Case Based Reasoning and Production Process Design: the Case of P-Truck Curing

Stefania Bandini, Ettore Colombo, Fabio Sartori, and Giuseppe Vizzari

Dipartimento di Informatica, Sistemistica e Comunicazione
Università degli Studi di Milano–Bicocca
Via Bicocca degli Arcimboldi 8, 20126 Milano, Italy
{bandini, ettore.colombo, fabio.sartori, giuseppe.vizzari}@disco.unimib.it

Abstract. This paper describes P–Truck Curing, a Case Based Reasoning system supporting the design of the curing phase for truck tyre production. The design of this process provides a trade–off between an optimal curing degree, to avoid imperfections in the final product, and the reduction of costs, related to thermal energy employed in the curing. Expert curing process designers store information about past episodes and exploit it to define new ones, without starting from scratch. A CBR system is thus a suitable approach to model this problem solving method: case structure, similarity and adaptation functions and a general system overview will be described. This work has been developed in the context of the P–Truck project, whose goal is the development of an integrated Knowledge Management (KM) system to support the Business Unit Truck of Pirelli Tyres in the design and manufacture of truck tyres.

1 Introduction

The work presented in this paper has been developed in the wider context of the P-Truck project, whose goal is the development of an integrated Knowledge Management system to support the Business Unit Truck of Pirelli Tyres in the design and manufacture of truck tyres. In particular this paper will describe a part of the system supporting the design of the curing process, the last phase of tyres production process.

A truck tyre is composed of both rubber compounds and metallic reinforcements: the former are responsible for all the thermal and mechanical properties of the tyre; on the other hand, metallic reinforcements give it the necessary rigidity. The P–Truck Project goal is to support Pirelli's experts in their decision making process related to different phases of the tyre cycle of life, that includes:

- Design of rubber compounds: a rubber compound is a blend of different ingredients, chosen with the goal of achieving required performances (e.g. tensile strength, resistance to fatigue). The designer determines the composition of the blend, identifying ingredients to be adopted and their amounts;

– Mixing: ingredients must be mixed in order to obtain a homogeneous blend. Machineries, timings and many other parameters of this stage must be suitably defined by the mixing process designer;
– Semi–manufactured production: metallic reinforcements are added to rubber compounds, in order to obtain the different parts the tyre will be composed of;
– Assembly: semi–manufactured parts are assembled into a semi–finished product, in jargon called *green–tyre*;
– Curing: the green tyre is "cooked" in order to give it the required thermal–mechanical features.

Four knowledge–based systems supporting the experts' decision–making process in some of those phases have been developed; a screen–shot of the uniform user–interface is shown in Figure 1. These systems are based on different problem solving methods (e.g. rule–based, case–based), reflecting experts' decision–making process in the main phases of the process above described (i.e. design of rubber compounds, mixing and curing).

Fig. 1. A screen–shot of P–Truck Compounding.

It is important to note that, although the problem solving strategy is typically diversified, the knowledge–base exploited by different modules is the same. In fact truck tyre production steps are highly correlated (e.g. most of them are related to the same rubber compounds). Thus, while the problem–solving strategy is distributed, it has been decided to design and implement a centralized knowledge–base: each module accesses it in order to create a dynamic view of knowledge needed to work. This choice, that resulted in the development of a specific knowledge elicitation tool (KEPT [5]), has allowed to build a complete and consistent knowledge model, devoted to represent complex knowledge structures concerning both case–based and rule–based modules of P–Truck. In particular, this paper will describe the design choices adopted in the development of *P–Truck Curing*, a case–based system that supports experts in their decision making process about the curing of tyres.

Problem analysis began with meetings and interviews with expert curing process designers, also referred to as curing technologists. Early stages of knowledge acquisition made clear that any of these experts uses to store information related to curing processes, designed both by himself/herself and by other technologists. These notes concern incidental problems, adopted solutions, variants of process and results, both positive and negative, about tyre curing. When a technologist has to design a new curing process he/she uses these information and his/her experience to define its details, without starting from scratch or using formally well–defined rules.

