

Towards a case-based computational model for the creative design of electromagnetic devices^{*}

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Abstract: In order to explore creativity in design, a computational model based on Case-Based Reasoning (CBR) (an approach to employing old experiences to solve new problems) and other soft computing techniques from machine learning, is proposed in this paper. The new model is able to address the four challenging issues: generation of a design prototype from incomplete requirements, judgment and improvement of system performance given a sparse initial case base library, extraction of critical features from a given feature space, adaptation of retrieved previous solutions to similar problems for deriving a solution to a given design task. The core principle within this model is that different knowledge from various level cases can be explicitly explored and integrated into a practical design process. In order to demonstrate the practical significance of our presented computational model, a case-based design system for EM devices, which is capable of deriving a new design prototype from a real-world device case base with high dimensionality, has been developed.

Key words: Case-Based Reasoning (CBR), creativity, computational model, electromagnetic (EM) device.

1. Introduction

Design is defined as a human activity for the making of an artifact or the constructing of a system and is normally described as a goal-oriented process. Such an activity often begins with presenting the specification of needs and detailing the problem with the existing prototypes; triggering new actions to solve the problem. Thus, it can be postulated that the design process is evolutionary in nature and could be implemented and optimized in a soft computing system.

Furthermore, in order to accomplish a design task, it is imperative to use different knowledge sources such as scientific principles, technical information, human imagination and ex-

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perience. The design experiences accumulated by experts and engineers in past successful achievements provide a fertile place for designers to draw inspiration, which might help them deal with current and future complex problems creatively [1]. As a class of problem solving, design can be formulated as a problem of searching through a design space of potential solutions for the target one that meets the given requirements. Treating designing as a search makes it possible to apply artificial intelligence (AI) techniques in the area of design research.

Design as problem solving is labelled “ill-structured” since the specifications are not always complete and functional goals are often inconsistent; and the corresponding definitions of algorithmic solutions lack clarity [2]. The difficulty of the design task increases as the designer addresses the complexities of a field such as EM devices.

1.1. Categories of design

Depending on the level of creativity required in the course of solving a design problem, design is categorized into three kinds (routine, non-routine and creative) in this paper. Routine design differs from an existing design strictly in terms of parameter values. Non-routine design is framed in the same overall topology as a previous design, but it needs some individual components to be updated. Creative design, on the other hand, has an overall topology different from all previous designs [3]. However, there are no clear-cut boundaries among these three kinds of design activities.

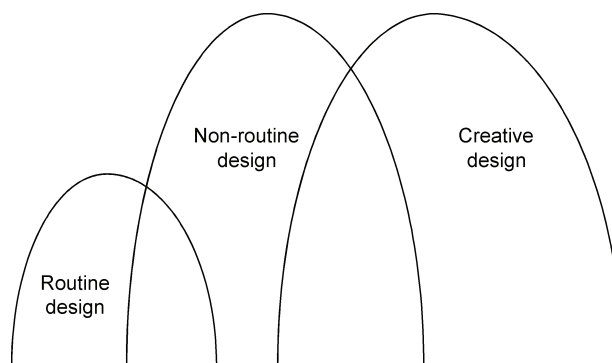


Fig. 1. Design spectrum relationship

Routine design is defined as a process that follows a defined schema in which the expectations of what follows are defined by the schema. It operates within a context which constrains the available ranges of a value [4].

Non-routine design falls somewhere between routine and creative design and includes replacement of components or structural behavior while maintaining functionality.

Creative design is defined as a reasoning process that is based on criteria and constraints that overstep the bounds of the stated constraints of existing solutions [5].

Based on our analysis in this section, we can define the spectrum of design in terms of routine, non-routine and creative design. As shown in Figure 1, non-routine design is a continuation of routine design; creative design is an extension of non-routine design.

While routine design is quite mundane, non-routine and creative design are much more interesting. Non-routine design can generate a design solution in which the alternatives for each of its sub-components can be synthesized; creative design can be carried out by employing a reasoning process that derives a solution from design experiences rather than from scratch, robust theories (such as CBR, data mining, machine learning and optimization) from AI can be applied to support the process.

