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Nature-inspired Process Model for Concept Selection and Evaluation in Engineering Design

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Abstract
A main challenge in engineering represents the evaluation and selection of concepts in the early phase of product development. This decision making process is highly complex due to the various influence factors that have to be considered simultaneously. Actual methods used involve much know-how and experience and often imply an increased work effort and costs. To overcome these challenges a more effective concept selection process is needed. In this paper an intuitive and easy to apply method for concept evaluation and selection in engineering design is presented. The method is based on selection mechanisms found in nature and can be used in engineering and other related disciplines for concept development and information filtering. The collected and adapted selection mechanisms from nature and engineering are embedded within an application process. The user can apply the nature-inspired process model to evaluate the designed concepts by using tailored K.O-criteria. The functionality of the process model is tested within two scenarios.

Keywords: product concept selection, decision making, nature-inspired design

1 Introduction

The evaluation and selection of concepts in the early phase of development is a very demanding task that engineers have to face during product design. This decision process involves many resources and can be, depending on the engineering teams experience and know-how, very time consuming. In engineering actual methods focus on product concept selection by using analytical methods based mainly on qualitative selection criteria or numerical methods based on calculations and therefore quantitative criteria [1]. These methods can only be applied by skilled users and demand training and a vast knowledge regarding product composition and integrated product functions.

To realize a faster and more intuitive selection process and to overcome the stated challenges the selection mechanisms found in nature can be very useful. In nature "selection" represents a part of the evolution process together with two other operators: "recombination" and "mutation" [2]. In engineering these operators are mainly used for the generation of solutions and variants and for information management [2]. By adapting the selection mechanisms regarding product concept selection a further application of biological operators is possible. Two research questions are focused in this paper:

- *How can biological selection mechanisms be adapted and used for intuitive product concept selection in engineering?*
- *How can the developed method be designed to be applied by different disciplines?*

The selection mechanisms identified have to be embedded within an application process. Compared to actual methods in engineering the application process and the generated methodology have to exhibit a higher degree of abstraction so that engineers can use it directly without further preparation. Every single step of the nature-inspired process model exhibits corresponding natural and engineering selection mechanisms. This duality is used as a translation mechanism regarding the terminology of the two disciplines. Nevertheless, the main application of the process model represents the selection of product concepts in engineering. Following main objectives have to be fulfilled with the application of the model:

- Optimized product concept pre-selection
- Optimized information collection
- Exclusion of additional training of engineers regarding method application

2 State of research and motivation

2.1 Solution selection in engineering

The narrowing of the solution space by evaluating and selecting adequate concepts which fulfill stated requirements best is supported in engineering by various methods and applications. This vast range of systematical approaches comprise analytical methods like for e.g. criteria checklists, score evaluations and estimation techniques, numerical methods like calculations, simulation methods and experiments and also several process models [1, 3]. A further trend in solution selection represents the development and application of decision making systems and models. The decision making process model developed by Avasthi & Varman [4] contains 12 factors which influence the decision making process. These factors refer to information access, quality, reliability and flexibility, to problem identification and solving and to decision rationality, speed, formalization, participation, influence and type. These factors can contribute to the future improvement of the nature-inspired concept selection model.

2.2 Solution selection in nature

In nature the evolution process is characterized by 2 main factors (see Figure 1).

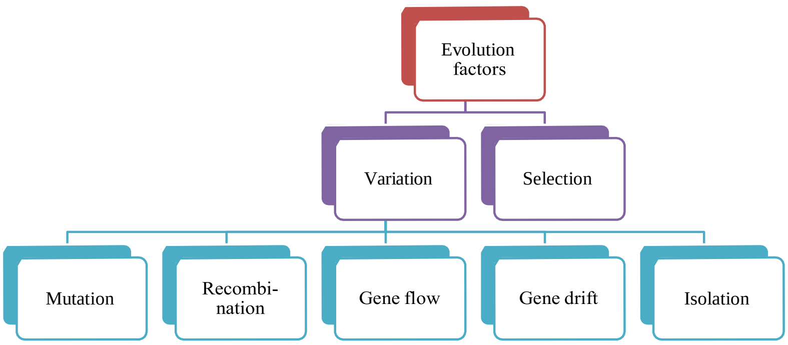


Figure 1 Natural evolution factors [6]

