A Knowledge-Based System for the Design of Rubber Compounds in Motor Racing

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Abstract. This work presents P-Race, a knowledge-based system designed to support the formulation of rubber compounds of tyre tread, in order to take part (and win) in motor racing. Because of the different competence involved in the decision making process (the compound designer and the race engineer), multiple knowledge representations have been adopted, and integrated into a unique Case-Based Reasoning (CBR) computational framework. The case-based approach captures the episodic knowledge characterising most of reasoning activity of the race engineer. Moreover, a dedicated representation formalism called Abstract Compounds Machine (ACM) has been created in order to allow the core knowledge about rubber compounds to be explicitly represented, computed and integrated in the CBR architecture. The most meaningful and innovative contribution of P-Race consists of a general case-based architecture where the adaptation step is performed by the ACM chemical formulation model. This system has been developed for the Motorsports Department of Pirelli Tyres, where it is currently in use.

1 INTRODUCTION

In motor racing the role of tyres is crucial. Among the parts that must be assembled in order to build a tyre, *tread* is one of the most important. It is made by a *recipe* which determines its major properties. The basic material composing tread obtained by the recipe is called in jargon *batch*. Tread batch comprises a set of ingredients: artificial or natural elastomers (rubber), active fillers (carbon black, silica), accelerants, oils, and some others. All these ingredients are essential for the acquisition of the desired chemical-physical properties determining the needed performance. In the case of large scale production, a set of standard lab tests is usually performed in order to obtain the best performance from a tread. In motor racing, however, only few tests can be performed, because of the particular raw materials used and the characteristics of the chemical compound of the tread. The global performances of tread can be verified therefore only during the trials or directly during the race. The evaluation of the performances is not absolute, but depends on several factors. The most important of them, *characterising each single race*, concerns car set-up, road ground, geometrical profile and severity of the tracks, weather conditions, and racing team. Quite obviously, the skills of the people involved in designing motor racing tyres (race engineers, tyre designers and compound designers) consist of their experience on the field and their knowledge about a very complex decision making problem. More in detail, the choice of the tread batch involves the race engineer and the compound designer. Since their choice is tied to a single race, it is usually strongly dependent on performances and results obtained in previous races on 'similar' tracks (usually in previous seasons of the championship, such as Sports Racing World Cup (SRWC), American Le Mans Series (ALMS), or others). Moreover, even if in the previous race both performances and results have been the best, the improvement of some performance (grip, warm-up, thermal and mechanical stability, resistance to wear) is anyway required, because of hypothetical improvement of the competitors. Basically, the choice of a tread for a particular race depends on the results of previously solved cases: the general problem solving mechanism used by race engineers and compound designers is strongly based on reasoning about past cases in order to solve a new case. Also, the use of *episodic knowledge* is one of the main characteristics determining the choice of the tread batch for motor racing. The modalities that allow to obtain solutions from the reasoning about past cases in this specific case are:

- *reuse* of a solution previously adopted, i.e. the same tread batch used in some previous race of a championship;
- *adaptation* of a solution previously adopted, i.e. the design of a new compound, modifying some elements in the recipe of the batch, in order to improve its expected performances;
- *creation* of a new solution, i.e. design a new compound from scratch.

The P-Race system is a Case-Based Reasoning system dedicated to design, developed for the Motorsports Department of Pirelli Tyres where it is currently in use. It supports the first two points mentioned above and has been integrated in the general information technology environment of the company.

In the literature, other CBR-based systems devoted to chemical formulation are presented in [1], and [2] (where an adapter module is explicitly shown).

The main purpose of this paper is to describe the features of the P-Race system. The general architecture of P- Race will be outlined in the next section. In Subsections 2.1 and 2.2 the CBR component and the ACM component supporting the adapting step of the CBR cycle will be presented. Section 3 will describe the application benefits. The paper ends with some concluding remarks.

