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Presenting a Consolidated Model of Bionic Product Design Engineering and Systems Engineering, New Approach in Product Design Engineering

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Abstract

Researchers and designers around the world have given a special attention to the design of bionic products in recent years. The importance of this issue has led the researchers to facilitating the use of solutions found in nature and providing systematic and methodological processes. On the other hand, systems engineering as an interdisciplinary approach for the realization of successful systems provides a comprehensive framework for understanding complex systems and products. The universal attentions, on one hand, and the lack of academic and industrial centers in the country to use this creative approach for the production of innovative product, on the other hand, are the reasons which this study was conducted to present a consolidated model of bionic product design engineering and systems engineering. In this study, after reviewing the literature related to bionic design process and systems engineering, a conceptual model is presented. The statistical population consisted of product design experts in industries manufacturing complex products. The participants were selected using census sampling. Data were collected through face to face meetings and questionnaire. Data were analyzed using two strong techniques, including Net Promoter Score (NPS) and within-group interior agreement (rwg). The results of statistical analysis and comparative analysis confirmed the structure of the proposed model.

Keywords*:* consolidated model; bionic product design; product design engineering; systems engineering; Net Promoter Score; within-group interior agreement

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1. Introduction

For smart and creative investigators, nature and biological structures to solve various problems have always been inspiring. Structure and function of plants and animals in the evolutionary process have been optimized over millions of years. Evolution continuously occurs in nature and vital technologies have the best order and organization. Therefore, it is necessary to consider a suitable model for inspiration in creating modern technologies and innovative products. Bionic product design has a known nature in the leading countries creating unique technologies and innovations. Bionic product design is growing in most disciplines such as engineering, medicine, architecture, etc. (Mansoorian, 2009). The process of design engineering for bionic complex products has several complexities: Complexity of the project (Size, Time, Cost of Project Quality) (Gogerdchiyan, 2012), the complexity of natural systems (static, dynamic, evolutionary, self-organization, etc.) (Makouei, 2014), and the complexity of the model (process, space, time, number of processes, integration) (wainwright, 2013). Thus, it is necessary to overcome the complexities and manage them in executive projects. Reviewing researches on designing bionic complex products indicates that there is no specific research on designing bionic complex products based on the systems engineering approach. Systems engineering is an effective way to manage complexities and changes. Services in our society today are institutionalized through complexities and changes in products. Reducing the risks associated with new systems and carrying out reforms in complex systems are considered as the main objectives of systems engineering (SE handbook, 2007). On the other hand, recent studies suggest that modeling based on the nature is dispersed while this process should systematically be used by engineers and technologists. They believe that systems engineering should not be limited by the existing technological solutions and pose this question that "What solution does the nature provide for the existing problems?" Moreover, they suggest that professional engineering organizations, such as International Council on Systems Engineering (INCOSE), National Aeronautics and Space Administration (NASA), American Institute of Aeronautics and Astronautics (AIAA), The International Society for Optical Engineering (SPIE), Bionics Competence Network (BIOKON), are seriously working for the use of natural systems in systems engineering (Studer, 2014). The researchers emphasize the enrichment of systems engineering using the bionic product design and want to facilitate this relationship (Kerschmann, 2014). Studies in Iran show that there is no considerable attention in the field of bionic product design and using potentials of this approach in the design of products and there are a few researches which only introduce and discuss the findings in other countries. The potential use of nature in the innovative design of complex products is considered as an appropriate approach for national leadership and competitive advantage in the world.

Hence, this study aims to present a consolidated model of bionic product design engineering and systems engineering as an interdisciplinary approach. In this study, after reviewing the literature related to bionic design process and systems engineering, a conceptual model is presented. The results of statistical analysis and comparative analysis confirmed the structure of the proposed model.

2. Theoretical Foundations

Bionic Product Design:

Organisms provide biological phenomena and strategies that we know them as biological systems. Nature Inspired Design is generally considered as a provider of innovative solutions in human affairs (Goel, 2014). The interaction of two fields of biology and engineering can be divided into two categories, including the use of engineering principles in solving problems of life sciences and the use of the principles of biological systems to solve engineering problems. According to the principles of biological systems to solve engineering problems, different resources use some terms including bionic,

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biomimetics, biomimesis, biomimicry, biognosis, bioinspiration, biomimetic design, bioanalogous design, and biologically inspired design (shu,2011). Bionic in the field of creativity and innovation is called as bionic engineering, Bionical creatology, Nature oriented creatology, and bionical creativity engineering. It can be considered as one of the important branches of creativity science (Mansoorian, 2010).

