A COMPARATIVE ANALYSIS AMONG THE CLASSIC METHODS OF FUNCTIONAL MODELING OF PRODUCTS IN THE PROJECT OF FATIGUE TEST APPARATUS

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Abstract. *This paper searchs to establish a comparative analysis of the classic methods of functional modeling through the methods of Pahl and Beitz, Roth, and Koller being looked for to raise its advantages and disadvantages with focus in the procedurais aspects. The methodologies used to describe the structures of the functions are described for the study of case of the project of a workbench for assay of fatigue in plastic materials, taking for base the list of requirements established through the matrix of the house of the quality (QFD - quality function deployment). Technique and suggestions are identified to the difficulties in the use of each method to adjust them it this type of analysis?. While the methodology of Pahl and Beitz makes possible a general agreement of the product under the functional optics, the authors consider an alternative procedure to assist the abstraction of the generic functions. However, the concepts can generate different interpretations and its sybologies can make difficult the elaboration of a consistent functional modeling, conditioning the process the experience of the project team. Despite this, the methdologies can be used in the development of new projects in case of reprojects.*

Keywords*: Products development methodology, functional analysis, fatigue test apparatus.*

1. INTRODUCTION

In the course of a product design process, the application of function synthesis techniques corresponds to the stage when, after the design requirements have been identified, solutions for the essential problem are sought. Such a distribution of the process in design stages is typical of the systematic approaches that have been developed in the last decades and are object of investigation.

Although the technique of function synthesis of the product had been easily accepted by design teams, consensus was not achieved on how to apply the general concepts that comprise the background of this kind of analysis. This is not surprising, for long as the subjective nature of the design activity is taken into account. As a result, Kirschman *et al.* (1996) report that several approaches have been proposed to model a product and that methods have been established in order to evaluate proposed solutions and to point out alternative ones. Even though these methodologies present a common working principle, they are distinct in the way information is treated, which results in their presenting of particular advantages and disadvantages depending on the kind of product being developed.

In this work, the classic methods proposed by Pahl and Beitz (1988), Roth (1982), and Koller (1985) are discussed in the context of the development of a fatigue testing apparatus for plastic materials. The aforementioned techniques were applied during the function synthesis stage and their procedure aspects were evaluated regarding the advantages and disadvantages of their application in this particular study case.

2. PRODUCT FUNCTION SYNTHESIS TECHNIQUES

The basic principle lying underneath the function synthesis methods is to analyzing the product from the point of view of the functions to be performed in its operation. The concept of "product function" is distinctly defined by different authors. Hashim *et al*. (1994) present it as an abstract formulation of the product, independent of any particular solution, or as an abstract description of a truth, in a concatenated and coherent way, by means of the inputs, the outputs and of the state of a system to perform a task (VDI 2222, 1997). Pahl and Beitz (1988) describe a function as the relationship between the input and the output of a system whose objective is to perform a task.

Observation that every system or part of a system has to perform a specified task originated the idea of the function synthesis. A task might represent a set of functions, which are defined by means of a concise combination of a noun and a verb, where the verb represents an action and the noun stands for the object of the action. Alternatively, a function might be defined by means of graphic symbols, in which input and output flows of material, energy and information are established. Under this point of view, the system is treated as a process in the course of which the input quantities are qualitatively and quantitatively transformed, and the objective of the design process is to determine the proper way by means of which this transformation should be carried out. Considering that each system or subsystem is related to a function, determining the solution principles for each sub-function is equivalent to finding the solution for the problem as a whole.

The several system-based function synthesis techniques present differences in the nature of the quantities represented by the functions and in the procedures adopted to organize them in a structural way. In these methodologies, the global function, which represents the general goal of the application of the system, is unfolded in partial less complex functions. Partial functions are related in order that, when executed conjunctively, the task defined by the global function be performed. The way the partial functions are structured is characteristic to each of the techniques. In the following, the methodologies proposed by Pahl and Beitz (1988), Roth (1982), and Koller (1985) are succinctly described, as these techniques comprise the classic techniques of the German tradition in product function synthesis.

