Methodology for the implementation of heuristics in the design process

Manuela Calle-Escobar [1], Ricardo Mejía-Gutiérrez [1], Jean-Pierre Nadeau[2] Jerome Pailhes[2]

(1) : Universidad EAFIT, GRID
050034 Medellín, Colombia
+57 (4) 2619500 ext. 9712
E-mail : {mcallees, rmejiag}@eafit.edu.co

(2) : Arts et Metiers ParisTech I2M, UMR 5295
F- 33400 Talence, France.
+33(0)556845428
E-mail : {jean-pierre.nadeau, jerome.pailhes}@ensam.eu

Short Abstract: This article explores the applicability of heuristic rules into the decision-making processes involved in design practices. For this purpose, the research focuses on the development of a methodology that seeks to facilitate the introduction of heuristics into particular stages of the design process, such as conceptualization and architecture definition, thus triggering creativity in problem solving. This will enable a more diverse concept generation and a more detailed product development process.

Key words: Heuristics, design methodology, decision-making, product design.

1- Introduction

Different stages of the design process face designers with problem solving situations that conduct them towards making decisions that can alter the course of a design project. Furthermore, the decisions that aim to solve design issues are often of iterative nature and are made under conditions of uncertainty. Ultimately, the choices made end up restraining the possibilities of a design process in terms of technical and conceptual direction.

Which of the concepts best embodies the initial requirements? How to solve the technical contradictions that arise from conflicting requirements? Is there a more straightforward way to approach a particular solution?

In environments where design practice is habitual, such as enterprises, R+D areas and academic surroundings, it is expected to encounter, whether tangible or not, existing knowledge regarding the most appropriate way to respond to these and other specific design problems. The answer to such questions is generally based upon praxis and experience that has been obtained when giving solution to similar problems in a systematic manner. The problem is precisely rooted in the fact that, when the design outcomes are drawn from a non-structured process, there is a certain risk that the knowledge generated from practice and experience will not be of use for the organization in the future. Consequently, it is important to count with methods and tools that guarantee the permanence of knowledge within organizations, thus allowing its utilization in future occasions. The value of making an effort towards the understanding, consolidation and structuring of knowledge being generated through the execution of design processes, is that it eventually enables the solution of design problems in a more effective way; specifically because counting with methodological strategies that enable the designer to consciously employ resources that have been previously used in other situations will conduce to the attaining of new design solutions in a more direct manner.

The purpose of this study is, therefore, to explore how heuristics can be used within design processes and what benefit can be derived from such implementation.

2- Literature review

Numerous methods and tools have been developed with the purpose of establishing guidelines for designers to follow in order to find optimal conditions for the problem solving activity. In the field of the implementation of heuristics in the product design process, in particular, the first approximations to the use of heuristics in design, such as Synectics **[G1]** and SCAMPER **[E1]**, emerged from the field of the theory of learning, and were implemented afterwards as creativity tools for the design processes. Its purpose is to generate new alternatives from the reconfiguration –architectonic reconfiguration, in the design context – of existing solutions. Synectics, on the other hand, is based upon the use of analogies and metaphors as strategies to enhance creativity.

CBR (Case Based Reasoning) **[KO1], [KO2]**, understood fundamentally as a cognitive process, is a reasoning strategy that draws upon previous solutions to explain, interpret or solve current problems. Consequently, the existence of a knowledge base is required as a starting point for problem solving, as well as a series of strategies that enable the adequate recognition and interpretation of the functional element of previous solutions that are applicable to the current problem.

These strategies offer, without a doubt, the possibility of obtaining diversity within creative processes. However, being tools derived from other areas of knowledge, their specificity in the application on design cases is limited, particularly because elements such as the language used are not design-specific.

The work of Yilmaz **[Y1]** seeks to solve to a certain extent the limitations spotted in the previously exposed tools. His studies, supported in the analysis of case studies with design experts **[YS1],** are oriented towards the identification of common strategies related specifically to product design, used during the conceptualization stage. The result of his research is a set of 60 heuristics named *Design Heuristics*, which, according to his analyses, facilitate the generation and diversification of concepts in practice. However, the heuristic rules proposed by the authors remain generic, and strongly linked to the initial concept generation stage. In this sense, the architectural definition processes as well as the detail design stage will not find great value in the proposed heuristics.

