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AXIOMATIC DESIGN THEORY APPLIED IN DEVELOPING A TECHNOLOGICAL DEVICE FOR AUTOMATED ASSEMBLY

BY

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Abstract. This paper includes a theoretical research approach referring to the applying of Axiomatic Design (AD) theory within Sustainable Product Design activities. A conceptual model for the research frame is firstly proposed, where AD theory is considered together with the principles of Design for Manufacturing and Assembly (DfX/DFMA) theory, as valuable tools for obtaining a good product structure solution. As case study, the application of the AD theory for the development of a technological device for automated assembly is presented. Further on, using advanced design capabilities of Solid Edge CAD/CAE software, the detailed product design has been purchased, including product specifications detailed defining and the 3D parameterized model of the technological device is presented in the paper as final result. Some related conclusions, together with some further research directions are finally included.

Keywords: Sustainable Product Design; Axiomatic Design; Design for Manufacturing and Assembly; CAD/CAE; automated assembly.

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1. Introduction. Research Problem Statement

In recent years, the consumer has become more demanding in terms of the quality of products and services he uses. Under these conditions, manufacturers have been forced to come up with improvements in the quality of the products and services they provide. To remain competitive in the marketplace, the organizations need to solve some vital requirements for improving product quality, reducing manufacturing costs, introducing new products and shortening delivery times for products on the market (Merticaru and Rîpanu, 2013).

To meet these requirements, Sustainable Product Design philosophies, such as DfX and AD, are considered together with CAD/CAE/CAx Integrated Engineering tools applied in the detailed design phase (Merticaru *et al*., 2015).

A sustainable design theory, which can be applied in the Concept Design phase and is capable of providing the most adequate product concept solution, is Axiomatic Design (AD), developed by Professor Nam Pyo Suh (Pișta *et al*., 2017).

The advantages of Axiomatic Design are, among other things, to stimulate creativity, eliminate earlier unacceptable solutions and better target and systematize the use of designers' efforts (Slătineanu *et al*., 2017).

This paper further on includes a theoretical research approach referring to the applying of Axiomatic Design (AD) theory within Sustainable Product Design activities.

2. Conceptual Research Frame Defining

A conceptual model for the research frame has been firstly elaborated and is proposed bellow (Fig. 1), where AD theory is considered together with the principles of Design for Manufacturing and Assembly (DfX/DFMA) theory, as valuable tools for obtaining a good product structure solution.

The theory of Axiomatic Design was developed by Professor Suh Nam Pyo in the Department of Mechanical Engineering at the Massachusetts Institute of Technology in the United States and supports axiomatic approach to products and production systems (Thompson, 2014). It has raised the interest of researchers around the world who have undertaken further research (Nagîț *et al*., 2017).

In the Axiomatic Design, two axioms are considered as fundamental (Suh, 2001):

A1. The Independence Axiom - according to this axiom, the functional requirements (FR) must be independent.

A2. The Information Axiom - according to this axiom, the amount of information required to develop the design activities must be minimal.

The scope of activity includes 4 domains (Fig. 1):
1) Customer's domain - includes customer requirements (customer needs, CN);
2) Functional domain - includes functional requirements (FR);
3) Physical domain - specifies design parameters (design parameters, DP);
4) Process domain - includes process variables (PV).

