MBSE (SysML) is the basis for the development of digital twins, machine learning and artificial intelligence. Digital twins are crucial for the achievement of zero defect production.

Currently a team of experts from 70 organizations, is working together to develop the next major version of the SysML v2. In general, the development of modeling languages has been going on for decades. The introduction of new ideas and approaches gets into conflict with the psychological inertia of people to work as they got used to. This is especially a serious shortcoming for countries (e.g., the Russian Federation (RF)), where there is a lack of localized regulatory and technical documents (RTD) for the use of SysML, QFD, HoQ at the LC stages of systems (space instruments (SI)) D&D. It means that the considered MBSE tools have drawbacks that prevent a wide audience of users to apply them. Therefore, these drawbacks must be identified and overcome.

The purpose of this article is to enable a wide audience of users to effectively apply MBSE (SysML, QFD and HoQ) during D&D of systems. To achieve this goal, the following tasks were set: 1) identification of SysML, QFD, HoQ drawbacks; 2) development, verification and validation (V&V) of solutions that overcome drawbacks.

The paper is structured as follows. Introduction is followed by analysis of drawbacks and problems of SysML, QFD, HoQ and SW tools for their use. Research results are discussed in the third section. Conclusions are made in the fourth section.

2. Analysis of SysML, QFD, HoQ and software for their use

2.1. Analysis of SysML, SysML software tools and identification of their drawbacks

Scopus statistics for the periods 2004-2011 and 2012-2019 show that the number of publications related to SysML increased by 3-4 times in Germany, France, the USA, and other countries. It correlates with the survey of 326 respondents from 19 countries from aviation, space, defense, automotive, IT and other industries (Cloutier & Bone, 2015). The survey showed that more and more ompanies practice and develop their own MBSE methods, tools, and training materials. This fact correlates with results of the analysis of SysML application during 13 years (Wolny et al., 2020) and also with the survey of more than 100 UK companies (Tower, 2013). It showed that respondents: 1) use different languages: UML, context diagram, SysML, and others; 2) 43% do not use known MBSE methods and standards; 3) 16% use their own methods. Also, it states that there were no recommendations for MBSE application. The most frequently used MBSE SW tools were: MS Visio (57%), Sparx Enterprise Architect (44%), IBM-Rhapsody (24%). The average amount of SW used was 2.6. This figure suggests that companies are striving to use SW that is widely available to users.

As the result, cost analysis of SysML SW tools that for 2020 government organizations of the RF can officially purchase was conducted. They include IBM-Rhapsody, System Modeling Workbench (Siemens PLM), Magic Cyber Systems Engineer (Dassault Systems), MS Visio from 2013 (Professional). In 2020 MS Visio Professional cost about 8 times less than the mentioned SW tools from IBM, Dassault Systems, Siemens PLM. University partners of Microsoft grant MS Visio licenses to their students and employees free of charge. Accordingly, MS Visio (especially Professional version) is recognized as potential SysML SW tool that is widely available to many users from the RF.

As the result of the presented above literature review (LR), analysis of implementation (Chami & Bruel, 2018), personal experience (Romanov & Shpotya, 2016; 2020; Shpotya & Romanov, 2019), SysML drawbacks were identified (see Table 1).

Table 1. Drawbacks of SysML and SW tools for its use

№	Drawbacks (speaking in other words the defects)	SysML	SW
1	Development and update of SysML requirement model require significant labor costs (from several hours to weeks). SysML SW tools are also very expensive.		
2	SysML requirement diagrams are not effective to track all relationships of requirements "inside" and "between" development elements of a system.		
3	There are no Russian-language teaching materials and examples of implementing SysML in industrial projects in the RF.		
4	In order to self-study MBSE (SysML) a person must invest the amount of time that is comparable to study modeling of SW, electrical and other disciplines.		

Source: compiled by the authors based on materials of Cloutier & Bone (2015), Wolny et al. (2020), Tower (2013), Chami & Bruel (2018), and personal experience Romanov & Shpotya (2016, 2020), Shpotya & Romanov (2019).

