LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Faculty of Technology
Master's Degree Program in Chemical and Process Engineering

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DETERMINATION OF SLURRY´S VISCOSITY USING CASE BASED REASONING APPROACH

Examiners: Prof. Andrzej Kraslawski
Dr. Sc. (Chem) Yuri Avramenko

Lappeenranta, 2011

ABSTRACT

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Determination of slurry's viscosity using case based reasoning approach

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Keywords: slurry, Case-Based Reasoning, Newtonian fluid, Bingham plastics fluid, viscosity, CBR.

Case-based reasoning (CBR) is a recent approach to problem solving and learning that has got a lot of attention over the last years. In this work, the CBR methodology is used to reduce the time and amount of resources spent on carry out experiments to determine the viscosity of the new slurry. The aim of this work is: to develop a CBR system to support the decision making process about the type of slurries behavior, to collect a sufficient volume of qualitative data for case base, and to calculate the viscosity of the Newtonian slurries.

Firstly in this paper, the literature review about the types of fluid flow, Newtonian and non-Newtonian slurries is presented. Some physical properties of the suspensions are also considered. The second part of the literature review provides an overview of the case-based reasoning field. Different models and stages of CBR cycles, benefits and disadvantages of this methodology are considered subsequently. Brief review of the CBS tools is also given in this work. Finally, some results of work and opportunities for system modernization are presented.

To develop a decision support system for slurry viscosity determination, software application MS Office Excel was used. Designed system consists of three parts: workspace, the case base, and section for calculating the viscosity of Newtonian slurries. First and second sections are supposed to work with Newtonian and Bingham fluids. In the last section, apparent viscosity can be calculated for Newtonian slurries.

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This research work is dedicated to my grandfather. I hope that you are proud of me.

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Alina Lozhechnikova

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Nowadays a variety of industrial processes involve various operations with slurries and suspensions. First of all, to be able to perform design and modeling of industrial process, it is necessary to research the properties of the slurry, which will be used in industrial process. And in this case the apparent viscosity is one of the most important characteristics of slurry. However, in some cases it is quite a difficult task to measure the slurry's viscosity. Especially when dealing with Non-Newtonian rheological fluids, whose behavior depends on time. Also some suspensions require special handling, due to their chemical and physical properties, concentration of solid particles, and tendency to aggregation or degradation under the deformation, etc.

To reduce the time and amount of resources spent on carry out experiments to determine the viscosity of the new slurry, it is possible to use the Case-Based Reasoning (CBR) approach. And today, the CBR approach is not simply an isolated research area, but a methodology that is widely used in various fields. The aim of this work is: to develop a CBR system to support the decision making process about the type of slurries behavior, to collect a sufficient volume of qualitative data for case base, and to calculate the viscosity of the Newtonian slurries.

Firstly in this paper, the literature review about the types of fluid flow, Newtonian and non-Newtonian slurries are presented. Some physical properties of the suspensions are also considered. The second part of the literature review provides an overview of the case-based reasoning field. Different models and stages of CBR cycles, benefits and disadvantages of this methodology are considered subsequently. Brief review of the CBS tools is also given in this work. Finally, some results of work and opportunities for system modernization are presented.

LITERATURE REVIEW

Slurry is a mixture of solids and liquids. Technical term slurry contains a wide range of solid-liquid blends. So, if a solid-liquid mixture has some liquidity, we can call it slurry. Solid particles can be different sizes: from very fine colloidal particles to coarse particles, which can precipitate. The solid concentration and materials of solid and liquid phase have a great influence on viscosity and other flow characteristics. The following parameters also affect the slurry properties: size and shape of the particles, level of turbulence, temperature, the particle size distribution, the diameter of the pipe and the surface properties of the solid particles. /1, 2/

2. CLASSIFICATION OF FLOW BEHAVIOR

Fluids can be divided on Newtonian and Non-Newtonian. The difference is how the fluid viscosity changes with the velocity gradient in a pipe.

2.1 Newtonian flow

In case of Newtonian liquids, the shear stress is proportional to the velocity gradient. And the constant of proportionality is called absolute or dynamic viscosity of the liquid. Figure 2.1 represents the Newtonian model in terms of plot of shear stress versus velocity gradient. /3/

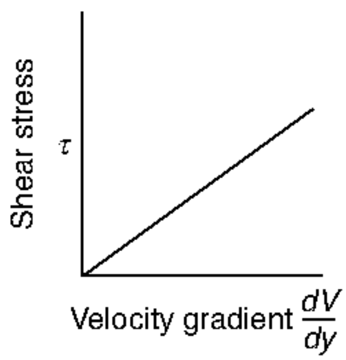

Figure 2.1 Newtonian flow /4/

The classical Newton's equation for Newtonian fluids is this relationship between shear stress and shear rate (also known as velocity gradient). Equation 2.1 represents the Newtonian model.

$$\tau = \mu \frac{dV}{dy} \tag{2.1}$$

where μ is a viscosity of fluid, τ – shear stress, and *dV/du* is a shear rate. /4/

For Newtonian liquids the slope of the shear stress versus shear rate is constant while the velocity is constant at a given pressure and temperature. Also at zero shear rate, the shear stress is equal to zero for Newtonian fluids, and thus the graph passes through the origin. Non-Newtonian fluids mostly don't satisfy these conditions. Thus, for them shear stress versus shear rate could be curved line and could have positive value at the origin. This is illustrated in Fig.2.2. /3, 5/