2.1. The Pahl and Beitz approach

Pahl and Beitz (1988) propose a decomposition of the global function in terms of the flows of material (M), energy (E) and information (I) that crosses the borders of the system, as schematically shown in Fig. 1.

At the start of the process, the system's global function is defined from the design specifications. This function is unfolded in partial functions if the system is complex, following the flows of material, energy and information crossing each parcel. If necessary, these sub-functions are submitted to further decomposition, until the solution principles can be determined. This procedure comprises the following steps (Pahl and Beitz, 1988):

1. Identify, among the design specifications, the functions to be performed by the product;
2. Define a preliminary structure of functions. This initial unfolding might be conducted having in mind the functional requirements identified in the prior step and the analysis of the main flux of quantities (E, M, and I) within the system. The complete structure is then obtained through an iterative procedure, starting from the main flux, returning to it, and complementing the structure, with identification of the repetitive functions and logical relationships and linking of the compatible inputs and outputs. This procedure is mainly applied in the development of new designs;
3. Divide the preliminary functions structure by solving complex partial functions. If necessary, Pahl and Beitz (1988) suggest that sub-functions be connected to solution principles in order to derive simpler partial functions. To help accomplish this, a questionnaire, analogies or simulations can be used to provide designers with guidelines for the seeking of solutions;
4. Starting from the preliminary functions structure, define alternative structures, and optimize them by dividing, combining and varying the sets of individual sub-functions and types of links, or by moving the boundary of the system;
5. Evaluate the structures and choose the one that yields the best understanding of the product from the functional point of view;
6. For the selected structure, combine functions in order to make it simpler and favorable to the attaining of more economic solutions;
7. Use simple informative symbols to represent the final functions structure.

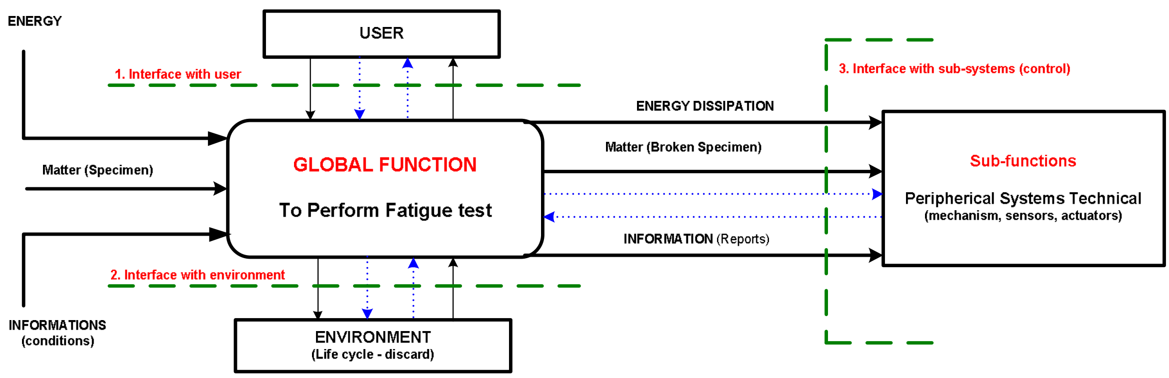


Figure 1. General structure of the functional synthesis technique, adapted from Pahl and Beitz (1988)

The method proposed by Pahl and Beitz (1988) allows for a general understanding of the product from the functional point of view. Moreover, this technique helps in the establishment of the logical relationship between the sub-functions and between the sub-function and its inputs and outputs. This aspect makes it easier to find out solutions for each part of the product and, consequently, for the whole problem. Nevertheless, the functions structure will be hardly established without the prior association of the sub-functions to some solution principle, which makes the search for alternative solutions a relatively complex task.

An alternative procedure suggested by those authors to help in the abstraction of the functions is to use generic functions (like, e.g., to transform, to vary, to connect, to transport, to store). However, these concepts might have different meanings and their symbolic representation might make it more difficult to realize and interpret the functions when one is not well acquainted with this kind of representation. In short, the method is strongly dependent on the intuition, experience and knowledge of the team of designers.