2.2. Analysis of QFD, HoQ, corresponding SW and identification of their drawbacks

Scopus statistics for the periods 1972-1999 and 2000-2019 show that the number of publications related to QFD increased by 2 times in the USA and by 60 times in China. It corresponds with the findings of Kathawala and Motwani (1994), Bouchereau and Rowlands (2000), Ginn and Zairi (2005), Wolniak (2018), who argued that the use of QFD (HoQ) reduces: 1) the risk of incorrect interpretations of requirements; 2) the cost of D&D of HW and SW products by 60%; 3) the number of technological changes by 30% – 50%; 4) and warranty claims by 20% – 60%.

According to the research of Kurunova (2018), MS Excel or Open Office Calc are the most accessible QFD (HoQ) SW. In another study (Sharma, 2010), it was found that Visual Basic is the optimal language for creating effective HoQ (QFD) SW. MS Excel contains a development environment based on the VBA. It proves again in favor of MS Excel to recognize it as QFD (HoQ) SW that is available to potential users from the RF.

As a result of the LR, analysis of implementation (Herzwurm & Schockert, 2006; Watanabe, Kawakami & Iizawa, 2012; Mazur, 2017; Abu-Assab, 2012), personal experience the drawbacks of QFD, HoQ and SW tools for their use that prevent their wide usage in D&D were identified (see Table 2).

2.3. Results of the analysis of SysML, QFD, HoQ and SW tools for their use

The identified drawbacks prevent study and dissemination of SysML, QFD (HoQ). These consequences and usually limited projects' resources create in the RF a number of problems, namely: 1) developers of complex technical objects (SI) do not see the reason to create besides the approved text document its "duplicate" in the form of non-official SysML and/or HoQ models; 2) investments in D&D of SysML, QFD and HoQ SW tools and education of MBSE specialists; 3) space industry does not conduct standardization in the area of SysML, QFD, HoQ application. This leads to the absence of MBSE SMT (accessible to a wide audience of users) for D&D of SI. As the result, digitalization follows the path of the "yesterday" – the application of CAE/CAD/CAM IT systems.

Mass usage of MBSE SMT can change this situation. In order to achieve it, it is necessary to overcome the drawbacks from Tables 1 and 2. For this purpose, the goal was set to develop the MBSE SMT appropriate for application during D&D of SI. Such SMT must be based on the specification, modernization and synthesis of SysML, QFD, HoQ, and realized in SW tools that are available to a wide audience of users. It should be V&V during D&D of a nanosatellite.

Table 2. Drawbacks of QFD, HoQ and SW tools for their use

№	Drawbacks	QFD	HoQ	SW
1	The classical QFD model (Abu-Assab, 2012) does not imply D&D of SI in accordance with user needs, SysML and requirements of RTD.	(shaded)		
2	The QFD (HoQ) method uses but does not generate input (e.g., customer requirements) and output (engineering requirements) data.	(shaded)	(shaded)	
3	The classical HoQ method does not consider correlations of output parameters when prioritizing them.		(shaded)	
4	A person can perceive, analyze and manage 20–25 requirements in the HoQ model (in the case of D&D of SI there are more) (Romanov & Shpotya, 2020).		(shaded)	
5	Filling data in the HoQ requires significant time (months) (Kane et al., 2007).		(shaded)	
6	It takes up to several days to create a HoQ model structure without a template.		(shaded)	(shaded)
7	MS Excel does not offer HoQ model templates.			(shaded)
8	Existing MS Excel HoQ model templates from "qfdonline.com" allow to build only 4 HoQ models with a given set of fields, which is not suitable for an analysis of complex objects (Kurunova, 2018).			(shaded)

Source: compiled by the authors based on materials of Kathawala & Motwani (1994), Bouchereau & Rowlands (2000), Ginn & Zairi (2005), Herzwurm & Schockert (2006), Kane et al. (2007), Sharma (2010), Abu-Assab (2012), Watanabe, Kawakami & Iizawa (2012), Mazur (2017), Kurunova (2018), Wolniak (2018), and personal experience Romanov & Shpotya (2016, 2020), Shpotya & Romanov (2019).

