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Algorithm for Designing Family of Modular Optoelectronic Devices

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Designing modular products covers a wider range of tasks than traditional design. There are publications presenting selected issues related to the design of modular products, but generally, there are no comprehensive descriptions of this process. The authors of the article are convinced that the development and implementation of a proven algorithm for designing modular products will increase the effectiveness and efficiency of such work. Designs of modular products, and especially families of such products, can be long-term, therefore, in addition to using the experience gained from such projects, it is justified to use model tests. It was decided to use Petri nets to build a model of the design process. The places of this network are individual tasks carried out during design, and the transitions are the decisions of selected process participants enabling the initiation of subsequent tasks. Decisions are made based on criteria for assessing the effectiveness of individual tasks. The schedule of an actual project of a family of modular devices carried out in one of the renowned centres of the optoelectronics industry was used to formulate them. Analysis of known varieties of Petri nets showed that model construction is possible using coloured time nets. Conclusions were formulated regarding the proposed algorithm of the design process and methods of its evaluation.

topics: Petri nets, modular products design, process modelling

1. Introduction

In the traditional methodology of designing devices, including mechatronic devices, the design team performs its tasks striving to meet the requirements set beforehand, describing, among other things, the main function of the device, its operating conditions, or the recommended manufacturing and assembly technologies [1, 2]. Often, an important requirement is to meet selected standards related, for example, to the anticipated market or legal regulations. Standard solutions are often used to comply with safety directives. This is not the case with the development of modular devices. In this case, the conceptual phase also includes the development of a new standard for interfaces between functional components, i.e., modules, which can then be easily and economically assembled into devices with functions and characteristics tailored to the requirements of specific users [3, 4]. Modularity is a concept that can be found in a multitude of technological fields, including mechanical and equipment engineering. However, the methodology for designing modular devices remains relatively under-researched. When considering the potential benefits and limitations of modularity in engineering design [5], it becomes evident that the methodology employed during the design process of modular devices is of paramount importance for their subsequent development and, concurrently, for the business prospects of organisations implementing such a solution [6]. A further challenge arises when a system of modules is employed to construct not a single device in multiple versions, but rather a range of distinct devices [7].

The authors seek to develop an effective and efficient algorithm for the design of such products, with the objective of providing engineers with a clear, transparent, and unambiguous guide through the process of designing the architecture of a family of modular devices [8, 9]. The objective of this algorithm is twofold: firstly, to demonstrate the cause-and-effect sequence; secondly, to facilitate simulations that reveal the potential gains and losses associated with a specific sequence of decisions at a given design stage. It is evident that specific decisions will remain affected by, for instance, company policy. However, by contemplating an array of potential solutions and analysing them through simulation, it is feasible to identify alternative courses of action that offer particular advantages in terms of the efficiency or effectiveness of the algorithm.

In this paper, the authors utilise the ongoing project at PCO S.A. to transform a collection of selected optoelectronic devices into a modular family as an illustrative example.

2. The design of a modular family of optoelectronic devices

The current business activities of PCO S.A. are primarily focused on the production of optoelectronic devices. The company's product range includes night vision and thermal imaging observation devices, sights, and rangefinders. Such devices are utilised both as standalone solutions for individual soldiers and as integral components of combat platforms. In order to meet the specific requirements of its customers, the company is able to adapt its products at the request of the customer. Consequently, despite the fact that the products in this category feature highly similar component assemblies, resulting from the input of multiple designers, they do, in fact, differ from one another. In pursuit of cost reduction across the product lifecycle, from design to component production to assembly, the company's management has initiated the development of a modular family of equipment for individual soldier equipment. The successful completion of this project is anticipated to yield not only reduced development and manufacturing costs but also a decrease in lead times. The advantages of modularisation are manifold and include the following [4, 5, 10, 11]: economies of scale, a reduction of costs through the use of prefabricated components belonging to a family in new products, convenient monitoring of changes made only in the module area and not in the whole device, easy diagnostics, maintenance, and disposal of devices. While modularity offers numerous advantages, it also presents a number of constraints. These range from mechanical and electrical, represented by fixed interfaces, to architectural, defining a closed standard with predetermined functions. These constraints can impede design optimisation, particularly in the longer term [12]. It is thus crucial that the design algorithm for modular systems, to the greatest extent possible, ensures the implementation of structural solutions that minimise these barriers for the duration of the established standards.