2.2. Roth's approach

In the chapter devoted to the functions structure, Roth (1982) proposes a functional synthesis method in which the elementary tasks are treated in a generic way, being defined as basic operations by the use of verbs and of the quantities energy, material and signal. The generic operations are to transport, to connect, to store, to change, to join, etc, as depicted in Fig. 2.

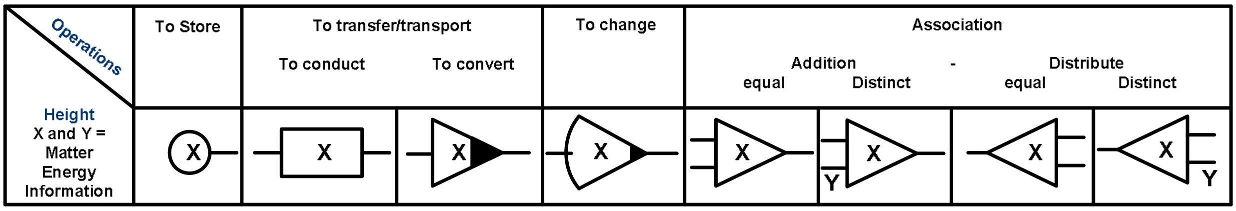


Figure 2. Generic structure proposes by Roth's method (Roth, 1982).

Although these functions are similar to those proposed by Pahl and Beitz (1988), Roth's proposal presupposes the usage of a catalogue of solutions principles which have been generically elaborated.

The procedure suggested by Roth (1982) is as follows. Initially, the structure of generic functions is established based on a list of the requisites of the design, with formulation of generic sentences. In this formulation of the generic sentences, successive abstractions are done of each requisite using the technical basic language. His work presents a list containing 225 technical verbs that help executing this task. To perform the abstraction of the tasks contained in the sentences the following steps are suggested:

1. Formulate the sentence that describes the task in current language;
2. Abstract and elaborate task sentences based on the objective and not on pre-existing solutions;
3. Extract the function sentence after further abstraction:
4. Subdivide the global function sentence into sentences corresponding to partial functions;
5. Separate the main partial functions from the secondary ones.

After having specified the tasks pertaining to a sentence, the development of the generic functions structure is started. The resulting structure is made to vary by means of the following steps:

1. Move the boundaries of the system;
2. Change the sequence of the generic functions structure;
3. Decompose individual elements of the generic functions structure into several elements;
4. Combine diverse elements of the generic functions structure to form one element;
5. Include generic transformer and carrier operations;
6. Change the position where signals are applied;
7. Multiply the branches of the generic functions structure by parallel structures.

The process ends with the selection of proper structure of variant structures.

Similar to the Pahl and Beitz method (1988), the Roth's approach is adequate for the functional representation of systems and subsystems. In the latter, however, representation of the functions is not dependent on the solutions principles, since Roth (1982) adopts a systematic procedure based on a generic representation in order to define the functions structures. Although both methods make it possible to manipulate functions structures as to obtain alternative structures, Roth's method enforces this procedure by taking it as part of the methodology. While Pahl and Beitz (1988) present procedures to help to find alternative solutions to the final structure, Roth's approach suggests the use of the solution principles catalogue to perform this task.

Besides the aforementioned advantage of Roth's method, the abstraction from generic sentences to formulate generic functions, as required in this methodology, consists in a complex task, since the way designers think of products is usually related to known functions or shapes. Another negative aspect of this technique is the need to apply rules of function variation which are not well defined and thus require some mental effort to be understood. Fiod Neto (1993) recommends that only one selected structure be worked out at a time in the stage of seeking of solutions, since the need to develop solution principles for diverse structures might mislead the designer.

2.3. Koller's method

Koller (1985) proposes a methodology to perform function synthesis in which the analysis is conducted by means of the development of a structure of basic operations starting from the structure of elementary functions. The operations structure is characterized by the definition of a sequence of operations to be performed by the product without defining input and output quantities. To be able to develop this structure, the author defined twelve basic operations and their respective inverses, which are shown in Fig. 3.