Bionic design process approaches:problem-driven approach & solution-based approach: According to studying examples of bionic design, we find that each engineering product or technical tool that can be made by the inspiration of nature follows one of these approaches. *Top-down approach*: design engineers recognize a technical issue and seek the solutions in the nature. *Bottom-up approach*: A natural phenomenon is investigated and its use is sought in the engineering world (Report of DTI, 2007).

Functional Representation:
A functional model in systems engineering is a structured representation of the functions (activities, actions, processes, operations) within the modelled system or subject area. Moreover innovative engineering design create added value (Khorasani , 2014).A functional model, similar with the activity model or process model, is a graphical representation of an enterprise's function within a defined scope. The purposes of the functional model are to describe the functions and processes, assist with discovery of information needs, help identify opportunities, and establish a basis for determining product and service costs (Erden, 2008).

Systems Engineering:
According to Sebok, a system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behavior and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected. Systems engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle (Sebok, 2013).

3. Background

3.1 A review on holistic processes of bionic design

As mentioned, there are many researches on the achievements of the bionic design in various scientific fields. In line with the present study, the previous researches have addressed the methodology and process of bionic product design. Reviewing these researches indicates that the process of bionic product design is more holistic and the steps in the research process are often not examined in detail. (table 1)

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Bionic product design process									**Researchers**
Eco-innovation by Integrating Biomimetic Design and ARIZ									Wang-Chih Chen,Jahau Lewis Chen 2014
					Conceptual soloutions developement	Existing resources analysis	Contradiction analysis & key words finding	Biology principles detection & contradiction formulation	
Design spiral methodology, problem-driven process									Adobted from Carlos A. M. Versos and Denis A. Coelho 2012
			Assesment &comparisson between soloutions & principles	Soloutions or models application	or Strategy pattern abstraction	Nature heros finding	Soloution finding in nature	Problem identification	
Using TRIZ method, problem-driven process									Maria G. Trotta 2011
			Geometric concept generation	Conceptual map presentation from functions	Special principles abstraction from triz	Geometric caracters abstraction from nature	Functions hiererchy description	Problb description	
problem-driven process									DTI global watch mission report 2007
				Implementation & test of empirical model	Abstraction from biologic model	Related principles identification	Search for Analogies in nature	Technologic problem formulation	
solution-driven process									DTI global watch mission report 2007
				Prototyping & test	Abstraction from biologic model	Principles realization	Biomechanic,morphologic and anayomy analysis	Biologic system identification	
BioTRIZ Method, problem-driven process									Julian F. V. Vincent, a Bogatyrev, Bowyer Anja-Karina Pahl 2006
				New technology invention	from general relation to engineering relation	Comparisson between biologic & engineering soloutions & general relationship making	Analysis & realization of problem	General defeniton of problem	
problem-driven process									Sarkar, Phaneendra, Chakrabarti
			System modeling	Learning from Modeling & simulation	Phisical modeling & simulation	Virtal modeling & simulation	Whole system modeling	Idea generation	

Received:6 July 2018/Accepted:19 September/Published:19 December 2018

									2008
problem-driven process									Vattam, Helms, and Goel 2007
		Principles application	Principle abstraction	Problem defenition	Search in nature	Problem redefine to biologic form	Problem decomposition	Problem defeniton	
solution-driven process									Vattam, Helms, and Goel 2007
			Principles application	Problem search	Problem/solution redefine to engineering form	Principle abstraction	Problem defenition	Biologic solouti on identification	
Methodology for product design based on the study of bionics, solution-driven process									Wilson Kindlein Junior, Andrea Seadi Guanabara 2005
		application	Accomodation Between natural system & product	parameterization	Samples analysis	Samples preparation	Samples collection	Samples selection	
Aalborg bionic design method, solution-driven process									Colombo 2007
					New product development base on environmental factors	Relationship between form & structure for new product developement	Principles abstraction & conversion to technical principles	Natural system selection & analysis	
Biomimicry Design Method, problem-driven process									Junior et al. 2002
				Design implementation	Natural system & product analogy	Sample Observation & analysis	Selection & sampling	Need defeniton	
problem-driven process									Helms et al. 2009
			Principles application	Principles abstraction	Biologic problem defenition	Natural soloution search	Problem Redefenition based on biologic principles	Problem defeniton	
solution-driven process									Adobted from Helms et al. 2009
		Principles application	Problem defenition	Problem search	Soloution redefine	Principles abstraction	Biologic soloution defenition	Solouti on observation in nature	
Innovative Methodology									Hui-I Wen

