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AN EVOLUTIONARY APPROACH FOR FUNCTIONAL LEVEL CONCEPTUAL DESIGN OF PRODUCTS

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1. Introduction

The conceptual design phase of the product development period involves the completion of functional, structural and behavioural construction of the artifact. In order to systemize this significant design phase, two well-known design strategies namely bottom-up and top-down design approaches are developed in literature. While the traditional approach, using bottom-up strategy produces solutions for the design task at component level, top-down design strategy looks for original ideas at functional level before investigating physical solution alternatives.

In the generation of innovative solutions, bottom-up strategy does not provide the designer with an effective tool. In this approach, which constitutes solutions by gathering physical components and modules, it is very difficult to reach an undiscovered design. For instance, in a design task, although preferring a chain-sprocket pair rather than a gear box generates a variance in the solution, the functional composition behind both of these solutions are the same and the main aim is to "*increase torque*" in a power transmission unit. In the same manner, in many cases, the advances in both hardware and software technologies also create variety in designs but these new designs also become functionally equivalent of their initial prototypes. Therefore, functional resolution of the design task is the key point of the generation of the creative solutions [Ulman, 1997].

On the other hand, a drawback of designing the artifact in functional domain is the possibility of generation of physically unrealizable solutions. In this approach, the generation of a working and efficient solutions highly depends on the past experiences and prejudices of the designer [Roston, G. P., 1994]. The previously developed modeling strategies for functional design in literature are limited to developing a formal description way of designed artifacts. Although, these strategies are very useful in archival and transmittal of design information, they do not assist to guide designer in generation of the novel designs [Güroğlu, 2003].

The methods that investigate novel designs in functional domain such as breadth first and depth first search need supervising to avoid generation of physically impossible solutions. In addition, since both the physical and functional solution spaces present infinite configuration possibilities, these search techniques are very time consuming and in many times practically inapplicable. Therefore, the automation of the conceptual design phase at functional level necessitates the development of an intelligent search strategy. For this purpose, this paper introduces an evolutionary strategy for the functional level conceptual design of engineering products. The results of the computer implementation of this strategy are also presented in further sections of this paper.

Unlike traditional optimization strategies, evolutionary techniques are not directionless. They use past experiences to guide future events. These techniques yield continually improving performance of functions being sought [Roston, G. P., 1994]. Evolutionary approach extracts many successful and interesting solution suggestions, some of which would be difficult to invent or build by traditional design approach [Sims, K., 1994].

In the remainder of this paper, section 2 presents an overview on evolutionary design comprising the theory behind the artefact representation, the objective function determination, the genetic operations and the termination function definition, section 3 introduces an application of the evolutionary strategy to functional design of household appliances, in section 4 conclusions and future work are summarized.

2. Evolutionary Design

An evolutionary strategy has the advantage to create novel designs without requiring understanding of procedures used to generate them. It only requires a *representation scheme* to describe the developed artifacts and an *evaluation metric* to determine the quality of generated alternatives. This feature makes the strategy computer implementable. Moreover, not being founded on understanding of procedures makes the methodology domain independent and applicable both for functional and physical design issues. In literature, some applications of evolutionary design strategies to the physical design tasks are available.

The evolutionary strategy starts creating an initial population according to accepted representation scheme. Population size (number of individuals in population) is determined empirically. Although larger populations gives better results, these populations needs more computation time. In the next step, by using the developed evaluation metric, fitness values of all individuals in the population is calculated. After the assignment of the fitness values, by using these fitnesses and the average fitness of the population, the first genetic operation named “reproduction” is applied to the population. Reproduction operation determines the fitter individuals in the current population and copies these individuals to the next generation with a probability proportional to their fitness. Therefore, fitter individuals in the population survives and others become extinct. While reproduction operation determines the new population, the next step is the modification of the individuals of the new population. This step comprises two genetic operations namely crossover and mutation. The crossover operation aims to generate new individuals by crossing the individuals. Crossover operation starts with two parents and ends with two new children. Parents are selected proportionate to their fitness values and crossover point is selected randomly. Then parent individuals are crossed at that point and two new children occur in the new population. These operations on population are repeated until satisfying the termination criterion.