3. Research results

3.1. Specification of the QFD model

To overcome the QFD drawback (№ 1 in Table 2), the classical cascade QFD model was specified in terms of the number of phases and their purpose. 5 phases were called the following way: 1) improved HoQ (iHoQ) № 0: Voice of the User (VoU) – Voice of the Customer (VoC); 2) iHoQ № 1: VoC – Voice of the engineer (VoE) (behavior); 3) iHoQ № 2: VoE (behavior) – VoE (hardware (HW) and SW structures); 4) iHoQ № 3: VoE (HW and SW structures) – requirements of RTD for the implementation of PLC stages; 5) iHoQ № 4: requirements of RTD for the implementation of PLC stages – requirements of RTD to reporting documentation of a PLC stage. The specified QFD model was called "improved QFD" (iQFD). Transition between phases was expressed in mathematical terms.

3.2. Creating a method of automated SysML requirement diagram development and its update

Considering that MS Visio allows to synchronize text in shapes with external data sources and to develop custom shapes, the method that allows to automate development of SysML requirement diagrams and update of information in them was created. It consists of 4 algorithms (see Figure 1).

The method passed V&V during the development of a SysML requirement diagram (Romanov & Shpotya, 2020). The proposed method allowed to create and fill in with data 300 new SysML requirement shapes in some minutes. By using the classical method, this task is completed in a few days or even weeks.

Developed SysML requirement diagrams with RTD requirements to the D&D process of SI were validated. They were used to check compliance of R&D projects results (at the "Draft design" LC stage) with RTD requirements. Normally such checking (inspection) requires reading lots of technical documents. Its final quality is mostly based on the knowledge of a person who conducts it, and it takes days or even weeks to do it. But application of SysML diagrams made it possible to complete checking in two hours and allowed to identify from 5 to more than 10 non-compliences of projects results with requirements from RTD. And in case when project results can not be accepted by a customer because they do not satisfy RTD requirements (or any other) contractor is obliged to pay large fines. In its turm SysML requirement diagrams (model) helped to identify non-compliences and to decrease labor costs for such checking. It means that SysML usage saves developer's money and speeds up the D&D process (because mistakes are eliminated beforehand). If to use SysML models not at the end of the project but at the beginning (planning) and during the project to conduct the cross checking (verification), then the probability to realize a project (a product) with zero mistake with initial requirements is very high. In addition, SysML requirement model allows to reduce the labor costs for planning of the D&D LC stages of new analog products by about 60%.

In order to apply this MBSE approach, developers (decision makers) must know the benefits of SysML models, and the way how to develop them in a cost-effective way. That is why the proposed method (simple and cost effective), which automates development and update of SysML diagrams based on the text data of official reporting documents with the help of MS Visio and Excel, is relevant and appropriate for application by a wide audience of potential users.