Another development of similar nature, but with a stronger orientation towards the solution of technical problems, is TRIZ **[A1]**, one of the most widespread tools in the field of design. It is a development which most relevant strength is the extensive knowledge base upon which it is built, created from the analysis and categorization of patented technical solutions. The idea behind the implementation of Altshuller's methodology is that, through the application of one or more of the 40 inventive principles available, the designer is capable of consolidating a feasible technical solution, which solves the design contradiction initially identified. However, an important limitation related to the implementation of this tool is that it requires the conception of the technical problem in terms of a functional contradiction, which is not always easily identifiable during conceptualization stages, particularly when the product definition is not yet concrete.

Subsequent developments have been built upon the work of TRIZ, such as Polovinkin's heuristics **[P1]** and de Carvalho's work **[D1]**. Fundamentally, these approaches aim to continue nurturing the extensive knowledge base of TRIZ, as well as explore new possible heuristic rules.

It is also worth noting the work of Stone **[S1]**, in which heuristics are proposed for the identification of possible modular configurations during conceptualization. The methodology establishes that, from the identification of the main flow, additional flows, conversion and transmission modules of a system, it is possible to propose concepts with a modular character. Subsequent methodological applications have been derived from his work **[FC1]**.

Finally, the usage of heuristic optimization, with the implementation of genetic algorithms **[KZ1]**, particle swarm algorithms **[KE1]** and Monte Carlo techniques **[H1]**, has led to the development of a whole new field of application for heuristics, particularly in mechanical design **[CC1]**.

As it can be seen, although previous studies have been carried out in the field of heuristics, its specific approximation to the field of design is still incipient. On the other hand, aspects related to the social, geographical and cultural conditions might have a significant impact in the way design processes are executed in the local context.

3- Heuristic rules: development and implementation

3.1 - Definition

By definition, heuristics refer to the proceedings or approaches that enable someone to reach a solution for a particular problem through the implementation of a "rule of thumb", derived from experience rather than an exhaustive process. In the design context, they refer to technical or conceptual solutions which implementation has been previously proven in another area or context, but which can be extrapolated to similar design problems.

The heuristic rules result from the existence of a knowledge base previously collected and categorized, which enables the determination of patterns that can be later structured in the shape of problem solving strategies. For this particular study, as a result of this work, a set of 78 heuristic rules has been proposed and categorized.

3.2 - Heuristic rules construction

The set of heuristic rules that have been incorporated to the present study are the result of an extensive analysis of the available resources related to problem solving strategies, such as those proposed by Altshuller and Polovinkin, and have been optimized and structured in a way that enables the designer to quickly interpret the knowledge behind it them and put it to use in any design situation. These heuristic rules are built up into a hierarchic structure (see Figure 1). Fragments of sentences, which level of abstraction decreases along the course of the arborescence, configure the structure of 78 rules. The branched structure also suggests that an initial portion of a rule can unfold into several different strategies.

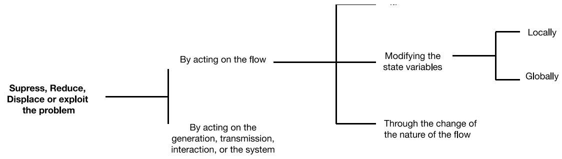

Figure 1: Heuristic rules hierarchy

As it can be seen, the rule is conformed by segments of sentences that grow in level of detail as they escalate throughout the structure of branches. The level of detail corresponds to a hierarchical organization that helps designers to identify the kind of approach they want to take on a problem, and determine the sort of solution strategy they wish to implement. It is important to note that, due to the systematic nature of the approach, one of its key advantages is that the functional principles explored in the heuristic tree can be of use for a vast range of design issues. In this sense, it is also important to state that the rules have been constructed taking into account the semantic value of the words and verbs that describe the actions, so as to simplify the interaction between the designer and the tool, and still provide valuable output for the creative process.