This approach to the design of the right curing process is very similar to Case Based Reasoning (CBR), that is a problem solving paradigm suitable to deal with domains whose problem solving methods have not been fully understood and modelled. Naturally suited to support the preservation and reuse of experiential and episodic knowledge, intrinsically stored into cases, CBR has been adopted for many KM systems, in particular for manufacturing applications (e.g. see [3, 4, 8]). Some of these systems concern the process design problem and, among these, several works concerning chemical processes have been proposed (e.g. see [12, 13, 16, 17]): the aim of these systems is the definition of the process structure (the flow-sheet of the chemical process, a sequence of phases to be performed). Another CBR system tackling a curing process design scenario is Clavier [11]. This system supports expert in the decision of autoclave loading for the curing of graphite–threaded composite materials. Even if the goal of P–Truck Curing is similar to Clavier (i.e. to obtain optimal curing degree of processed materials and to minimize costs) the latter is mainly focused on choosing the optimal placement of parts to be cured inside the autoclave. P–Truck Curing instead focuses on an optimal definition of curing phases features (e.g. timing, energy), in a generally fixed process structure.

According to [1], the CBR cycle of P–Truck Curing, given a problem and a case base of solved problems, can be summarized as follows (see Figure 2): the system receives a description of the problem to be solved, made up of a list of performances to be achieved and the type of machinery to be adopted for the curing process. Then, it retrieves a sequence of past cases with a similar description, chooses one of them and tries to modify its solution in order to derive a new curing process.

The following Section will describe the results of the knowledge acquisition campaign, while Section 3 will show the representation of a case in P–Truck Curing, highlighting the most significant attributes involved in the decisional process of a curing technologist. Then, the paper will focus on how the attributes were used to build a similarity function among cases to be used in the retrieval phase. In Section 5 a brief explanation of how adaptation has been intended will be supplied. Section 6 will briefly describe system architecture, and finally conclusions and future works related to P–Truck Curing will be briefly introduced.

2 Curing Process Description

Vulcanization is a chemical process of treating crude rubber or similar plastic material to give it desired properties, such as elasticity, strength, and stability. In particular, tyre vulcanization is often referred to as curing, and it is during this process that the tread impression, brand, and information on the kind of tyre are printed on the green–tyre, in order to give it the desired shape and appearance. The green–tyre is made up of different rubber compounds, steel reinforcements and other components. During the curing process it undergoes a thermal treatment that activates reactions between polymers (i.e natural or synthetic rubber) and sulphur molecules, that bind themselves and create a lattice. A correct and uniform degree of cure is thus a crucial factor influencing tyre performances (for instance handling on wet or dry surface, fuel saving, dimensional stability and mileage, fatigue and abrasion resistance).