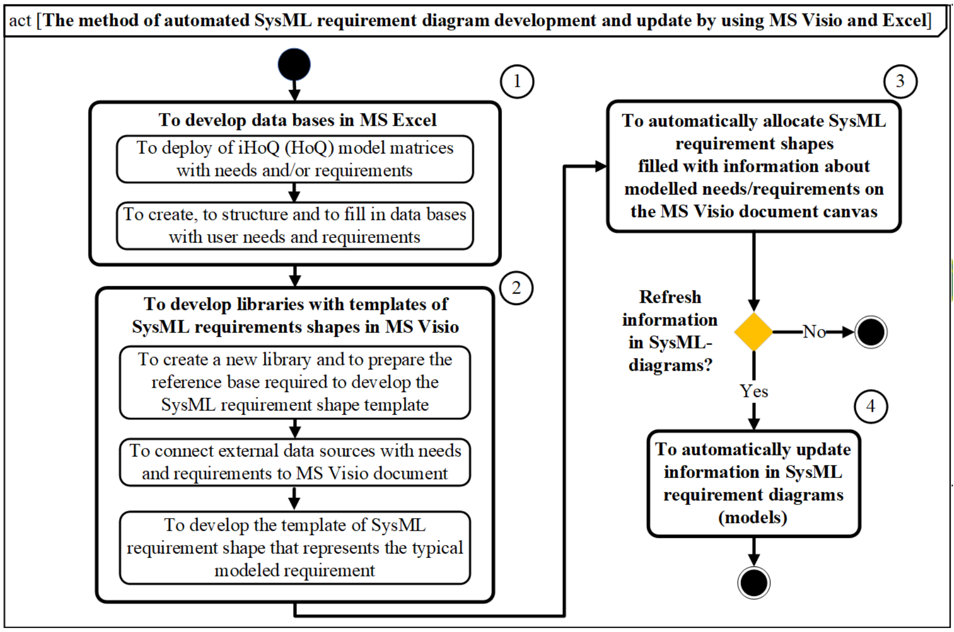

Figure 1. The method of automated development and update of a SysML requirement diagram
Source: designed and compiled by the authors.

3.3. Development of a new HoQ method for output parameters prioritization

According to the classical HoQ method (see at Figure 2 numbers 1 and 2), determination of the priority weights B_j of output parameters (requirements) j is conducted without considering of how they correlate with each other (number 3 at Figure 2).

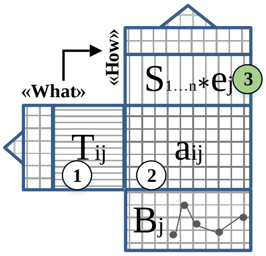

Figure 2. The drawback of the HoQ method
Source: designed and compiled by the authors.

That is why classical method does not allow to take into account all factors that influence the final priority weights. To overcome this drawback (№ 3 in Table 2), a synthesis of classical HoQ algorithm (formula (1)) with quantitative expert estimates of output parameters correlations (formula (2)) was conducted (see Table 3).

Table 3. Classical and improved HoQ algorithms for output parameters prioritization

Algorithm	**Classical HoQ**	**Improved HoQ**
Formula	$B_j = \sum_i (T_i * a_{ij}),$ (1)	$B_j = (\sum_i (T_i * a_{ij})) * (S_{1\ldots n} * e_j),$ (2)
where T_i is the normalized importance weight of the *i*-th input parameter of a HoQ model (calculated by using analytical hierarchy process (AHP)); i – all input parameters of a HoQ model from 1 to n; a_{ij} - the coefficient of a degree of dependence of the *i*-th input parameter on the implementation of the *j*-th output parameter; $S_{1\ldots n}$ – the quantitative estimate (numerical weight) of the correlation of the selected category (subsystem) of output parameters calculated by using AHP; e_j – the quantitative estimate of the correlation of the *j*-th output parameter in the selected category *S* calculated by using AHP.		

Source: constructed by the authors.

The proposed iHoQ algorithm was used to analyze requirements of different design aspects of the CubeSat "Mayak" (Romanov & Shpotya, 2016). Table 4 represents two functional CubeSat's subsystems called "Power supply" and "Creating a bright visible flash in the night sky" with the results of their parameters prioritization by using classical HoQ and proposed iHoQ algorithms. Analysis of these weights was done from the standpoint of how (in each subsystem) the parameter with the highest weight correlates with weights of all other parametrs from its subsystem.