Once the designer has a full perspective on the strategies provided by a particular heuristic rule, a brainstorming process can be carried out, towards the generation of ideas for the problem under question. In this sense, the heuristic rule helps the designer to define the desired action to be taken over a particular problem, the area where said action will take place, and the solution strategy itself.

For the analysis, the methodology was supported with the development of a tool that consolidates both the heuristic rules and application examples from different fields (e.g., engineering, industrial design and biomimicry) that facilitate the comprehension of the functional principle behind it. (See Figure 2) The goal is to help designers understand how the different solution principles can be integrated into their creative process.

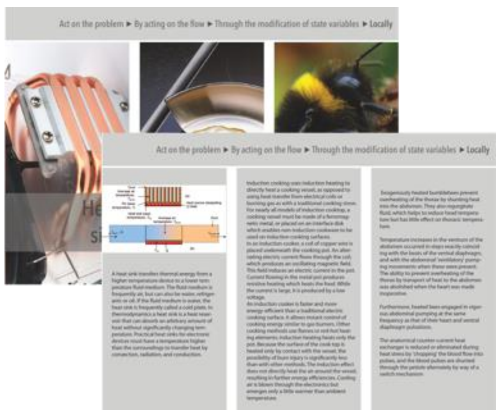

Figure 2: Example of heuristic card

4- Methodology

The proposed methodology aims to offer a problem solving approach that helps designers to concretize design tasks more effectively, by resorting to existing knowledge in a structured manner. The methodology is based upon the TRIZ approach, but it provides additional tools for the structuring and evaluation of the resulting solutions. The procedure comprises three successive stages, as shown in Figure 3.

4.1 - Structuring

The first step towards the resolution of the design problem requires the designer to fully understand the nature of the problem itself. For this purpose, the first requirement is the development of a functional decomposition of the overall system into functional blocks and flows.

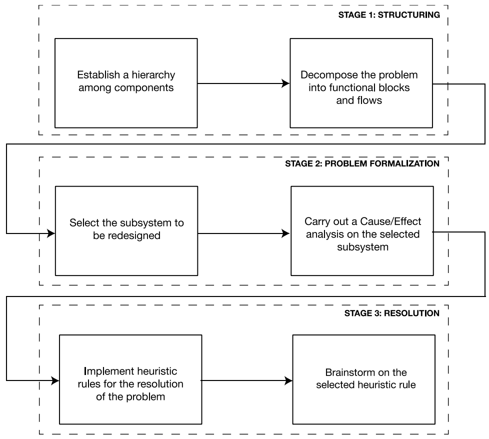

Figure 3: Methodology overview

This will enable the designer to have a visual representation of the design situation. For the functional disaggregation process, the methodology initially defines the utilization of a Technical Organization Chart. In order to develop the tool, the designer must describe the product at three main levels: (a) Products and components, (b) Outdoor environments and (c) interactions within the product and with external factors that incise in the product **[PS1].** Once these elements have been identified, the components must be hierarchized.

Afterwards, the designer can determine the conflicting components, and select the level at which the problem will be attacked. At this point, the next step is the determination of functional blocks, which involves zooming into the selected level and describing the interactions within a subsystem. The determination of functional flows is of crucial importance for the subsequent work. The diagram will help classify the flows according to their characteristics (e.g., matter, energy or signals) and identify their provenance.

4.2 - Problem formalization

In this step, the goal is to set a number of ways in which the identified problem can be solved. The methodology proposes a cause-effect approach, described in Figure 4, which fundamentally poses that every problem can be disaggregated into the following components: (a) a first element (S1), which originates the problem; (b) a second element (S2), the subsystem that suffers the consequences or effects of the problem; (c) a functional flow transmitted from S1 to S2; and (d) an interaction flow derived from the existence of contact between S1 and S2. The element in which the cause is located can also be disaggregated into 2 sub-components: (i) the generation, meaning the element that creates the problem, and (ii) the transmission, which is the element that conducts the effects of the problem to S2.