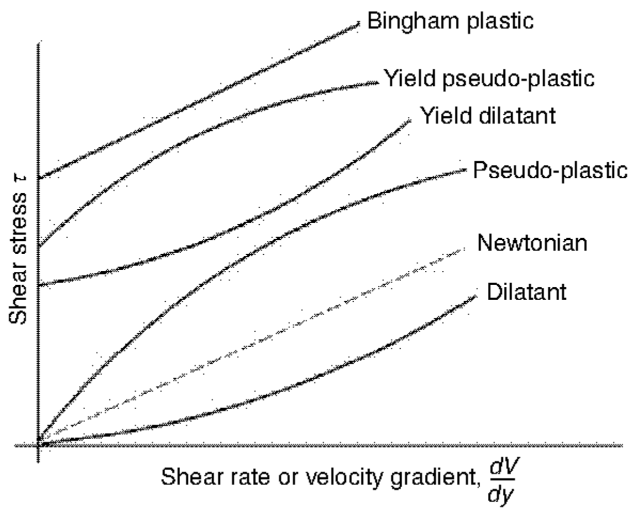

Figure 2.2 Newtonian and Non-Newtonian fluids /4/

As you can see on the Fig.2.2, Newtonian and Bingham plastic fluids have straight lines on the plot, due to constant dynamic viscosity. And in contrast with them, pseudo-plastic and dilatant fluids have curved plots and inconstant viscosity which depends on the shear rate. Also Dilatant, Newtonian and Pseudo-Plastic liquids have zero shear stress at a zero shear rate, so they don't need minimum shear stress to start flow. Slurries are basically non-newtonian fluids, but if concentration of particles decreases, they can become Newtonian fluids. /4, 6, 7/

2.2 Non-Newtonian flow

Liquids containing finely ground solids and long-chain polymers, with a nonlinear relationship between the rate of shear and the shear stress under laminar-flow conditions display non-Newtonian flow properties /8/. Usually, non-Newtonian fluids are divided into two groups:

- fluids, which properties are independent from time or rate of shear;
- more complex fluids, the duration of shear affects on the relationship between shear stress and shear rate. /9/

On the Fig.2.2 were shown several possible rheograms for non-Newtonian liquids with different flow types.

Factors influencing non-Newtonian flow behavior:

- *Size and shape of particles.* The smaller the size of the particles, the greater the chance, that fluid will show a non-Newtonian behavior. But too small particles which are suspended by Brownian motion may flocculate and reduce the degree of behavior. If slurries with the same solids concentration, the slurry with fine particles will have higher consistency. Also with concentrations higher than 35% by weight, particle shape affects the consistency of slurry. Slurries with round-shaped solids have smaller consistencies than substances with chaotic-shaped particles. /9, 10/
- *Concentration.* The level of non-Newtonian behavior is increasing with grows the concentration of solids. While concentration is increasing, consistency (apparent viscosity) increases proportionally with the specific gravity of the suspension, until a critical concentration will be reached. At this point consistency grows a little faster. After reaching the critical concentration, even a small change in the specific gravity will leads to the significant changes in consistency, until flow stops finally. /9, 10/
- *Reynolds number.* In turbulent flow of non-Newtonian fluid, the inertial forces increase compared with viscous forces. Therefore, the non-Newtonian characteristics or behavior of liquids decreases with high

Reynolds numbers. And vice versa, the non-Newtonian behavior of liquids increases in laminar flow and at low Reynolds numbers. /9/

2.2.1 Bingham plastic fluids

Bingham plastic fluids are characterized by a constant slope of the shear stress versus shear rate curve and by positive shear stress with zero shear rate. These fluids maintain a rigid structure and do not flow, if the shear stress less than yield stress. It's only at stresses in excess of the yield value that flow occurs /13/. Equation 2.2 represents the shear stress for the Bingham plastic model:

$$\tau = \tau_0 + \eta \frac{dV}{dy} \qquad (2.2)$$

where τ is a shear stress at distance *y* from pipe wall, τ_0 is a yield stress, η – rigidity coefficient, *dV/dy* is a shear rate.

The coefficient η is called also plastic viscosity and has the same units like an absolute viscosity. This type of liquids includes concentrated suspensions of fine particles and pastes. There are some examples of Bingham plastic fluids: fly ash, paint, coal slurry and clay suspended in water. /4, 14, 15/

2.2.2 Pseudo-plastic fluids

When the flow curve is non-linear and passes through the origin, the Power-law model is used to characterize the shear stress versus velocity gradient relationship. The equation for a power-law (or Ostwald-de-Waele) fluid is:

$$\tau = K \left(\frac{dV}{dy}\right)^n \qquad (2.3)$$

where τ is a shear stress at distance *y* from the pipe wall, n – power law exponent, *K* is a power law coefficient and *dV/dy* – velocity gradient.

