Integration of system design and production processes in robust mechatronic product architectures development – extended M-FBFP framework

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Abstract

The complexity of mechatronic products, such as climate chamber subsystems, results in enormous difficulties in understanding where the main design process inefficiencies are. It is therefore extremely difficult to determine which improvements will have the most significant impact on a company or on a specific project. Mechatronic products are characterized by a high level of interdisciplinarity and complexity in the technical system and the relevant development processes. The main challenge in this respect is how to deal with the high complexity of and a variety of interdependencies in such products. We are therefore presenting a framework for integrated mechatronic product and process modelling – extended M-FBFP framework. This framework provides different independent perspectives of the overall product to improve their architecture. As a result of the proposed framework, risk analysis through subsystems in the components domain and through processes in the technical processes domain is enabled and it is now possible to provide feedback on product architecture. To obtain optimally robust product architectures from available alternative solutions, an evaluation analysis was performed across all stages, including the initialization and subsequent refinements with several evaluation criteria: complexity, interdependency and process duration. To test the validity of the proposed framework, we are presenting a case study involving a climate chamber with heat regeneration.

Keywords: complexity, mechatronic product design, product architecture, extended M-FBFP framework, technical process, risk analysis, evaluation.

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The design issues and decisions encountered in the early stages of product design relate to certain information, including requirements, functions, components and engineering characteristics, which capture the performance measures of the system [1]. As such, several design tools have been developed to structure this conceptual design information using matrices. However, these existing tools do not provide algorithms for evaluating this conceptual design information [2]. Numerous system analysis methods have been developed in order to identify potential areas of design improvement in terms of requirements, functionality, and components. Many risks inherent in a product and/or development process are defined within the product architecture. Such product information and specifications, as well as the development of certain criteria, are considered to be important for product robustness. Product robustness therefore includes a combination of both product and production engineering [3].

Successful product development is determined by the fulfilment of customer needs using a product under constraints of time, cost, and quality [4,5]. Risk or uncertainty adds a new dimension that is very difficult to address [6]. Effective risk management in new product development can reduce the likelihood of cost, schedule, and performance deviations during the execution. Risk management is therefore closely related to the success of a product development process. It offers promising approaches to dealing with uncertainties in early product development phases. Uncertainty in customer requirements and input data results in an uncertain number of design iterations in parallel with the specification's evolution.

This paper presents the integration of certain matrix methods (extended matrix – function-based failure propagation method framework) aimed to provide a designer with feedback about expected behaviour (properties) of predefined subsystem architecture and technical processes. In product modelling, it focuses on the relationship between functions using the function

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based failure propagation method [7] and extends their impact on the Quality Function Deployment (QFD) method [8] and other domains (requirements, technical processes and components) in a Multiple-Domain Matrix (MDM) [9]. In regards to process modelling, on the other hand, it deals with modelling of risk interactions based on their identification and evaluation and risk propagation and re-evaluation [10–12]. Based on the result derived from process modelling, improvements are made to the QFD and technical process domain in the MDM matrix. All of this is carried out in the early design phase (conceptual design) by presenting a mapping as an iteration process to improve product architecture. The feedback generated by the product design and production process phases should highlight the elements within the system architecture that are unable to operate within the given parameters, thus resulting in unstable system behaviour. To obtain optimally robust product architectures from available alternative solutions, an evaluation analysis was performed across all stages, including the initialization and subsequent refinements with several evaluation criteria: complexity, interdependency and process duration [13,14].

The section below presents research motivation and the background for this research. The fourth section will provide a more detailed description of the proposed framework. The fifth section will evaluate and test the validity of the proposed framework. An actual case study will be presented here. Discussions on obtained results and a conclusion with regard to future research close this paper.

Motivation

Mechatronic products, in particular, have become significantly complex because of technological competition and reduced product development cycles [15]. They are characterized by a high level of interdisciplinarity and complexity in the technical system and the belonging development processes. As a result, achieving high quality has gradually become more difficult. At the same time, as a product becomes more complex, the corresponding development project also becomes more complex. A need for early estimations development processes arises, especially in the early stages of product development. In system design, an interdisciplinary design team needs to decide very early on which product concept they will implement and which they will abandon. This decision needs to be taken on the basis of limited information, but should consider the different costs amongst competing product design concepts [16]. To focus on product design and development, most project budgets are defined during the design phase before any actual work is done. Adequate planning is one of the key elements required to meet project quality, reduce financial and schedule risks, and help a project achieve success [17]. As a result, a systematic approach to robust product architecture development and evaluation, including integration of system design and the production process with mutual impacts, is needed.

Background

Product and process modelling techniques currently developed and applied to industry do not sufficiently enhance the overall system understanding and fail to create sufficient awareness of the importance of discipline-integrating milestones. This is due to a distinct decoupling of the representations of the technical system itself on the one hand and the relevant development processes on the other.

The Characteristics-Properties Modelling / Property-Driven Development (CPM/PDD) approach [18] can be used in product development to model products and product development processes. The essence of the CPM/PDD theory is clear distinction between characteristics and properties. The CPM/PDD approach defines product development as a sequence of synthesis, analysis and evaluation steps. In each evaluation step, one or several property value(s) (it is not always possible to measure a property using a countable value, *e.g.*, the haptic of a surface) is (are) compared with the required properties. The difference between the existing and required properties indicates which properties need to be customized by modifying the related characteristics.

Change Prediction Method (CPM) tool, a software tool for predicting change propagation. It was developed at the Engineering Design Centre in Cambridge [19,20]. The CPM tool supports the design change process in two different ways. First, it supports abstract product-model building [21]. It helps both individual designers and team leaders understand how components in their area of responsibility are connected to other product parts and where any interfaces with other teams may exist. Another benefit provided by the CPM tool is a platform to analyse change propagation data based on combined component interrelations. For that purpose, algorithms for calculating combined risk based on direct impact and likelihood values were developed and integrated into the tool [22]. This allows designers to quickly assess the probability of change propagation from one component to others, as well as the overall risk associated with a change to a component.