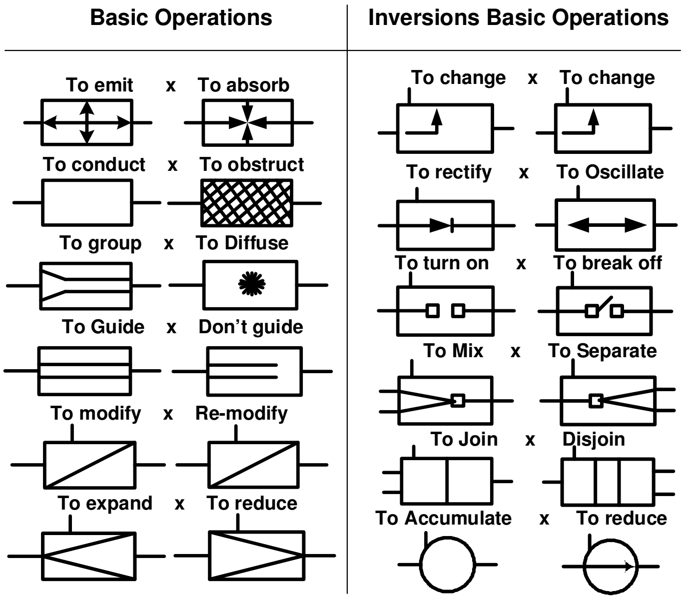


Figure 3. Diagram structure used in Koller's method (Koller, 1985).

The method consists in dividing the global function into partial functions until a structure of elementary tasks is obtained. After that, abstraction of the elementary functions is performed in order that basic operations are found along with the respective logical relationships, which results in the determination of the basic functions structure. The next step consists in varying this latter set to obtain alternative solutions and finally select the proper variants.

The method proposed by Koller (1985) allows for the development of a structure characterized by a low level of complexity and a high level of abstraction, which are strong assets for the next stages of the design of systems. The inconvenient in the process is that a basic operation often involves the transformation of more than one quantity (energy and material, for instance) and these relations are not well defined in the way they are treated in this methodology.

3. PROBLEM FORMULATION

The methodologies described in the previous section were applied in the context of the design of an apparatus to perform fatigue tests of plastic materials. In such a machine, a specimen is held in a vise and bent at the other end in periodic cycles, in a way to produce controlled stresses and deformations. The project design specifications were defined by Cavalcanti (2007). These are shown in Table 1.

Table 1. Design specifications of the apparatus for fatigue testing of plastic materials (Cavalcanti, 2007).

Requirement Project	Goals (nº)	Observations	Desirable exit	Undesirable exit
To realize fatigue test	1	Functional requirement	Machine applies bending cycles	Machine does not apply bending cycles
Final product cost	2		Less than R$ 50.000,00	Greater than R$ 50.000,00
Positioning error	3	Functional requirement	Less than defined in ASTM standard	Greater than defined in ASTM standard
Measument uncertainty	4	Functional requirement	Lower than 3%	Higher than 3%
To produce reports	5	Functional requirement	To emit report	Do not emit report
Amplitude range	6	Functional requirement	Greater than or equal range defined in ASTM standard	Less than range defined in ASTM standard
Frequency range	7	Functional requirement	Greater than or equal range defined in ASTM standard	Less than range defined in ASTM standard

To show test data	**8**	Functional requirement	Real time display of data	Do not display data
Number of ready solution	**9**		As high as possible	To have to project all components
Number of control devices	**10**		As high as possible	Complete manual operation
Number of control parameters	**11**		As high as possible	No control parameters
Manufacturing time	**12**		Less than six months	Greater than six months
Maintenance cost	**13**		As low as possible	High maintenance cost
Life cycle	**14**		Greater than ten years	Less than five years
Number of safety devices	**15**		As high as necessary	Less than necessary
Weight of movable parts	**16**		Less than 5 kg	Greater than 5 kg
Total weight	**17**		Less than 150 kg	Greater than 150 kg
Tolerance	**18**		Less than or equal (0,001±3%) in	Greater (0,001±3%) in
Volume	**19**		Less than 1 m^3	Greater than 1 m^3
Range of testable materials	**20**		As high as possible	Engineering plastics can not be tested
Maintenance frequency	**21**		As low as possible	Many stops for maintenance procedures
Setup time	**22**		As low as possible	Long time
Number of visible steps during the tests	**23**		As high as possible with provision for safety	No visible steps
Number of patents	**24**		As high as possible	No patent generated
Energy consumption	**25**		As low as possible	High consumption
Noise level	**26**		Less than 64dB	Greater than 64 dB

4. FUNCTIONS STRUCTURE

The functions structure of the apparatus for fatigue testing of plastic materials was determined by applying the methods proposed by Pahl and Beitz (1988), by Roth (1982) and by Koller (1985). The results are discussed in the continuation.