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							Phisical & chemical functions	Function base design	, Shu-jun Zhang , Kevin Hapeshi , Xiao-feng Wang 2008
Aesthetics analysis	Border detection & 3d modelling	segmentation	refinement	2d scan	2d picture	Free hand design	Art & design method	Geometric caracters base design	
					Surface caracteristics data	3d geometric scan	Engineering method		
solution-driven process									Lu method 2015
			Technical & bionical manufacturing	Biologic principles abstraction	Biology & technology comparisson	Technologic selection	Technical search	A biologic solouti on	
problem-driven process									Lu method 2015
			Technical & bionical manufacturing	-Biologic techmologic principles abstraction	Biology & technology comparisson	Biologic selection	Biologic search	A technical question	
problem-driven & solution-driven process									K. S. Nagel, Robert B. Stone and Daniel A. McAdams 2014
				Concepts generation	Making conections	search	decomposition	Need analysis or curiousity	
problem-driven & solution-driven process									Ashok K. Goel, Swaroop Vattam, Wiltgen , Helms 2014
			First & second soloution combination	Second soloution generation	First soloution assesment	Mapping & transfer	retrieval	Problem/solution abstraction	
problem-driven process									Gramman 2006
					Biological systems assesment	Biological systems analysis	Biologic system search	Search target formulation	
problem-driven process									Hill b.

Received:6 July 2018/Accepted:19 September/Published:19 December 2018

		Description of Optimum solouti on detail	Soloutio ns assesme nt& optimum choise selection	Change & combination of principles	Biological principles conversion to technical principles based on requirements	Biological systems analysis & principle abstraction	Related biologica l systems identifica tion	Basic functio ns identifi cation	2005
problem-driven process									Schild, K., Herstatt, C., and Lüthje, C. 2004
					Verification& evaluation	Analogy search	assesmen t	Proble m formul ation	

3.2 Problem-driven approach and solution-based approach for the process of bionic product design

There are two approaches for the process of bionic product design. Problem-driven approach identifies the statement of a problem which will be the starting point for problem-solving process. After analyzing the problem, and identification and extraction of the natural elements, the engineering design is carried out. According to solution-based approach, the designer tries to find a problem in the engineering world by taking a natural element as the arbitrary element. Then, the principles derived from natural elements will be used as solutions to the engineering design (Goel, 2014). Some researches consider problem-driven approach or solution-based approach and some others consider both of them. Some researches try to combine the two approaches and provide a comprehensive process. Hence, the present study uses both approaches to universalize the process.

3.3 Functional modelling for the bionic design

Helms et al. (2010) investigated the effect of functional modelling on understanding complex biological systems. In this study, they sought to understand how functional representations, in particular Structure-Behaviour- Function (SBF) models, enable understanding complex biological systems. Results from this study indicated that SBF representations may enable more accurate inferences about biological systems for complex and abstract questions than purely textual, or textual and diagrammatic, representations. An SBF model of a complex system explicitly represents its structure [S] (i.e., its configuration of components and connections), its functions [F] (i.e., its intended output behaviours), and its behaviours [B] (i.e. its internal causal processes that compose the functions of the components into the functions of the system). The SBF language provides a vocabulary for expressing and organizing knowledge in an $F \rightarrow B \rightarrow F \rightarrow B \ldots \rightarrow F(S)$ hierarchy, which captures functionality and causality at multiple levels of aggregation and abstraction. Vattam et al. (2011) investigated an interactive learning environment called ACT in which middle-school students construct SBF models of complex systems as a vehicle for gaining a deeper understanding of how such systems work. They concluded that FBS models are effective in creating a deeper understanding of the behaviours and the creative design. Chakrabarti et al. (2005) conducted a study to initiate similar work in the area of systematic biomimetics for product development, so that inspiration from both natural and artificial worlds can be used systematically to help develop novel, analogical ideas for solving design problems. A generic model for representing causality of natural and artificial systems was developed, and used to structure information in a database of systems from both the domains. These were implemented in a piece of software for automated analogical search of relevant ideas from the databases to solve a given problem. Preliminary experiments at validating the software indicated