The factor "selection", which represents our main focus, involves internal and external selection mechanisms. The internal selection mechanisms test the organism regarding general survivability as an individual. External selection occurs for e.g. due to predators or natural cataclysms. The first two factors within "variation", "mutation" and "recombination" represent the classic evolution operators which are used in genetic algorithms to create variants and product families. The last three factors: "gene flow", "gene drift" and "isolation" characterize the types of genetic information exchange between populations [5, 6]. These factors represent the basis of developing the nature-inspired concept selection model in engineering design.

2.3 Nature-inspired solution selection in engineering

There are several approaches of integrating nature-inspired processes as methods for solution finding, evaluation and selection in engineering design. Most of these approaches have been developed as tools for systematic product development in biomimetics. Hereby a very common method is the solution search with the use of catalogues. These catalogues are based mainly on basic functions like for e.g.: forming, joining and storage [7]. Evolutionary algorithms represent a further possibility to use natural evolution in engineering design. The nature processes are described hereby mathematically. The two most known methods to describe evolution by using algorithms are the evolutionary strategies by Rechenberg & Schwefel [8, 9] and the genetic algorithms by Holland & Goldberg [10, 11]. The operator "mutation" represents the key aspect of the evolutionary strategies. On the other side genetic algorithms focus on the operator "recombination". Within evolutionary algorithms the selection process has almost no similarity regarding the complex processes in nature. The selection is based hereby on mathematical quality functions.

2.4 Motivation

During product development many different decisions have to be made which can be very important for the market success of the developed products and therefore for the success of the company. Decisions made during concept selection are very important because in this early phase a large part of the design of a product is assessed. The displayed methods for concept selection in engineering are characterized by a difficult and time consuming application and the need of specific know-how and training. The quality of the solution evaluation and selection depends on the evaluation criteria established and therefore on the experience and know-how of the method user.

Decision making and concept selection can also be found in nature. Hereby "decisions" are made regarding the survivability of an organism and its selection for reproduction. These mechanisms have been partially adapted and used as evolutionary algorithms to support the product development process in engineering. The quality functions used hereby for selection represent a very pragmatic approach. They reflect only one analysis criteria and rarely integrate criteria combinations. An approach which uses the complex processes in nature to support developers regarding concept selection in engineering does not exist yet. Therefore a detailed analysis of natural selection mechanisms and the development of a methodical concept to support the selection process in engineering are very important.

3 Realization and results

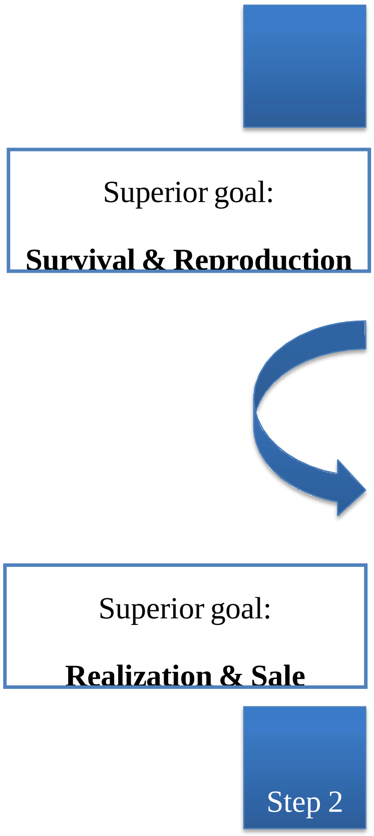
The design of the nature-inspired concept selection model follows 7 main steps:

1. Situation analysis and problem definition
2. Requirement collection
3. Collection of selection mechanisms from nature and engineering
4. Selection of relevant selection mechanisms for model development
5. Comparison of selection mechanisms and identification of relations and similarities
6. Embedding of selection mechanisms in an application process
7. Process-model application

The first step consists in analyzing and structuring existing methodology for solution selection and the determination of problem areas and challenges regarding main objectives stated. From the gathered information, requirements and criteria for selection mechanism analysis are assessed. Next the collection of technical and biological selection mechanisms and the definition of properties are realized. From this pool of selection mechanisms the concept-relevant mechanisms are selected and allocated to topic-groups. The selected mechanisms from nature and engineering are then compared and dependencies and similarities determined. To be able to apply the identified and adapted selection mechanisms an application process is needed. Through the integration of the selection mechanisms within a consistent process model with predefined process steps the solution selection can be conducted systematically. The last step represents the application of the process model in two representative scenarios. The results and expertise generated from scenario application are used for the improvement of the process model.

3.1 Selection mechanisms development

The development of the process model starts with the general collection of selection mechanisms from nature and engineering and the definition of type and functionality. In nature and engineering a vast number of factors, which can be seen as selection factors, exist. For example the natural environment influences an individual organism and acts as a selection factor. In product development several functional and non-functional requirements have to be considered. To be able to analyze the identified selection factors a classification has to be introduced. Hereby, selection factors which are similar regarding type, application field and effect are grouped. These groups are then analyzed regarding reciprocal influence and importance for concept selection. The selection factors from nature are classified within the groups: man, individual properties, intraspecific competition, food sources, enemies, chance, environmental factors and camouflage/self-protection. The selection factors in engineering are classified in following groups: customer, individual properties, external competition, company standards, requirements, production, environmental factors, external resources, chance, internal competition, prospects and rights/engineer standards. In the following these groups are analyzed regarding mutual interaction (see Figure 2).



Selection factors in nature	Corresponding selection factors in engineering
Man	Environmental factors
Intraspecific competition	**Internal competition**; external competition
Chance	Chance
Individual properties	**Individual properties**
Environmental factors	Company standards; requirements; environmental factors; **rights/engineer standards**; prospects
Enemies	**Rights/engineer standards**; external competition, company standards
Food sources	Customer; production; **external resources**; prospects
Camouflage/self-protection	-

Selection factors in engineering	Corresponding selection factors in nature
Customer	Internal competition
Individual properties	Individual properties
External competition	**Man**; **enemies**; **intraspecific competition**
Company standards	**Environmental factors**
Requirements	**Environmental factors**
Production	Food sources
Environmental factors	**Environmental factors**
External resources	Food sources
Chance	Chance
Internal competition	**Intraspecific competition**
Prospects	-
Rights/engineer standards	**Environmental factors**

Figure 2 Corresponding selection factors in nature and engineering and main objectives

To be able to compare the processes in nature and engineering superior goals have to be defined. The superior goal in nature represents "survival and reproduction". The superior goal

in engineering design is on the other side “realization and sale”. The goals with corresponding selection factor groups and marked active and passive elements are displayed in Figure 2.
Analyzing the constellation presented in Figure 2 similarities between selection factors can be depicted. In nature an organism has to survive. It has to stand up to competitors, enemies and adverse environmental conditions. An engineering product must also intermingle with competitor products, company and engineering standards, laws and requirements. The selection factors can be further divided into active (marked “red” in Figure 2) and passive (marked “green” in Figure 2) elements. This classification is important regarding change management. To compare the selection factors in nature and engineering correlating factors are established. In step 1 engineering selection factors are allocated to natural selection factors. In step 2 natural selection factors are allocated to engineering selection factors. With the help of the identified correlations in step 2 the selection mechanisms can be transferred into engineering design. The starting point represents however always the surrounding nature while the depicted correlations represent mainly an agent for terminology translation and transfer into engineering design.