The first element to consider when using this approach is the classification of the flows that connect both entities, S1 and S2. In this sense, it is important to determine whether the system's flows correspond to matter, energy or signals. The effects caused by the interaction between said flow and the entities are the origin of most of the problems. Therefore, it is important to understand the impact that the action of the flows will produce.

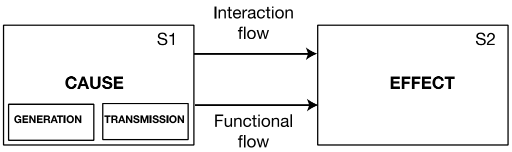

Figure 4: Cause-effect model

Once the nature of the flows is understood, the next step is to identify the following: (a) Where in S1 is the problematic flow produced?; (b) how does S1 transmit said flow to S2? and (c) how do S1 and S2 interact?

This will give the designer an overview on how the source and the receptor of the problematic flows relate to each other. At this point, the next stage is to determine what specific effects are produced in S2 by the flow coming from S1, and the induced effects that are derived from them.

The evaluation of the impact of the induced and produced effects (See **Table 1**) will determine the kind of action required for the solution of the problem **[PS2].**

Table 1: Produced and induced effects

State variables	Time variables	Produced effects	Induced effects
Force	Speed	Strain	Gap/Clamping/ Stresses/Vibrations
		Friction	Wear/Heat transfer/ Dilation/Retraction/ Gap/Clamping/Stresses/ Creep
Pressure	Volume flowrate	Strain	Leaks/Stresses
		Friction	Dilation/Retraction/ Gap/Clamping/ Stresses Pollution/Clogging
Tempera-ture	Capacity rate	Heat flow	Dilation/Retraction/ Gap/Clamping /Stresses/Creep/ Icing/Icing up
		Friction	Dilation/Retraction/ Gap/Clamping/ Stresses/ Pollution/Clogging

This means that the designer can choose whether to act on the generation, transmission or interaction within the system, or in the overall system itself. From this point on, the designer can relate the situation to the heuristic hierarchy, therefore implementing heuristic rules to solve the problem under question with the purpose of taking action over the identified effect.

4.3 - Resolution

As it has been previously stated, the present research proposes the incorporation of a set of 78 heuristics arranged in a branched structure, so as to enable the designers to explore the different strategies according to the characteristics of the problem.

The following is the approach suggested for the utilization of the heuristics:

- Determine the desired kind of action to be taken over the problem: (a) eliminate, (b) reduce, (c) exploit or (d) displace the problem.

- Locate the efforts of said action in a particular point of the system, understood from the perspective of a cause-effect model: (a) the flow or (b) the system. If the designer choses to take action over the system, the specific location of the action must also be defined (generation, transmission, interaction, or the overall system itself)

- Select, from a range of possible strategies, what kind of specific action does the designer want to implement for the achievement of the set goal. The choice made depend largely on the possibilities of the system itself, the capabilities within the company and the skills of the designer.

- A consecutive set of choices will drive the designer through the branched structure, all the way to a final, highly specific heuristic strategy that offers a particular functional principle to be explored and implemented into the creative process.

At the end of the decision-making process, the designer will encounter a card that shows examples of application of the functional principle under question, and details how the principle works in each of the cases.

The ultimate goal is to trigger creative thinking in the designer, by providing them with tools to explore an ensemble of solution strategies applicable to a wide range of design problems.

5- Case study

5.1 - Validation method

In order to obtain relevant data for the improvement of the methodology and the tools associated with it, the process has been evaluated in a preliminary case study, where it has been subjected to comparison with a conventional design approach.

The pilot study was carried out with two teams of designers with different backgrounds (mechatronics, industrial design, biomedics, etc.), who were given the same task: to rethink a conventional coffee maker. The purpose was to compare the performance of both teams, with one of them using regular design techniques, and the other one implementing a set of heuristic rules.

5.1.1 - Team A

The first team approached the redesign starting from a brainstorming process for the detection of issues in the coffee machine. Afterwards, they carried out a functional analysis loosely based upon the Pahl & Beitz model. This led to the identification of functional blocks later translated into components that were employed for the construction of product architecture. Finally, the team carried out a concept generation stage, where different product alternatives were derived from the single architecture defined in the previous stage, and a simple evaluation process led to the definition of a final concept.