2 GENERAL ARCHITECTURE OF THE P-RACE SYSTEM

The design activity of tread batches for tyres dedicated to motor racing at the Motorsports Department of Pirelli Tyres can be represented in terms of Case-Based Reasoning in Design (CBRD) [3, 4]. As in other cases of design activity supported by CBRD, the P-Race system supports the Motorsports Department team both for the reuse of

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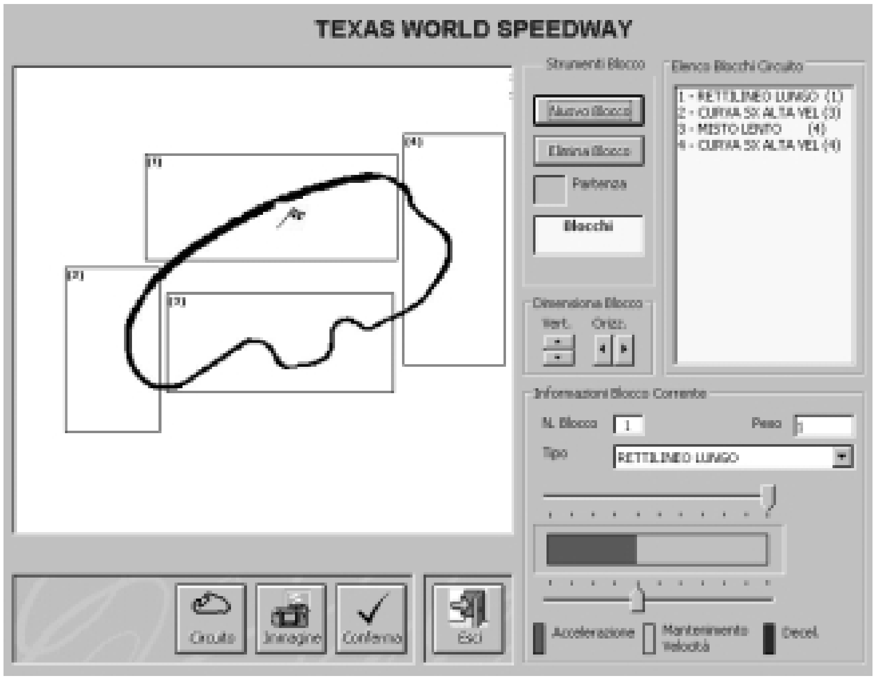

Figure 1. User interface for the track description

a solution adopted in past experiences and the generation of new solutions adapting an old case to the current problem. In particular, P-Race assists the two main characters of the team: the race engineer and the compound designer. The race engineer needs a workstation where his activity is supported by the following components:

- a database containing all meaningful data about the racing activity (dates, kind of championship, car, team, drivers, trial times, warm-up times, race times, coded recipe of the used tread batch, coded information about the tyre structure, and so on);
- a dedicated system containing quantitative and qualitative representations of the tracks where races take place; these descriptions capture the experience and the knowledge of the race engineer in terms of crucial information about the track (e.g., the features of track bends in terms of their severity and the required tyre performances, the characteristics of the track surface, the thermal variation from a straight stretch to a bend and vice versa);
- a case base which indexes (starting from the above database and description components) and structures in cases the pragmatic features of a race to be used in the design of solutions for a new race;
- a dedicated user interface for access to the three components mentioned above.

In Figure 1 is shown an example of the user interface dedicated to the race engineer, with the description of the College Station (Texas) track.

The compound designer needs a dedicated workstation whose main components are:

- a dedicated integration interface with the recipes database and other confidential data contained in the information system of the company;
- a generator of modified recipes;
- an explanation module;
- a dedicated user interface for access to the three components mentioned above.

The general architecture of P-Race is outlined in Figure 2. It can be divided into three main conceptual parts (drawn by dotted lines in the figure). Part A contains the main components devoted to the race engineer: a dedicated user Interface designed in order to access both the Tracks Description component and the Races Data component. Data contained in the last two components are indexed in order to be transformed into cases.

Part B consists of the main components supporting the activity of the compounds designer: a dedicated user Interface, the ACM component which represents the adapter and comprises the generator of recipes and an explanation module, and the integration interface for access to the Recipes Archive belonging to the information system of the company.

Part C is the Case-Based Reasoning core, composed by a Case Memory component and the Indexing, Reuse, Retrieve, and ACM Adapter modules.

In the following two subsections the main features of the CBR core system and the ACM component will be described.