1.2. A general design process

The basic design process consists of two phases and is shown in Figure 2. The first critical phase of a design process is to generate a prototype device.

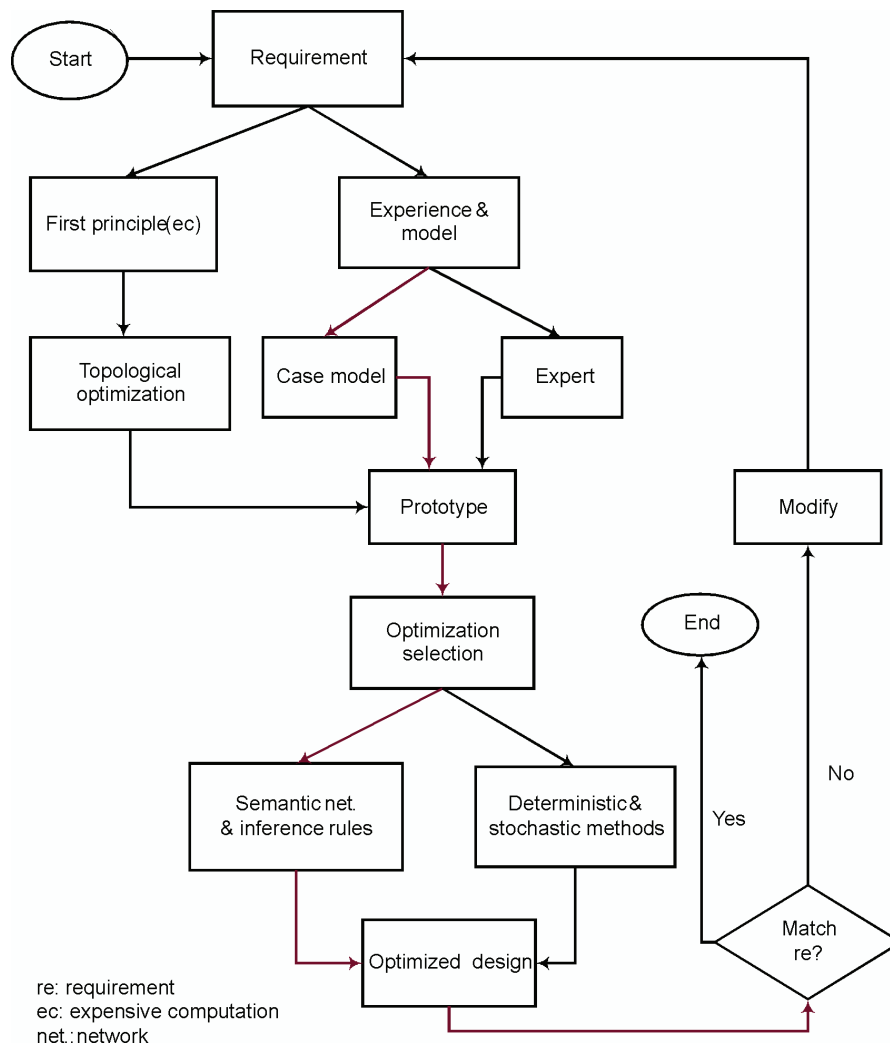


Fig. 2. A general design process

As seen in Figure 2, there are usually two approaches to deriving a prototype: either starting from first principles, then going through a topological optimization (a mathematical technique used to optimize the material layout of a device within a given design space) to obtain one; or reusing past experiences from an expert or automatically finding a similar design model from an existing device case base by a computer-based system, to derive one.

The second phase deals with how to apply appropriate optimization techniques (such as deterministic or stochastic optimization methods, or an inference rule system based on semantic networks in [6]) to accelerate the derivation of a “real” device. The purpose of optimization is to find an improved solution to meet the requirement. Researchers select deterministic optimization methods if they have information about the derivatives of the requirements with respect to the design parameters and the scale of the design space is not too “big”; otherwise they prefer to make use of the stochastic optimization approaches.

