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IMPLEMENTATION OF MODULAR ARCHITECTURE OF COOLING GENERATORS

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Key words: modular architecture, product, modular function deployment, cooling generator

1. Introduction

Due to the increasingly high market demands, certain changes occur in production to make the manufacturing process as efficient as possible. Our objective is to establish a manufacturing process having features of serial production. Companies wish to reuse the same components, documents and technology as much as possible, which results in additional positive effects: smaller volumes of documents and easier use of such documents, resulting in an overall reduction of costs. Technology and production have developed into a very complex area requiring new knowledge and experience, and providing new opportunities. This paper aims to contribute to the understanding of the roles of module, modularity and modularization. This paper's objective is to propose engineering methods for more rational engineering activities base on the idea of modularization and design for reuse. The basic goal of the research is to help the designer in the conception and design of a design solution, reduce the time of preparation of design documents, and thus reduce the overall product development costs.
The methodology of the research described in this paper is based on critical rationalism and inductivism [Jorgensen, 1992]. According to the methodology, theories, methods and models are known, and further developed by studying the relevant literature, logical structuring and practical reviews. In this paper it is need to research possibility of development cooling generator product family based on modular architecture. For this purpose it is used Modular Function Deployment method [Erixon, 1998.], consisting of five main steps and which describe structuring products in modules.

2. Previous Work

In their well-known 1996 book "Engineering Design", Pahl and Beitz published a chapter entitled "Modular Product Design", where they adapt Borowski's terminology from 1961. However, certain differences do occur, and they are not insignificant. They focus on functionality, i.e. determination of different types of modules based of the scope of functions (basic, ancillary, special, adaptive and customized). The module is perceived as implementation of functions. According to them, the modular product design process is as follows:

1. Clarify the tasks,
2. Establish functional structures,
3. Search for solution principles and combine them,
4. Design of the entire product.

In production and traditional engineering, module is perceived as a subassembly representing a set of components that may be reused in several versions of products limited by complexity and integrity. Some authors have extended the reasons for modularity, including other product life phases, except for

assembly. Erixon focused his research on the impacts modularity can have on a product's life phases – development, production, testing, servicing, maintenance and recycling [Erixon, 1998.]. He presumed the term „cause of module" providing specific reasons of a company for modularity. He does not define modules strictly - he defines modularization in relation to the causes of module. According to Erixon, „modularization is decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific reasons" [Erixon, 1998.].
Driven by Pahl's and Beitz's research, Erixon proposed the Modular Function Deployment method. The method consists of five main steps and describes structuring of products into modules.

3. Modular Function Deployment

The Modular Function Deployment (MFD) is a systematic method and procedure for development of modular products, consisting of five main steps [Erixon, 1998]. The method analyzes the functional requirements for a product and determines the technical solution and modular concept.
In definition of potential modules, we also use the Modular Indication Matrix, testing the interrelations between the cause of modularity and the technical solution. MIM (Modular Indication Matrix) also ensures a mechanism for researching the possibilities of integrating multiple functions into individual modules. MFD consists of the following steps:

1. Clarify customer requirements,
2. Technical solutions,
3. Define possible modules,
4. Evaluate concepts,
5. Improve each module.