Table 4. Comparison of normalized prioritization weights of functional parameters

Prioritization algorithm:	**HoQ**		**iHoQ**	
VoE № 1 (functional parameters)	Weights	Correlations of weights *	Weights	Correlations of weights *
Subsystem: Power supply				
Energy carriers must be of the required capacity.	7,19	1,18	1,49	9,47
Such energy carriers had to fly into space or pass all the necessary tests.	8,51	1	14,12	1
Subsystem: Creating a brihght visible flash in the night sky				
A large-size reflective construction (LRC) should produce a bright visible flash.	6,61	1,10	2,29	1,10
The LRC should provide as complete an exposure as possible to the visible side of the Earth.	2,74	2,66	0,32	7,18
The LRC should be made of cheap and affordable materials, easy to operate.	3,66	1,99	1,27	1,99
The thickness of the reflective material of the LRC should be minimal.	2,19	3,33	0,76	3,32
The reflective material of the LRC must be tested in space conditions.	7,30	1	2,53	1
* Correlations of weights are found by dividing the parameter value with the highest score within the subsystem by each weight of all other parameters within the same subsystem.				

Source: constructed by the authors.

In the subsystem "Power supply", correlation of weigths obtained by using HoQ algorithm is equal to 1,18, and obtained by using iHoQ is equal to 9,47. In the subsystem "Creating a bright visible flash in the night sky" the highest HoQ's correlation value is equal to 3,33, and iHoQ's is equal to 7,18.

This example illustrates that the additional consideration of numerical expert estimates of correlations of output parameters increases the contrast of the prioritization weights by two and more times compared to the weights obtained by the classical HoQ algorithm. This contrast proves that the proposed iHoQ algorithm allows to identify requirements of critical importance.

It is also important to state that iHoQ algorithm provides a different ranking order of output parameters (if to compare with the HoQ algorithm results, for more details see Romanov & Shpotya, 2016).

3.4. Development of a unified algorithm for input and output data generation of the iQFD model phases

To overcome (to compensate) the drawbacks № 2 and 5 from Table 2, analysis of SE (MBSE) approaches and tools for the identification of user needs, the definition of customer requirements, and the formulation of engineering requirements was carried out. Based on it, a unified algorithm called "iQFD for iHoQ" for generating data for iQFD model phases (stages) was synthesized (see Figure 3) (Romanov, Zav'yalova, & Shpotya, 2020).

The concept of this algorithm is conditionally divided into 5 parts: 1) **Input** – source data (user needs, customer requirements, engineering requirements); 2) **Output** – customer or engineering requirements (prioritized and structured by using iHoQ and SysML); 3) **Correction upon feedback** based on the results of analysis, tests, V&V (as an example); 4) **SW tools for digital processing** of requirements and application of methodological tools; 5) **Data generation** – accurate definition of the "problem area" and its transformation into the "solution area" (for an example, user needs into customer parameters) by using the following SE tools that were divided into three groups:

- **Data acquisition:** context diagram, interview, survey, brainstorming.
- **Qualitative analysis:** verbal analysis of system requirements (VAST), work and product breakdown structures, SysML models, SWOT analysis, N2 diagram, Kano model.
- **Quantitative analysis:** AHP (ranking), iHoQ (prioritization).

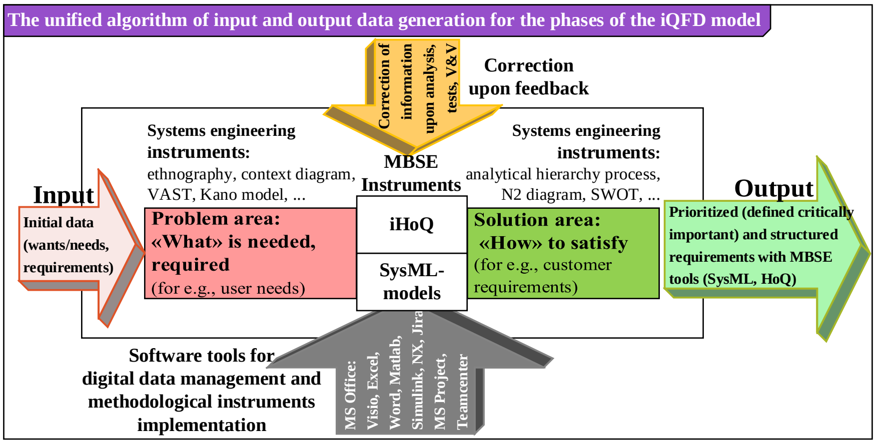

Figure 3. The unified algorithm for generating data for the iQFD model phase
Source: designed and compiled by the authors.