The signposting framework was also developed at the Engineering Design Centre in Cambridge [23,24]. It is a dynamic framework describing design tasks in terms of input and output parameters, where the term “parameter” may be used to refer to a description of any aspect of a product or process that change over time [25]. Designing is characterized as identification and iterative refinement of parameters. Design processes are represented as a set of parameters and tasks, each defined in terms of one input state and one or several output state(s). An input state describes the parameters used for a task, including a numerical description of the minimum level of confidence in each that is deemed appropriate to initiating the task. Similarly, output states describe the parameters produced after a task is completed, including the level of confidence the task provides to each parameter. At any time, the state of a process may be represented by a vector describing the level of confidence in each parameter.

Pedersen *et al.* [26] have presented a design method that can help design aligned modular product and production architectures. The idea behind the method is to modularize a concept process similar to how products are modularized, which means that the process would be divided into two phases: a preparatory phase and an executive phase. The product concept consists of several sub-solutions or technical solutions. Each of these solutions corresponds to a transformation that needs be carried out in the manufacturing set-up. The process chosen corresponds to the overall set-up, so the production layout depends on the product concept and this dependency is modelled and visualized instantly. Once the dependency is optimized in accordance with the best possible product concept and the best possible production set-up, we might say the product and production architectures are aligned.

Multiple-Domain Matrix (MDM) [9] is one of the most commonly used matrix approaches. It is described in detailed in the paper background [17], so only the most important aspects will be addressed here. When applying MDM to a complex system, the classification of implied domains and dependency types can help users keep track of the relevant system aspects and linkages. Users are then able to specify the most important domains. The alignment of MDM automatically indicates all possible combinations of domains for subsequent specification of dependency types. Conversely, users can start with familiar dependency types and subsequently derive the corresponding domains of the complex system in question. In either case, the system of MDM supports the complete capturing of all basic aspects of a complex system.

3D-MDM [27] is an interactive 3D visualization, generation of a transparent view of dependencies between different domains of interest. It uses the open source scene graph library "Open Scene Graph" and is linked to the software tool LOOMEO [28] *via* an XML interface. It allows for an intuitive and transparent view of complex mechatronic products. By increasing the transparency and with it the understanding of the system, this representation assists engineers within the mechatronic development process.

The Integrated PKT approach [29,30] was developed at the Institute for the Product Development and mechanical engineering design in hamburg. This approach adapts product architecture to offer high external variety on the market without increasing the internal diversity in the company to the same extent. The elements of the approach are the Design for Variety and Life Phases Modularization modules.

A methodological approach to assessing product robustness [3,31] was developed at TU Munich, Institute for Product Development. It begins with a discussion on the focus and the requirements for the tool, both areas are modelled, a measure is generated, and documents are prepared for the implementation. In addition, the modelling phase in this project is extended to different companies to obtain more feedback regarding the practicability. The stepwise evaluation focuses on the modelling part. This enables us to understand the industrial need more clearly and to derive as early as possible such types of models that can be applied to industry after the project is completed. In contrast to the DFX shell, we focus more on the interdependence analysis on different levels and on the issue of which abstraction levels in the design process with regard to certain production aspects are best implemented.

The framework for integrated modelling and planning of mechatronic processes [32] combines different views of complex systems and provides an overall model to combine and analyse relations within the system. The various elements of such system are referred to as domains (*e.g.*, functions, persons and milestones) that interact in different ways and on different levels. The main idea behind the approach is to use functional validation of high level mechatronic functions during the integration and testing phase as a basis for the structuring and planning of the development process.

The MDM-based approach to the interrelation of lifecycle phases based on their association with DFX-guidelines [33] is a procedure to process generic information by using non-company-specific design guidelines and a set of lifecycle phases, which can be recognized in many products and has helped understand which lifecycle phases and which DFX-guidelines play more central roles in their respective networks than others. This information can be valuable to a product planner; it may help involve respective stakeholders throughout the lifecycle and provide support to consider and prioritize certain DFX-guidelines already included in the planning phase.

Autogenetic Design Theory (ADT) [34], developed at Otto-von-Guericke-Universität Magdeburg, Chair for Information Technologies in Mechanical Engineering, Germany is the genesis of a product during the development process is viewed as an analogy to the evolution of living creatures. With ADT, this process is described as an evolutionary development process of technique and technology in a turbulent environment, which consists of requirements, starting conditions, boundary conditions, and constraints, which all may change dynamically along the process. Finally, ADT provides a better understanding of the nature of the development process.

EXTENDED M-FBFP FRAMEWORK – DESCRIPTION

The extended M-FBFP framework (Figure 1) presented in this paper is based on the Theory of Technical Systems (TTS) [35,36] and the VDI 2206 standard [37]. It focuses on making system performance immune to variations under uncertain operating conditions. Variations are everywhere, both wanted and unwanted, but unwanted variations can impair the quality of the resulting products. A robust design does not aim to attempt to eliminate such variations, but rather to make the product insensitive to them. Feedback to the structural design is clearly only based on the results from the product and process modelling phases. In addition to the above disadvantages pertaining to this link only, a long period will elapse between structural changing iterations. The steps in the framework are presented as follows:

Forecast the overall customer requirements

Mapping of the overall design requirements [38] regarding the market segmentation grid is the first step. The market segmentation grid is an attention-directing tool providing a link between management, marketing and engineering designers to help identify potential opportunities. Thus, the overall design requirement could be generated by integrating all such market segmentation. During the product definition phase, marketing and data collection efforts should be completed before the beginning of procedure modelling.