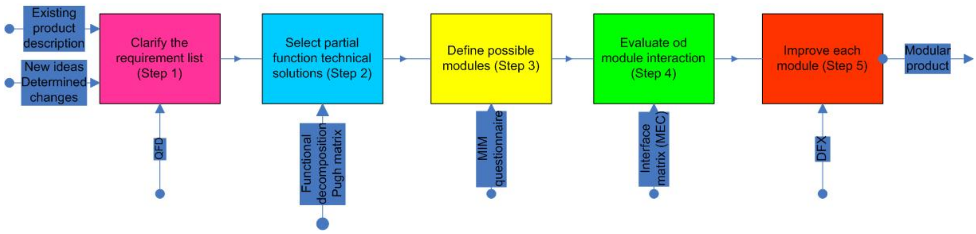


Figure 1. Modular Function Deployment

Figure 1 presents the MFD method steps and procedure. The method begins with the Quality Function Deployment, clarifying the customer requirements and defining the design requirements with a special review of the product modularity possibilities. The product features need to meet the current and future requirements determined by market analysis and customer requirements.
When the essential customer requirements are determined, they are transformed into product specifications. The relations between the customer requirements and product specification are presented in the QFD matrix. The normal QFD matrix is changed by making modularity the primary design requirements.
In the next step, we need to determine the functions and sub-functions from the preceding step and select the appropriate technical solutions. Functional independence is a prerequisite for achieving optimal modular design. It enables modular design where the relations between the modules are minimal. When functional decomposition is carried out, several technical solutions are selected for each function. Experience has shown that the best way to present the relation between functions and technical solutions is by a matrix. This matrix [Pugh, 1981 or Suh, 1990] represents a method for determining the advantages and flaws of different solutions. The verification of the selected solutions is based on the first step of the method and the company's abilities (development potential, manufacturing objectives). In the third step, the reasons for the modular design of the technical solution selected within the preceding step are analyzed. The criteria used for the analysis are the causes of modularity. Causes of modularity may be used as the base for evaluation of a technical solution within a product. For the purposes of this task, a matrix is designed, in which each technical

solution is accompanied by the causes of modularity. This matrix, known as MIM (Modular Indication Matrix), is a fundamental part of the MFD method.

In the fourth step, we evaluate the concept. In modular design, the interfaces between the modules have a significant impact on the final product and the variability within the range. Therefore, the interface testing is an important part of concept verification. The interface between two modules has to be solid, mobile or medium-transmitted. A good overview of interface relations between modules may be achieved by an interface matrix [Erixon, 1998]. The modules within the interface are connected in a assembly, and their interfaces are marked with an S for solid interfaces, or M for mobile and medium-transmitted interfaces. The matrix serves as an indicator of the interfaces to be observed and extended as necessary. All indications outside the direction of the arrows indicate undesirable relations, and should be either avoided or improved [Pavlić, 2003]. For a good evaluation, economic impacts also need to be observed. Pahl and Beitz presume that pre-evaluations may be made in the concept phase based on economic factors that are important in the design of modular systems [Pahl, Beitz, 1988]. The designer should estimate the production price of each module, their relative impact on the price of the modular system as a whole, and their interaction. Typical economic analyses cannot evaluate all the additional benefits and impact provided by a modular range, which is why new tools need to be developed [Erixon, 1998].

In the final step, specifications are made for each module. They contain the technical information, expected price, planned development, variant descriptions, etc. Module specifications represent the base for product platforms.

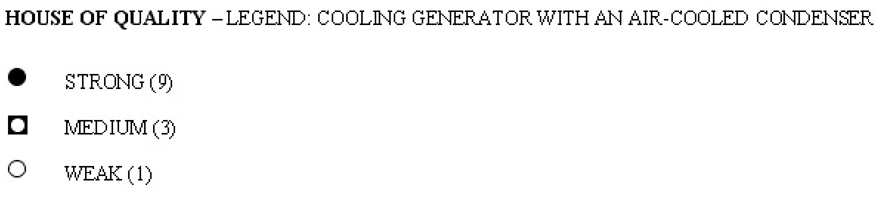
The MFD method is a method of achieving the desired result for each module. In such case, MIM serves as an indicator of what is important for each module; for example, a module selected for maintenance and servicing reasons needs to be designed for easy disassembly.

The final result of modularization must be documented. Each module is presented in the Module Specification Sheet.

3.1 Analysis of the Requirement List

The requirement list is a list of customer's requirements and wishes arising from analysis of needs. After defining the requirement list, requirements and wishes are evaluated. Wishes should be taken into account where possible during the development, provided that non-fulfillment of wishes does not impair the solution to the problem. To serve as basis for subsequent decisions, the requirement list should be prepared in a very precise and complete manner, although supplementations and corrections will be made during the elaboration.