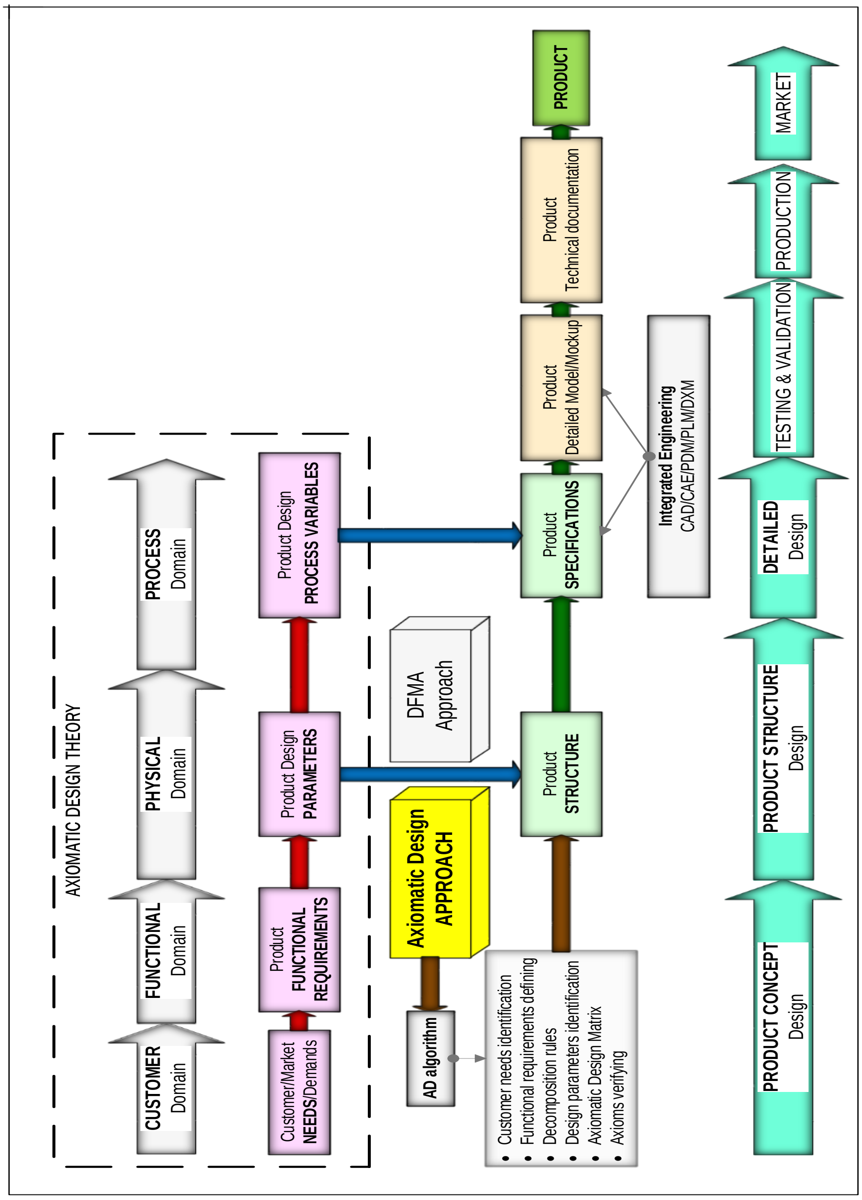

Fig. 1 – Conceptual model of the research approach.

In his work, in 2008, Ion Grozav defines the conception as the activity situated between “what we want” to achieve and “how we choose” to satisfy the needs. Thus, the client domain represents the “what” or the requirements domain, while the process domain represents the “how” or the solutions domain (Grozav, 2008).

The proposed conceptual model (Fig. 1) recommends, for obtaining an adequate structural solution of the product, to take into account, in particular, the functional requirements based on the needs/demands of the client/market and the identification of the design parameters and process variables. The transition from the functional requirements of the product to the design parameters was done according to the Axiomatic Design theory and the DFMA analysis principles (Pișta, 2017), for choosing the most appropriate conceptual solution. The Axiomatic Design technique (AD) follows the run of the analysis algorithm starting with identifying the customer needs, defining the functional requirements, identifying the design parameters, drawing up the axiomatic design matrix and applying the two axioms (The Independence Axiom and The Information Axiom), appreciated as fundamental principles of designing.

Based on the selected product structure, the proposed approach model considers as necessary to apply CAD/CAE/CAx Integrated Engineering tools (Merticaru *et al*., 2017) to define specifications and to achieve the detailed product model. The next step is drawing up the technical documentation and manufacture of the product.

The axiomatic design (AD) theory can be applied in various areas such as the constructive design of different equipment, the design of manufacturing technologies, planning of various activities (Dodun *et al*., 2014). To support this statement, we will apply forwards AD principles to designing an automatic assembly device.

3. Case Study. AD Theory in Designing a Technological Device for Automated Assembly

As case study, the application of the AD theory for the development of a technological device for automated assembly is bellow presented.