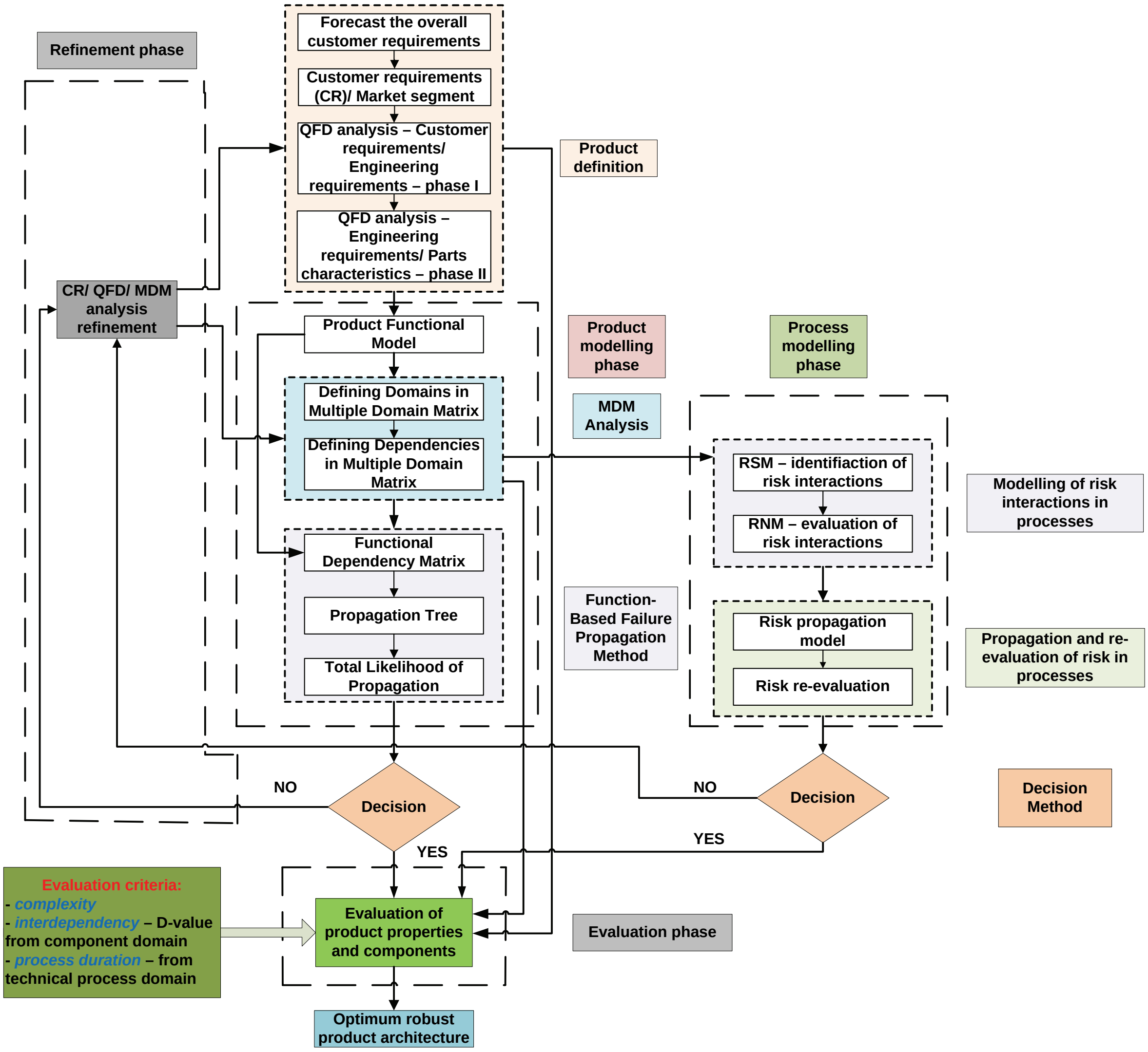


Figure 1. Schema of extended M-FBFP framework.

Customer requirements/market segment

This is where we will try to determine the overall customer requirements [38] for each group within the customer base. This includes different requirements from different market segment grids. The customer base is provided on the basis of a list generated in the first step. The market segmentation grid is created based on the size of the product family. Importance data is provided to match the customer requirements and market segment (importance is set to zero in certain cases to imply that there is no requirement).

QFD Analysis – Phase I

This step imports the overall customer requirements (CRs) rating and customer requirement to House of Quality (HoQ) [8] to obtain the engineering characteristics. On the left side of the QFD matrix, the importance value is presented by the overall rating from the preceding step. The engineering requirements (ERs), which can satisfy customer requirements, are determined as shown on the top and the relationships between them are provided.

QFD Analysis – Phase II

Following the QFD procedure [8], the engineering requirements (ERs) are input with weighting to the left side of QFD phase II, and the parts characteristics and relationships between engineering requirements and parts characteristics (PCs) arealso obtained. Furthermore, the interdependencies between parts characteristics are presented on the roof of QFD phase II.

Product modelling phase – with several intermediate steps:

a) Product functional modelling

Functional modelling is a design tool that describes a product or system in terms of the functions it performs [38]. Our model is based on the function of a product.

b) Multiple Domain Matrix (MDM) analysis

According to the procedure of structural complexity management [9], we first defined the system using the Multiple-Domain Matrix (MDM). The key domains that can be found here are: requirements, technical processes, functions and components (according to the Theory of Technical Systems – TTS [35,36]). In the next step, the types of dependencies between domains (inter-domain) were defined. As we can see in Figure 5 later on, the dependency meanings were not indicated for all possible domain combinations represented by the matrix subsets. Those not shaded indicate dependency information that is available, but not required forfurther system investigation (architecting and refinement). Finally, we defined the meanings for the intra-domain dependencies of components, functions, technical processes and requirements.

c) Functional dependency matrix

To perform the function-based failure propagation method [10], a functional dependency matrix was generated on the basis of the system's functional model using the flows as the common interface. Functions are directly dependent on the functions connected to them by one or more flows. The functional dependency matrix is then populated with the likelyhoods failure propagation to a particular function from the one it is dependent on. The initiating functions are the functions that fail initially, and the dependent functions are those that failure propagates to. For this method, the likelihood values are decimal values between zero and one, zero denoting no likelihood of propagation, and one representing certain propagation of failure. This is done to allow the use of Boolean operators [39] in the calculation of the total likelihood of propagation. Where there is no dependency, there is no likelihood of propagation, and thus place is completed with a zero or left blank (see Table 3 later on).

d) Propagation tree

Next, using the functional dependency matrix [7], propagation trees are built for each function in the model. These trees trace the path of potential failure to each possible function that can propagate its failure to the end function. Each branch represents a different starting function, travelling to the same "root".