2.1. Conceptual design

A sequence of work was planned when proceeding to the conceptual development of a family of devices, as presented in the form of a diagram in Fig. 1. The presented algorithm extends the design assumptions known from the traditional methodology of developing mechatronic devices [1, 2] with assumptions on the construction of a family of modular products [3, 5, 13]. In accordance with the aforementioned plan, the project was initiated with a comprehensive examination of the products manufactured by the PCO company and the devices available on the market. Based on this analysis, the products were decomposed to identify the functional blocks that are common to devices [4]. An illustrative list of these repetitive functional blocks is presented in Fig. 2 [14].

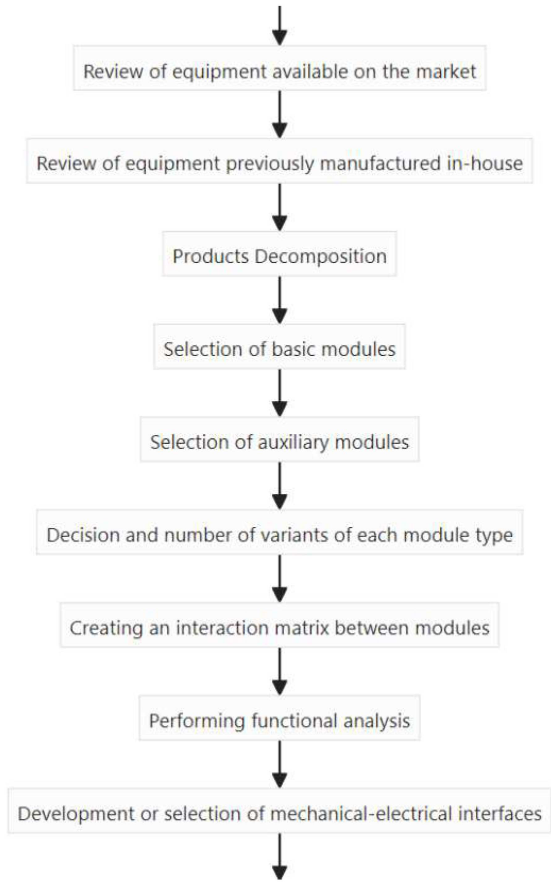

Fig. 1. Sequence of work on the concept of family.

Fig. 2. Distinguished functional blocks on the example of night vision goggles PVS-31D from Armasight and PSQ-42 from L3Harris, see [14].

TABLE I

The matrix of desired monocular–bridge interactions

	M11	M12	M13	M14	M15	M16	M17	M18	M19
M1	1	1	1	1	1	1	1	1	1
M2				1	1	1		1	
M3					1	1		1	
M4					1	1		1	
M5							1		1
M6							1		1

TABLE II

The matrix of bridge — auxiliary modules.

	M11	M12	M13	M14	M15	M16	M17	M18	M19
Battery compartment	1	0	0	0	1	0	1	0	1
IR illuminators	1	1	0	0	1	1	1	0	1
Knobs	1	1	1	1	1	1	0	0	0
COLE switches	1	1	1	1	1	1	0	0	0
Keyboard	0	0	0	1	1	1	x	0	x
Peripherial devices connector	0	0	1	0	1	1	0	0	0

TABLE III

The matrix of monocular–bridge interactions.

	M11	M12	M13	M14	M15	M16	M17	M18	M19
M1	(G1,G1)	(G1,G1)	(G2,G2)		(G1,G1)↓	(G1,G1)↓	G1	G1	G1
M2				(G2,G3)	(G3,G1)	(G3,G1)		G3	
M3					(G4,G1)	(G4,G1)		G4	
M4					(G5,G1)	(G5,G1)		G5	
M5							mech.		mech.
M6							mech.		mech.

After analysing the compiled list, the role of each block in the modularisation process was determined. Monoculars and the bridge were designated as basic modules, while the keyboard, power switch, *infrared* (IR) illuminator, power modules, and battery compartments were classified as auxiliary modules.