The paper follows the use of the Axiomatic Design method in connection with the necessity of conceiving and designing a constructive solution for the materialization of a technological equipment for automatic assembly for a low complexity device from the electrical equipment industry.

3.1. Assembled Product Description

The assembled product (Fig. 2) is a low voltage electrical plug inlet consisting of five main components: the housing of the product, two washers, and two threaded rods.

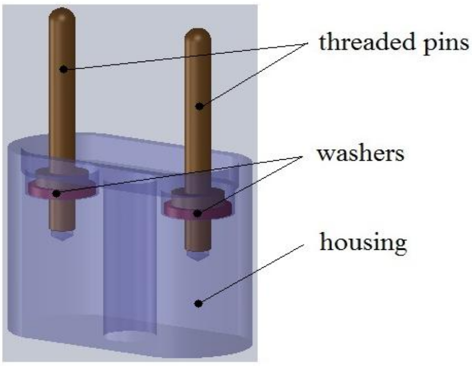

Fig. 2 – 3D view and components for the studied assembled product.

The assembling process consists of attaching the threaded rods and washers to the electrical plug inlet housing, under conditions of technical-economic efficiency. The assembly process is carried out in five distinct stages. The first stage consists of the insertion and orientation of the plug inlet housing into the clamping device. In the second stage of work, the washers are applied to the plug inlet housing body. In stages three and four the insertion and fixing of the threaded rods take place, and in the final stage, the assembled product is released.

3.2. AD Algorithm in the Concept Design for the Indexing Mounting Table

The technological device for automated assembly is necessary in order to achieve maximum productivity for the manufacture of the product, in the conditions of production of large series or mass. It has been chosen to use a device that must realize a main carry movement of the product in the assembly process from one workstation to another. In principle, in this technological device are used gripping devices that are meant to fix the main component of the product. The indexing mounting table must ensure optimal transport speed and precise positioning of the clamping device corresponding to the workstations where the component insertion takes place.

Intending the developing of some experimental researches on the assembly process using a device for automated assembly, we can formulate the following customer requirements:

CN1: The equipment could be used in an automated assembly laboratory or in a specialized factory for the manufacture of electrical components;

CN2: Intending to realize some research on the automated assembly process and the possibility of feeding with parts, the equipment must ensure operating safety and constructive simplicity.

The main functional requirement has the form:

FR0: Design a device for developing a research activity of the automatic assembly process of an electrical plug-in product, in the conditions of a production of large series or mass.

In the here analyzed situation, the product is of high complexity and requires decomposition of functional requirements into level 1 and level 2, because taking into account only the requirement of level 0 is not enough.

As functional requirements corresponding to the first level, one can consider:

FR1: Ensure assembling the product;

FR2: Ensure feeding with parts during the assembly process;

FR3: Ensure a product transport mechanism during assembly process;

FR4: Ensure monitoring the assembly process.

The functional requirements corresponding to the second level could be:

FR1.1: Ensure orienting-fixing of the housing of the product;

FR1.2: Ensure inserting of the washers;

FR1.3: Ensure inserting and fixing of the threaded pins;

FR2.1: Ensure feeding with housing of plug-in;

FR2.2: Ensure feeding with washers;

FR2.3: Ensure feeding with threaded pins;

FR3.1: Ensure circular movement of workstations;

FR3.2: Ensure precise indexing of rotating movement;

FR4.1: Check the correct positioning of the plug-in housing

FR4.2: Check the washers insert

FR4.3: Check the threaded pins insert

The design parameters (DP) that can meet each functional requirement could be the following:

DP1.1: Human operator;

DP1.2: Delivery chute;

DP1.3: Automatic screwdriver (with pneumatic delivery tube);

DP2.1: Bulk type container;

DP2.2: Vibratory bowl feeder;

DP3.1: Rotary indexing table;

DP3.2: Indexing mechanism;

DP4.1: Photo camera;

DP4.2: Magnetic sensor;

DP4.3: Optical sensor.