1.3. EM device design

The design of an EM device or system, such as an electrical machine, often starts from the choice of a suitable previous design prototype which is fairly close in performance to the desired specifications. The design process is then one of modifying this structure to satisfy the new requirements. Once an appropriate prototype is found, it is adapted to meet the new requirements. Although the concept is relatively simple, there are a large number of problems which need to be solved. Many of these are domain dependent. For example, in the case of electrical machines, there are often relatively few previous designs – new designs are expensive and take considerable time to develop. In addition, the ideal solution to a posed design task varies with time and technology, i.e. as technology changes, previous solutions become obsolete and thus the current device prototype has to be continuously updated and modified. The problem is in knowing how good the existing devices are, i.e. how capable are they likely to be for generating a new solution? All these problems can be answered through the development of a new computational model that demonstrates how an intelligent design system is able to attack issues related to EM device design.

As an extension of [7], this paper presents a computational model based on CBR for investigating some creativity related to design problems. Also, a case-based design system for EM devices has been developed and tested on a large real-world database consisting of induction motor examples.

2. Related work

2.1. Case-based reasoning background

CBR stems from the research in cognitive psychology as a model of human memory and remembering, and is founded on a group of well-established scientific disciplines: cognitive science, machine learning and mathematics [8].

The reasoning ability of CBR is based on two principles. The first one is that it is very natural to employ old solutions to solve similar current or future problems. The second is that new problems are not absolutely different from the previous ones. These two principles actually hold in any domain [9].

As a problem solving method, CBR touches on some of the most basic issues in AI such as knowledge representation, reasoning and learning from experience.

At a high level, a CBR process consists of the following main steps [10]:

- 1) *Represent* information and domain knowledge as cases.
- 2) *Retrieve* the most similar case(s) from an existing case base.
- 3) *Adapt* the retrieved cases to match the new requirements of a problem at hand (if necessary).
- 4) *Retain* the new solution in the case base for future use.

2.2. Case based design system

Since previous successful experiences can play a key role in the process of deriving new or future design solutions, it seems well suited to apply CBR to solve complicated given problems.

For the sake of demonstrating the powerful reasoning ability of the CBR method, we present several successful practical case-based design systems as follows.

CYCLOPS: It is considered to be the first case based design (CBD) system (developed by Navinchandra in 1987) at the Massachusetts Institute of Technology and used in the domain of landscape architecture. A new algorithm, Demand Posting, is proposed in CYCLOPS. This new technique breaks down a design problem into goals and sub-goals, and then retrieves appropriate cases and sub-cases to satisfy the goals and sub-goals using an iterative process. A search algorithm is employed to combine sub-components of retrieved cases using cross-domain analogy to generate an innovative solution [11].

CASECAD & DEMEX: CBR systems for building designs. These systems share the characteristic that each attribute is associated with a finite list of ranges of values employed to classify the design solutions. It is from these values that individual design solutions can be inferred. However, these systems lack an adaptation component and find new design solutions using only a retrieval mechanism. This type of system, therefore, functions primarily as a browsing tool allowing the user to search for information and perform manual modifications [12].

FAMING System: An interactive design system investigates the design of a particular kind of mechanism embodied in antique wall clocks and was developed by Faltings & Sons in 1996. This design system integrates functional reasoning with complex structural reasoning regarding shapes and spatial relations [13].

CBR-Non-routine Design System for EM Devices: A relatively new case based reasoning design system (developed by Vo and Lowther) for the non-routine design of electromagnetic devices. It combines the strength of multiple reasoning paradigms built on top of CBR, flexibly uses different knowledge sources fully exploiting its database of experiences, and provides a dynamic environment where different alternatives can be examined under different views. The salient advantage of the system is that it broadens the spectrum of possible design solutions [14].

CBE-Conveyor: A case-based reasoning system used to assist engineers in designing conveyor systems. In the system, Woon et al. combine the use of CBR with numerical engineering models as a general architecture to create the new domain “Case Based Engineering” (CBE). They solve the problems related to CBE, such as: flexibility of query forms, interpolation, multi-valued case mapping, and constraints. Furthermore, this new technique has been applied to the design of conveyors [15].