Received:6 July 2018/Accepted:19 September/Published:19 December 2018

substantial potential for the approach. Nagel et al. (2011, 2014) investigated a general method for functionally representing biological systems through systematic design techniques, leading to the conceptualization of biologically inspired engineering designs. Functional representation and abstraction techniques were used to translate biological systems into an engineering context. The goal was to make the biological information accessible to engineering designers who possess varying levels of biological knowledge but have a common understanding of engineering design. Creative or novel engineering designs may then be discovered through connections made between biology and engineering. Two concept generation approaches were presented that use a biological model to discover corresponding engineering components that mimic the biological system and use a repository of engineering and biological information to discover which biological components inspire functional solutions to fulfil engineering requirements. Nagel et al. (2011) presented an approach using biology for the engineering design. This approach was to create a functional model of biological organisms at multiple levels. They suggested the steps of a functional model as follows: Step 1: Generate Black Box Model. Step 2: Create Function Chains for Each Flow. Step 3: Aggregate Function Chains into a Functional Model. Step 4: Model revisions. Nagel et al. (2010) considered categories and scale of functional modelling in the bionic design and presented the steps as follows: 1. Find a suitable resource, 2. investigate the biological systems, 3. define the design question to which the functional model responses, 4. specify the category of the functional model (physiology, morphology, behaviour, strategy) 5. Define the desired scale of the model, 6. Develop a functional model of the biological system using functional basis with regard to restrictions of the design questions, category and scale of the model, 7. Review the model based on the design questions or black box. Cohen et al. (2014) conducted a study and based on the analyses of 140 biological systems derived from biomimetic sources by a TRIZ based method, provided a list and examples of structure–function patterns that repeat in biomimetic applications.

3.4 A review on the interaction between bionic product design and systems engineering

Kerschmann et al. (2014) conducted a study implementing natural systems-inspired design in systems engineering for Mars surface operations. According to their study, natural systems-inspired design (NID) is the transfer of design solutions from biology and other natural sciences to the creation of human-engineered products. Despite the promise of improvements in cost, performance, and reliability, there has been little application of NID to spacecraft engineering. NID falls into two broad categories: 1) structural- and 2) process-inspired solutions. The researchers suggest that NASA is a successful process for complex products, such as systems engineering, especially in the design of the spacecraft. However, the bionic design is not used in standards, such as systems engineering, for the application of this field to remove the main obstacle to the process of systems engineering.

Studer (2014) conducted a study on adding natural systems to the process of systems engineering in complex products. He believes that modelling based on the nature is dispersed while this process should systematically be used by engineers and technologists. They believe that systems engineering should not be limited by the existing technological solutions and pose this question that “What solution does the nature provide for the existing problems?” According to this study, nature should be used in the system life cycle and its application in the design of future systems that are based on system of systems (SOS) is not inevitable. He suggests that professional organizations for engineers are seriously working on the use of natural systems in systems engineering.

4. Research methodology

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4.1 Presenting the research model

Figures 1 shows the proposed model for design engineering of bionic product.