4.1. Functions structure obtained according the method by Pahl and Beitz

The establishment of the functions structure by means of the method proposed by Pahl and Beitz was made easier by the fact that the functional requirements are presented in the list of design requirements. Since the sequence of operations to be performed is well defined by the flux of materials, determination of the preliminary structure is almost automatic and association of functions with solution principles is avoided. The greatest difficulty found was in the identification of the auxiliary functions, because the method does not provide any guidance to help in this task, even though the need to proceed with this step is stated.

The optimization and simplification of the resulting structures require that an association be made between partial functions and solution principles, since a simplification step might result in the need for a complex solution, which might violate several requisites of the design. However, the nature of the operations has again contributed to facilitate this task, since only a few operations needed to be executed simultaneously.

In spite of the simplification of the process due to the characteristics of the product, the final structure, which is shown in Fig. 4, does not represent all the functional details of the parts of the elements, and this makes it more difficult to define solution principles.

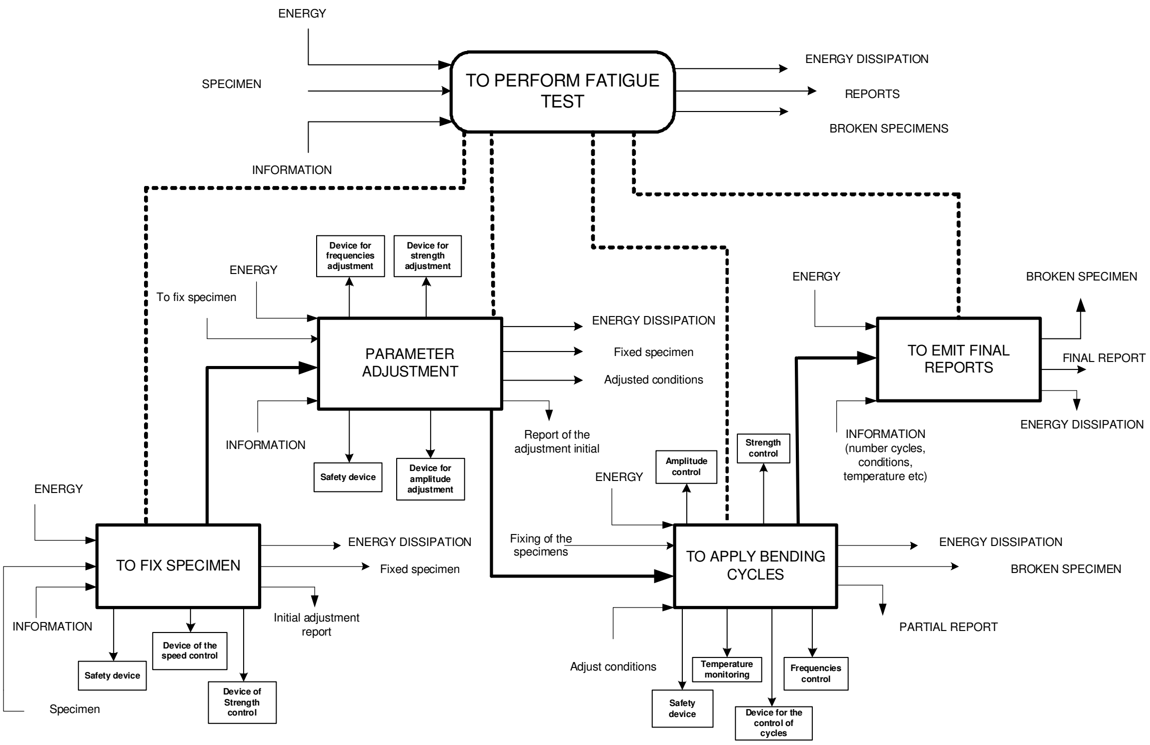
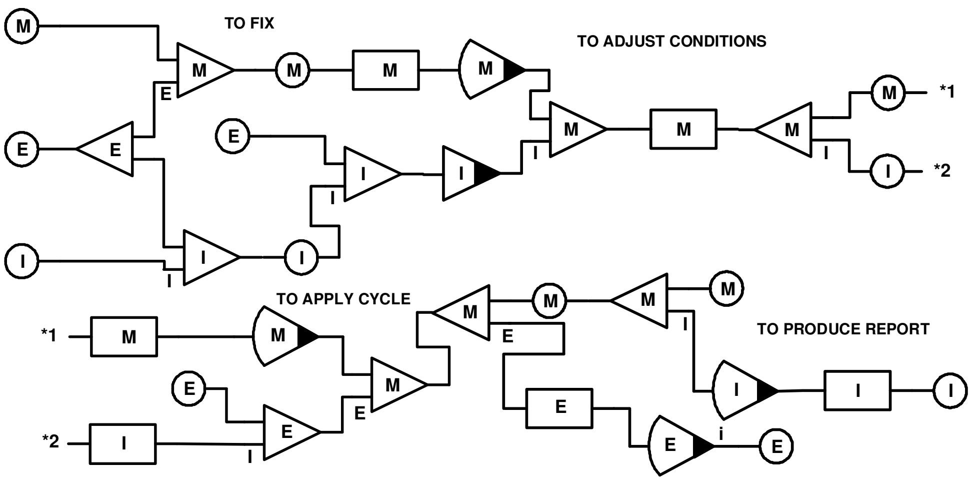