CaSyn-MEMS: A knowledge-based tool for microelectromechanical systems (MEMS) design synthesis and its complete name is: Case-based Synthesis of MEMS. Through integrating parametric optimization and a multi-objective genetic algorithm (MOGA) into a case based reasoning paradigm. CaSyn-MEMS is able to extend the reasoning ability of a traditional CBR system. Its practical effect has been demonstrated by synthesizing new MEMS design topologies that have optimal properties [16].

Based on the proposed definitions in Section 1, we can consider CYCLOPS as a routine design system, the FAMING System and CBR-Non-routine Design System for EM Devices as non-routine ones, and CBE-Conveyor and CaSyn-MEMS as ones with some sort of creative design.

So far, there is no doubt that impressive progress has been achieved since the beginning of CBR; however, most existing case-based design systems do not live up to their full reasoning potential. They restrict their reasoning ability to reusing and adapting the old solutions in ordinary ways without involving enough creativity.

3. A case-based computational model for EM device design

In order to achieve a significant advance in reasoning capabilities of CBR, it has to effectively take advantage of powerful and full-grown AI techniques and explicit domain knowledge. This has the possibility of extending the sphere of CBR methodology, thus really realizing creative design.

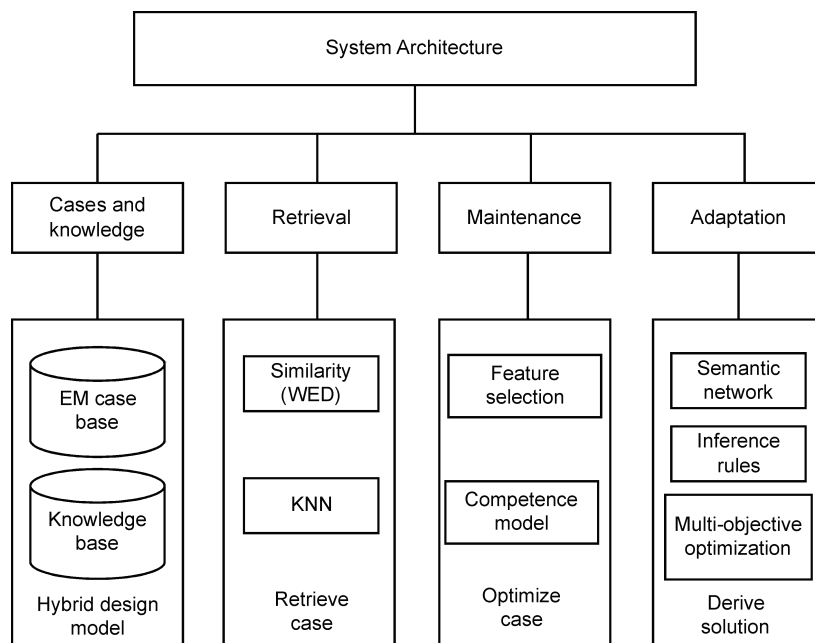
3.1. A case-based computation model

To extend the creative reasoning ability of CBR, we propose a computational model that involves the following four main sub-components.

- 1) *Design knowledge representation*: a hybrid design model has been adopted to organize all design knowledge for a generic EM device in an object-oriented framework. It plays the role of the reasoning engine for the whole case-based intelligent design process. The case base of this model is designed as a hierarchical structure that starts with an abstract design entity at the top and ends with concrete physical electromagnetic devices at the bottom. The knowledge base consists of a set of “if-then” rules and mathematical equations which characterize the relationships among design components [17].
- 2) *Case retrieval*: the retrieval searches the case base for similar examples by using the k-nearest neighbour (k-NN) technique [18]. In this method, a case is selected when the

- weighted similarity sum of its features that match the corresponding ones of the given design problem is greater than that for other cases in the case base.
- 3) *Case maintenance*: a feature selection technique is adopted to choose a pivotal feature subset from the design space. A competence model is used to generate a “good” case as the starting point for exploring the design space [19].
 - 4) *Case adaptation*: is regarded as a multi-objective optimization process, and derives an approximate solution by constructing a rule-based inference engine based on semantic networks which are capable of modelling the global and local qualitative constraints of a device. These rules are employed to implement an adaptation process.