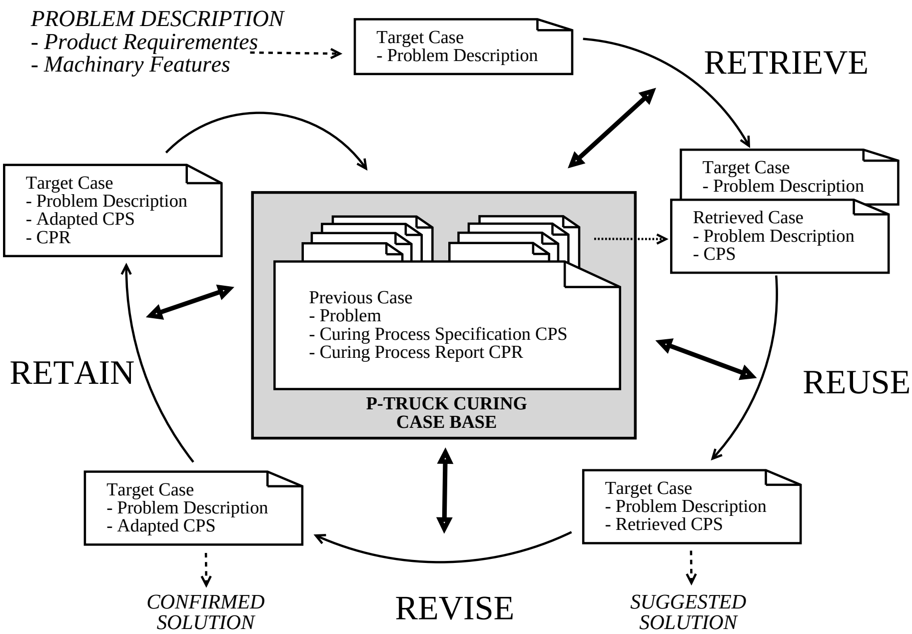

Fig. 2. The P–Truck Curing CBR cycle.

The process takes place inside a machinery called curing press; its main components are the mould, the bladder and a pipe system to supply heating fluids. A sketch of a curing press is shown in Figure 3. Thermal energy is supplied to the mould, containing the green–tyre carcass, in a different way according to the curing press type: it may derive from hot steam surrounding the mould or from its direct contact with heated platens. The green–tyre must be pressed to the mould in order to impress the tread and other information on it. An internal pressure must thus be applied to the carcass, and therefore the bladder must be inflated during the process. The inflating fluid may also contribute to the thermal treatment, if it is a good heat conductor.

The curing process thus provides different phases of external or internal heating, and internal inflation of the green–tyre carcass. To design a curing process the technologist evaluates the characteristics of the green–tyre, that is the output of the last phase before the curing and the kind of machinery to be used, then, for every step of the process, he decides starting instant and duration, temperature and pressure of the involved fluids. Variants to standard procedures can also be suggested (for instance to slightly modify the typical value of factory dependent parameters).

Production tests that can be performed are essentially normal curing processes, but thermocouples are inserted in the green–tyre to monitor its temperature while it is being vulcanized. By doing so an indication on the curing degree in different points of the tyre can be obtained. Results of this test are used by the technologist to guarantee the satisfaction of requirements and constraints, give comments on the obtained product or highlight possible anomalies and imperfections on the tyre.

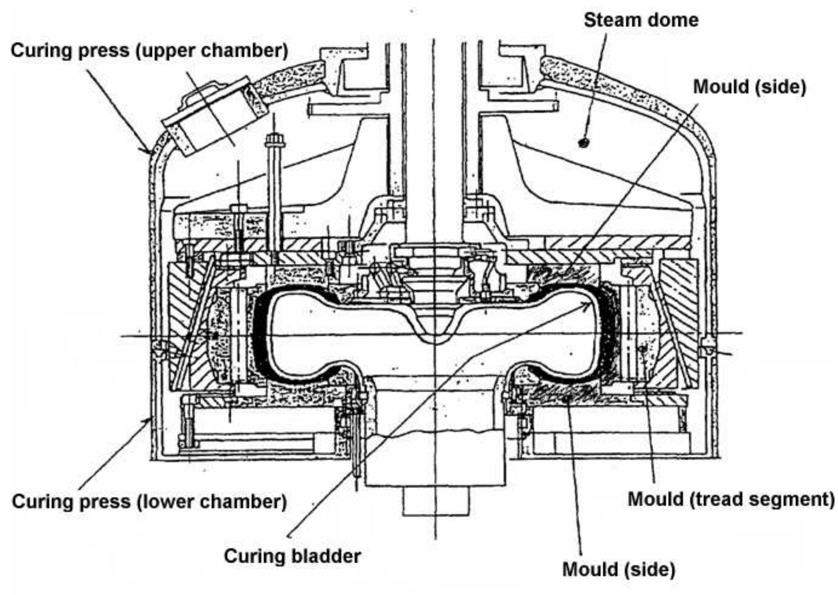

Fig. 3. Curing press sketch: this is a vertical section of a steam–dome curing press, highlighting mould, bladder and other components.