K and n are parameters that describe the rheology of the power-law fluid in Eq. 2.3. Parameter K is also known as fluid consistency index. The higher the viscosity of the fluid, the greater the coefficient K. The constant n is also called the flow index; n is a measure of difference from Newtonian fluid behavior. For pseudo-plastic (shear thinning) fluids, coefficient $n < 1$; for dilatant (shear thickening) fluids, parameter $n > 1$ /4, 18/. Rather small values of power-law index are encountered in the fine suspensions, such as kaolin in water, bentonite in water, water mixtures of limestone and hydrocarbon grease, etc. And logically, that the lower the value of n, the more shear-thinning is the material. /3, 4/

2.2.3 Yield pseudo-plastic fluids

Yield pseudoplastic fluids are time-independent liquids; they follow the power-law model, but have a positive intercept on the τ axis, representing the yield stress τ_0. Thus, if the power-law fluid has a yield value, we can describe it by the equation, which was suggested by Herschel and Bulkley:

$$\tau = \tau_0 + K\left(\frac{dV}{dy}\right)^n \qquad (2.4)$$

where τ is a shear stress at distance y from the pipe wall, τ_0 is a yield stress, K - power law coefficient, n – power law exponent, dV/dy – velocity gradient. /4, 18/

If the parameters values will be equal to as follows: $n = 1$ and $K = \eta$, Bingham plastic fluid equation will be obtained, this can be seen from the Eq. 2.4 and Eq. 2.2. /4/

2.3 Classes of slurries according to the type of flow

In general there are two types of solid-liquid suspensions (i.e. slurries) according to the type of flow:

- *Homogeneous slurries*. This type of mixtures flows like a single-phase fluid, and has a uniform concentration of particles along the pipe axis. This definition includes non-settling suspensions and also those which are homogeneous only in a turbulent regime. In pipeline flow, homogeneous mixture behaves as a pure liquid which has the same density, as a slurry and the viscosity depending on the concentration of particles. /8, 10/

- *Heterogeneous slurries.* This type of liquids behaves as a multiphase fluid. Liquid and solid phases are separated after some time. There is no uniform distribution of particles across the pipe cross-section. Also particles can settle and form a stationary bed at the bottom of the tube at low velocities. Usually the size of the particles in heterogeneous mixtures higher than in homogeneous. /8, 9/

2.4 Time-dependent flow behavior

In practice some fine particle slurries show not only the non-Newtonian behavior but also time-dependent flow characteristics. Sometimes with increase of shear rate, slurries show the time-dependent decrease of apparent viscosity. But when the slurry is settled at rest, viscosity will recover its initial value /2/. Thus, apparent viscosity could depend not only on the rate of shear but also on the time during which the liquid was subjected to shearing. There are some examples of time-dependent fluids: bentonite-water suspensions, red mud suspensions, crude oils, cement paste. When these materials after a long period of rest are sheared at a constant rate, their apparent viscosities become less as the internal structure of the material is broken. Because the number of structural bonds capable of being broken down reduces, the rate of change of viscosity with time drops to zero. And vice versa, when part of the linkages is destroyed, the rate at which bonds can re-form increases. Thus, the dynamic equilibrium is reached when the rates of formation and destruction of linkages are balanced.

Time-dependent fluid behavior can be divided on two groups: thixotropy and rheopexy (or negative thixotropy) /6/. Figure 2.3 shows a schematic shear stress versus shear rate behavior for time-dependent fluid.

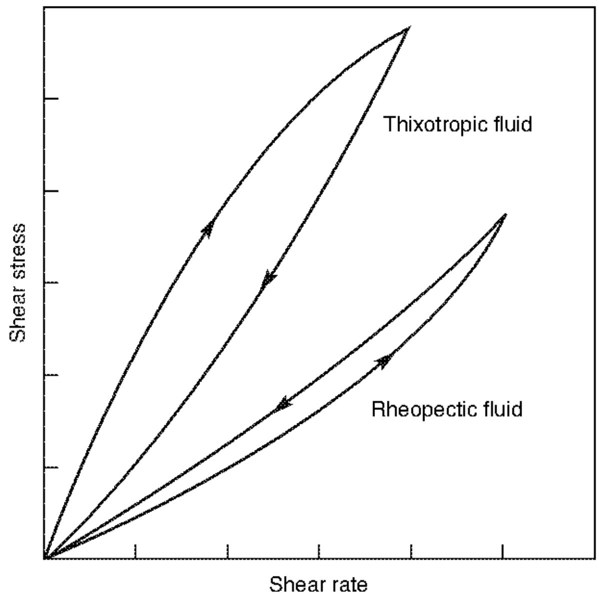

Figure 2.3 Flow curves for a Thixotropic and Rheopectic fluids /6/

In case of *thixotropic fluids*, the apparent viscosity decreases with the continuance of shearing, when fluid is sheared at a constant rate. If thixotropic material after shearing is allowed to stand for some hours, the original viscosity will be recovered. Sometimes if these liquids have too high apparent viscosity, they can recover their structure only partially. This could be because of incomplete dispersion of the particles, for example. /13/

Rheopectic fluids behavior is much less known than thixotropic behavior. In this case, apparent viscosity is increasing during the shear. With these fluids, small shearing motions lead to the formation of structure, but above the critical value decay occurs. The structure doesn't form, if the shearing is too rapid. Most rheopectic liquids restore to their original viscosity very quickly. Vanadium pentoxide, sols of bentonite and aqueous gypsum suspensions are some examples of rheopectic liquids. /3, 13/

3. PHYSICAL PROPERTIES OF SLURRIES

3.1 Density

The density of slurry it is a function of some variables: the density of the solid particles, the density of the liquid, the concentration of the solid phase by volume.