Another analysis concentrated on the diversity of modules and their function within the family. It was established that basic modules would exhibit variants that differed in equipment according to the specifications of a particular device. This form of modularity is referred to as "component swapping" [3]. Additionally, it was determined that auxiliary modules would be constructed as a singular variant utilised in all products. This type of modularity is designated as "component sharing" [11].

The decisions described formed the basis for the creation of two modularity matrices. The first (two-stage) matrix links the basic modules and the monocular power module between them (see Table I). The second matrix bridges the interaction between the auxiliary module and the bridge (see Table II).

In view of the aforementioned interactions, the power modules are presented in the matrix in Table III as ordered pairs. The first element represents the left monocular, while the second element corresponds to the right monocular.

As can be observed from the aforementioned matrices, in each of the bridges with two power interfaces, the left module is a simple monocular.

The next phase of the project involved the development of common elements, namely auxiliary modules, to equip each bridge. Prior to initiating this phase, an interaction matrix was created (see Table II). This matrix was designed to provide a visual representation of the equipment to be installed on each bridge while also identifying potential areas for the development of specific modules in subsequent stages of the project.

In consideration of the aforementioned matrix, it is evident that the development of the M11 module, which serves as the inaugural component, entails the necessity for the formulation of four of the six auxiliary modules. The utilisation of said modules in the remaining modules must be strategically planned from the outset. The M18 module does not

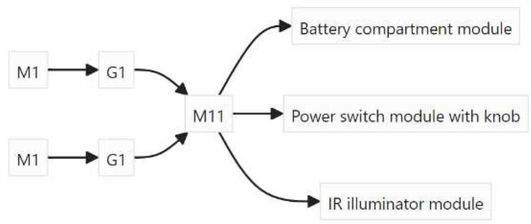

Fig. 3. Diagram of the basic goggles.

require any of the aforementioned modules, which is a crucial piece of information, as it allows for more independent work to be conducted on this module. Modules M17 and M19 necessitate the inclusion of only two of the aforementioned modules, although a different keyboard may be required.

In view of the necessity for a distinctive module for the keypads of the M17 and M19 modules (due to the requirement for a more compact keypad size), it was resolved that a second keypad size could be developed for these modules exclusively, potentially by scaling up the solution for the other bridges. This will facilitate the development of the solution and speed up the design work while maintaining a uniform design. Even if this proves unnecessary at the present time, the two keypads developed could be used in future module designs, not least because of the trend towards miniaturisation of devices observed in recent years in the armament industry.

The case of differentiating keyboards, despite previous assumptions, demonstrates that, in certain instances, extending the diversity of modules may be a justifiable means of enhancing the openness of a modular architecture.

The presented matrices demonstrate that specific products can be created from a set of modules.

Figure 3 illustrates an example of a solution comprising six modules, including a monocular module (M1) and two power modules (G1).

Subsequently, a comprehensive functional analysis was conducted on all modules. Based on this analysis, a list of technical requirements was developed for each module. The next phase of the project involved the development of mechanical–electrical interfaces. This included the selection of connectors, connections, and preliminary mechanical development.

2.2. Engineering design

The positive outcome of the conceptual development phase enabled the initiation of further work on the modular product family. A schedule for this work was devised employing an algorithm that is typical of the majority of projects undertaken at PCO (Fig. 4).