2.1 The CBR component

As previously introduced, the part C drawn in Figure 2 outlines the general architecture of the CBR cycle of P-Race, containing:

- the *case memory*, where each case represents a set of chronometrical measurements, concerning a race or a trial, relevant for the performance or the technical solution adopted. As in any CBR system, the three major parts of a case are problem/situation description, solution, and outcome [5]. In P-Race the description of

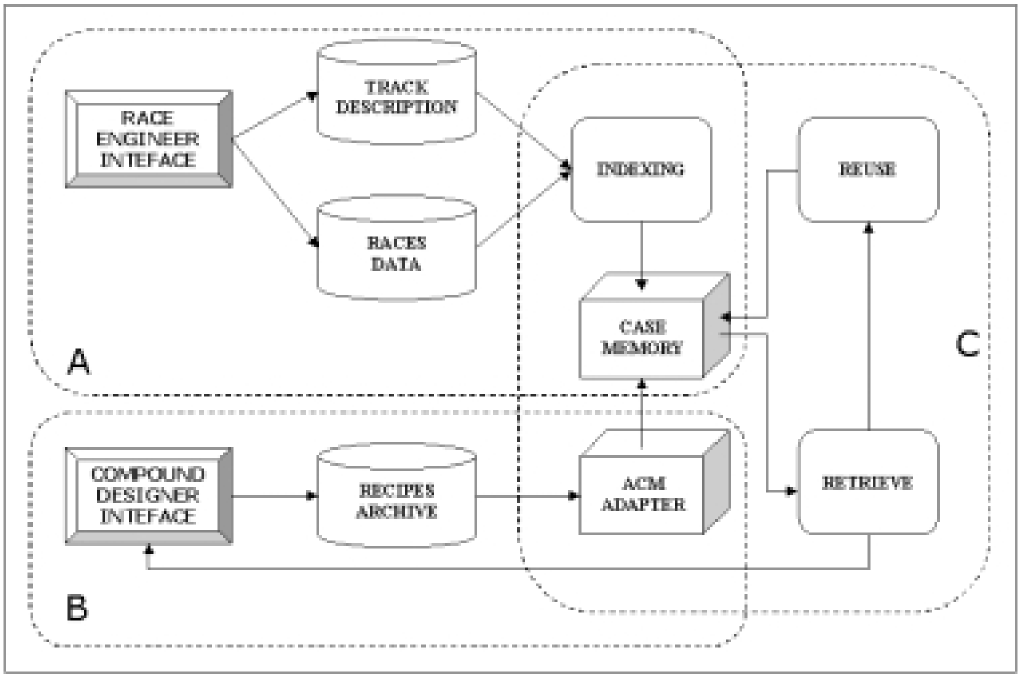

Figure 2. The architecture of P-Race

the problem contains descriptive information (date, time and location of the event) and a set of parameters used by the system to retrieve from the case memory the most similar cases (the description of this set of parameters is both quantitative and qualitative, that is, expressed by a fuzzy representation). The solution for a case describes the coded recipe of the batch for that case, while the outcome represents the resulting state in terms of performances obtained when the solution was applied.

- the *case memory manager* able to store and retrieve solutions from the case memory and to evaluate the similarity between the current case and the stored ones. Similarity is defined as a weighted distance between attributes describing the cases in the case-base. Both the solution and the outcome of a retrieved case must be controlled by the compound designer (through the Compound Designer Interface), who activates the Adapt module.
- the *ACM Adapter*, that adapts retrieved solutions to the current problem. It activates the integration interface with the recipes archive of the company in order to provide to the ACM component the decoded recipe expressed in terms of quantity of ingredients (see *Description Rules* in the next subsection). That is, it modifies the recipe of the proposed batch in order to improve the performance observed in the outcomes of the past case, or to obtain new performances in relation with the description of the new case (where some of the most meaningful data are the thermal severity of the track, the required performance and the decoded recipe).

The reasoning process starts with the representation of the current problem as a case to be solved. Starting from the new description, the system examines the case base containing past cases already solved, and proposes a list of solutions (the most similar cases). The main task of the retrieval algorithm is to apply a function giving a measure of similarity among cases. In the P-Race system, the similarity function has been defined as the weighted sum of differences between attributes. Case retrieval is based on knowledge about tracks, weather conditions, and type of track surface. The list of solutions proposed by the system could, at this point, include a feasible solution for the problem at hand that could be directly applied. Otherwise, an adaptation process has to modify one of the proposed solutions.

2.2 The ACM Adapter component

The main part of the adapter module is dedicated to the design of a rubber compound, that is, the generation of the chemical formulation of a specific recipe. Since information concerning this part of the system is strictly confidential, only an abstract description of this mechanism and some simple examples will be given.

The Abstract Compound Machine (ACM) [6] is a model created for the representation and the computation of the knowledge involved in the chemical formulation of a compound. It is derived from the CHAM (Chemical Abstract Machine) formalism [7]. In particular, the implementation of the ACM model presented in this paper regards the formulation of rubber compounds.