To implement the QFD method [Erixon, 1998], customer requirements should be defined by precisely specifying the requirements of the product designed. The method may be described as a "method for developing design quality for the purpose of satisfying customers and transforming customer requirements into the desired design objectives and achieving a higher quality of product [Akao, 1990]. In the first step, a "Needs – Specification" matrix was formed for a cooling generator with an air-cooled condenser (see Figure 2). The needs (requirements) are provided in the matrix rows, while the columns contain the technical specifications. After determining the specifications, the following step is to establish the relations between the needs and technical specifications by using a weighting scale: strong (9), medium (3), and weak (1). Based on these marks, the essential needs (requirements) are determined, and the technical specifications by which they are achieved.



	SPECIFICATIONS	Generator's thermal performance up to 530 kW	Electricity connection 3x220 V,	environment temperature: -20 °C	Mechanical protection IP XX	Generator dimensions: HxLxW [mm]	Operating generator weight: <3000 kg	Corrosion protection	Air cooling	Interior temperature: < 50 °C	Protective functions
NEEDS											
Converter price		●									
Uninterrupted operation		●									
Electrical engine power supply			●								
Easy operating conditions				●	●			□			
Cooling method						□	□		●	●	
Resistance to shock and vibrations						□	□				
Service vents											
Generator size and weight						●	●				
Safe transport and packaging											
Noise reduction								□			
Generator operation management											
Operator protection											

Figure 2. The „Needs – Specifications" matrix for a cooling generator with an air-cooled condenser

3.2 Functional Decomposition of Cooling Generators

In the second step of the MFD procedure, we need to determine the functions and sub-functions meeting the requirements from the first step, and select the appropriate technical solutions. To achieve this, we need to perform functional decomposition. The method used for such decomposition is IDEF0. IDEF0 is a method intended for modelling activities in the system, derived from the graphic language SADT (Structured Analysis and Design Technique). On the first functional level, we define the overall function of the cooling generator. On the second functional level (see Figure 3), we define the functional structure of the technical system, expressed by a certain number of partial functions (PS). The overall function consists of several partial functions existing alone as partial systems (PS), and the logical interrelation between these subsystems provides the functional structure of the technical system. The cooling generator functional structure shows that it consists of the following partial systems:

- air-cooled condenser (PS1)
- evaporator (PS2)
- compressor (PS3)
- cooling generator casing (PS4)
- storage and expansion vessel (PS5)
- automatic control (PS6)

- electric power supply (PS7)

The functional decomposition shows that each sub-function may have several technical solutions. A design matrix [Suh, 1990] (see Figure 4) was selected as a way of displaying the results of sub-function and technical solution dependence. By forming a matrix where the technical specifications are contained in rows and the columns contain the technical subsystems (PS), we determine which technical specifications each subsystem has.