The density of the slurry could be calculated with the following equation:

$$\rho_m = \frac{100}{(C_\omega/\rho_s)+[(100-C_\omega)/\rho_L]} \quad (3.1)$$

where ρ_m is a density of slurry mixture, C_ω – solids concentration by weight (%), ρ_L is a density of solid particles in mixture and ρ_s is a density of the liquid phase in mixture. /1, 4/

The density of the solid particles is determined through many experimental methods. For some materials, density also is a function of particle size, due to their packing ability. Due to precipitation of particles in heterogeneous suspensions, the measurements of density are performed after intensive mixing. Otherwise, the results of the measurement will be incorrect. /1/

3.2 Concentration

Amount of solids in the mixture by weight is represented by the C_ω variable. In the case of the volume value the variable C_v should be used. The concentration of solids by volume and the concentration of solids by weight are related by the following Equation 3.2:

$$C_v = \frac{C_\omega \rho_m}{\rho_s} = \frac{100 C_\omega/\rho_s}{C_\omega/\rho_s+(100-C_\omega)/\rho_L} \quad (3.2)$$

The concentration by weight of solids in a mixture is expressed as:

$$C_\omega = \frac{C_v \rho_s}{\rho_m} = \frac{C_v \rho_s}{C_v \rho_s+(100-C_v)} \quad (3.3)$$

By using volume concentration, it’s possible to calculate approximately the viscosity of a dilute suspension consisting of solids in a liquid phase. /1, 4/

3.3 Viscosity

The shear stress is proportional to the shear rate and the constant of proportionality is the coefficient of viscosity, but it’s only for Newtonian fluids.

Viscosity is constant parameter, if temperature and pressure are constant too. Non-Newtonian fluids do not obey to this rule /13/. Absolute (or dynamic) viscosity for Newtonian slurries could be determined by using some equations given below.

Absolute viscosity of mixtures with volume concentration smaller than 1%. For these diluted slurries Einstein created the following equation for the viscosity of laminar slurry:

$$\mu_m = \mu_L(1 + 2.5C_v) \qquad (3.4)$$

where μ_m is a absolute (dynamic) viscosity of the slurry mixture, μ_L is a absolute viscosity of a liquid phase; and ϕ is a total solid volume fraction (ϕ = C_v /100). This equation is based on the assumption that solid particles are sufficiently rigid and there is almost no interaction between them, due to dilute solution. /1, 20/

Absolute viscosity of mixtures with volume concentration smaller than 20%. To calculate the viscosity of more concentrated solutions of Newtonian slurries, it's possible to use a modified Einstein equation (Eq. 3.5). In this equation, the interactions between solid particles in the solution were taken into account. /1, 2/

$$\mu_m = \mu_L(1 + 2.5\phi + 14.1\phi^2) \qquad (3.5)$$

Absolute viscosity of mixtures with high volume concentration of solids. Thomas /21/ suggested the following equation with an exponential function for calculating the viscosity of slurry with a high concentration of solid particles:

$$\mu_m = \mu_L(1 + 2.5\phi + 10.05\phi^2 + 0.00273e^{16.6\phi}) \qquad (3.6)$$

Based on Eq.3.6, was built a graph, which is very widely used in slurry industry for heterogeneous mixtures of a Newtonian rheology. Ratio of viscosity of mixture versus viscosity of a carrier liquid phase, in accordance with the Thomas equation for coarse slurries is shown on the Figure 3.1. For Non-Newtonian slurries the term viscosity has no meaning unless it is related to a particular shear rate. For such fluids the shear stress vs. shear rate is not a constant, but a function of shear rate and is called the *apparent viscosity*. /22, 23/

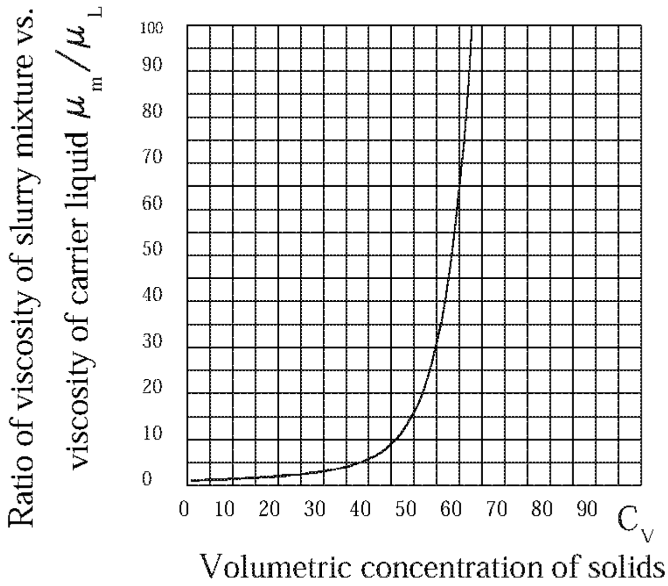

Figure 3.1 Ratio of viscosity of mixture versus viscosity of carrier /1/

4. INTRODUCTION TO CASE-BASED REASONING

Case-based reasoning (CBR) is a very successful technology developed in recent years. CBR is based on the idea that new problems can be similar to some old problems, solutions for which have already been found. And consequently, these solutions can be used in the current new situation. Nowadays CBR is commonly used for diagnosis (in a more general meaning – for classification tasks), for assessment tasks in the finance domain, also in decision support and process design. Industrial and commercial applications can be developed very quickly and existing databases can be used as data and knowledge sources. /24/