The relation between the second level information of the functional requirements (FR) and the design parameters (DP) of the same level corresponding to the functional requirements, has the form:

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \\ FR2.1 \\ FR2.2 \\ FR2.3 \\ FR3.1 \\ FR3.2 \\ FR4.1 \\ FR4.2 \\ FR4.3 \end{Bmatrix} = \begin{pmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{pmatrix} \begin{Bmatrix} DP\,1.1 \\ DP\,1.2 \\ DP\,1.3 \\ DP\,2.1 \\ DP\,2.2 \\ DP\,2.2 \\ DP\,3.1 \\ DP\,3.2 \\ DP\,4.1 \\ DP\,4.2 \\ DP\,4.3 \end{Bmatrix} \tag{1}$$

From this relationship, we can see that there are subassemblies or components that contribute to the fulfillment of several functional requirements. For example, the design parameter DP2.2 (DP2.2: Vibratory bowl feeder) ensures the fulfillment of the functional requirement FR2.2 (FR2.2: Ensure feeding with washers) and the functional requirement FR2.3 (FR2.3: Ensure feeding with threaded pins). In this case, the conclusion is that there could be possibilities to improve the constructive solution, by identifying possibilities that lead to the respect of the first axiom (The Independence Axiom).

If we take into consideration that each of the two functional requirements is fulfilled by two distinct subassemblies with the same role, we can thus consider as the recommendation from the first axiom is respected.

Based on the identification of the functional requirements and design parameters, Table 1 was developed in which the correspondence between the functional requirements and the design parameters capable of meeting the required requirements was highlighted by means of X.

3.3. Results and Discussions of AD Analysis. Product Structure Solution

Accordingly to the above presented results and considerations, a product structure solution has been identified and designed as it is shown in Fig. 3 for the orienting-fixing subassembly and in Fig. 4 for the indexing mounting table.

The energy required to operate the automatic assembly table is provided by an electric motor located inside the lower case. The kinematic structure of the mechanism includes a worm gearbox, a flexible coupling to reduce shocks in the system and inertial effects, and a spur gear that rotates the main shaft together with the rotary plate on which it is located the five workstations.

Table 1
Matrix that Includes the Functional Requirements and Design Parameters Established for a Technological Device for Automated Assembly

Line no. 1	Design parameters			Design parameters DP									
2				Design parameters DP of the first level									
3				*DP1:* Subsystem for inserting and fixing component parts			*DP2:* Subsystem for supplying component parts		*DP3:* Subsystem for the transport of workstations		*DP4:* Computerized monitoring subsystem		
4				Design parameters DP of the second level									
5	Functional requirements			*DP1.1:* Human operator	*DP1.2:* Delivery chute	*DP1.3:* Automatic screwdriver	*DP2.1:* Bulk type container	*DP2.2:* Vibratory bowl feeder	*DP3.1:* Rotary indexing table	*DP3.2:* Indexing mechanism	*DP4.1:* Photo camera	*DP4.2:* Magnetic sensor	*DP4.3:* Optical sensor
6	Functional requirement FR of zero level	Functional requirements FR of the first level	Functional requirements FR of the second level	Highlighting the design parameters DP corresponding to each functional requirement FR									
7			*FR1.1:* Ensure orienting-fixing of the housing of the product	X									
8		*FR1:* Ensure assembling the product	*FR1.2:* Ensure inserting of the washers		X								
9			*FR1.3:* Ensure inserting and fixing of the threaded pins			X							
10			*F2.1:* Ensure feeding with housing of plug-in				X						
11		*FR2:* Ensure feeding with parts during the assembly process	*F2.2:* Ensure feeding with washers					X					
12	*FR0:* Designing a device for automatically assembling plug-in parts		*F2.3:* Ensure feeding with threaded pins					X					
13		*FR3:* Ensure a product transport mechanism during assembly process	*FR3.1:* Ensure circular movement of workstations						X				
14			*FR3.2:* Ensure precise indexing of rotating movement							X			
15			*FR4.1:* Check the correct positioning of the plug-in housing								X		
16		*FR4:* Ensure monitoring the assembly process	*FR4.2:* Check the washers insert									X	
17			*FR4.3:* Check the threaded pins insert										X

The rotary plate supports the fixed prism on which the housing is supported. During rotation, the roller "climbs" and "descends" on the fixed cam according to the position of the roller against the cam. Moving the roller to the cam causes the follower rod to travel through the cylindrical guide, moving the fixing jaw in a tightening and releasing motion of the plug-in (Fig. 3).