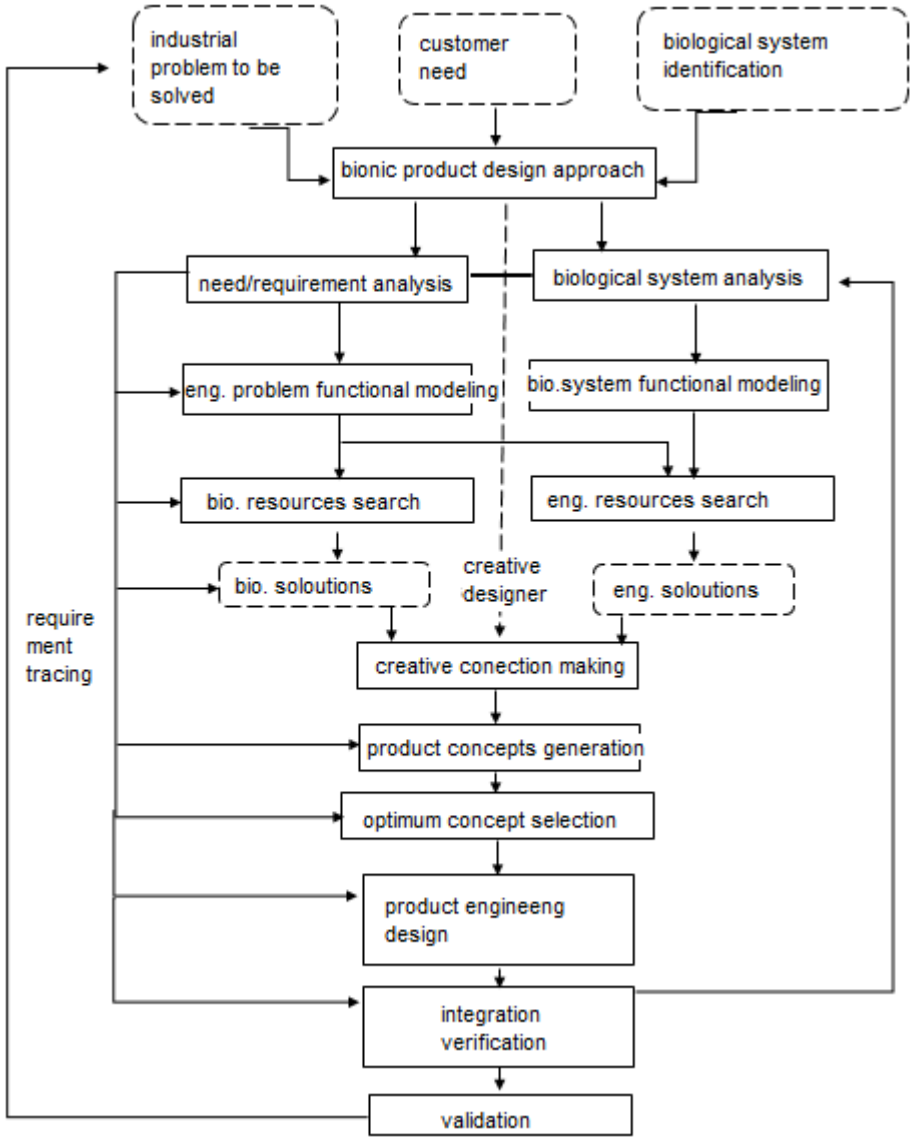


Figure 1: the consolidated model of bionic product design engineering and systems engineering

Description of the steps in the model is as follows:

Need analysis / solution analysis: in this step, stakeholders' need is considered for bionic product design. Another approach is to consider a biological system as the pattern of the product design.

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Functional modelling: in this step, stakeholders' requirements or the principles of biological system are modelled based on the functional modelling.

Search and make connections: In this step, the search is done in the field of engineering resources and biological resources by referring to the functional model. Then, the solutions with appropriate communication are identified among the potential solutions.

Concepts generation: In this step, the conceptual design of one or more basic concept can be achieved according to the solutions related to the biological engineering. After evaluating all solutions, the most optimal options are chosen.

Engineering design: In this step, configuration of the product bionic design and the detailed design of bionic product is carried out using the basic concepts of the reference. Modelling and simulation of bionic product is also done in this step.

Integration and verification: according to the maps and the detailed design, system is aggregated by the smallest parts of the design and based on the integration strategy. Verification process is carried out to ensure the fulfilment of the requirements in each step of the system development.

Validation: In this step, the final system is validated to assess the fulfilment of all the requirements of the stockholders or the principles of biological systems.

4.2 Data Analysis

The data were collected through library studies for the literature review and survey research using face to face meetings and questionnaire. In-person interview is a powerful and interactive way of getting information from people. However, its analysis, comparison, and results are challenging and difficult. On the other hand, there is no possibility for interaction and clarification of the issue due to the absence of the questioner with the respondents. The inputs for this approach may be limited but the analysis, comparison, and results are possible well (Muller, 2013). Thus, the present study used a combination of both approaches, including questionnaire and interview, to obtain the advantages of them and minimize the disadvantages. For this purpose, face to face meetings were held with attendance of all industry experts in the product design. After describing the proposed model and interacting with experts in order to get their opinions, the questionnaire was given to them in two forms of "necessity of steps "and" sequence of steps". One of the most common methods in designing the questionnaire is Likert Scale. The format of a typical five-level Likert item could be: very high, high, medium, low, very low. One of the methods for data analysis of Likert Scale in research fields of systems engineering is Net Promoter Score (NPS). According to NPS, it was assumed that respondents with "very high" are agreed with the proposed ideas and those with "medium, low, and very low" are disagreed with the ideas. Respondents with "high" are passive and are not taken into account. The total score was obtained by subtracting the number of agreed respondents from disagreed respondents. If the output is greater than zero, it will be considered as a positive result. The positive effect of this method is that the good result is obtained using the respondents with "very high" and those with "high" are not included. The mean value 3 is usually considered as the threshold value which is not appropriate from the perspective of NPS technique (Muller, 2013).