4.1 History review of CBR field

The roots of Case-Based Reasoning are found in the Schank and Abelson works in 1977. The work on dynamic memory defines that in problem solving and learning, the most important part is remembering of previous situations (cases, episodes) and situation patterns. Development in this area was also accompanied by works on analogical reasoning, decision making theory and experiments in psychology and philosophy. /25/

CYRUS was the first system which can be called a Case-Based reasoner. It was developed by Janet Kolodner in 1983 at Yale University. Basically it was a question-answering system with knowledge of the various travels and meetings. The case memory model of this system later was used for some other CBR systems (such as MEDIATOR, CHEF, JULIA etc.). /25/

4.2 Case-based reasoning conception

Case-Based Reasoning approach is based on two principles. Firstly, the world is regular and similar problems have similar solutions. Therefore solutions for similar past problems can be a good starting point for finding solutions to new problems. Secondly, the types of problems have a tendency to occur again. In such a way, it can be assumed with high probability, that future problems will be similar to existing problems. When the two tenets hold, it's expedient to remember and reuse the current reasoning; in this case CBR will be a quite effective method. /26/

The basic idea of *Case-Based Reasoning* is quite simple: "A case-based reasoned solves new problems by adapting solutions that were used to solve old problems" /27/. In CBR, a reasoner remembers preceding situations similar to the current one and uses them to solve new problems. CBR can mean adapting old solutions to satisfy new requirements, using old cases to critique new solutions, using old cases to explain new situations; and reasoning from cases to interpret a new situation or generate an equitable solution to a new problem. /28/

In CBR terminology, *case* can be considered as an experience situation. For example, case can be presented as a rule, advice, general law or simple past event. If the episode of experience provides some solutions, which could be useful, it's necessary to record this episode to the case. In decision making applications, a case usually means a problem-solving episode, which includes a problem and solution for it. In such a way, one record is represented as a pair: the problem and solution. But in many commercial applications, problem and solution parts of the case aren't distinguished, and case means a record with piece of experience, which includes a set of special features. All cases are collected together to form a case base. /29/

5. THE CBR PROCESS

In general, all Case-based reasoning tasks are divided into two groups: interpretive CBR and problem-solving CBR. To classify or describe new situations, *interpretive* CBR uses previous cases as an anchor points. *Problem-solving* CBR uses old cases to propose solutions that might apply to new situations /26/. Both styles will be considered in this chapter. Interpretive and problem-solving CBR are dependent on the mechanism of retrieval of cases that can recall useful cases at the relevant time. For both of them, the storage of new situations in memory allows to learn through experience. In order to create new solutions, to interpret the processes, and to judge derivatives solutions, problem solving case-based reasoning heavy uses adaptive processes. /28/

5.1 Case-based interpretation

In this type of CBR, reasoner classifies new situations and forms judgments about them, by comparison with old cases. Interpretive style can be used during problem solving, for situation classification, evaluation of a solution, argumentation, justification of a solution, and for diagnosis tasks. For example, to determine the best diagnosis, current symptoms can be compared and contrasted with the old cases.

Interpretive CBR includes four stages. Firstly, in order to decide which features of the new situation are really important, reasoner has to perform an assessment of the situation. Then, based on the results of situation evaluation, reasoner retrieves a relevant prior case. Thirdly, the reasoner needs to decide which interpretation applies, by comparing the obtained cases with new situation. The last task is to save current situation and interpretation as a new case for further reasoning. /26/

The interpretive style uses cases to ensure substantiation for solutions, to evaluate solutions when clear-cut methods not available, and to interpret the situations with open-ended or fuzzy boundaries. There are usually a lot of unknowns in these situations, thus even if computational methods are available there is not enough knowledge for their work. In that case, reasoner justifies his lack of knowledge with the assumption, that the world is consistent. /28/

5.2 Case-based problem-solving

Like previous type, problem-solving CBR includes situation assessment, retrieval of the case, and similarity evaluation. Similarities and differences between old and new cases are used to determine how the previous solution can be adapted to the new situation. In addition, old solutions can prevent potential warnings and failures in the future, as well as provide almost right solutions for new problems. Case-based problem solving can be used for wide range of tasks, such as diagnosis, planning, and design. /28/

There are two different types of similarity, which are used in case-based problem-solving. These two types belong to two different spaces: the space of problem description and the space of problem solutions. Both spaces are illustrated in Fig. 5.1. When new problem enters the CBR system, it makes the assessment of the situation to obtain a description of problem, and then searches for problems with similar descriptions. To generate a solution for new problem, the solutions of those problems are used as a starting point. If the right way to describe the problem was chosen, it will be easier to adapt solutions to the new situations, because similar problems have similar solutions. /26/