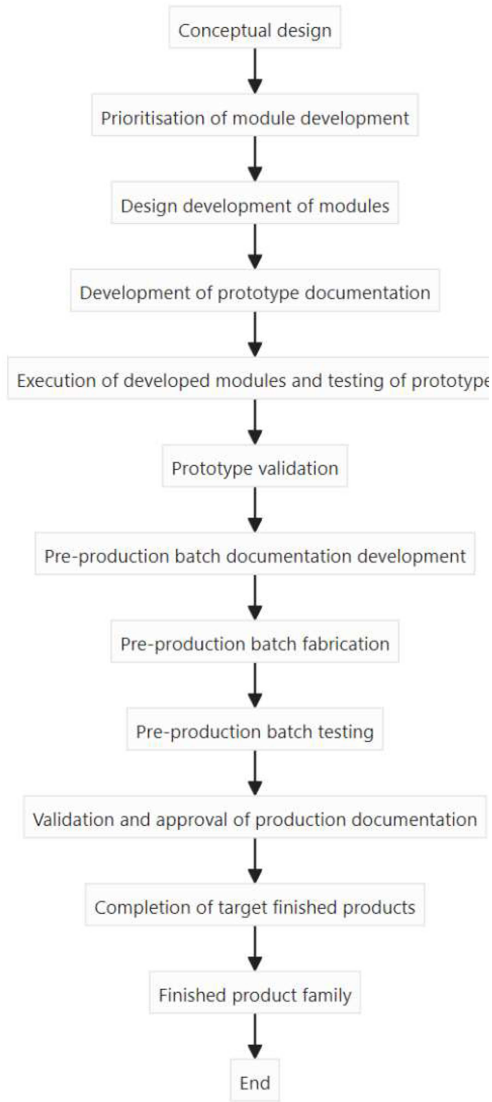

Fig. 4. The engineering design and implementation work plan.

The preceding conceptual phase may be subjected to further analysis and refinement, with the objective of optimising the selected steps of the algorithm. Figure 5 illustrates the proposed progression of the phase entitled *"Design development of modules"*.

One of the key aspects of project management is the monitoring of project progress through the use of carefully selected metrics, including effectiveness and efficiency. These metrics/criteria provide managers with the information needed to accept the results of a project thus far or to make decisions regarding the initiation of subsequent stages of work. When planning the modelling and subsequent simulation of a process, it is essential to gather information about the evaluation criteria used in a given organisation and subsequently convert them into a format that is compatible with the capabilities of the simulation tool.

3. Criteria for evaluating the results of the design work

As indicated by sources specialising in the design of device families, the criteria for evaluating the design process are intricate and multifaceted. The most significant of these are outlined below [15].

(i) *Relevance*: Assessing whether the design of equipment meets the real needs of the users and whether it is in line with the objectives of the organisation or institution. It is crucial that the design of the equipment is adapted to the context of its intended use, taking into account both the technical and social aspects [8, 12].

(ii) *Coherence*: The term "coherence" refers to the extent to which the design in question is aligned with the wider organisational strategy and with other activities undertaken by the organisation. Such assessments should also consider the extent to which the design aligns with the broader business and technological context [8].

(iii) *Efficiency and effectiveness*: Measuring the extent to which design achieves its objectives while minimising costs and resources. Effectiveness refers to the extent to which the design meets users' expectations and influences their experience, while efficiency focuses on outcomes and the achievement of design goals [16, 17].

(iv) *Durability and adaptability*: The ability of a design to maintain its utility over time, especially in the context of changing user needs and technological environment. Durability means that the designed equipment remains relevant and functional in the long term, while adaptability refers to the ability to make changes in response to new challenges and needs.

(v) *Influence and impact*: An analysis of how the proposed facilities will affect the social and natural environment. This assessment includes an understanding of the potential positive and negative impacts and how they can be minimised or maximised [12].