2.1 Artifact Representation

Evolutionary strategies differ in representation scheme. While genetic algorithms (GA) prefer string based representation scheme, genetic programming (GP) utilizes trees to represent the individuals. The preferred representation scheme for functional design has to be general enough to cover all possible solutions and permit the generation of new designs. It also has to be suitable for computer implementation. As a result of the studies on different representation schemes, graph based representation is selected as the most suitable scheme for an evolutionary approach to the functional design task. Graph based representation is preferred by all problems in which the optimization of the topology (arrangement of the parameters) is essential as well as the parameters. Some application examples of graph based GA in literature are truss design optimization problems and nanotechnologically design of molecules.

In functional design, graphs, which represents the design alternatives, are constructed by the functions (as vertices) and flows (as edges), which are defined in reconciled functional basis study [Stone R. B., 2001]. Reconciled functional basis groups all functions used to define all machines and systems under eight classes. These classes are detailed into secondary and tertiary levels. The degree of specification

increases with the level of the function. In addition, the flows described in this basis are also grouped under three major classes namely material, energy and signal.
In a graphical representation of a design alternative, functions and flows are taking their places in the sequence of their operations. In order to represent this sequence, directed graphs are preferred. Cycles are allowed and therefore all flow motions in a product can be observed in the functional model. In addition, the functions which need more than one input flows can easily be defined.
In figure 1, functional structure of a hair dryer is represented using a graph representation. In this product, the input flows are air (gas), human energy and electricity, the desired output flows is (gas+thermal energy+pneumatic energy) hot air flow. These flows are at the boundaries of the system and present the interactions between the environment and the product.

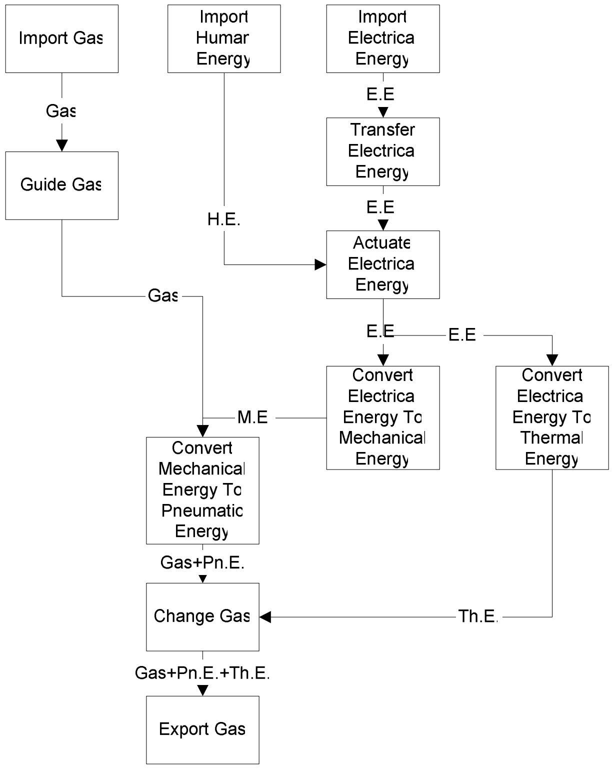

Figure 1. Functional Structure of Hair Dryer

2.2 Objective Function

In order to guide the evolution of artefact designs, an evaluation metric which awards or penalizes the generated individuals is required. This metric should be capable of evaluating all possible individuals that can be encountered in the steps of evolution.
The first evaluation measure in functional design is the mission check of the generated individuals. It should be considered that the individuals, which have the same input and output flows with the goal product, should have greater fitness values. For instance, if the goal product is a kettle, the individuals, which take liquid as input and give hot liquid as desired output become fitter than the others.
As another evaluation measure, complexity can be taken into account. The individuals, which have more subfunctions, become more complex than the others [Stone R. B., 1999]. Therefore, this evaluation measure gives values inversely proportional to the number of subfunctions.
As a result, the objective function will be the sum of these two evaluation measures. Development of new evaluation criteria such as a cost function is also allowable, in addition, the weighted sum of these measures can be used according to importance of the evaluation measure.

2.3 Genetic Operations and Termination Criterion

In the developed evolutionary strategy, the mutation operation, which is a secondary genetic operation is not employed. Mainly, this operation is not used to reach the global optimum. Instead of this, it provides a way to restore the genetic diversity lost in the generations of the population [Koza, J.R., 1992].The other genetic operations reproduction and crossover are explained in the following sections.

2.3.1 Reproduction

Fitness proportionate reproduction algorithm is choosen for reproduction operation. By applying this selection method, members of the new generation is selected.