3.2 Nature-inspired selection process model

In engineering the evaluation and selection process focuses on concept characteristics and requirements trying to find weak spots within concept design. The nature-inspired selection model focuses concept strengths and tests the solution ideas regarding their robustness to negative influencing factors, suitability for the problem stated and „survivability“ facing requirements and stakeholder needs. The process model to be developed has to enable a more simple, intuitive and faster pre-selection of product concepts. For this purpose processes and selection mechanisms found in nature have to be integrated. The adapted selection mechanisms and actual decision making approaches serve as a basis for the development of the nature-inspired process model. In natural evolution different selection mechanisms play in different time periods an important role within the development of an organism. Not before these selection mechanisms are overcome the genetic material can be handed over to the next generation. The selection factor “chance” has to be considered overall selection mechanisms. Chance and accidents can occur at any time and cannot be predicted.
Based on the realized literature review a nature-inspired process model was developed. Figure 3 displays the 6 steps of the generated process model in nature, showing simultaneously the corresponding steps in engineering. In addition selection factors and a set of predefined methods are assigned. Each step relies on the results generated in the previous step considering occurring internal and external iterations. In every step the solution space is narrowed considerably giving the process model the character of a pyramid. The displayed selection factors represent „K.O.-criteria” which the concepts have to fulfill completely to be selected for further development. The basis of the pyramid consists of chance and represents a randomized selection of organisms in nature and of product concepts in engineering. The first real selection step represents the selection by internal mechanisms where the survival of an individual is important. The abiotic and biotic selection factors contained in the next two steps are based on each other. Biotic selection factors cannot be effective if the abiotic factors are already lethal. Because the environment changes all the time both factor types can operate simultaneously. The abiotic factors are represented by environmental factors and food source available. The biotic factors are characterized by the enemies and intraspecific competitors against whom the organism has to assert and the available food sources. The next selection step involves the selection by sexual factors where the individual characteristics of the organism are analyzed. The peak of the pyramid represents the genotype transfer who completes the fulfillment of the superior goal in nature “survival & reproduction”.
The basis of the selection pyramid in engineering design consists also of chance and therefore of a randomized concept selection. In the next step the functionality of a product must be

tested regarding individual properties. The product has to function to be taken into consideration for the next step. Hereby the requirements and boundary conditions that a product has to fulfill are analyzed. Only when all requirements are fulfilled the product can be compared with other competitors. In the next step customer requirements are analyzed. If the customer selects the product then the superior goal in engineering of “realization & sale” is achieved. The analysis has to focus on the selection factors generated and on specific properties to achieve valid results and to enable a considerable narrowing of the solution space.