Because the automatic assembly table requires precise positioning for the five workstations, the system is provided with an indexing mechanism.

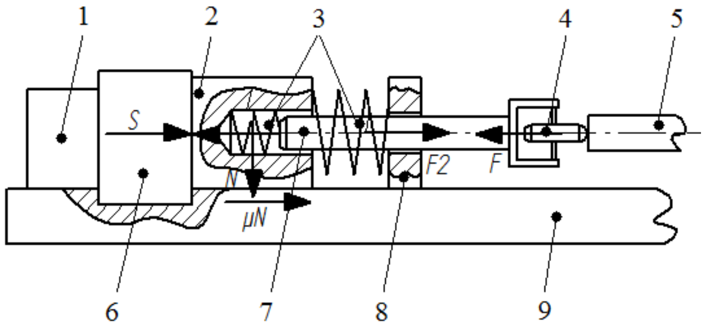

Fig. 3 – Conceptual design scheme for the orienting-fixing subassembly.
1 – orienting prism; 2 – fixing jaw; 3 – springs; 4 – roller; 5 – cam; 6 – plug inlet;
7 – follower rod; 8 – guiding element; 9 – mounting table.

At the first workstation the insertion and fixation of the plug-in housing are made, during the movement to the second station where the washers are applied. At the third and fourth workstation, the insertion and fixing of the threaded pins take place, and finally, at the fifth workstation, the assembled product is released. The insertion and fixation of the product housing in the assembly process are carried out by a human operator, the insertion of the washers is done with a vibratory bowl feeder, and the feeding of threaded pins and their fastening is accomplished by a vibratory bowl feeder and automatic screwdriver device provided with pneumatic delivery tube.

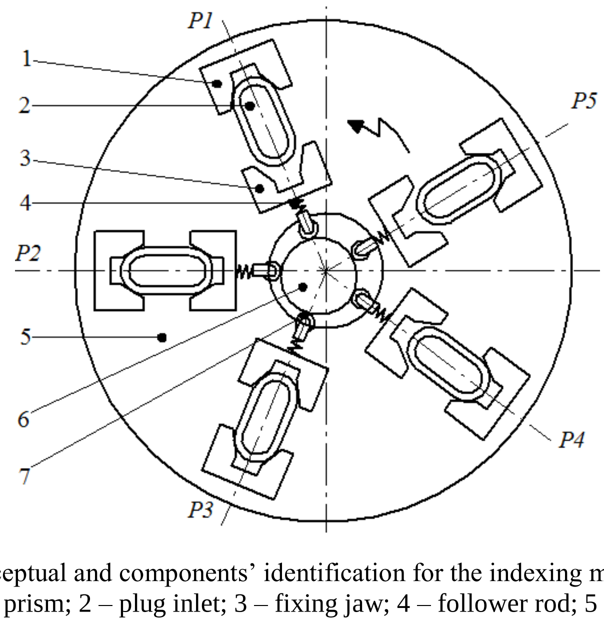

Fig. 4 – Conceptual and components' identification for the indexing mounting table:
1 – orienting prism; 2 – plug inlet; 3 – fixing jaw; 4 – follower rod; 5 – rotary plate;
6 – fixed cam; 7 – roller.

To verify the correct positioning and insertion of the component parts, a photo camera for the plug-in housing, a magnetic sensor for washers and an optical sensor for the threaded pins are used.

3.4. CAD/CAE Detailed Design for the Indexing Mounting Table

Following the application of the axiomatic design theories went to the detailed design of the automatic assembling device (Pișta, 2015) as in Fig. 5. Thus, the conceptual solution proposed based on the application of the axiomatic design theories was developed and 3D modeled, as in Fig. 6, using a specific design tool, Solid Edge (Siemens, 2017).