3 Case Structure

Describing a problem is one of main activities in the definition of a CBR system: the choice of significant attributes is essential for the definition of a suitable similarity function among cases, that is fundamental in order to retrieve past situations similar to the current one. A problem C is usually viewed as a n–tuple of features $C = \{f_1, f_2, \ldots, f_n\}$. This structure may be fixed or variable [6], depending on the complexity of the involved knowledge. P–Truck Curing provides a fixed structure for case representation, since knowledge acquisition sessions have highlighted that curing process technologists do not change the set of significant attributes from the similarity calculus point of view.

The technologist stores all the information about new processes in a *curing process specification (CPS)*. Each CPS concerns one and only one process, summarizing all the choices made by the technologist about it. Curing is a crucial phase: since it is the last one, an error during its execution or an improper design would cause the failure of the whole production process, and, consequently, loss of time and money. The task of these experts is very difficult, as they have to design the curing process in order to obtain an optimal degree of curing, minimizing costs and avoiding imperfections in the final product. A short curing process may not guarantee a good degree of curing, but a long one will be very expensive, requiring a lot of thermal energy and perhaps could even produce imperfections in the cured tyre. Moreover the tyre thickness is different in distinct points (e.g. the tread is quite thicker than the side), but the curing degree should be as uniform as possible.

At the end of the process, the technologist carries out activities needed to produce a *curing process report (CPR)*, a document containing information related to process results.

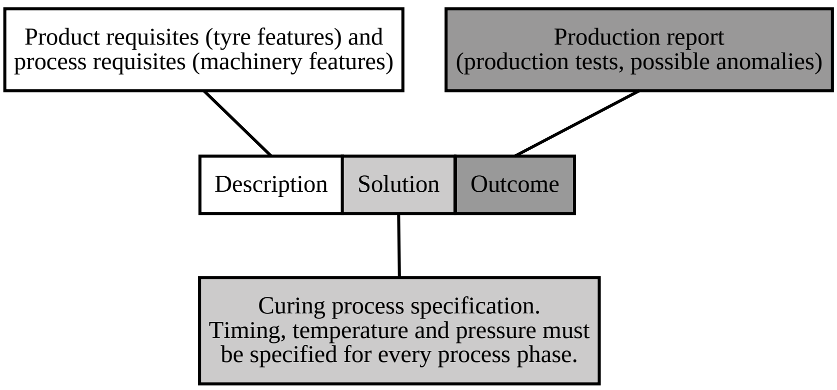

Fig. 4. Case parts: information related to case description, solution and outcome is illustrated.

Figure 4 shows high–level P–Truck Curing case composition, built according to the typical case structure [14]; more precisely:

– *case description* is made up of the evaluation of final product requisites and machinery features (type, temperature of fluids and so on) to be used in order to satisfy them;
– *case solution* is the CPS;
– *case outcome* is the CPR.

A tree–structure was adopted for case representation as it is more suitable to describe complex knowledge structures, given the possibility to model hierarchies. Many concepts described in the previous Section can be linked with *is–a* and *part–of* relations that would be lost in a flat structure. Moreover this is a modular representation, allowing flexible management of related information (e.g. in terms of case structure modification) and the definition of composite and efficient retrieval algorithms (e.g. different case parts, represented by distinct sub–trees, may be handled in a different way). For more details on this kind of case representation in the context of P–Truck see [15].