Figure 4. Functions structure of the apparatus for fatigue testing of plastic materials, as derived following the methodology by Pahl and Beitz (1988).

4.2. Functions structure obtained according the method by Roth

Similarly to what happened in the case described in the previous section, the nature of the product contributed to make it easier to determine the preliminary functions structure using the methodology proposed by Roth (1982). Another positive asset of this technique was the easiness in the identification of the auxiliary functions, which contributed to simplify the search of solutions when combined with the usage of the catalogue of solution principles suggested by Roth and even when combined with the morphologic matrix method.

The symbology applied to represent the generic function is complex and gives no explanation to the corresponding action. In other words, the structure does not represent the transformed material, but only indicates that a transformation took place, as is depicted in Fig. 5. This requires an enhanced familiarity of the designer with the nomenclature in order to use it and to understand what the structure represents. In the case under study, the knowledge of the product from the point of view of the functions to be performed contributed to facilitate the development of the structure, in spite of the innovative nature of the design.



LEGEND: M = Matter, E = Energy and I = Information

Figure 5. Functional structure of the apparatus for fatigue testing developed according Roth's approach.

4.3. Application of the function synthesis method suggested by Koller

The methodology proposed by Koller (1985) was applied in the design of the apparatus for fatigue testing of plastic materials. The resulting functions structure is presented in Fig. 6.