In this work, the term *similarity* considered as a fuzzy relation between two cases. It is intended to adapt available knowledge about previous problems to solve new ones. There are two different techniques to determine the similarity in CBR. The first one is *computational* approach. In this approach, an explicit similarity function is calculated for all cases in the case base. New problems and cases from past are vague matched, to determine their degree of similarity. The degree is determined by a numerical calculation and result is a single number, which reflects all aspects of the similarity. The second one is *representational* approach. The case base is pre-structured for this method. Retrieval is done by traversing the index structure. And it is assumed that neighboring cases according to the index structure are similar. Some techniques combine both these methods. /30/

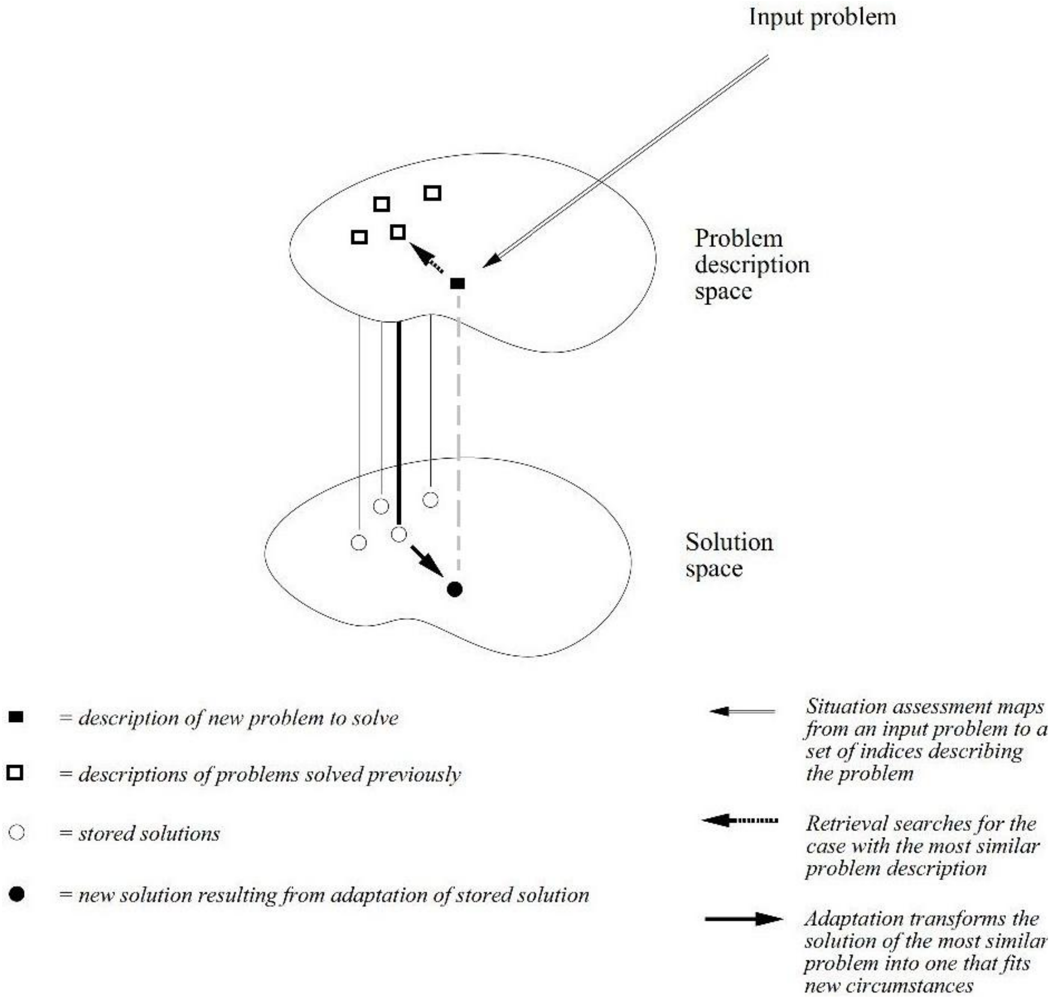

Figure 5.1 Relationship between problem and solution spaces in CBR /26/

6. REVIEW OF CBR MODELS

Several models have been developed to describe the CBR process. The most well know are presented below.

6.1 Kolodner's CBR model

On the Fig. 6.1 the structure of CBR cycle proposed by Kolonder (1992) is shown. She offered that for case-based reasoners, the major processes are case retrieval and case storage. New ballpark solution is proposed by extracting the solution from retrieved cases. This is followed by adaptation process – fixing of old problem to fit a new situation. The next step is criticism, it is necessary to preliminary evaluate the new solution. This is followed by justification – creating an argument for the proposed solution and criticism again. After that reasoner need to ensure that poor solutions are not repeated with the good ones, and it requires an evaluation stage. /28/