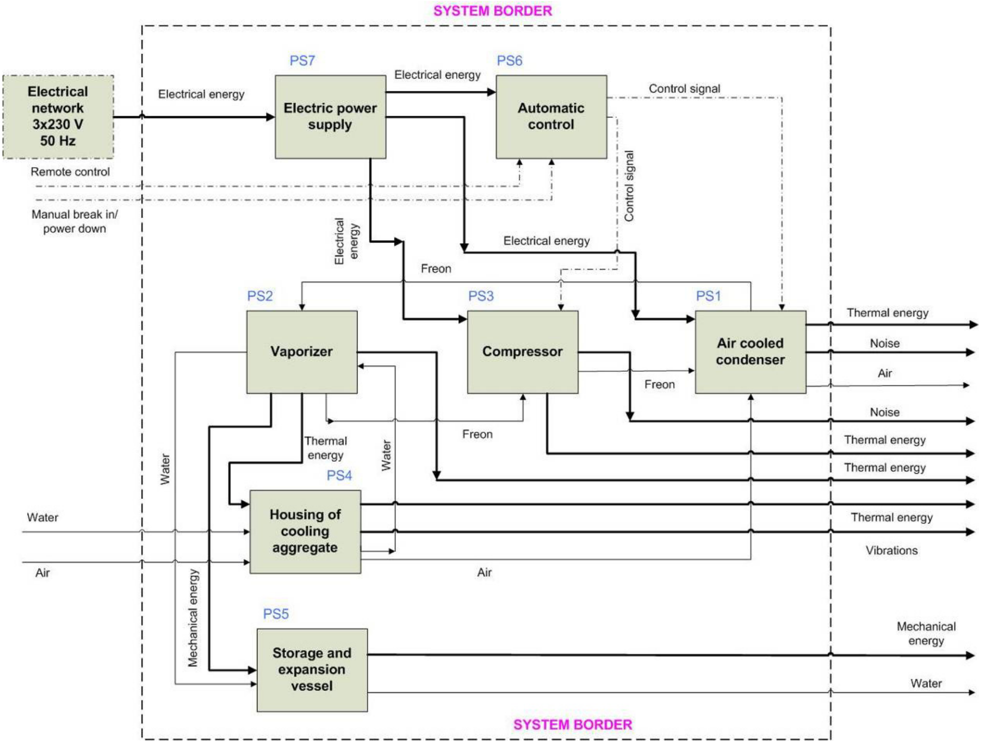


Figure 3. Functional structure of a cooling generator with an air-cooled condenser

The next step is to determine the relations between the technical specifications and the technical subsystems by using a weighting scale: solid (9), medium (3), weak (1). Based on the aggregate number of points, we determine partial subsystems as candidates for modules (see Figure 5). In this step, the functions and technical solutions for more complex products need to be put in a hierarchical relation for an easier display of the whole. One of the ways to display is the function tree [Erixon, 1998]. This is the second step in the MFD procedure, resulting in the display of the hierarchical function tree and solutions selected for the cooling generator with an air-cooled condenser.

3.3 Defining the Possible Modules

In the third step, we analyze the reasons of modularity for the technical solutions selected in the preceding step. The causes of modularity are the modularity analysis criteria. To carry out this task, a matrix is formed where each technical solution is associated with the reasons of modularity. The resulting matrix is referred to as the Modular Indication Matrix (MIM). It indicates which sub-functions (technical subsystems) could become modules. The causes of modularity are contained in the rows, and the partial subsystems are contained in the columns of the matrix.

We should define the appropriate weighting scale for evaluation of causes of modularity, containing the following values: 9 (strong cause), 3 (medium cause), 1 (insignificant cause). Evaluation of the weighted amount depends on how much a cause of modularity/specification affects the technical solution. At the end, the evaluations of the respective technical solutions are added up, and the technical solutions that achieve the highest number of points become candidates for modules.

FUNCTION	TECHNICAL SOLUTION	Contactors	Screws	Semi-conductor switchgears	Electronics modules	Buses	Cables	Measuring converters	Light pipes	Switch cabinets	Generator casing frame	Casing shell	Equipment supports in the casing	Semi-hermetic single-screw compressor	Circulation pump	Pipelines
PS1 – air-cooled condenser																
Increase the air circulation speed																
Receive heat from Freon																
Reduce noise																
Transfer forces on environment			X													
PS2 – evaporator																
Convey heat to Freon																
Transfer forces on environment			X													
PS3 – compressor																
Compress Freon														X		
Reduce noise																
Transfer forces on environment			X													
PS4 – cooling generator casing																
Ensure equipment																

Figure 4. Design matrix for a cooling generator with an air-cooled condenser

The technical solutions that achieve the lowest number of points could be related to one of the candidates for modules. The number of modules in a product is approximately equal to the value of the square root of the total number of parts in a variant of such product [Erixon, 1993]. Causes of modularity exist throughout the life of a product, and are related to different functions in the company [Erixon, 1993]. Figure 6 present an analysis of modularity for a cooling generator with an air-cooled generator. It has been determined that the candidates for modules are the subsystems identified as: PS1, PS2, PS3, PS4 and PS6 (grey cells). Criteria that was used in this paper for defining modules was: low cooling generators dimensions, low cooling generators mass and low cost of cooling generators.