5.1.2 - Team B

The second team was instructed in the use of heuristic rules in the creative process, and was given a brief overview of the proposed methodology.

With this input, they began with the identification of components and external factors that have an incidence in the product, arranged in the shape of a Technical Organization Chart, of which Figure 5 is an excerpt. With this visual representation of the product, they were able to spot problematic areas at different levels of the product.

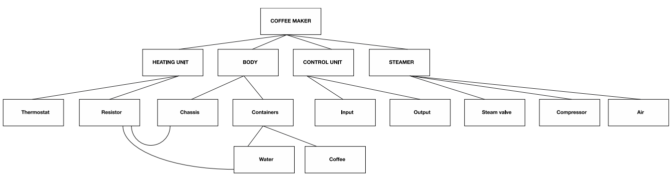

Figure 5: Technical Organization Chart

The team encountered design issues in three different categories: (a) Poor physical interactions among components (adjustment between parts); (b) Conflicts in variable management (temperature isolation and control) and (c) Poor signal management

Once the main design issues were identified, the team conformed a set of functional blocks, and defined and classified the interactions between them and the flows that connect the blocks.

This led to the construction of the FBD visualization, where the main effects derived from the interactions were spotted.

Each of the subsystems was later analysed under the perspective of a cause-effect model (See **Figure 6**), helping the designers to define where to locate the redesign effort.

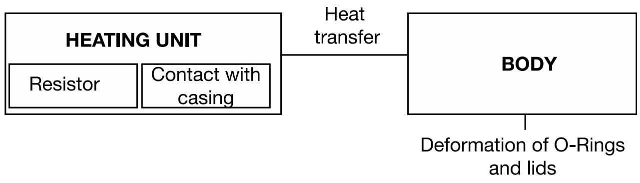

Figure 6: Cause-Effect Diagram

At this point, the team approached the exploration of the heuristic rules, by the means of the tool created for that purpose. The designers were given a set of 9 cards, each of them detailing a different functional principle. The team studied each of them, and immediately jumped to the generation of solution alternatives for each of the subsystems.

The final step of the process consisted on integrating all the redesigned subsystems into a single product concept.

5.2 - Results

The performance comparison between both teams can be seen in **Table 2**.

Table 2: Results

Variable	Team A	Team B
Total time	1h 24 min	1h 52 min
Number of problems identified	8	8
Number of functional blocks identified	11	9
Number of product architectures developed	1	2
Number of concepts generated	4	1 (6)

As it can be seen, the design approach of both teams was significantly different; while Team A made a strict differentiation between functional and formal aspects of the design, Team B deepened in the functional aspects of the design, which determined the appearance of the product. This is reflected in the amount of concepts generated, where Team A created 4 formal concepts, while team B defined a single concept, but 6 different functional arrangements were devised before defining the final design.

The analysis of time throughout the process shown in **Figure 7** explains that the team without heuristic tools invested less time in conceptualizing than Team B.

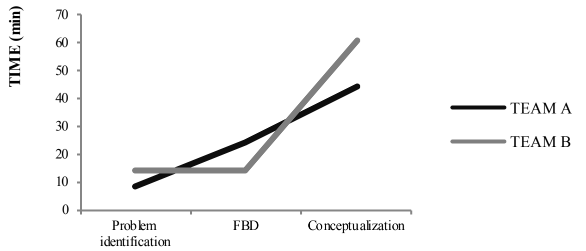

Figure 7: Time performance

This explains why Team B reached a higher level of detail than Team A, although team A had a wider variety of formal proposals.

In general, the study suggests that, when exposed to heuristic tools, design teams can reach more detailed functional concepts, thus saving time and effort in the subsequent stages of the process because less efforts are required in adjusting functional and formal solutions to a same design problem.

5.3 - Discussion

It is important to note that the contribution of the present work is focused on providing the designer with a set of possible solution principles for diverse design problems. This implies that, in order to fully exploit the potential of the tools explored here, the designer must approach the methodology with an existing problem at hand, in order to be able to identify the action to be taken over said problem.