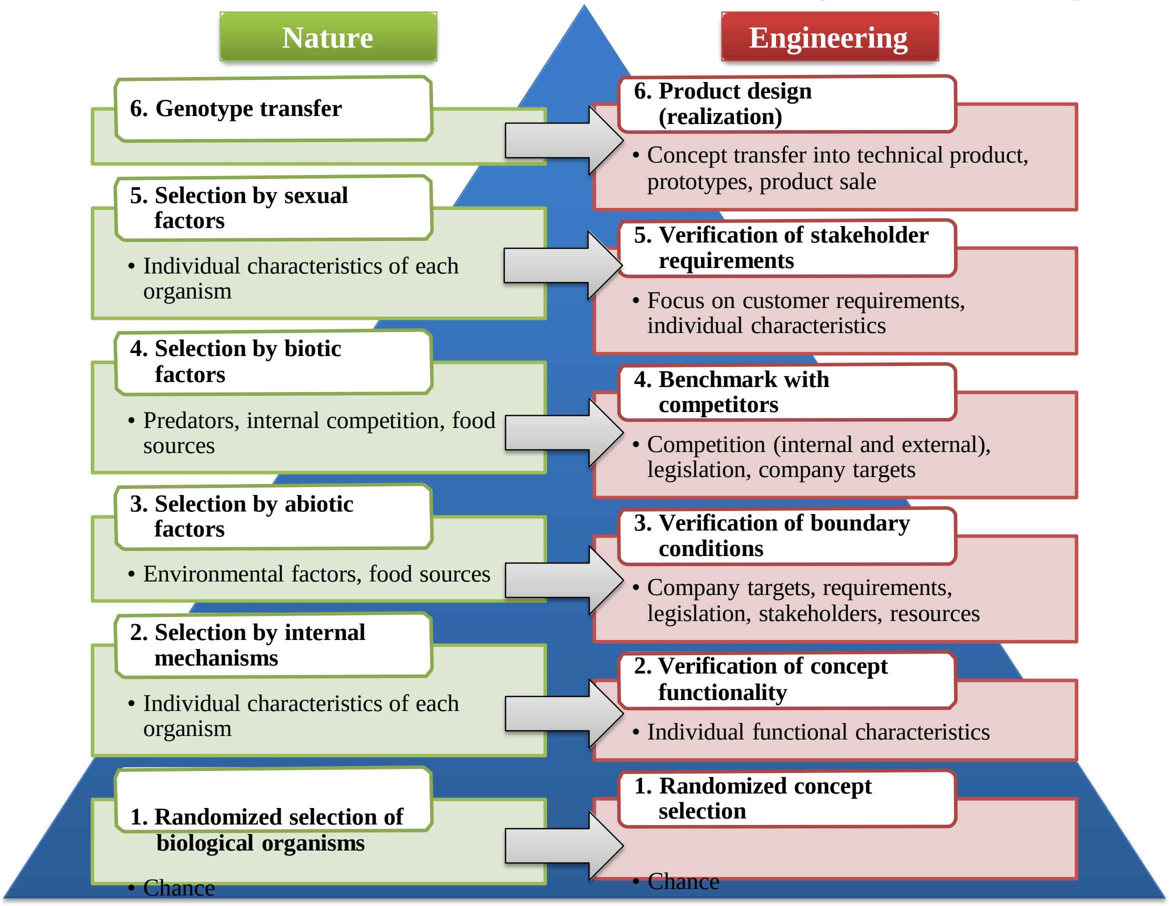


Figure 3 Nature-inspired concept selection process model

4 Process model application example

The functionality of the nature-inspired process model is tested within 2 scenarios based on several use cases researched and adapted in content and complexity to fit the objectives stated. The first scenario discusses the development of a new wallet. The designers of the wallet producing company generate several solutions for a new and innovative wallet. A wallet has to fulfill 3 basic requirements:

- Acceptance of coins
- Acceptance of banknotes
- Acceptance of documents (e.g. identity card, credit card etc.)

All possible wallet design solutions are tested regarding stated functions. Only the solutions which fulfill all the three requirements displayed are taken into consideration. The requirements represent therefore K.O.-criteria.

In the second scenario a football is developed. For this purpose a company is hired as an external supplier. Following main requirements have to be fulfilled by the football concept:

- The form should be as round as possible (best: perfect sphere)
- Optimal and predictable flying trajectory of the football

- Fast acceleration and high speed of the football possible
- Flexible football design (color, engravings etc.)

Several design concepts of the football are generated. The designs differ from each other regarding material, surface structure and design.

Regarding the development of the wallet all steps of the selection pyramid could be run-through. First all solution concepts are analyzed regarding stated requirements. Next boundary conditions are considered. The transfer to the next step is realized with several iterations involved. Hereby individual strengths of the wallet design for e.g. the positive properties of the selected material or that many different types of documents can be accepted are identified. The particular strengths give a significant selection advantage and therefore a positive selection reporting systems is achieved. An important role plays also the internal and external comparison with competitors where significant properties of the wallet can be identified and improvement possibilities derived. Regarding the development of a new wallet concept the nature-inspired process model resulted as useful and suitable.