e) Total likelihood of risk propagation

Finally, we calculated the total likelihood of risk propagation. Using the direct likelihoods generated from the functional dependency matrix and the propagation trees, the total propagation likelihood is calculated using the Boolean operators "AND" and "OR" [39]. Wherever there are multiple functions that failures can propagate from, the "OR" calculation is used. If a branch can only propagate failure to a single function, the "AND" calculation is used. In order to properly use this method, historical data pertaining to failure propagation must exist. Finally, these failures were then tabulated into a matrix showing the number of times each function pair had appeared. These numbers were then normalized using the most frequently occurring failure propagation pair as the normalizing factor. In this way, each value collected becomes a decimal value between zero and one. It is unlikely for each possible failure mode that a function might fail because it has the same likelihood of propagation. Some failure modes may have higher or lower likelihoods of propagation than others. However, to facilitate the calculation of those likelihoods, each failure mode for a function is assumed to have the same likelihood. Using a modified form of the likelihood mapping form [40], the likelihood of each function pair was then calculated (Table 1).

Table 1. Collected failure propagation data for final concept of climate chamber

Branch	Total likelihood
F0 – F1	0.1
F0 – F1 – F6 – F7 – F8 – F13 – F14	0.000054
F0 – F5 – F6 – F7 – F8 – F13 – F14	0.000108
Full tree	0.100162

Process modelling phase – with several intermediate steps:

a) Modelling of risk interactions in processes

– Identification of risk interactions in processes – Risk Structure Matrix (RSM)

Using identification, we are able detect and establish cause-effect relationships between risks. For this purpose, we defined the Risk Structure Matrix (RSM) [10–12], a binary and square matrix where the value $RSM_{ij} = 1$ if there is an interaction between the two risks R_i and R_j.

– An evaluation of risk interactions is provided using the Risk Numerical Matrix (RNM) [10–12] based on AHP-based principles [41]. The numerical values in the matrix were obtained from a Saaty scale for both the causes (inputs) and effects (outputs) to provide a risk pair wise comparison [41,42]. Using a combination of eigenvalues from two square matrices, the Numerical Effect Matrix (NEM) and the Numerical Cause Matrix (NCM), we can define the Risk Numerical Matrix (RNM) using a global weighting operation:

$$RNM(i,j) = \sqrt{NCM(i,j) \times NEM(i,j)},\quad \forall(i,j),\ 0 \le RNM(i,j) \le 1 \tag{1}$$

b) Propagation and re-evaluation of risk in processes

We used an approach where risks is propagated and re-evaluated by taking into account their propagation behaviour in the network. This approach is referred to as the Risk propagation model [43]. After such risk re-evaluation, we can see the result of the probabilities of the respective risks using a re-evaluated risk probability vector and a re-evaluated risk critical vector between elements in network (technical processes) [44]. Based on this result (high probability of risk in interactions), we are able determine whether there is a need make certain refinements in product architecture. This can help designers make improvements in product architectures in the evaluation phase.

Refinement phase

The refinement phase can be conducted after the product and process modelling phase through changes in a CR/QFD/MDM analysis. According to the feedbacks received in the refinement phase, we are able to evaluate product parts and properties.

Evaluation of product parts and properties

Such evaluation is based on three pieces of information (evaluation criteria) obtained from the QFD and MDM analyses: complexity, interdependency and process duration [13] (Table 2). We choose these criteria for an early evaluation of product properties. The degrees of complexity are determined based on the designer's experience. On the other hand, process duration data is adopted from an activity-based DSM (technical process domain in MDM), while interdependency is adopted from the D-value (sum of columns) from a component-based DSM (component domain in MDM) (see Figure 4 later on).

Each data is converted to the level of importance (Table 2). We then input the importance data to the upper side of QFD phase II, the rating corresponding to each part's characteristics obtained by summing up the values in the column. The lowest row and the rightmost column are calculated using the level of importance, the ratings for evaluation criteria, and the relationship between engineering requirements and parts characteristics, after which the summed up ratings of all engineering requirements and parts characteristics are obtained (based on which we are able to see the critical components and critical properties).

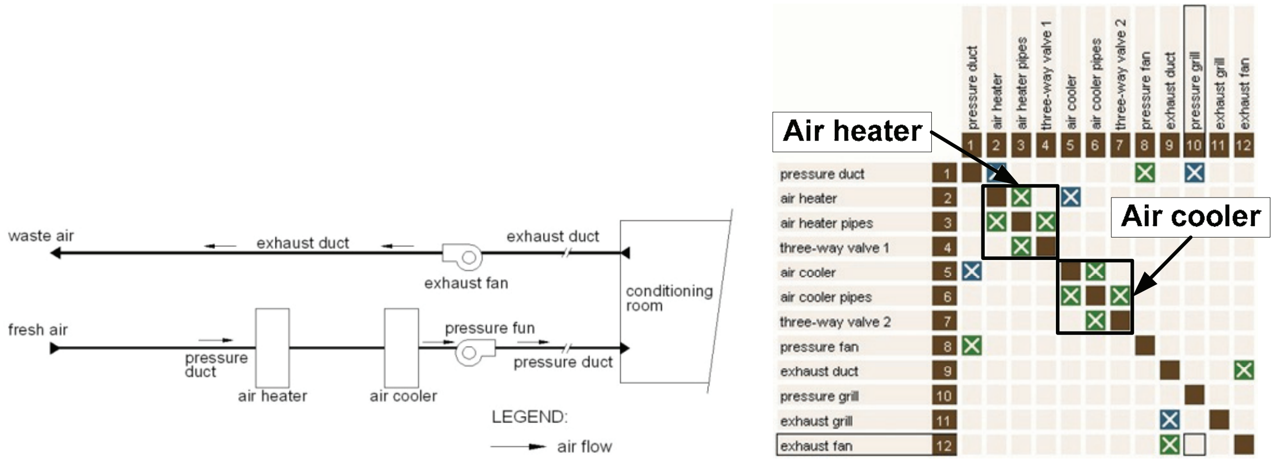
CASE STUDY

The objective of the case study is to demonstrate how the proposed matrix approach can support mechanical designers during conceptual designing. For this purpose, we used the example of a climate chamber, which is very often an integral part of HVAC systems for large facilities (*e.g.*, office buildings). We started with the initial climate chamber concept with operating conditions based on designer experience (Figure 2a). Our goal in the case study was to propose architecture for such operating conditions using the procedure concerned.