The unified algorithm was specified. Each specification consists of: 1) the physical meaning of the iQFD phase that was formalized (e.g., formulas (3) and (4)); 2) the recommended structure of the iHoQ model; 3) the framework with the proposed SE and MBSE approaches and tools, and sequence of actions for their application at the given iQFD model phase (e.g., Figure 4) (Romanov & Shpotya, 2020). Algorithms were named "iQFD for iHoQ № n", where n is the iQFD model phase number.

$$\{\overrightarrow{UN_p}\}[CRA_{pm}] = \overrightarrow{HoQCR_m}, \tag{3}$$

$$\left\| \overrightarrow{\frac{(CR_j^* \cdot HoQCR_j)}{\sum_j CR_j^* \cdot HoQCR_j}} \right\| = \|\overrightarrow{\imath HoQCR_m}\| = 1,\ j = \overline{1,m}, \tag{4}$$

where UN – User Needs (input); $\{\overrightarrow{UN_p}\}$ – vector of dimension *p*, consists of normalized importance weights of UN calculated by AHP method; CR – Customer Requirements (output); $[CRA_{pm}]$ – central matrix of iHoQ № 0 model with dimension *pm* that contains the numerical expert estimates of dependence of each UN from the achievement of each CR; $\overrightarrow{HoQCR_m}$ – vector of dimension *m*, consists of non-normalized priority weights of CR calculated by HoQ method; *j* – the column number of the HoQ (iHoQ) model central matrix; CR_j^* – the importance weight of the *j*-th CR parameter, calculated by AHP; $\overrightarrow{CR_m^*}$ – vector of dimension *m*, consists of normalized importance weights of CR parameters; $\overrightarrow{\imath HoQCR_m}$ – vector of dimension *m*, consists of normalized priority weights of CR calculated by using formula (4) (result of iQFD for iHoQ № 0).

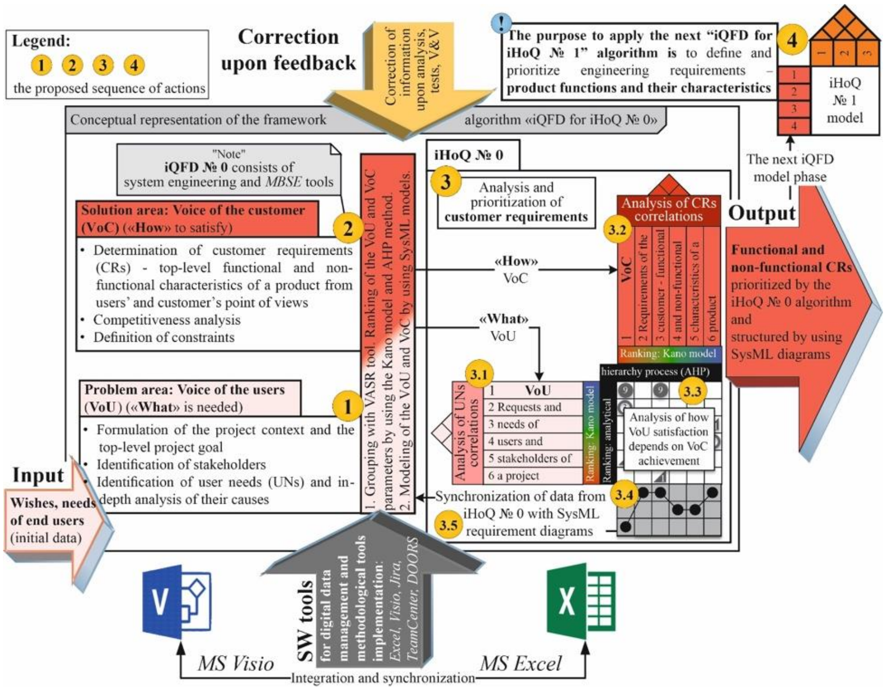

Figure 4. The specification of the unified algorithm "iQFD for iHoQ № 0"
Source: designed and compiled by the authors.