3.2. The system architecture of a case-based design system



KNN: k-Nearest Neighbor
 WED: Weighted Euclidean Distance
 EM: Electromagnetic

Fig. 3. System architecture for a CBR system

In addition, to demonstrate the practical significance of the presented computational model in this section, a system architecture (Fig. 3) is presented and employed to integrate all the sub-systems related to a case-based system for EM device design.

Collectively, this architecture includes four main interacting sub-components: 1) a case and knowledge organization model, 2) a retrieval sub-system, 3) a maintenance part, and 4) an adaptation module.

4. Empirical study

4.1. The process of designing an EM device

The design of an EM device is an iterative process which ends when the derived design prototype meets the given requirements. The flowchart of designing a device is described in Figure 4.

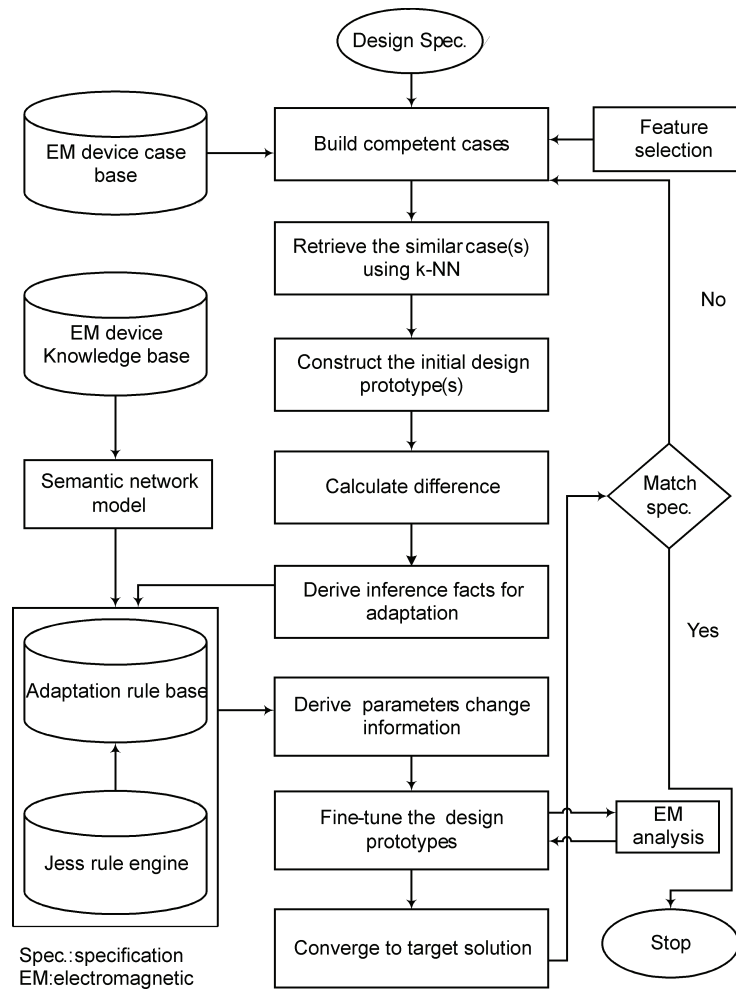


Fig. 4. The process of designing an EM device

Triggered by design specifications, the case-based design system will first build a competent case library based on the feature information from the specifications. The competent case library is clustered into case subgroups. The centres of the subgroups are chosen as preferred potential cases to be retrieved. Then the retrieved case(s) are used to launch an adaptation process. The process starts with calculating the feature differences between the input require-

ment and retrieved cases in order to collect initial inference facts. After combining the facts and adaptation rules, the adaptation is capable of deriving all the appropriate parameter change information that is used to fine-tune the related design features. These changes determine whether the potential candidates might converge to the target solution(s). If the adaptation is successful, the derived device case(s) are added to the case library for future problem solving.