HOUSE OF QUALITY – LEGEND: COOLING GENERATOR WITH AN AIR-COOLED CONDENSER

● STRONG (9)

◘ MEDIUM (3)

○ WEAK (1)

	TECHNICAL SUBSYSTEMS	PS1	PS2	PS3	PS4	PS5	PS6	PS7	
SPECIFICATIONS									
Generator's thermal performance up to 530 kW		●	●	●	●	□	●	□	
Electricity connection 3x220 V, 50 Hz		●		●			●	●	
Operating environment temperature: -20°C do 45 °C		●	●	●			●		
Mechanical protection IP XX		●		●			●		
Generator dimensions: HxLxW [mm]		□	□	□	●				
Operating generator weight: <3000 kg		□	□	●	●	●			
Protection against corrosion					●				
Air cooling		●	●	●					
Interior temperature: < 50°C		□	□	●	●				
Protective functions (as specified by the customer and manufacturer)		●		●			●	●	
Protective functions (as specified by the customer and manufacturer)		●		●			●	□	
Protective functions (as specified by the customer and manufacturer)		●		●					
Modularity		●	●	●	●				
Installation method: exterior/interior		●	□	□	●		●		
Side vents					●				
Number of vents					●				
Vent dimensions					●				
Exploitation time		●	●	●	●		●		
Deviation from the cost price (10 % in relation to the competition)		●	●	●	●				
Solid and flat surface				●	●				
Styrofoam and PVC foil lining					●				
Materials with a return recycling cycle							●	●	
DIN EN 10025, DIN EN 10088		●	●	●	●				
		126	75	141	135	12	81	33	

Figure 5. Specification matrix

3.4 Evaluation of Interaction between Modules

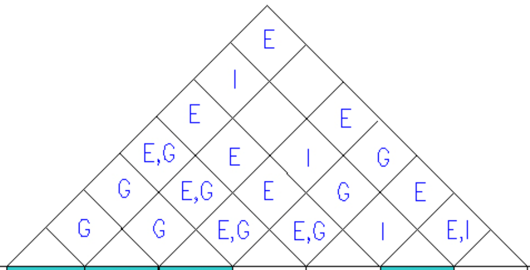
Verification of a modular concept is based on testing of the interfaces between the modules. The interface matrix [Erixon, 1998] is used as a tool for this. It is designed as a house of quality for the cooling generator with an air-cooled condenser (see Figure 6). It is very easy to determine from it the characteristics of the interfaces between the respective partial systems. The analysis established that energy transmission (E) occurs or solid relations (G) are established between most of the interfaces in generators. Figure 6 shows that the candidates for modules are partial systems PS1, PS2, PS3 and PS6, and that energy transmission (E) occurs or solid relations (G) are established between most of the interfaces in generators. We can see that the essential affecting causes of modularity are: technological development, separate function testing, supplier availability, servicing and maintenance, upgrading and recycling.

HOUSE OF QUALITY – LEGEND: COOLING GENERATOR WITH AN AIR-COOLED CONDENSER

● STRONG (9)

□ MEDIUM (3)

○ WEAK (1)



		66	48	66	9	24	66	6	
		PS1	PS2	PS3	PS4	PS5	PS6	PS7	
Development	Reuse	●		●					18
	Technological development	●	●	●			●		36
	Production change planning				□				3
Changes	Technical specification	□	□	□	□	□	□		18
	Appearance				□				3
Production	Common parts								0
	Reuse of processes and organizations						●		9
Quality	Separate function testing	●	●	●		□	●		39
Supply	Supplier availability	●	●	●		●	●	□	48
After sales	Servicing and maintenance	●	●	●		●	●		45
	Upgrading	●	●	●			●		36
	Recycling	●		●			●	□	30

Figure 6. Modular Indication Matrix and Interface Matrix

3.5 Improvement of Each Module

In the final step of the MFD procedure, specifications are generated for each module, containing: technical information, expected price, planned development, variant description, etc., thus representing the base for the product platform. This paper does not include module specifications, so this is a production task.