2.3.2 Crossover

The parents, which participate the crossover operation are selected among the fittest individuals of the population. Selected parents can have different sizes and shapes. After selection, the common flows (edges) between two parents are investigated. One of the common flows is randomly selected and the edges representing this flow in both parents are cut. Therefore, both parents are separated into two parts. Then, these seperated modules are replaced with each other in both of the parents. Hence, the crossover operation is completed and two new children are generated. This is a single point crossover operation. It is also possible to define a multi point crossover by conserving the consistency of input and output flows of separated modules.
As an example to single point crossover, the figure 2 and 3 illustrate the parents on which the crossover operation will be performed. The parents, electric grill and solar water heater are cut from the common flow of thermal energy. Both of the modules bordered with red circles are subjected to crossover operation. By replacing the separated modules with each other, the new grill design will obtain the required thermal energy by converting the solar energy. In the same manner, the thermal energy necessary to heat water is provided by the conversion of the electricity.

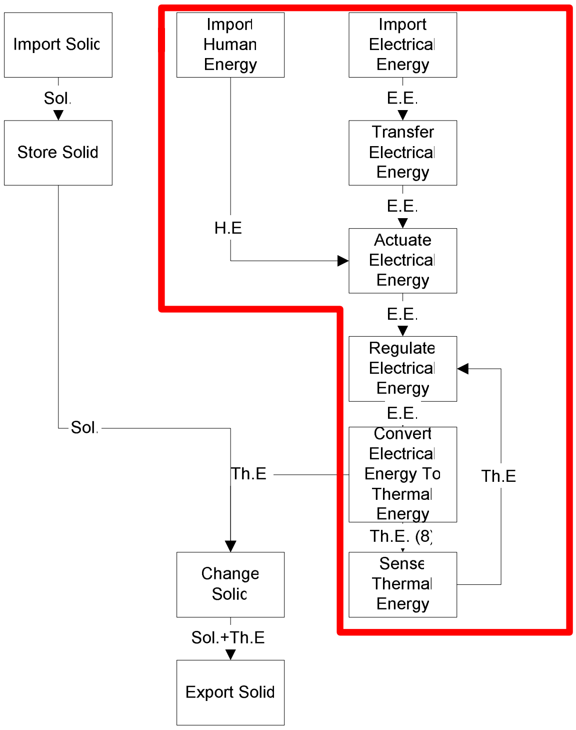

Figure 2. Functional Structure of Electric Grill

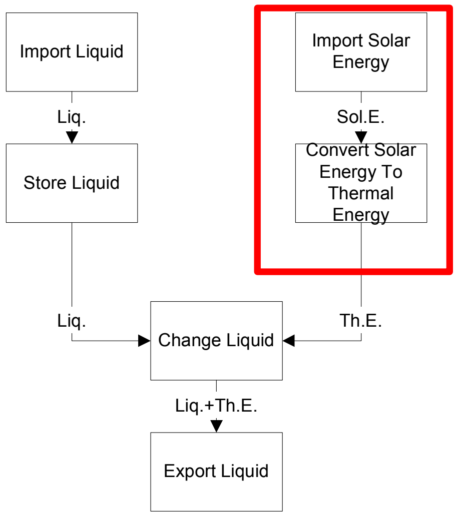

Figure 3. Functional Structure of Solar Water Heater

2.3.3 Termination Criterion

In this study, evolutionary strategy does not try to converge a unique solution, which is defined as the best design for the goal product. Instead of this, the main aim is to generate innovative solution alternatives which can satisfy the customer needs. Therefore, rather than defining an error function that measures the distance of the individual to the exact solution, the evolution is terminated by the execution of the predefined maximum number of generation. The operation is terminated when the maximum number of generation to be run is reached.

3. A Case Study: Evolutionary Design of Household Appliances

3.1 Goal

Design a product, which cooks food (e.g potato, mushroom etc.). Black box representation of this task is given in figure 4.

Figure 4. Black Box Representation of the Design Task

Black box representation of the product consists of the necessary flows and functional description of the task at the most abstract level. In this design study, these flows are "*solid*", which corresponds to raw food, as input flow and "*thermal energy*" + "*solid*", which represent cooked food, as output flow. In addition to these flows, in order to perform this task, product needs some other input and/or output flows (e.g. energy, information). The variations of these missing flows correspond to different functional solutions of the design problem.