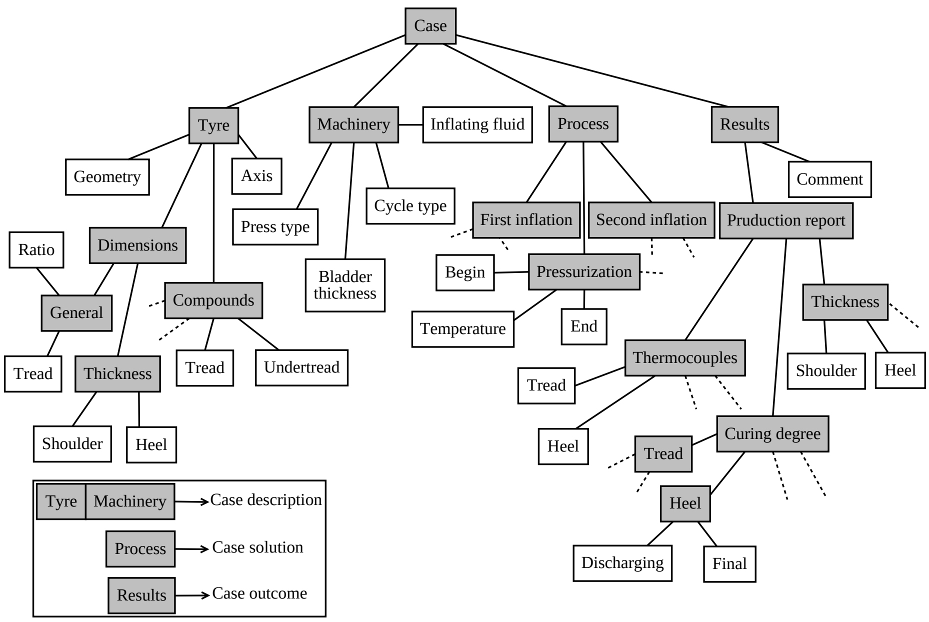

Fig. 5. Case structure: the diagram shows a partial view of the tree–structure related to a case.

Figure 5 illustrates a partial view of the tree–structure representing the case in P–Truck Curing: in particular there are four sub–trees, respectively related to the description of tyre, machinery, curing process and obtained results. A tree inner node, named *category* (i.e. gray filled boxes), represents a collection of *attributes*, which are drawn as tree leaves (i.e. white filled boxes). Note that a category can be made up of other categories too. The tyre is described in terms of its dimensions (e.g. thickness in specific points of its section, width of the tread), usage (e.g. tractive axis, drive axis), morphological features and components (i.e. blends related to its composing parts). The machinery is mainly characterized by its type and the type of the inflating fluid while the process contains information related the starting instant, duration and other parameters of various phases of the curing process. Results contain information related to the tests described in the previous Section and an evaluation of the expert on the process outcome.

The case structure illustrated in this section is not variable at the present, so that the classical *Nearest Neighbor Algorithm* [9] has been adopted to build a similarity function for the retrieval phase of the system, that will be the subject of the next section.

4 Similarity and Retrieval

One of the main steps in a CBR system is the retrieval phase, whose result is a subset of the case–base. Its elements are cases whose problem description is considered *similar* to the one concerning the new problem. Designing P–Truck Curing, it has been introduced a two step retrieval to increase system flexibility, configurability and maintenance in the system.

In Figure 6 there is a description of the two step retrieval designed for P–Truck Curing. This approach is very similar to MAC/FAC [10] (Many Are Called, Few Are Chosen), a psychologically founded model of similarity–based retrieval. In fact the first phase, named *Pre–selection*, has been defined to select from the case base only those cases having a rate of similarity higher than a particular threshold and whose feature values verify some relations with new problem ones. Pre–selection phase can be considered something more than a traditional Indexing because it involves particular relations among features in addition to equality. In the following phase, named *Selection*, the system only works on the set of cases obtained by the Pre–selection, computing their actual similarity to the current one. Whenever the Pre–selection phase returns cases with different solutions to the same problem, Selection can choose the best case, basing on the interpretation and the comparison of reported results (e.g. rates of curing and tyre dimensions at the end of curing process).

Using two different steps to retrieve analogous cases allows to employ different similarity criteria. In fact, even if currently Pre–selection and Selection are completed following the same approach (i.e. comparison of attribute values and categories), it would be possible to exploit a structural similarity measurement in the first phase. In this way, retrieval shows a subset of the case base both as possible solutions and as possible starting points for the adaptation process.