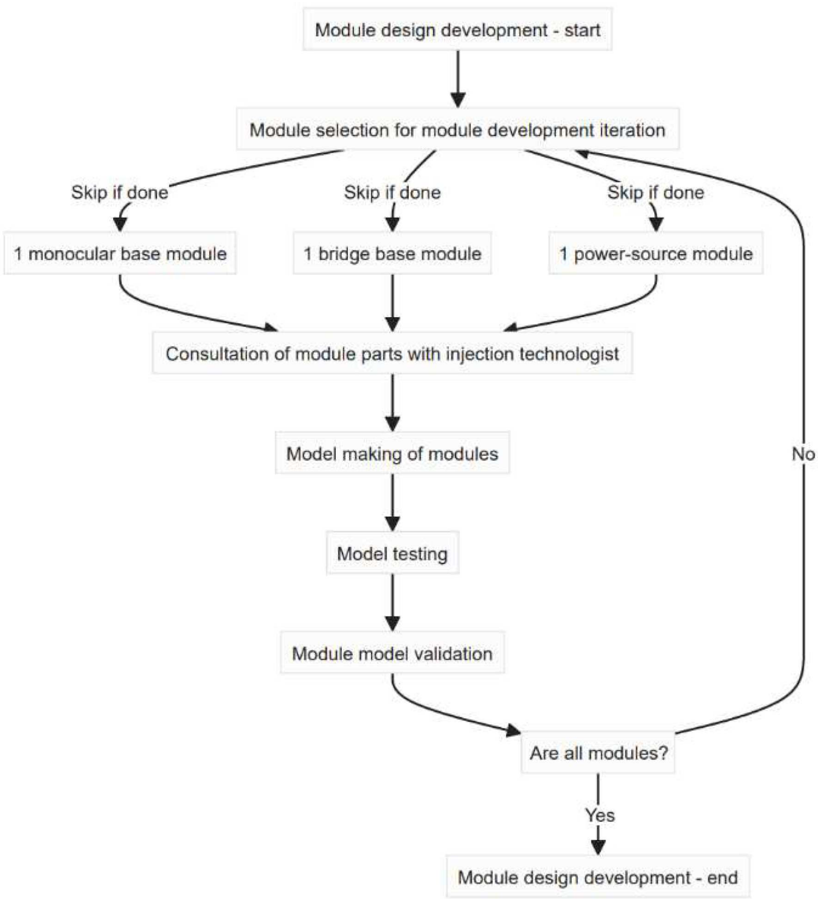

Fig. 5. The engineering design work plan for the device modules of the family of products currently under development at PCO company.

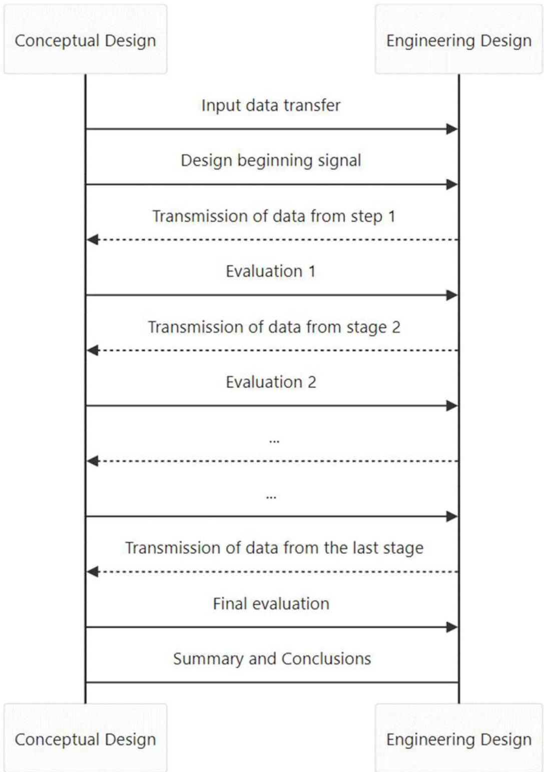

Fig. 6. The process of evaluating the engineering design on an iterative basis, utilising data obtained from the conceptual design phase.

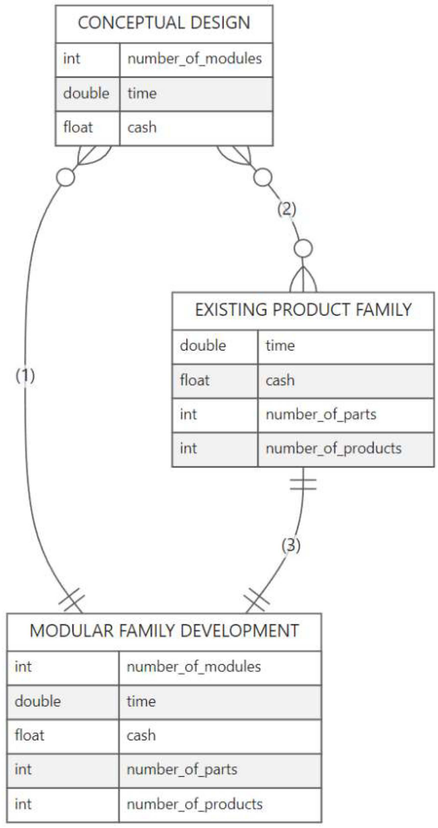

Fig. 7. Data exchange between conceptual and structural design and numerical comparison of design results with the pre-modularisation family.