This means that the tool will not provide equally useful results for the generation of initial concepts, given that at this point of the process, in most cases, designers do not have a tangible problem to attack through heuristic rules.

6- Conclusions and future work

During the study a particular advantage of the implementation of heuristics became apparent: lateral thinking processes started appearing in the ideation stages, meaning that designers did not limit themselves to the generation of concepts within the functional spectrum of the proposed rules. The rules often triggered ideas not directly related to the functional principles explained, but somehow connected to them. This opened the opportunity for more diverse concepts.

However, the statistical validity of the present study is limited, and therefore it is recommended to carry on with the validation process until a statistical relevance for the research is reached.

The current validation process has covered the scope of a design task from the problem definition to the general architectural structuring of a solution. However, it is important to assess what kind of input can be provided to the rest of the process by the implementation of heuristics into conceptualization, detailed design and materialization. Furthermore, it is crucial to evaluate the overall design process from conception to materialization, in order to fully understand the effects of heuristics in design.

It is also necessary to approach the dilemma designers face when having to decide which branch to follow towards the resolution of the design problem. In this sense, it is important to evaluate how to guide designers effectively through the decision-making process associated with the selection of particular heuristic rules, and provide them with the appropriate rules for the specific problems being explored.

7- References

[A1] Altshuller, G. (1997) *40 principles: TRIZ keys to technical innovation*. Technical Innovation Center, Inc..

[CC1] Ceruti, A., Caligiana, G., & Persiani, F. (2013). Comparative evaluation of different optimization methodologies for the design of UAVs having shape obtained by hot wire cutting techniques. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1-16.

[DT1] De Carvalho M., Tessari R. (2011) *Compilation of heuristics for inventive problem solving*. ETRIA. TRIZ Future, Dublin, Ireland

[E1] Eberle R.F. (1972) *Developing imagination through SCAMPER.* Journal of Creative Behaviour. Vol 6. Issue 3.

[FC1] Favi, C., & Germani, M. (2012). A method to optimize assemblability of industrial product in early design phase: from product architecture to assembly sequence. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *6*(3), 155-169.

[G1] Gordon W.J. Synectics. Harper & Row, New York, 1961.

[H1] Householder, A. S. (Ed.). (1951). *Monte Carlo Method*. US Government Printing Office.

[KE1] Kennedy, J. (2010). Particle swarm optimization. In *Encyclopedia of Machine Learning* (pp. 760-766). Springer US.

[KO1] Kolodner J. (1992) *An introduction to Case Based Reasoning*. Artificial Intelligence Review. Vol 6. Issue 1.

[KO2] Kolodner J. *Case-based reasoning*. San Mateo, CA: Morgan-Kaufman.

[KZ1] Koza, J. R. (1992). *Genetic Programming: vol. 1, On the programming of computers by means of natural selection* (Vol. 1). MIT press.

[P1] Polovinkin A. I. (1991) *Theory of New Technique Design: Laws of Technical Systems and their Applications*. Moscow: Informelektro.

[PS1] Pailhes J. et al. (2011), *Energy based functional decomposition in preliminary design*. Journal of Mechanical Design. Vol. 133, p051011-1-10.

[PS2] Pailhes J. et al. (2007), *Knowledge base formulation for aided design tool*, in Trends and Recent Advances in Integrated Design and Manufacturing in Mechanical Engineering II. Edited By Serge Tichkiewitch, Michel Tollenaere et Pascal Ray, Springer, pp 231-244

[S1] Stone R.B, et al. (2000) *A heuristic method for* *identifying modules for product architecture.* Design Studies Journal. Volume 21. Issue 1.

[Y1] Yilmaz, S. et al. (2012) *Design Heuristics in Engineering Concept Generation*. Journal of Engineering Education. Vol 1. Issue 4.

[YS1] Yilmaz, S., Seifert, C. M. (2011) *Creativity through design heuristics: A case study of expert product design*. Design Studies. Vol 32. Issue 4.