During the knowledge acquisition campaign, with the help of curing experts, an order of importance among attributes and categories has been identified. Nonetheless, for a complete definition of the *similarity function*, in addition

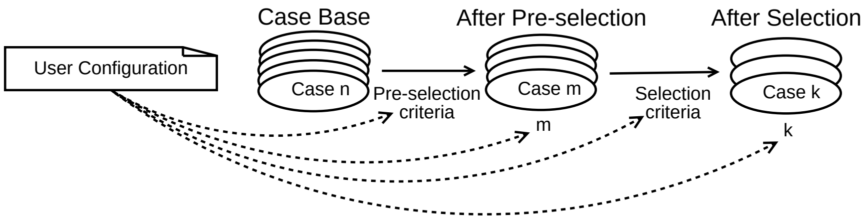

Fig. 6. Retrieval in P–Truck Curing.

to weights, for each node of the tree case structure, a function indicating how to calculate the distance among two analogous nodes in the case–space must be specified. Thus, the rate of similarity of a past case to the current one is recursively calculated starting from the root of the structure: for each category the rate of similarity is obtained aggregating the contribute of each sub–node. When a sub–node is an attribute, the evaluation of the similarity consists in a comparison function (e.g. euclidean distance) of attribute values.

Since more than one end-user can access P–Truck Curing and that each of them may have a different point of view with reference to the similarity function, it has been decided to allow them to specify a personal configuration of the similarity function. This means that for each node of the tree case structure the user can decide weights and functions to be considered when measuring distances in the case space, for both Pre–selection and Selection phases. Figure 7 shows a draft of this configuration structure.

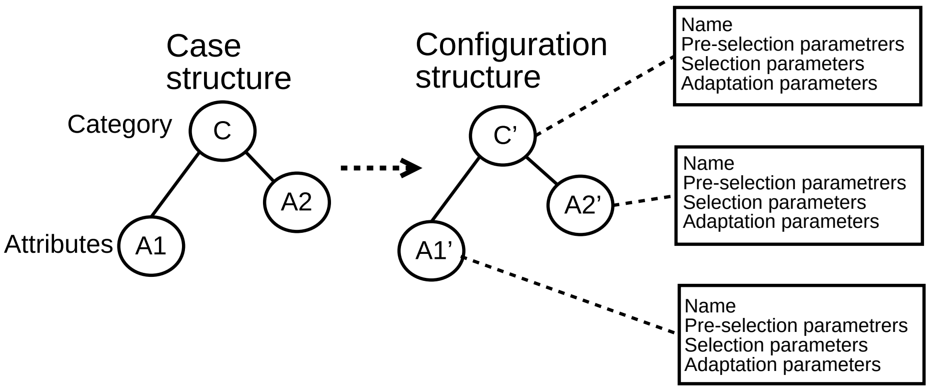

Fig. 7. The structure of the configuration.

Collections of functions have been designed in order to measure the distance between two feature values. An attribute value can belong to different kind of sets, that could be non-ordered or ordered, continuous or discrete. For the interpretation and comparison of curing results and for the management of categories (both in Pre–selection and in Selection), other collections of functions have been defined.

The number of cases considered in Pre–selection and Selection can be configured by the user (parameters m and k in Figure 6), and these values are also included in the configuration structure. The level of configurability, obtained with the adoption of these solutions, increases the quality of P–Truck as a Knowledge Management system: for instance a curing technologist can obtain an indication of other experts' point of view on case similarity. Moreover this configurability allows high level of system maintenance: in fact it is easy to modify the importance of an attribute or a category, varying the associated weight, or even changing parts of the similarity function, associated to a node of the case structure.

5 Adaptation

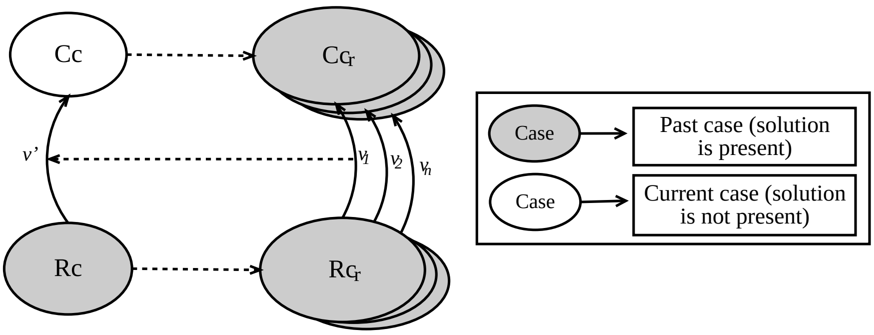

Fig. 8. Couples of past cases representing the current and the retrieved one can be used to adapt the retrieved solution.