In OFD Phase I, customer requirements are input in relation to the engineering requirements that can meet them. According to the calculation of the importance of customer requirements, the engineering requirements that can meet them were determined and presented on the top, including their mutual relationships. Phase I of the QFD procedure contains a roof, which represents the correlations between engineering requirements. This data is not relevant to this research, so the roof part has been removed. During phase II of the QFD procedure, the engineering requirements with a weighting factor are put to the left side and the part characteristics are then determined. This was followed by determining the relationships between engineering requirements and parts characteristics. Furthermore, the interdependencies between part characteristics are

Table 2. Importance level for criteria information (for final concept of climate chamber); importance: high, 9, medium, 3, low, 1

Components	Process duration		Interdependency		Complexity	
	Day	Importance	Degree	Importance	Degree	Importance
12	5	3	1	1	Medium	3
44	1	1	10	9	Low	1
10	10	9	3	1	High	9
42	4	3	0	1	Medium	3
16	15	9	1	1	High	9
14	5	3	1	1	Medium	3
45	1	1	13	9	Low	1
13	14	9	18	9	High	9
51	4	3	1	1	Medium	3
19	5	3	1	1	Medium	3
46	1	1	10	9	Low	1
18	10	9	10	9	High	9
29	15	9	0	1	High	9
22	15	9	0	1	High	9
25	5	3	1	1	Medium	3
47	1	1	19	9	Low	1
24	10	9	2	1	High	9
48	4	3	10	9	Medium	3
5	4	3	3	1	Medium	3
41	2	1	13	9	Low	1
37	2	1	20	9	Low	1
2	12	9	1	1	High	9
50	4	3	1	1	Low	1
39	2	1	3	1	Medium	3
49	4	3	1	1	Medium	3
52	4	3	1	1	Medium	3
40	2	1	5	3	Low	1
43	2	1	4	3	Low	1
31	4	3	4	3	Medium	3



(a) (b)

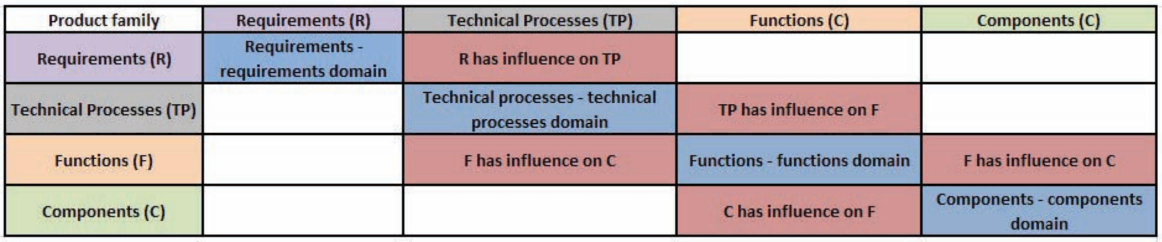
Figure 2. a) Simplified schema of initial concept of climate chamber; b) Component domain representation in MDM with possible modules (subsystems) identified in proposed product architecture for initial concept of climate chamber (screenshots from LOOMEO® software).

represented on the roof of phase II of the QFD procedure. After presenting the functional model of the system, an MDM analysis was provided (using LOOMEO® software [28]). It starts with domains for our initial climate chamber concept (Figure 3). This case study presents a component-based DSM (component domain) for the initial (Figure 2b) and final climate chamber concepts (Figure 4), after a few steps of refinement. After determining the dependencies between domains (inter and intra), we can proceed to build a functional dependency matrix for our product's functional model of the initial climate chamber concept. Figure 6 shows the functional dependency matrix for final climate chamber based on the product's functional model, Figure 5. We can see that the initiating functions are shown across the top of the matrix and the dependent functions are listed alongside. Next, based on the propagation tree created and starting from the "top" function and linking it to each function, we are able to calculate the total likelihood for each system. Each of these chains (branches) is linear because they only have one path from the initiator to the top function. Table 1 presents the failure propagation data collected for the final climate chamber concept, after a few steps of refinement. As we can see in Table 1, if we follow this procedure (as a Function-Based Failure Propagation Method), we can see for the entire tree (our proposed system with subsystems) the individual likelihoods of each branch and determine which branch of the tree has the highest likelihood. Based on this, we can add some new elements within our refinement phase (Figure 1).

We obtained an improved model after several feedback loops within the proposed framework to reduce risk likelihood and build our system that will fulfil our initial operating conditions (see the matrix representation of the system with its subsystems after clustering [45] – Figure 4).

The problem was solved by adding some new elements: a heat regenerator, a bypass duct, a recirculation duct, a humidifier and an air warm-up heater.

As we can see, each data element (Table 2) is converted to a value to represent a level of importance (9 stands for strong, 3 stands for medium and 1 stands for



Product family	Requirements (R)	Technical Processes (TP)	Functions (C)	Components (C)
Requirements (R)	Requirements - requirements domain	R has influence on TP		
Technical Processes (TP)		Technical processes - technical processes domain	TP has influence on F	
Functions (F)		F has influence on C	Functions - functions domain	F has influence on C
Components (C)			C has influence on F	Components - components domain

Figure 3. Domains in Multiple-Domain Matrix (MDM).