In the ACM model, a recipe of n ingredients is a finite non ordered set $\{ Q_1 \dots Q_n \}$, where each Q_i represents the quantity of the i-th ingredient. A given ingredient belongs to one or more families of ingredients. Each family F_k is described by a set $\{ P_1^k \dots P_m^k \}$ of attributes. Therefore, each element of a family (an ingredient) is described by a value V_{ij}^k for each of its own attributes P_j^k. The values of each attribute belong to the interval $[V_{ij}^k - T_j^k, V_{ij}^k + T_j^k]$, where T_j^k is a constant of tolerance. If an ingredient i does not belong to the family F_k, the corresponding values V_{ij}^k are undefined. Starting from a recipe R, a modified recipe is a recipe R' where some quantities have been changed. Modifications follow the application of four sets

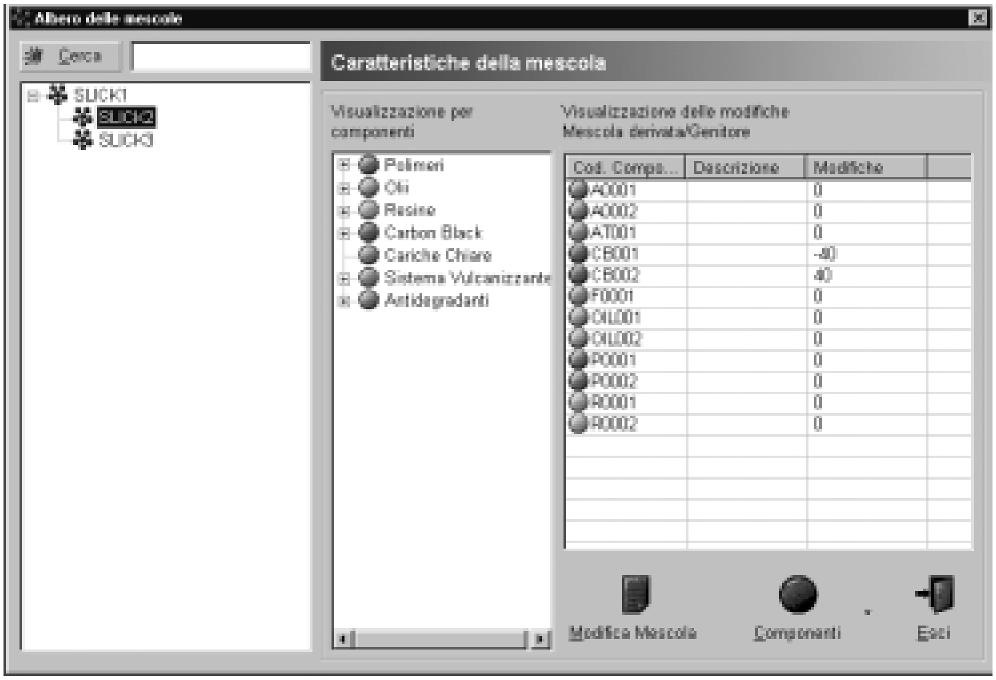

Figure 3. Presentation of the adapted recipe (all data in this figure are fictitious)

of rules, where rules take the form of productions:

1. *Description Rules*, describing a recipe taken from the company database expressed in terms of quantity of ingredients, according to the ACM model.
2. *Performance-Properties Rules*, defining which changes are needed in the chemical-physical properties of a batch defined by a recipe, in order to obtain a change in performance (for example, 'in order to increase thermal stability, hysteresis must be decreased').
3. *Ingredients-Properties Rules*, defining which attributes of the ingredients of a recipe are involved in the variation of the chemical-physical properties of the batch (e.g., 'in order to increase hysteresis, transition glass of polymer is involved').
4. *Formulation Rules*, generating a modified recipe R' starting from R. Three types of formulation rules have been defined:

   - *Substitution*, replacing the quantity of an ingredient i with an equal quantity of another ingredient l of the same family F_k (chosen by the Ingredients-Properties Rules), in order to change the value of one or more attributes (V_{ij}^k):

   $$if\ (Q_i \neq 0);\ (i \in F_k);\ (l \in F_k); (|V_{ij}^k - V_{lj}^k| > T_j^k)\ then$$
   $$\{Q_1, Q_2, \ldots, Q_{i-1}, Q_i, Q_{i+1}, \ldots, Q_l, \ldots, Q_n\} \rightarrow$$
   $$\{Q_1, Q_2, \ldots, Q_{i-1}, 0, Q_{i+1}, \ldots, Q_i + Q_l, \ldots, Q_n\}$$