The adaptation phase in P–Truck Curing guides the designer towards the determination of a good solution to curing process design problem (i.e. time scheduling of curing steps) even if there are no identical problems already solved among the available cases. The approach that was adopted in order to adapt the solution of an old case to a new one is influenced by the limited procedural knowledge that is available with reference to this specific activity. As previously specified, a green–tyre is a composite object, and even if some basic principles are known (e.g. thicker parts of a tyre require more energy to reach an optimal curing degree), to compose them in order to obtain a globally optimal process result is a very complex task. For instance, different tyre parts could require a completely different process modification (i.e. sidewalls are thinner and thus require less energy, while shoulders are thicker and require more), and some components have not a clear influence on the global result (e.g. metallic parts).

Nonetheless the adopted approach aims to supply to the designer an indication of how to adapt the retrieved solution to the current case according to past experiences.

It has been considered that, as the current case and the retrieved one have different descriptions, maybe the case base contained other couples of cases presenting the same (or significatively similar) differences among the related descriptions. In other words we may find cases that could act as *representatives* respectively for the current case and the retrieved one. The difference between the related solutions (vector v_i) is an indication of how to modify the solution of the retrieved case Rc in order to adapt it to the situation described in the current case Cc, that is the v' vector. The idea behind this choice, in the framework of a substitutional adaptation (see, e.g., [18]), is that the same difference in problem descriptions indicates that the solutions of the current case and the retrieved one should present a difference similar to those related to the representatives of these cases. Figure 8 shows that this approach provides a passage from the current couple $< Cc, Rc >$ to couples of past cases $< Cc_r, Rc_r >$. The adaptation vector v' represents the modification that must be applied to the solution of case Rc to obtain the solution to the current problem. In this approach vector v' is obtained through an aggregation of $v_1 \ldots v_n$, differences among solutions related to representatives of the current and retrieved cases; currently an average of $v_1 \ldots v_n$ weighted according to the related results has been adopted.

This approach provides an adaptation proposal that can be modified or accepted by the expert. The solution generally undergoes a test whose results can lead to a different form of adaptation, also referred to as solution correction [7], that is focused on the continuous improvement of a specific solution. While the previously described adaptation mechanism can indicate modifications for all parts of case solution (e.g. timings but also temperatures, pressures, and so on), this phase only focuses on the duration of various steps of the curing process. The idea is that, according to the results, these timings can be changed in order to obtain a better curing process. The modification will be higher for processes which brought to poor results, while successful processes will not be substantially changed. The direction of these modifications (increase or decrease process duration) is related to different factors such as costs (i.e. longer processes require more energy and decrease the tyre production rate) and curing degree (too short processes do not bring to an optimal curing degree).

Both of these mechanisms are user–configurable: for instance the concept of representative involves a sort of similarity metric that can be modified by the user as shown in Section 4. Moreover the modifications to process duration related to the solution improvement are also configurable.

6 System overview

The computer system implementing a support for the design of curing processes is a component of an integrated KM project, shortly described in the introduction. To introduce such a composite system in an important business unit of a company like Pirelli, several non–functional requirements must be taken into account.

System components must coexist and also interact with each other, if needed, and with the current information system, that contains particular data needed by those modules. This kind of access should only be performed when necessary, to keep limited the impact on the existing information system and supported procedures.

The development of this kind of computer systems requires an active involvement of domain experts, whose time is very valuable. The knowledge acquisition campaign must thus be carefully planned, in order to be effective and not excessively divert experts from their day–to–day activities. Various phases of analysis, design and development of different system components have been necessarily carried out in different times, by various groups, and using disparate approaches (e.g. rule–based and case–based).

Finally, Pirelli is a multinational corporation and users can be situated in different locations, and might need to access P–Truck modules through the network, possibly using a PC without the chance to install additional programs: therefore the adoption of a web–based user interface is almost mandatory.