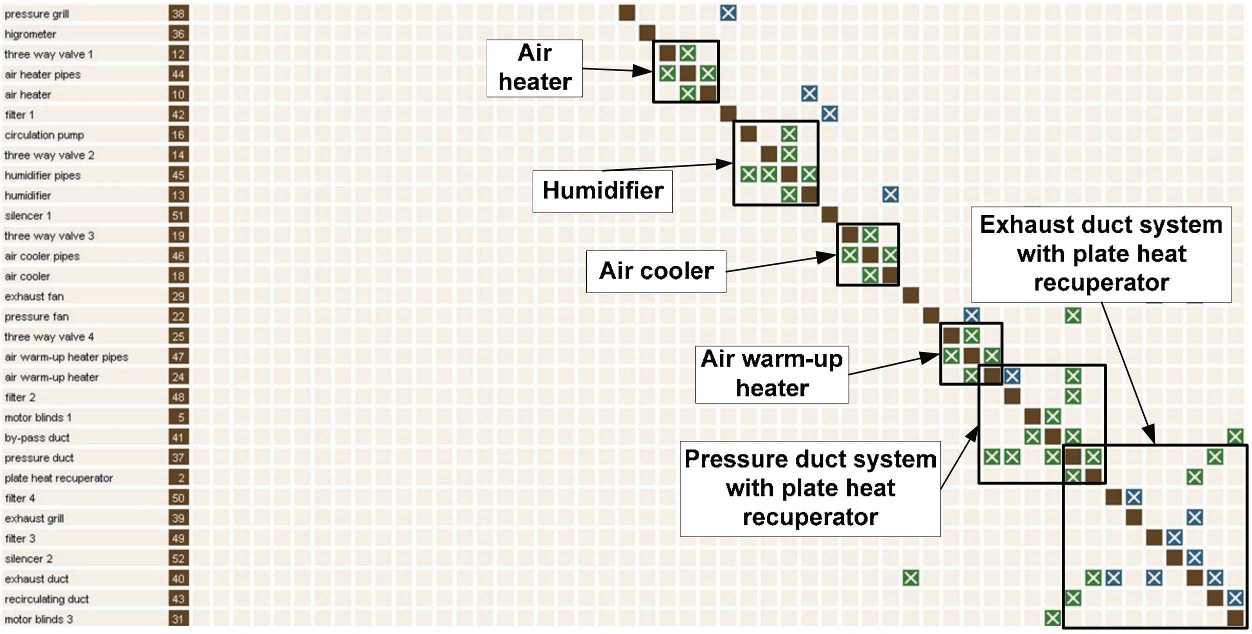


Figure 4. Component domain representation in MDM with possible modules (subsystems) identified in proposed product architecture for final concept of climate chamber (screenshots from LOOMEO® software).

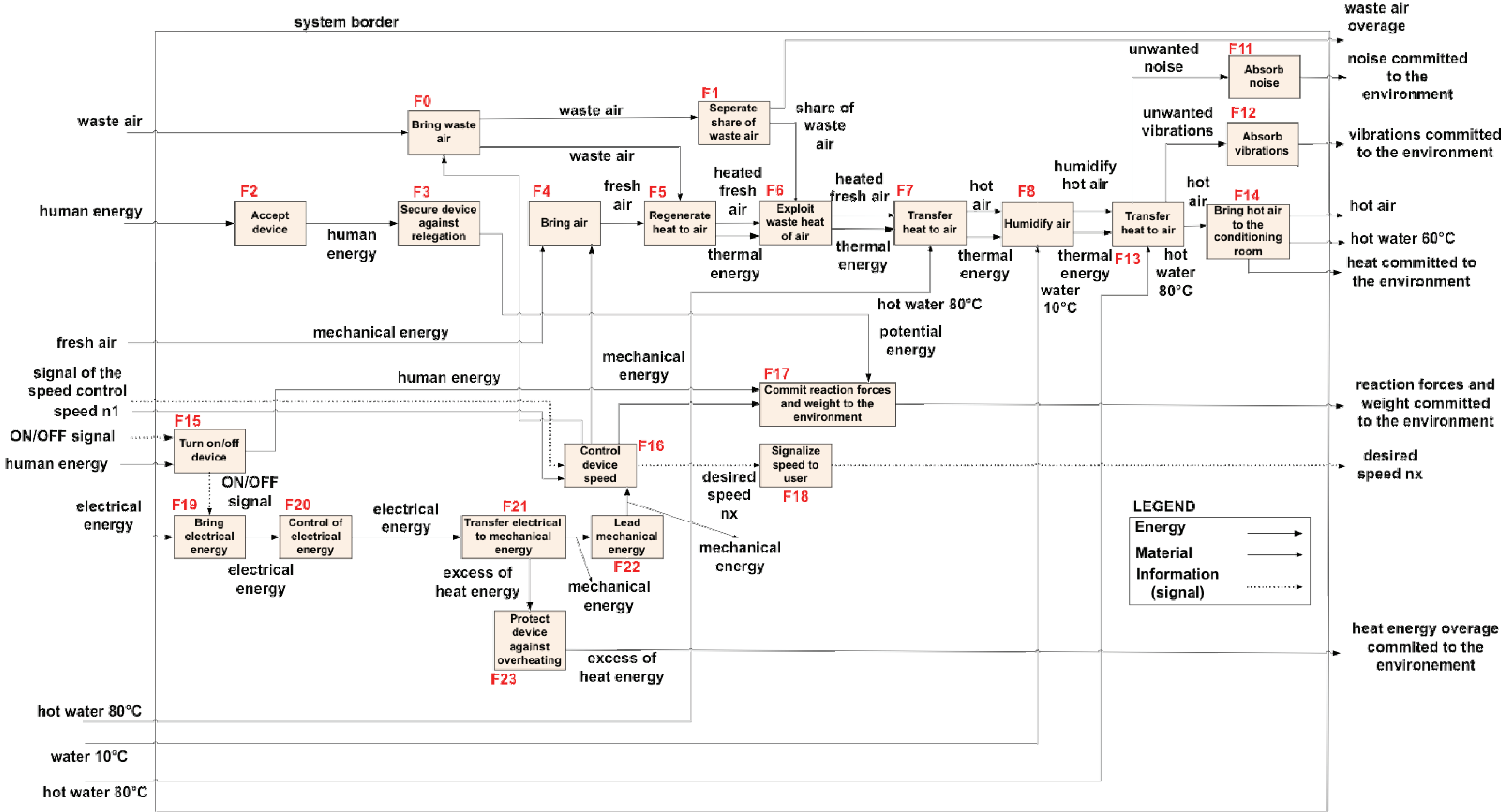
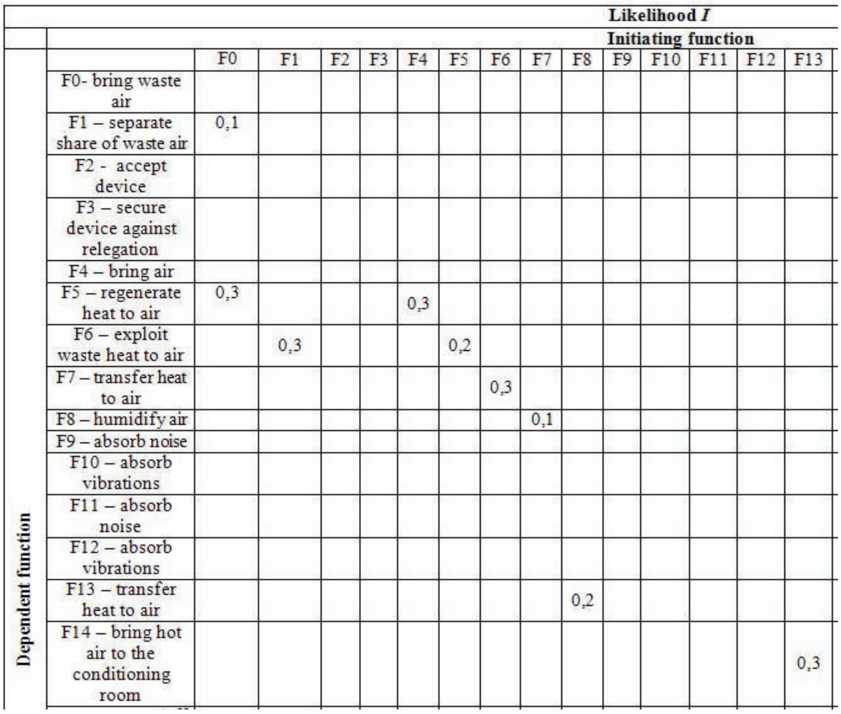