In the system, MagNet (V7), a simulation software tool for EM fields, is utilized to test and predict the performance of derived possible candidate device prototypes [20].

4.2. An example: designing an induction motor

An induction motor is the most common of all electromagnetic devices, and has been used for over a century in a wide range of applications due to its robustness and low construction cost. The underlying principle on which it is based is the rotating magnetic field concept. A stationary winding produces a rotating magnetic field, which induces an alternating current in the rotor. The motor torque is produced by the resultant interaction of the induced rotor-current with the rotating field of the stationary winding. A real-world induction motor case base has been constructed by using MotorSolve [21], and includes 266 cases. Each case has 69 critical features which reflect the overall characteristics of a motor.

For example, in order to design an induction motor with a rated output power of 1.6hp and full load speed of 3340rpm, two cases (case 16 with 0.5hp and 2829rpm and case 147 with 1.269hp and 2829rpm) from our motor case base are retrieved because each of them maximizes the weighted similarity sums of their features that match the given design task. A combined motor model in which the stator part is from case 16 and the rotor part is from case 147 is selected as a starting point to carry out an adaptation process.

The objective function is constructed as follows:

$$\text{target} = \sum_1^n w_i(\text{feature}_t(i)), \quad (1)$$

$$\text{actual} = \sum_1^n w_i(\text{feature}_a(i)), \quad (2)$$

$$\text{error_bound} = \text{abs}(\text{target} - \text{initial_actual}), \quad (3)$$

$$\text{objective} = \text{abs}\left(\frac{\text{target} - \text{actual}}{\text{error_bound}}\right). \quad (4)$$

Here, $\text{feature}_t(i)$ denotes the i th feature of the desired target device and $\text{feature}_a(i)$ indicates the i th feature of an actual case; $\text{abs}(\)$ represents a function used to calculate the absolute value of $(\)$ and w_i is a weighted value corresponding to the i -th feature.

The error_bound (Eq. 3) is defined as the difference between the target and the initial value of the actual parameter or feature (represented as initial_actual).

The objective function is defined in Equation 4.

The adaptation module computed the difference between the retrieved case and the input requirements; and then obtained the following inference facts:

To meet the design requirements, it is necessary to increase the mechanical power and the mechanical speed.

According to the derived facts, the adaptation module determined that increasing the input voltage (Vs), stack length (Sl) and the diameter of air gap (Dag), or decreasing the air gap (g) and motor slip (s), will increase horse power; increasing the frequency (fs) or decreasing the number of poles (p) will increase the mechanical speed.

4.3. Experimental results

The experimental results (Figs. 5-7) show that It takes 7 steps to derive an approximate solution, case 7 (with 1.55hp and 3382rpm); the detailed convergences of the main parameters (VS, Sl, Dag, g, slip, fs and poles) are shown in Table 1.

Table 1. The convergence process for fine-tuned parameters

Feature	Vs [v]	Sl [mm]	Dag [mm]	g [mm]	slip [%]	fs [Hz]	p
case1	730	130	65.693	0.36	0.05	50	2
case2	810	137	65.695	0.3495	0.049725	52	2
case3	877	143	65.696	0.339	0.049519884	55	2
case4	931	147	65.698	0.3285	0.049366682	56	2
case5	975	151	65.699	0.318	0.049252136	58	2
case6	1009	153	65.701	0.3075	0.049166426	59	2
case7	1035	155	65.702	0.297	0.049102255	59	2