4. Conclusion

The research objective in this paper was the development of a cooling generator product family based on modular architecture. The focus in the paper was on the application of the Modular Function Deployment (MFD) method. Its use increases for potential for planning and forecasting, with easier control and management, thus enabling the estimation of the economic results in the early stage of the project. Its advantage is in the simplicity of use in project and the possibility of application throughout the life of a product. Modularization of cooling generators aims to provide a base for development of a cooling generator product family, and use the advantages provided by the application of a modular approach to design in production. The application of this research method defines the proposal for modular architecture of cooling generators.

Further research may be continued in several different directions. One of the directions would pertain to research of the modularization process. Due to a small number of applicable methods for determination of modules in product structure, there is a need for further research in the area of product modularization. Further research should focus on development of computing devices to support the Modular Function Deployment because its full implementation is only achieved when it becomes a normal tool for designers. Research of records of knowledge is currently one of the leading research areas in the world. Frequent changes in knowledge (caused primarily by changes on the market or changes in technology) lead to major changes in the computing model [Pavlić, 2003.]. In addition, the next direction in research could continue by describing a family of cooling generators and their parametrization. In this paper, a product family implies a group of related products, their relation arising from the structure of these products [Tichem, Andreasen, Riitahuhta, 1999.]. Their development is a key activity in the product variant development process. Achievement of the basic features of a product family: creating diversity, reducing complexity and increasing similarity. [Riitahuhta, Andreasen, 1998.].

The use of modular architecture in design and production provides many benefits both to the manufacturers and the customers, [O'Grady, Liang W.Y., Tseng T.L., Huang C.C., Kusiak A., 1997.], namely: reduction of product variant prices, increase of module replacement possibilities, increase of product variance, quicker product delivery, and simpler maintenance and assembly.

References

Akao Y. :"QFD – Integrating Customer Requirements into Product Design", Productivity Press, 1995.

Borowski K-H. J. :"Das Baukastensystem in der Technik", Springer – Verlag, Berlin, Götingen, Heidelberg, 1961.

EN, DIN and HRN standards

Erixon G. :"Evaluation Tool for Modular Design", Int. Forum on DFMA, Newport, USA, 1993.

Erixon G. :"Modular Function Deployment – A Method for Product Modularization", Doctoral Thesis, KTH, Stockholm, 1998.

Jorgensen K.A. :"Paradigms for research", Department od Production, Alborg University, 1992.

Miller T.D. :"Modular Engineering – An approach to structuring business with coherent, modular architectures of artifacts, activities and knowledge", PhD Thesis, Technical Univesity of Denmark, 2000.

O'Grady, Liang W.Y., Tseng T.L., Huang C.C., Kusiak A. :"Remote Collaborative Design With Modules", Technical Report TR 97-03, Univesity of Iowa, USA, 1997.

Pahl G., Beitz W. :"Engineering Design: A Systematic Aproach", Edition 2nd, Springer – Verlag, ISBN 35401000179, 1996.

Pahl G., Beitz W. :"Engineering Design", The Design Council, London, 1988.

Pavlić D. :"System for Configuration of Modular Architecture Products ", Master's Thesis, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, 200.3

Pugh S. :"Concept Selection – A Method that Works", ICED '81, Rome, Italy, 1981.

Riitahuhta A., Andreasen M. M.: "Configuration by Modularization", Proceeding of Nord Design '98, Stockholm, Sweden, 1998.

Suh N.P. :"The principles of design", Oxford University Press, 1990.

Tichem M., Andreasen M. M., Riitahuhta A. :"Design of product families", International Conference on Engineering Design, ICED 99, August 24-26, Munich, Germany, 1999.

Vukobrat M. : "Modular Architecture of Converters of Electrical Values in Railway Vehicles", Master's Thesis, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, 2007

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