3.2 Application of Evolutionary Design

The first step of the evolutionary method is the definition of the initial population. The individuals in this population must include all function chains required for the generation of a solution. Therefore, it would be beneficial to select more of the individuals among the members of similar product families to the goal product. Moreover, the proper selection of the other individuals, which belongs to other product families, will provide the design process with creativity. For that reason, several household devices such as kettle, rice cooker, espresso machine, microwave oven are choosen as some of the individuals of the initial population and graphical representation of the functional composition of these devices are derived. In addition, in order to provide diversity in the population, some energy conversion modules are also appended to the initial population. Consequently, an initial population with a size of thirty is obtained.

During the generations, many different kind of cookers have been designed. These designs have significant differences from the devices described in initial population. A popcorn popper design shown in figure 5 and a boiler design presented in figure 6 are only two of these new designs generated by the evolutionary computer program.

4. Conclusions and Future Work

This study has developed a strategy which generates innovative designs at conceptual level without need of human supervision. This new technique starting in a way similar to adaptive design ends with the development of creative solutions by randomness in evolution. By the help of the evaluation criteria defined by the designer, this evolutionary technique is capable of searching feasible design alternatives in unlimited functional solution space.

As the future work of this study, new tests will be performed for different evaluation measures under different constraints. A study will be carried out to define an evaluation criterion to measure the creativity in design. By the development of this new criterion, it is expected that the originality of generated individuals will increase.

Moreover, it is required to do some other tests to determine the optimum size of the initial population, ideal shape of the individuals in initial population and the best values for parameters of the genetic operations.

By the completion of these studies, an important step will be taken in the automation of the conceptual design stage.

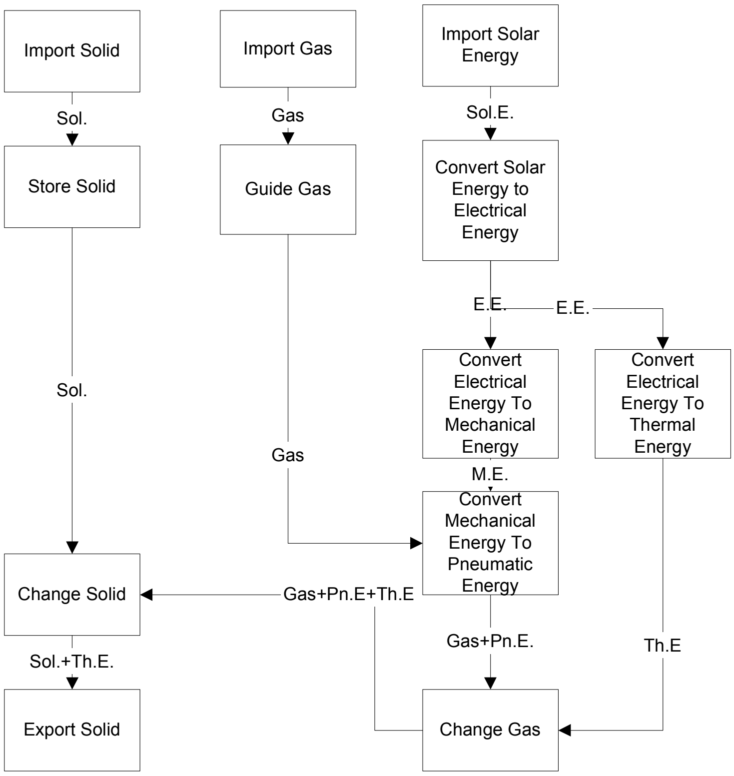

Figure 4. Functional Structure of Popcorn Popper

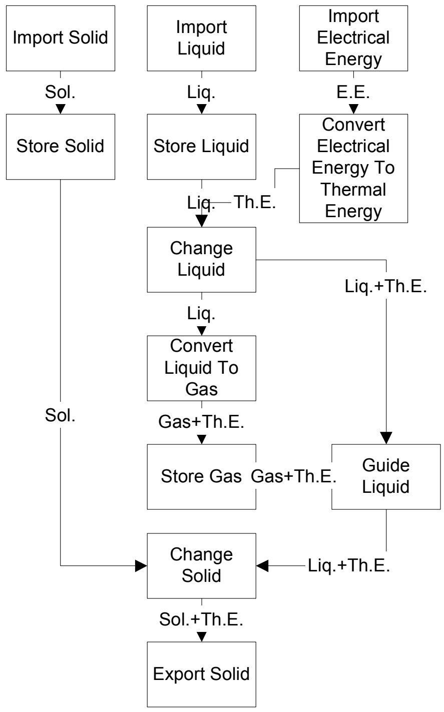

Figure 5. Functional Structure of Boiler

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