The adopted platform and architecture must thus provide a high degree of flexibility and extensibility, allowing the integration of heterogeneous components, and a separation between business and presentation logic, that must be web–oriented. The J2EE platform supports the development of heterogeneous components (Enterprise Java Beans), that can be integrated through the use of standard technologies (e.g. Remote Method Invocation, CORBA, XML), providing support for database access and web–based user interface development. It meets all the previously expressed requirements and was thus adopted for the development of the P–Truck system.

A diagram showing a high level view of system architecture is shown in Figure 9. The module implementing the CBR system is separated from the user interface manager and from the database access component, a module that acts as a gateway to the case base, physically stored in Pirelli's enterprise database and in P–Truck private one. Pieces of information related to cases are already available in the existing information system, but some specific data is required by P–Truck system modules. For security and confidentiality reasons it was chosen not to use the existing database management system (DBMS) to store this data, but to install another one dedicated to the P–Truck system. The Database Wrapper does not directly offer services to users, but is meant as a support for other application modules. In particular it is shared by all components requiring an access to the data storage facilities, and represents a uniform and centralized access to the two DBMSs. The user interface module is based on JavaServer Pages and servlet technology, and thus provides web accessibility to the Curing module.

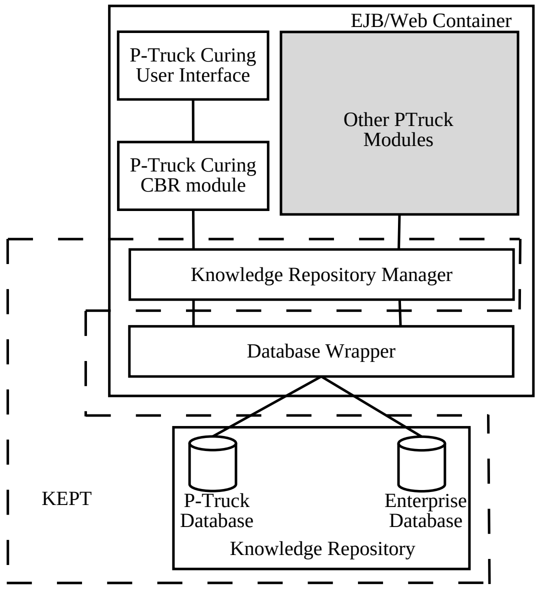

Fig. 9. High level system architecture: this is a diagram showing main system components and collaborations.

7 Conclusion and Future Developments

This paper has presented P–Truck Curing, a CBR system supporting expert technologists in the design of curing processes for truck tyres. The case is represented in a hierarchical structure, whose sub–trees are related to tyre and available machinery (case description), to the curing process (CPS), and to the obtained results (CPR). The two–phase retrieval and the adaptation mechanism were described, with reference to the possibility to configure both of these steps of the CBR cycle. A brief description of the P–Truck Curing system was also given. The system is currently being installed in order to start a test campaign. An evaluation of the system on day–to–day problems, performed by curing technologists, will likely lead to an adjustment of the configurable aspects related to the retrieval and adaptation phases.

This system will allow a persistent and organized storage of evenly described cases, shared and accessible by different users. It will be integrated into Pirelli's information system, but it will represent a dedicated module specifically developed taking into account curing technologists' needs.

One of the main reasons to adopt a CBR approach was the similarity to the expert problem solving method, but it also seemed suitable because knowledge on the domain is not exhaustive. A future analysis of the case base, possibly with the support of data mining techniques (e.g. see [2]), could thus represent an instrument for a deeper study of relationships between elements of the case description and process features.

A correct and systematic use of this system will also allow an incremental learning, typical of a CBR approach. This also means that the system will not necessarily be able to help experts when a new strategy or technology is introduced in curing process design. Anyway, as long as the case description is valid, the system is ready to receive manually designed cases, related to those innovations, and allow their reuse. Moreover the flexibility of the adopted tree–structure for case representation allows to modify it in order to keep it up–to–date with changes in curing technology.

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