The validation process showed that the use of the proposed algorithms allows to uniformly obtain data for the iQFD model phases. These algorithms helped to obtain: 2 VoU, 6 VoC (see Figure 4), 22 VoE № 1 (functions) and 27 VoE № 2 (HW and SW structural elements) parameters of a CubeSat satellite (Romanov & Shpotya, 2016), and also the list of RTD requirements. Parameters were structured with SysML and deployed in iHoQ models.

To overcome the drawbacks associated with the large labor costs for the deployment of HoQ models (see № 5–7 in Table 2), MS Excel templates of iHoQ models were developed. Templates were developed in accordance with the iQFD model phases and the proposed structures of the iHoQ models, and were automated with macros written in VBA language. Templates' usage reduced labor costs for the development of new iHoQ models by up to 20% (expert estimation).

3.5. Combining research developments into a single methodological toolkit

In 2003 J. Koski analyzed the modifications of QFD and HoQ. He concluded that HoQ transmits information less efficiently than UML diagrams (UML is the basis of SysML) (Koski, 2003). In 2016 Stansfield and Mazur announced their intention to combine QFD with model-based design (Stansfield & Mazur, 2016), but the results have not been published yet. By taking this into account, two assumptions were made: 1) the use of SysML diagrams compensates the drawback № 4 from Table 2 of iHoQ models; 2) the use of iHoQ models compensates the drawback № 2 in Table 1 of SysML diagrams. To investigate them, an experiment was conducted. It was based on the synthesis of the iHoQ model with the SysML requirement diagrams of into a single workspace implemented in MS Excel (see Figure 4).

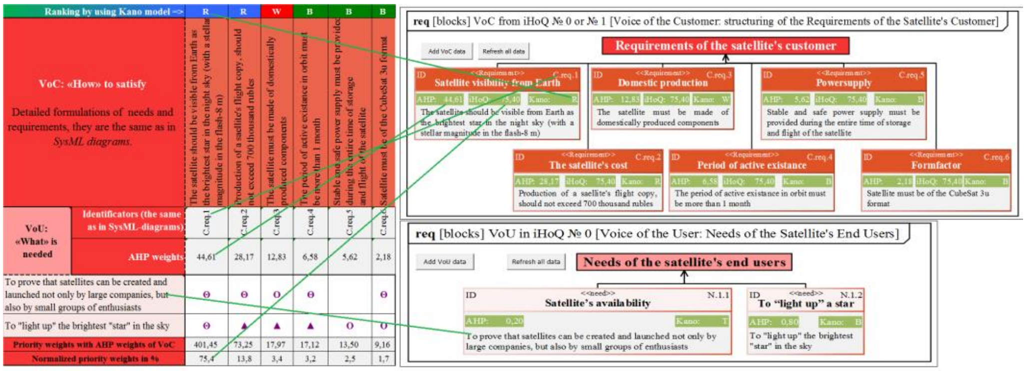

Figure 4. Combining and synchronizing iHoQ № 0 model with SysML requirement diagrams
Source: designed and compiled by the authors.

The experiment confirmed both assumptions that the SysML diagrams are more effective in communication of iHoQ model data and iHoQ models are more effective in tracking the relationships of requirements. It also proved the possibility to synthesize SysML and iHoQ models as a single MBSE SMT.

The achieved results allow to:

1. dramatically reduce time of SysML requirement diagrams development (from several weeks/days to several hours/minutes) by using MS Visio and MS Excel SW tools;
2. reduces psychological barriers and rejections from modeling in the SysML, HoQ languages caused by the reluctance of people to spend a lot of time on "double work" – preparing obligatory text documents and their "duplicates" in forms of SysML and/or iHoQ models;

3. reduce expenditures on training MBSE (SysML, QFD, HoQ) specialists and SW for their use (Romanov & Shpotya, 2020).