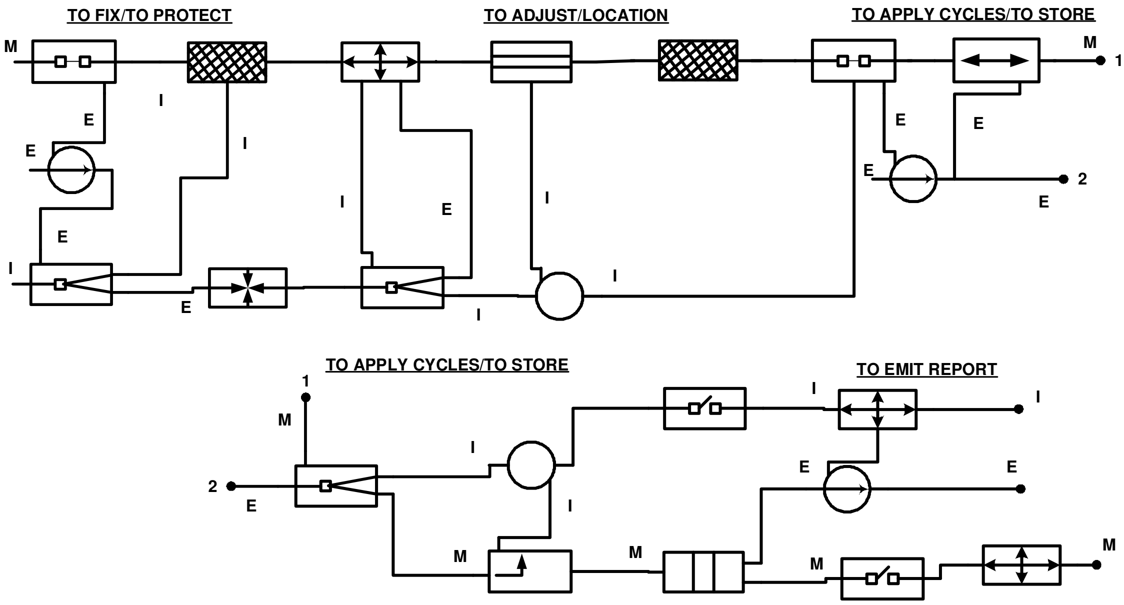


Figure 6. Functions structure of the apparatus for fatigue testing obtained according to Koller's method (1985).

The process presented similar aspects when compared to the application of the method suggested by Roth (1982). In this case, it is even more difficult to understand the symbology used and to establish the association between action and operation. Another difficulty found was in the representation of operations that take place simultaneously, like, for instance, filtering, protecting and supplying or recording and guiding. The positive asset of the method is that auxiliary functions are easily identified.

According to Koller's procedure, the initial work makes it easier to obtain the solution principles, although there is a decrease in the possibility to get alternative general solutions. To accomplish that, it is necessary to evaluate more than one functions structure, which results in more work to be done.

5. CONCLUSIONS

Classical methods for the product function deployment constitute effective tools to model systems in terms of the functions to be executed when the nature of these functions is known. These techniques are strongly dependent upon the experience of designers and on deep knowledge of the problem to be solved. Even though, the referred methodologies might be applied in the development of new designs or in case of redesign.

In spite of its innovative nature, the product considered in this study presents features that help in the application of the function deployment process. It was noticed that the degree of detail of the information gathered at the stage of definition of the task, namely on the functional aspects, contributed decisively to facilitate the development of the functions structures. When applying the function synthesis method according to Pahl and Beitz (1988), it was observed that the optimization and simplification of the resulting structures require that an association be made between partial functions and solution principles, since a simplification step might result in the need for a complex solution, which might violate several requisites of the design. However, the nature of the operations has again contributed to facilitate this task, since only a few operations needed to be executed simultaneously. There would be a greater difficulty if the characteristics of the quantities that cross the boundaries of the system were not known.

Association of the functions with the solution principles is unavoidable when function deployment methods are used, mainly during the analysis of the general operation of the product. In the application of the methods proposed by Roth (1982) and Koller (1985) there was no need to obtain solutions for the partial functions, since these are represented by generic functions and operations in these methodologies. Additionally, the symbols used in both methods helped to make it easier to identify the auxiliary functions, even though the detailed representation of transformations that take place simultaneously was not possible. The symbology applied to represent the generic function is complex and gives no explanation to the corresponding action, but only indicates that a transformation took place.

Another difficulty that was noticed in the application of the symbols regards to the representation of the nature of the output quantities at each step in the process of transformation of the generic functions and basic operations. The absence of this information demands great ability and knowledge of the designer regarding the problem to be solved, in order that s/he can interpret the resulting structure.

Owing to the specificities of the methods proposed by Koller and Roth, their application is likely to be more advantageous in the redesigning of products whose subsystems offer an opportunity for optimization. The usage of legends associated to the symbolic language is suggested as a way to improve the application of these methods. Nevertheless, owing to its generality, the function synthesis method is likely to be more adequately applied in the design of new products, as it allows for greater stimulation of creativity.

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