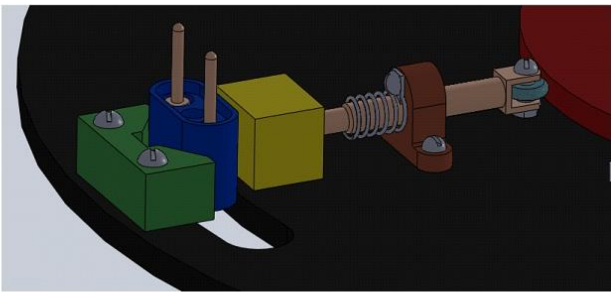

Fig. 5 – Solid Edge 3D parameterized model for the orienting-fixing subassembly.

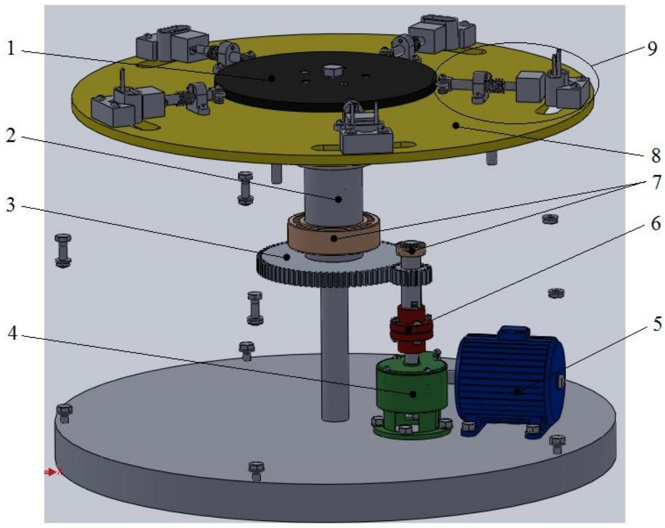

Fig. 6 – Assembly 3D view and components' identification for the indexing mounting table (Solid Edge 3D parameterized model): 1 – fixed cam; 2 – shaft; 3 – spur gear; 4 – worm gearbox; 5 – electrical motor; 6 – flexible coupling; 7 – radial ball bearing; 8 – rotary plate; 9 – orienting-fixing device.

4. Conclusions

The theoretical approach and case study from the paper is part of a broader research on optimizing automated assembly processes and optimizing assembled products by incorporating CAD/CAE/PDM/PLM/DXM design tools and the extensive application of DfX philosophies along with the AD.

The results presented and discussed above illustrate the achievement of some of the objectives proposed for the mentioned research.

Considering the state of the art in Product Development, in accordance with market requirements, there are many tools and philosophies for developing and optimizing products or processes. The present research has considered such a design tool as the axiomatic design theory that has been applied to define the functional requirements more clearly and to set the design parameters for an automatic assembly device.

The research above mentioned and the realized study has made it possible to identify and design at least one sustainable solution for the considered automated assembly device.

In the future, there is an intention to extend the analysis of assembled products on the fabrication processes with the help of new DfX tools such as DFM/DFA.

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TEORIA PROIECTĂRII AXIOMATICE APLICATĂ
ÎN DEZVOLTAREA UNUI DISPOZITIV
TEHNOLOGIC PENTRU ASAMBLAREA AUTOMATĂ

(Rezumat)

Această lucrare include o abordare teoretică de cercetare referitoare la aplicarea teoriei Axiomatic Design (AD) în cadrul activităților de proiectare sustenabilă a produselor. În primul rând se propune un model conceptual pentru cadrul de cercetare, în care teoria AD este considerată împreună cu principiile teoriei Design for Manufacturing and Assembly (DFX/DFMA) drept instrumente valoroase pentru obținerea unei soluții structurale bune a produsului. Ca studiu de caz, este prezentată aplicarea teoriei AD pentru dezvoltarea unui dispozitiv tehnologic pentru asamblare automată. Mai mult, folosind capabilitățile avansate de proiectare ale software-ului CAD/CAE Solid Edge, a fost realizat proiectul detaliat al produsului, iar modelul parametrizat 3D al dispozitivului tehnologic este prezentat în document ca rezultat final. Unele concluzii similare, împreună cu alte direcții viitoare de cercetare sunt incluse în final.