The application of these criteria in the design process helps to ensure that the products created are not only functional and efficient, but also meet the real needs of the users and are in line with the long-term goals of the organisation [9, 12]. The listed categories of criteria are not only used internally within the PCO company, but also by external bodies, e.g., the purchaser or recipient of the product.

Relevance is assessed through a series of internal interviews with product specialists and future users of the product, most often by presenting the product at a stage where it is already possible to see it, hold it in the hand or on the weapon, and test its functionality. Often the product is presented at a stage where it is still possible to introduce changes suggested by the testers.

Project efficiency is measured by management based on an assessment of the potential to bring the product into production. This assessment is made by analysing information from the design, engineering, and manufacturing departments and is often binary in nature. At an advanced stage in the project, it also takes into account the results of testing prototypes of the device to ensure that they meet the intended characteristics of the device and its features. It often happens in industry that product development takes so long that by the end of the project, the product proves to be obsolete, and production is abandoned. The effectiveness of a project is determined by the effort expended on the project over a given period of time.

Impact is also measured in binary terms, by looking at whether the production of the product launched by the company is responding positively to the requirements and needs of the user on the battlefield at any given time.

Criteria can be formulated both to evaluate individual stages of the process and to consider selected parts of the design process that are a collection of successive stages, e.g., the total cost and development time of each successive module in the family. On this basis, it is possible to estimate the efficiency of the design process and the rate of return and to predict the risks associated with new modules. Estimating these risks allows better decisions to be made about the development of the business, and the risks taken become more predictable.

4. Assessing the design process

Sources on methodological aspects of design [7–9] emphasise that the evaluation of a developed method can only be carried out after it has been

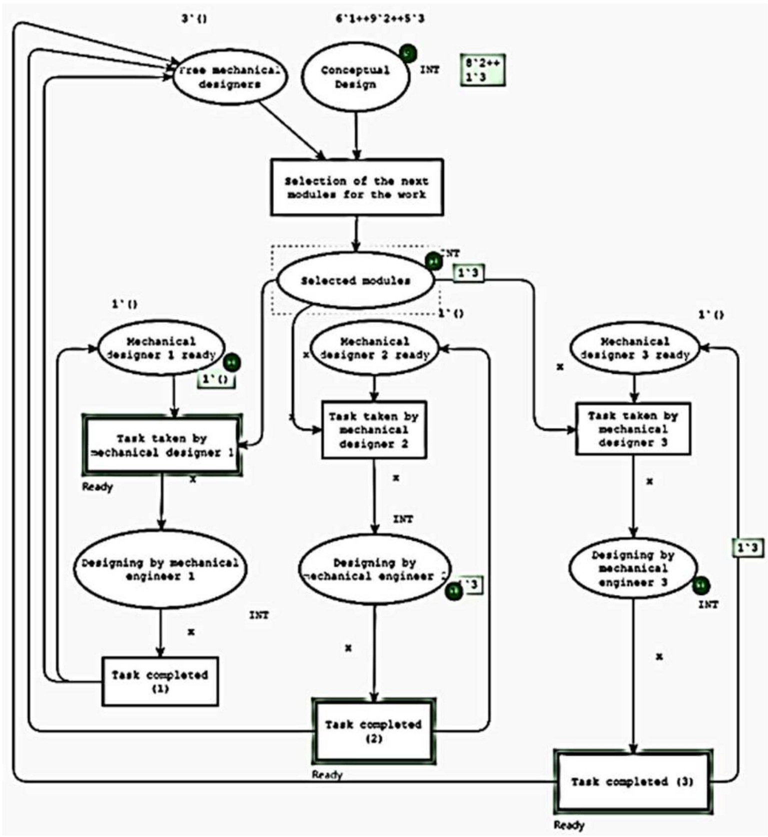

Fig. 8. A selected part of the model of the design process of predefined modules, carried out by three design engineers working in parallel, expressed using a Petri net.

used, preferably in a real project or in a computer simulation. Three possible methods are mentioned:

- verification — defined as the process of ensuring that the system developed as part of the process aligns with the end-result specifications of the initial design process; serves as a crucial step in the development process;
- validation — the process of ensuring that the resulting system is fit for purpose in accordance with its original purpose [18–20] and that the system has been constructed correctly and will achieve the initial objective;
- evaluation — the process of assessing the extent to which a system fulfils its objectives and leads to success. In this context, success is not binary; rather, it is a relative concept that depends on the degree of success achieved [12, 15].