Figure 5. Product functional model for final concept of climate chamber.



		Likelihood *I*													
		Initiating function													
Dependent function		F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
	F0- bring waste air														
	F1 – separate share of waste air	0,1													
	F2 - accept device														
	F3 – secure device against relegation														
	F4 – bring air														
	F5 – regenerate heat to air	0,3				0,3									
	F6 – exploit waste heat to air		0,3				0,2								
	F7 – transfer heat to air							0,3							
	F8 – humidify air								0,1						
	F9 – absorb noise														
	F10 – absorb vibrations														
	F11 – absorb noise														
	F12 – absorb vibrations														
	F13 – transfer heat to air									0,2					
	F14 – bring hot air to the conditioning room														0,3

Figure 6. Functional dependency matrix for final concept of climate chamber.

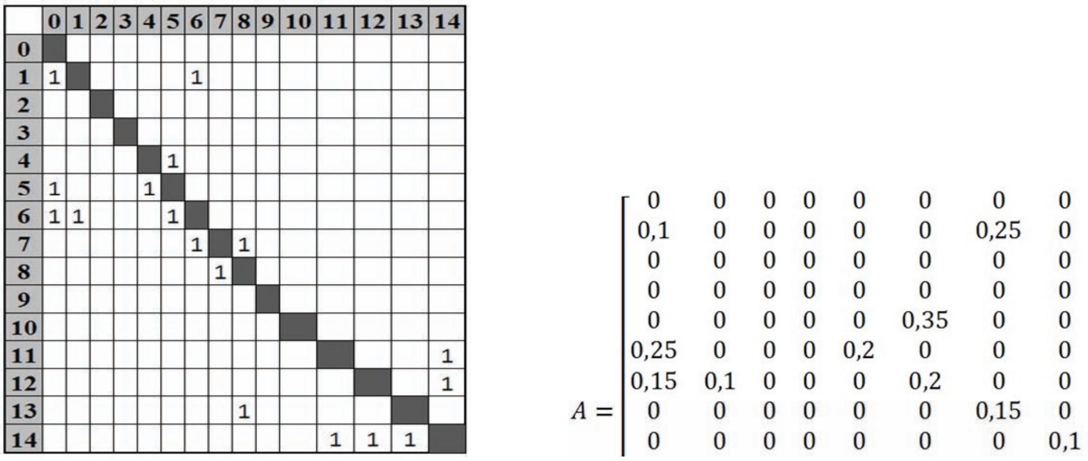
weak). Using the information provided in Table 2, we can determine the critical properties and critical parts of our proposed product architecture within QFD Phase II.

Putting the given criteria information on the upper side of QFD Phase II, we can recalculate the ratings for all engineering requirements, as well as the ratings for all part characteristics.

In the process modelling phase, we first provided a modelling of risk interactions through technical processes (using the technical processes domain in MDM). We thus created the Risk Structure Matrix (RSM) (Figure 7a) to identify risk interactions and the Risk Numerical Matrix (RNM) (Figure 7b) to evaluate risk interactions.

Now we can use the approach based on the Risk Propagation Model (Table 3) for risk propagation and re-evaluation. Based on such results, we are able to decide whether we need to make any improvements in product architectures within the refinement phase (see Figure 1). As we can see, we need to provide a few feedbacks to make improvements in product architecture.

The final climate chamber concept following a few feedback loops in the refinement phase is presented in



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0															
1	1						1								
2															
3															
4						1									
5	1				1										
6	1	1				1									
7							1		1						
8								1							
9															
10															
11															1
12															1
13									1						
14												1	1	1	

$$A=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0{,}1 & 0 & 0 & 0 & 0 & 0 & 0{,}25 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0{,}35 & 0 & 0\\ 0{,}25 & 0 & 0 & 0 & 0{,}2 & 0 & 0 & 0\\ 0{,}15 & 0{,}1 & 0 & 0 & 0 & 0{,}2 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0{,}15 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}1 \end{bmatrix}$$

(a) (b)

Figure 7. a) Risk Structure Matrix for final concept of climate chamber; b) Risk Numerical Matrix for final concept of climate chamber.