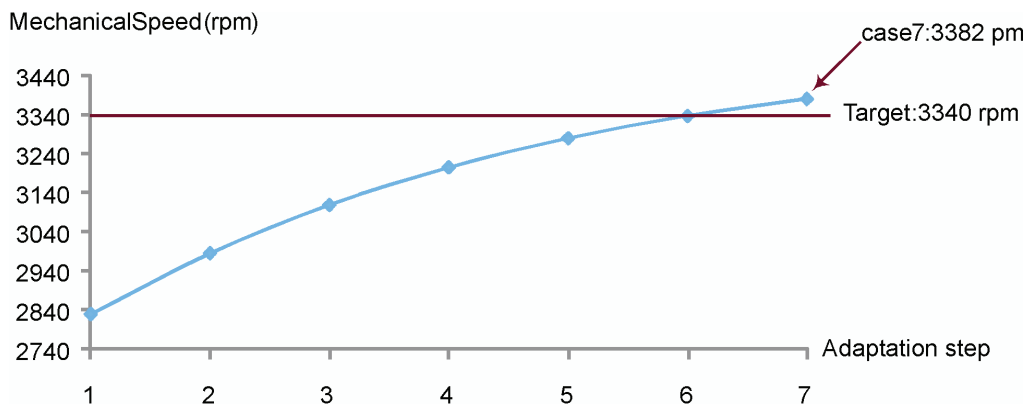


Fig. 5. The convergence process of N

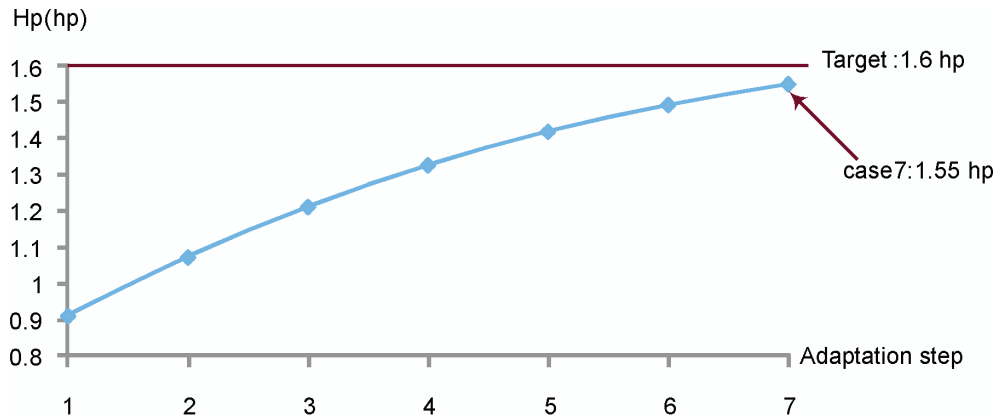


Fig. 6. The convergence process of Hp

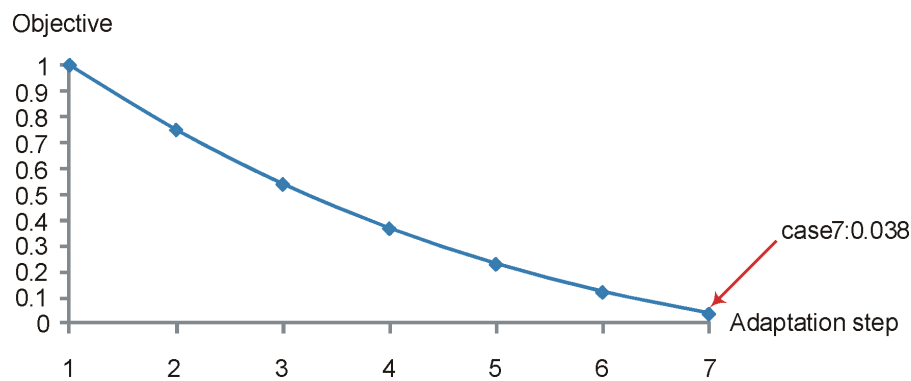


Fig. 7. The convergence process of the objective

5. Conclusion

This paper presents a case-based computational model, which is used as a guide to develop a creative design system for low frequency EM devices. This developed system is able to break the impasse that cannot be overcome by a routine or non-routine design process and derive a solution to satisfy the incomplete given requirements based on component substitution. The reasoning ability of the system comes from the idea of integrating domain knowledge from a design case base, and inference rules, into a full design process.

Acknowledgements

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