Also, the obtained results create a scientific and methodological basis for the design, construction and operation of integrated interactive automated complexes for the analysis and synthesis of design solutions, as well as for the creation of design and other types of documentation.

As a part of overcoming the SysML shortcomings that prevent its study by potential users (№ 3 and 4 in Table 1) educational and methodological materials based on this research results were developed and used at MIPT in the educational process. During lectures and seminars master degree students were taught how to D&D nanosatellites (Shpotya & Romanov, 2019) and other systems in the MBSE paradigm as a single project. This educational experience showed that students quickly understand benefits of the proposed MBSE SMT and the way of its implementation and usage.
Thus, new methodological bases (toolkit) were created, V&V for the combined usage of the MBSE (SysML, iQFD, iHoQ) and SE tools (that are implemented in SW tools accessible to a wide audience of potential users) at each D&D PLC stage.

4. Conclusions

The mass application of the MBSE SMT will allow to reach the bifurcation point necessary for widespread MBSE engineering paradigm acceptance and dominance. But available in the RF MBSE software tools based on SysML are expensive and complex. That is why it was necessary to conduct a researh with the goal to develop the MBSE SMT that is available at minimal financial and labor costs, and at the same time increases the efficiency of the current document-based approach.

To achieve this goal during research: a) the drawbacks of SysML, QFD, HoQ and SW for their use and the problems caused by them were identified; b) MS Visio was recognized as the SW tool for SysML, and MS Excel was recognized as the SW tool for the development of customized HoQ models, that are available to a wide audience of users; c) the MBSE SMT, that allows to overcome the drawbacks was developed, V&V.

As part of the developed MBSE SMT, the following new results were achieved:

1. The MBSE SMT based on the synthesis of SysML diagrams and iHoQ model as the united toolkit was developed. Such digital synthesis was realized in MS Excel.
   V&V of the proposed SMT proved that: a) iHoQ (HoQ) model is more appropriate methodological tool to track requirements' relationships that are modeled within SysML requirement diagrams; and b) SysML diagrams are more approriate to communicate more than 25 requirements modeled within iHoQ (HoQ) model. Besides, SysML requirement models application can reduce labor costs: a) for the inspection of the project results (documents) compliance with RTD requirements from several days to several hours; b) for the planning of LC stages of analog products up to 60%; and c) it can increase the compliance of the reporting documents of PLC stages with the requirements of RTD by 10%. Application of the proposed MBSE SMT improves the D&D processes of new technical products and allows to speed up the implementation of the D&D LC stages of analog products by 5-10%.
2. The method for SysML requirement diagrams automated development and update of data in them was created. V&V of the method proved that it minimizes labor costs for the development and update from days to several hours and minutes.

3. The new algorithm (method) for output parameters prioritization in the HoQ (iHoQ) model was proposed. The iHoQ algorithm is based on the synthesis of classical HoQ algorithm with AHP method. It allows to obtain new ranking order of output parameters and to increase the contrast of prioritization weights by two or more times, compared to the HoQ algorithm. Such difference in contrast allows to identify output parameters of critical importance.
4. The classical QFD model was specified for the D&D of SI (technical deveices) in accordance with user needs, SysML approach and requirements of RTD.
5. The unified algorithm for generating input and output data for the phases of the specified QFD model was developed. It unites SE and MBSE (SysML, QFD and HoQ) tools.
6. iHoQ model template structures were proposed and developed in MS Excel. Templates application allowed to reduce labor costs for creation of new iHoQ models by 20% (expert estimation).
7. The teaching materials for the proposed MBSE SMT dissimination were developed and applied at MIPT during D&D of nanosatellites and technical devices.

Successful V&V allow to conclude that the developed MBSE SMT overcomes the identified drawbacks of SysML, QFD, HoQ and of the selected SW tools for their use. It means that a wide audience of users can D&D systems with MBSE aproaches and tools with minimum costs.

Therefore, the presented research results imply feasibility for their further theoretical and practical development and application by scientists, system and software engineers from space and other industries.

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