Table 3. Risk Propagation Model for final concept of climate chamber

Spontaneous probability		Re-evaluated probability	
Risk ID	Value	Risk ID	Value
R1	0.1	R1	0.087
R2	0.25	R2	0.311
R3	0.35	R3	0.288
R4	0.25	R4	0.265
R5	0.2	R5	0.225
R6	0.15	R6	0.186
R7	0.1	R7	0.119
R8	0.2	R8	0.224
R9	0.15	R9	0.157
R10	0.1	R10	0.119
R11	0.1	R11	0.122
R12	0.25	R12	0.283
R13	0.25	R13	0.278
R14	0.2	R14	0.186
R15	0.2	R15	0.177
R16	0.2	R16	0.177
R17	0.2	R17	0.133

Figure 8. In this current research stage, the feedback loop is performed manually based on the results provided by the Total Likelihoods in Function-Based Failure Propagation Method from the product modelling phase and the Risk Propagation Model from the process modelling phase.

CONCLUSION AND FUTURE RESEARCH

This paper proposes an extended M-FBFP framework, which combines a number of different methods to deal with complex mechatronic systems. It could help designers obtain optimally robust product architectures using continuous risk analysis throughout all stages from initialization to subsequent refinements within the product and process modelling phase using several evaluation criteria: complexity, interdependency and process duration in early design stages. It enables analysing different product architecture arrangements of function interactions against changes in product architecture and production processes. Designers could make refinements to existing subsystem structures by adding new features to them. They could also see the impact of the whole analysis on other domains (requirements, technical processes and components) to enable their refinement and changes. The framework also enables designers to evaluate robust design alternatives using the evaluation phase. The

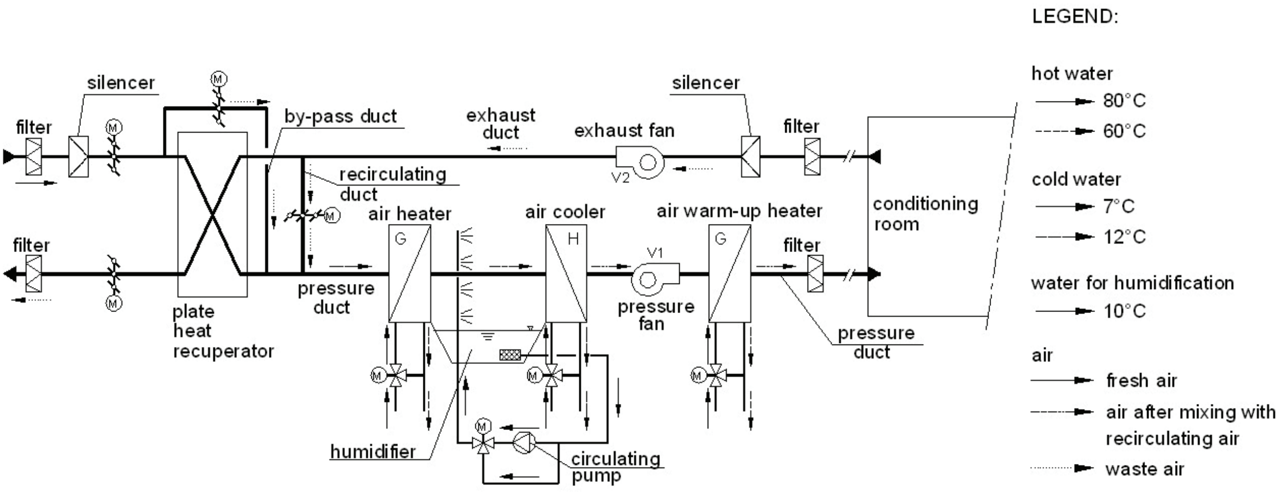


Figure 8. Simplified schema of final concept of climate chamber.

evaluation phase shows us that the framework and its methods are applicable in practical applications and that the results are meaningful and useful to the designers involved.

Future research could be continued through several options. One of them could extend the approach to all types of product development rather than just the modular or the present one. The second option could involve the elaboration and implementation of a decision-making method in the approach on which it will be based if it is necessary to make refinements in the QFD and MDM methods. Finally, the overall framework needs to be implemented in a software prototype as computational support is essential.

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IZVOD

POVEZIVANJE SUSTAVA I PROIZVODNIH PROCESA U RAZVOJU ARHITEKTURA ROBUSNIH MEHATRONIČKIH SUSTAVA – PROŠIRENO M-FBFP OKRUŽENJE

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Složenost mehatroničkih proizvoda, kao što su sustavi klima komora, dovodi do ogromnih poteškoća u sagledavanju gdje su glavne neučinkovitosti u procesu. Dakle, vrlo je teško odlučiti koja će poboljšanja imati najznačajniji utjecaj na tvrtku ili za određeni projekt. Mehatronički proizvodi se odlikuju visokim stupnjem interdisciplinarnosti i složenosti u tehničkom sustavu i pripadajućem razvojnom procesu. Ovdje nam kao glavni izazov predstavlja kako se nositi s visokom složenošću i raznolikošću međuovisnosti u takvim proizvodima. Stoga je ovdje predstavljeno okruženje za integraciju modeliranja mehatroničkih proizvoda i proizvodnih procesa – prošireno M-FBFP okruženje. Ono nam nudi različite nezavisne poglede na cijeli proizvod kako bi se poboljšala njegova arhitektura. Kao rezultat predloženog okruženja, analize rizika u podsustavima kroz domenu komponenata i u procesima kroz domenu tehničkih procesa postaje moguća, te putem dobivenih povratnih informacija mogu se raditi izmjene u arhitekturi proizvoda. Da bi se testirala valjanost predloženog okruženja, ovdje je predstavljen primjer s klima komorom s regeneracijom topline.

Ključne reči: Složenost • Konstruiranje mehatroničkih proizvoda • Arhitektura proizvoda • Prošireno M-FBFP okruženje • Tehnički proces • Analiza rizika