In the second scenario the functionality of the football concept is examined. In the third step of the process model the different requirements and engineer standards are analyzed. The fourth step represents also hereby an iterative process. Within this step concept improvement possibilities can be depicted. In this scenario no comparison with competitors was available. This fact represented a problem regarding further concept selection. Natural evolution is based on the comparison with competitors and also the nature-inspired process model. The iterations, which emerge due to the comparison with competitors, cannot be realized. Thus in worst case no improvement of the generated football concepts can be achieved. The next problem within the second scenario represents the missing real-life experiments. In nature every solution possibility is "tested". Due to reduced resources only a small amount of existing solutions can be tested in engineering. The importance of systematic solution pre-selection is here obvious. The two scenarios show that competition and testing represent an important factor regarding product functionality analysis. If these are not available the identification of improvement potential can become a problem and the application of the selection process model is less successful.

5 Discussion

The nature-inspired concept selection model describes a structured approach regarding the development of engineering products according to evolution and especially selection in nature. The development of the process model focuses on a simple and intuitive application. Also inexperienced users can apply the process model fast, effective and successful. The previous displayed application scenarios show that the single steps of the selection pyramid correlate well with the intuitive development of concepts during product design. The first step of the process model involves the selection mechanism "chance" where concepts are randomized selected. In the next step product functionality is analyzed followed by requirement testing in the third step. The fourth step represents the core of the process model. Hereby the actual concept evaluation and selection is realized. The product is facing hereby internal and external competition. The next step concentrates on decision making. The remaining concepts are compared and strengths, according to the pre-established positive reporting system strategy, identified. Main requirements have to be fulfilled but decisive are the positive concept characteristics. This analysis strategy is common to nature processes where primarily the strengths are important for survival and reproduction. This strategy correlates with the developers mind set and is therefore more intuitive. The transfer from the requirements analysis step to the step of comparison with competitors is iterative. Hereby improvement potential can be identified. The next step represents reproduction in nature and product sale in engineering where individual properties are analyzed. The displayed concept is based on the identified selection mechanisms in nature and engineering and their classification into topic groups. This collection reflects the actual research state and can be enhanced by further mechanisms. The application of the process model was realized in two theoretical scenarios based on literature research. This application reflects some of the strengths and weaknesses of the process model. The process model is rather abstract and can be applied by different users as individuals or in teams. The generative character of the process model offers benefits regarding an intuitive application. The support of team-work can be widened-out regarding for e.g. different disciplines in mechatronics and biomimetics. The concept addresses strongly the processes and approaches in nature. This leads to a more intuitive application of the process model and offers help to different types of users.

6 Conclusions

The natural evolution process is already used as a source of ideas in many different methodologies. Nevertheless especially for the process of concept selection support in engineering no suitable approaches exist at this moment by using evolution theory. Within the development of the nature-inspired concept selection model the mechanisms of natural selection are analyzed and a new approach for concept selection in engineering developed. The development of the nature-inspired process model focuses on “selection” and integrated mechanisms.

For model improvement a more detailed analysis of natural selection factors is important. For e.g. the observation of the influences that occur due to food sources on enemy species is an interesting aspect to be transferred into engineering. An important but less considered aspect within the process model represents the selection factor “chance”. The role of chance is in nature and engineering very important and implies high consequences. Regarding future research accidental events and incidents in nature can be analyzed. The insights derived could be used for better assessment of decision making systems in companies and also for developing new methods and approaches for action in critical situations. Biological selection mechanisms are well suited for application in engineering decision processes. By using biological mechanism a more intuitive selection is possible. Requirements, characteristics and boundary conditions of the analyzed concepts are integrated in the model design. The selection model is adequate for concept pre-selection before applying more complex methods.

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