Validation is a binary process that determines whether the objective has been achieved or whether the requisite threshold has been met. It is used to ascertain whether the system has been constructed correctly [19, 20]. The purpose of evaluation is to ascertain the correctness of a system's functioning. The outcome of the process (method) is a key factor in this assessment, as are other considerations such as the potential for improvement in performance, efficiency, and effectiveness, and the ease and adaptability of the method for use in different projects. Evaluation enables the identification of problems and the formulation of solutions to address them [12, 21].

In this study, the authors propose that processes carried out using the modular device design method should be accompanied by evaluation. This evaluation should be conducted using the method as a measurement tool, whereby individual aspects of the process are measured to provide a numerical assessment of the efficiency and effectiveness of both the whole process and its individual stages. This approach allows questions about the quality and correctness of the method to be answered [8]. It should be noted that the evaluation is not intended to discredit any aspect of the design method [22].

As previously stated, the design process for modular devices is divided into two principal phases: the formulation of the family assumptions (conceptual design process) and the subsequent engineering design process [23–25]. The initial process should be evaluated in accordance with the extent to which the initial assumptions are met. In the second phase of the design process, it is possible to collect information iteratively as the work progresses, although this is challenging in industrial practice. Gathering up-to-date information after each stage of the project can be a time-consuming and absorbing process for the project manager. Therefore, it is worth considering the possibility of including relevant activities in the process algorithm itself, defining how the data should be aggregated and in what form [21, 26]. Furthermore, the format of the data should facilitate straightforward measurement of the process's effectiveness and efficiency. Additionally, this evaluation approach enables an iterative assessment of the conceptual design's feasibility (Fig. 6).

The project, conducted at the PCO company, concerns the modularisation of an existing set of products, namely devices with a high degree of integration. In this case, the characteristics of the existing products should be used to measure the effectiveness of the process, as this allows for the determination of modularisation indicators, such as a reduction in the variety of subassemblies, a reduction in the cost of manufacturing a single device, a reduction in the variety of subassembly technologies, a reduction in the assembly times of entire devices, and an increase in the potential for serial production of repetitive subassemblies (Fig. 7).

A review of business process modelling and analysis methods [27] led the authors to the conclusion that, for the purposes of the planned research, Petri nets, which enable the modelling and analysis of concurrent systems, would be an appropriate tool. In addition to their graphical representation in the form of graphs, Petri nets also possess a mathematical structure, which is of significance in the context of the planned simulation [19, 28]. Among the numerous variants of this methodology, the decision was taken to employ the so-called coloured networks. The network's locations represent the individual tasks carried out during the design process, while its transitions depict the decisions of selected participants of the process that enable the commencement of subsequent tasks. In order to construct the model, a graphical environment with CPN IDE simulation capabilities was employed [29, 30]. Figure 8 illustrates a selected part of the developed model.

5. Conclusions

This paper presents a piece of work on an algorithm for designing a family of modular devices. In order to ensure the accuracy and relevance of the research, it is essential to utilise data from a real, ongoing development project. The planned outcome of the research is a simulation model of the design process that will enable alternative design workflows to be evaluated. The results of the work to date lead to the following conclusions:

(i) The construction of the algorithm can be based on a typical mechatronic device design flow, with the scope of each stage extended to include elements pertaining to modularisation. The most significant alterations occur in the conceptual development stage.

(ii) The utilisation of established design support instruments, exemplified by a device assembly linkage matrix, facilitates the work of engineers and should, therefore, be incorporated as a mandatory action item in the algorithm currently under development.

(iii) In order to prepare a comprehensive construction work plan, it is essential to have a clear understanding of the results of the conceptual design, as this will inform the subsequent stages of the project. Accordingly, the general algorithm outlines a two-stage approach to planning, namely before the conceptual phase and immediately before the engineering design phase.

(iv) It is possible to assess the progress of project work in accordance with company (or the industry as a whole) practice using either numerical or binary criteria.

(v) In the event that a new product family is to be based on an existing set of products, the evaluation of the design process should be based on numerical criteria for modularisation.

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