The index of within-group interior agreement (rwg) is a measure of agreement among judges' ratings of a single target. There are three key factors to use this method: 1) the problems should be identical within groups, 2) there should be a similar discrete scale for all respondents, 3) the vote scale for all people has the same meaning (Agha Mohammadi, 2015). In this study, the first and second factors were applied through the questionnaire and the third factor was applied through face to face meetings and presenting the model. For analysis, random error variance was used (equation 1). For the questionnaire with the 5-point Likert scale, the variance value was 2 using the equation 1. Equation 1 is as follows:

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$$\sigma_x^2 = \frac{A^2 - 1}{12}$$

The value for rwg was calculated using the equation (2). The number agreement was between 0 and 1. The number 1 shows the highest agreement between the group members. Equation 2 is as follows:

$$r_{wg} = 1 - \left(\frac{\delta_x^2}{\sigma_x^2}\right)$$

5. Research Findings

The statistical population consisted of 20 product design experts from industries manufacturing complex products. The participants were selected using census sampling. Cronbach's alpha was used to determine the validity of the questionnaire. The validity of the questionnaire for "the necessity of steps" was 0.79 and for "the sequence of steps" was 0.8. Forasmuch as the obtained value was higher than 0.7, both of them were confirmed. As mentioned, the table 2 shows the highest agreement between the experts. If NPS>0, the experts are agreed with the proposed idea. The obtained value indicated the highest agreement between the experts**.**

Table 2. NPS and rwg indicators calculation

NPS	rwg	Sequence of steps	NPS	rwg	Necessity of steps
+12	0.61	From need to need analysis	+13	0.83	Customer need
+9	0.61	From bio. System identification to bio. System analysis	+5	0.64	Industrial problem to be solved
+3	0.62	From need analysis to functional modeling	+6	0.84	Natural system and its function identification
+6	0.60	From bio. System analysis to functional modeling	+13	0.88	Need analysis
+4	0.53	From problem functional modeling to search in bio. & eng. resources	+7	0.77	Natural system analysis
+9	0.66	From bio. Functional modelling to search in eng. resources	+2	0.74	Problem functional representation
+8	0.70	From search in bio. Resources to creative connection making	+3	0.72	Biological system functional representation
+8	0.62	From search in eng. Resources to creative connection making	+3	0.70	Search in biological resources to solve problems
+5	0.60	From making connections to concept generation & selection	+2	0.74	Search in engineering resources to solve problems
+13	0.66	From concept selection to eng. design	+4	0.76	Search in engineering resources to find existing solutions
+16	0.92	From eng. Design to integration & verification	+6	0.78	Creative designer role in making connections
+17	0.93	From verification to validation	+13	0.88	Concepts generation
			+11	0.82	Optimum concept selection
			+5	0.76	Product engineering design
			+10	0.88	integration
			+10	0.88	Verification process
			+12	0.87	Validation process
			+13	0.83	Requirement tracing in design process

6. Conclusion

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In the present study, after reviewing the literature related to bionic design process and systems engineering, a conceptual model is presented. The proposed model was examined using a questionnaire in two forms of "necessity of steps "and" sequence of steps" completed by 20 product design experts in industries manufacturing complex products. Reviewing the index of Net Promoter Score (NPS) and within-group interior agreement (rwg) indicated the high validity of the proposed model from the perspective of industry experts. The comparative analysis of the proposed model with related researches in the literature indicated that the proposed model has the high innovation and significant strengths in the following items:
1- Using a consolidated approach of problem-driven and solution-based approach
2- Employing a system approach by a systems engineering approach
3- Risk-taking ability and stability of the process
4- Considering the full cycle of design or product development and tracking requirements throughout the design process
5- Using the functional representation

7. Suggestions for future researches

- Using FBS modeling in the systematic design of bionic products
- Presenting bionic tool oriented models
- Development of existing databases for biology and engineering in terms of bionics
- The practical application of this research to create innovative products

The proposed model with a strong base of the other researches and the high validity from the side of product design experts in industries manufacturing complex products is considered as a practical methodology for designing innovative product and modeling using the nature as a rich source of inspiration for creative ideas to solve industry problems. Global efforts are continuously making to provide systematic methods and processes based on the biologically inspired design and the Iranian researchers should try to do more researches in this field

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