   - *Increase in quantity*, adding to the quantity of an ingredient a given constant U_k, defined according to the family F_k of the ingredient:

   $$if\ (i \in F_k)\ then$$
   $$\{Q_1, Q_2, \ldots, Q_{i-1}, Q_i, Q_{i+1}, \ldots, Q_n\} \rightarrow$$
   $$\{Q_1, Q_2, \ldots, Q_{i-1}, Q_i + U_k, Q_{i+1}, \ldots, Q_n\}$$

   - *Reduction in quantity*, decreasing the quantity of an ingredient by a constant U_k, defined as in the previous point:

   $$if\ (i \in F_k);\ (Q_i > U_k)\ then$$
   $$\{Q_1, Q_2, \ldots, Q_{i-1}, Q_i, Q_{i+1}, \ldots, Q_n\} \rightarrow$$
   $$\{Q_1, Q_2, \ldots, Q_{i-1}, Q_i - U_k, Q_{i+1}, \ldots, Q_n\}$$

The implementation of the module described above has been developed in a Java production rules environment (JESS). The knowledge base has been partitioned in *knowledge sources* corresponding to the defined type of the rules formalized above. The firing of these knowledge sources starts from the application of the *description rules*, that split the coded recipe contained in the retrieved case into the quantities of its ingredients, invoking the integration interface to the Recipes Archive component. Then, the *Performance-Properties Rules* knowledge source is activated, in order to determine the needed chemical-physical properties of the batch starting from the required performance. From the global properties of the batch, the *Ingredients Properties Rules* knowledge source finds out which ingredients are involved in order to obtain a variation of the chemical-physical properties satisfying the required performance. The *Formulation Rules* knowledge source is the core of the ACM Adapter component. It formulates the modified recipe applying *Substitution*, *Increase in quantity* or *Decrease in quantity* rules. The choice of the rules determines how the recipe is adapted to the current case. Figure 3 shows a snapshot of the compound designer interface illustrating a modified recipe.

3 APPLICATION BENEFITS

The Motorsports Department of Pirelli Tyres comprises two groups. The first (composed by race engineers, tyre engineers, and other technicians) is entirely dedicated to the racing activity . The second is composed by people shared with departments dedicated to large scale production, like rubber compounds designers whose main competence is chemistry. The role of the compound designer is crucial: he is like a 'two ways bridge' linking the large scale production world to the racing world. The most significant strategic contributions to large scale production deriving from racing are:

- test of compounds when subjected to extreme stress conditions;
- test of new solutions in the compound design;
- validation of properties of single raw materials;
- evaluation of the declarations of the ingredients suppliers and of new products.

The knowledge concerning the design of rubber compounds (about the formulation of chemical compounds) is one of the most important corporate assets, composing the core knowledge of a tyre company. Several large scale products have been designed and produced taking into account tests, results and suggestions derived from the car racing world. The most meaningful benefits obtained from the development and the use of P-Race can be summed up as follows:

- the organisation of information and data concerning the racing activity in a conceptual framework, corresponding to the main characteristics of the episodic knowledge involved (Case-Based Reasoning - CBR);
- the development of similarity criteria among circuits and information about races in order to optimise the reuse modality;
- the formalisation of a knowledge model for the chemical formulation of rubber compounds (Abstract Compound Machine - ACM);
- a support for the decision making process, proposing solutions to the modality previously mentioned, i.e. adaptation changes in a recipe in order to satisfy some required performance;
- the creation a computational framework shared by all the members of the Motorsports Division of Pirelli Tyres.

4 CONCLUDING REMARKS

The P-Race Project has been developed by a team composed of a group of the Department of Computer Science, Systems and Communication of the University of Milano-Bicocca and members of the Motorsports Department of Pirelli Tyres. It took about three years to be designed and implemented. Nowadays, P-Race is in use at the same department and supports the decision making process for the main championships where Pirelli Tyres takes part. The chemical formulation component (which is the crucial point of the entire system) has been adopted after an experimental campaign testing the quality of the responses on past solutions. The future development of the system will include the integration of P-Race with existing software systems devoted to the acquisition and the description of track data with telemetric devices. This integration will permit to support qualitative representations (by fuzzy descriptions) of knowledge concerning tracks described by quantitative data .

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