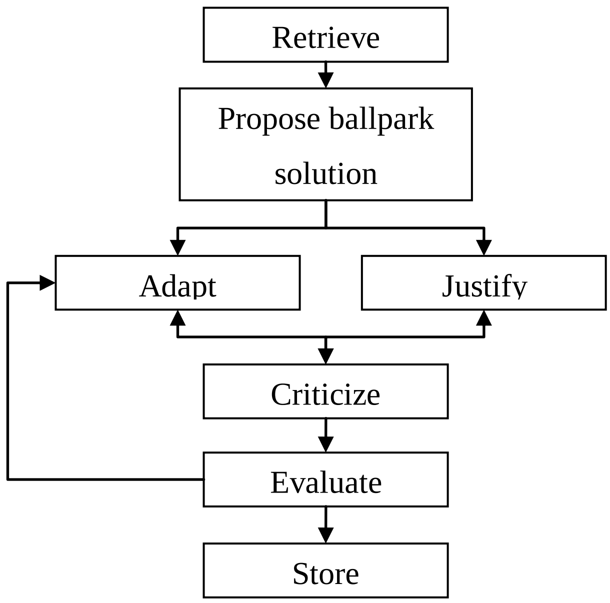

Figure 6.1 The CBR cycle by Kolodner (1992) /28/

The described steps in a certain sense could be recursive; for example adapt and criticize steps frequently require new cases to be retrieved. Process also can have some loops. For example: when the process of reasoning goes bad with chosen case, it might be necessary to choose new case and to restart procedure from the beginning; also sometimes after criticism or evaluation stage additional adaptation is required. /28/

6.2 Aamodt & Plaza's CBR model

Classic Aamodt & Plaza's (1994) problem solving cycle is shown on Fig. 6.2. The individual steps in the CBR cycle, i.e. retrieve, reuse, revise, and retain, are known now as the "4 REs".

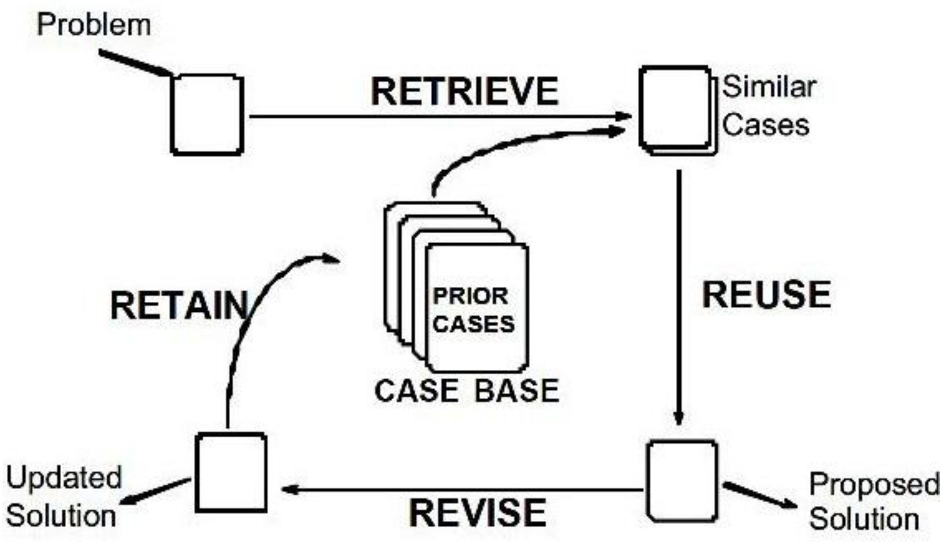

Figure 6.2 The CBR cycle by Aamodt & Plaza (1994) /25, 31/

CBR can be described as a cycle of the four following processes:

- ***Retrieve*** old cases, the most similar to new one, from the case base;
- ***Reuse*** retrieved cases to fit the new case;
- ***Revise*** the proposed solution;
- ***Retain*** the final solution as a part of a new case.

A new problem is compared with the cases in the case base and one or more cases are retrieved. Then solution from case base is reused and tested for success. If the retrieved case is a close match, the solution could be retained. Thus the new case is formed, which can be retained subsequently.

Revision may include other methods of reasoning, such as the use of the proposed solutions as a starting point to search for a solution. Adaptation in an interactive system also could be done by human. After that new case with the solution can be retained during last stage. /32, 33/

6.3 Six-REs CBR model

Ian Watson /34/ considers CBR process as a cycle from six activities; they are presented on the Fig. 6.3. As you can see, in comparison with Aamodt & Plaza's model, two new steps were added to this model – *review* and *retain*.

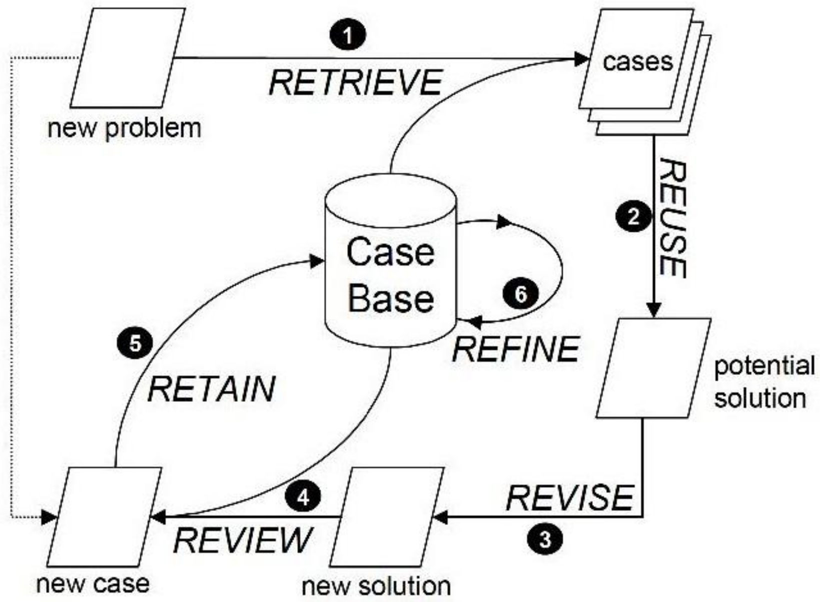

Figure 6.3 The CBR cycle by Ian Watson (2001) /34/

The six-REs of the CBR cycle can be mapped to the activities required by a knowledge management system. In this cycle, first three steps (retrieve, reuse and revise) are completely the same with previous model steps, so only last three steps (review, retain, refine) will be considered further:

- ***Review*** the new case by comparing it against cases already retained in the case base;
- ***Retain*** the new solution (if it was founded useful);
- ***Refine*** the case-based index and feature weights as it's necessary. /34/

6.4 Finnie & Sun's CBR model

This model is an enhanced version of Aamodt & Plaza model. The main steps are: repartition, retrieve, reuse, revise and retain. Repartition step builds a satisfactory case based on utilizing similarity relations to the possible world of problems and the world of solutions. This five-REs model, unlike previous ones, takes into account the fact, that to build a case base it is also important CBR task. Thus in their model, Finnie and Sun have included the process of preparation of case bases /29/. The whole cycle of five-REs model is shown on the Fig. 6.4.

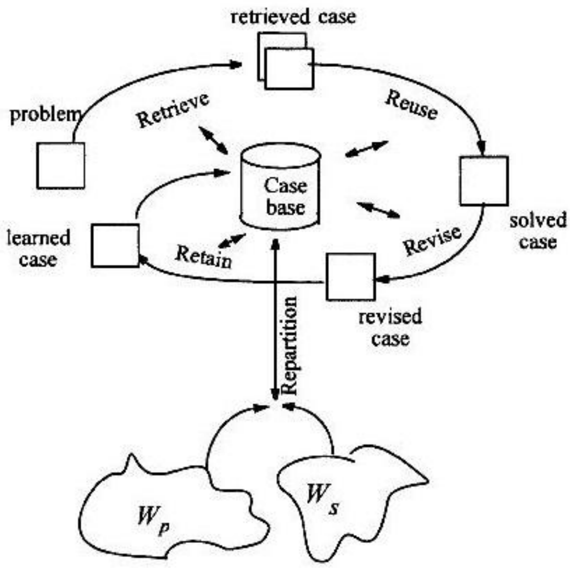

Figure 6.4 The CBR cycle by Finnie & Sun (2003) /35/

Furthermore, repartition provides the theoretical basis for case retrieval, because of one-to-one correspondence between the similarity relations and the partitions. In this way, both case-base building and case retrieval can be considered as a similarity-based reasoning in a uniform way. Thus, the proposed model can unify case base building, case retrieval, and case adaptation process. /35, 36/

7. REPRESENTATION OF CASES

The efficiency of CBR process is very dependent on the structure of its collection of cases, the so-called case memory. Problems are solved be recalling a previous experience suitable for solving new problems, so searching process should be both effective and reasonably fast. The process of storing new cases in the case base must also satisfy these conditions. The representation problem in CBR is primarily the problem of deciding what to store in a case, finding an appropriate structure for describing case contents, and deciding how the case memory should be organized and indexed for effective retrieval and reuse. An additional problem is how to integrate the case memory structure into a model of general domain knowledge, to the extent that such knowledge is incorporated /25/. The dynamic memory model of Schank and Kolodner, and the category-exemplar model of Porter and Bareiss are the most well-known case memory models. Both of them will be briefly reviewed in this chapter.

7.1 The dynamic memory model

In this method, the case memory model consists of memory organization pockets or MOPs. MOPs are the basic unit in dynamic memory. MOPs are a form of frame and they are used for knowledge representation about classes of events. There are two groups of MOPs:

- ***Instances.*** Group represents cases, events and objects;
- ***Abstractions.*** This class represents generalized versions of instances or of other abstractions. /30/

As it was mentioned before, Kolodner's CYRUS system /37/ was the first system, which could be called case-based reasoner. The system was based on Schank's more general MOP theory /38/. The case memory in this model is a hierarchical structure of what is called episodic memory organization pockets or E-MOPs, from other sources known as generalized episodes. The basic idea is to organize specific cases which share similar properties under a more general structure (i.e. a generalized episode). There are three different types of objects which constitute a generalized episode, they are: norms, cases and indices. Features, which are common to all cases indexed under a GE, are called norms. Indices are features which discriminate between a GE's cases. An index may point directly to a case or to a more specific generalized episode. An index consists of two parts: an index name and an index value. /39, 40/

Structure of cases and generalized episodes is shown on Fig. 7.1. The figure illustrates a complex generalized episode, with its underlying cases and more specific GE. Whole case memory is a kind of discrimination network, where a node is either a GE, an index name, index value or a case. Each index-value pair leads from one generalized episode to the case or to another generalized episode. One index value may only leads to a single case or a single GE /25/. The figure illustrates that the indexing scheme is redundant, since there are multiple path to a particular case, i.e. case1 on the picture.

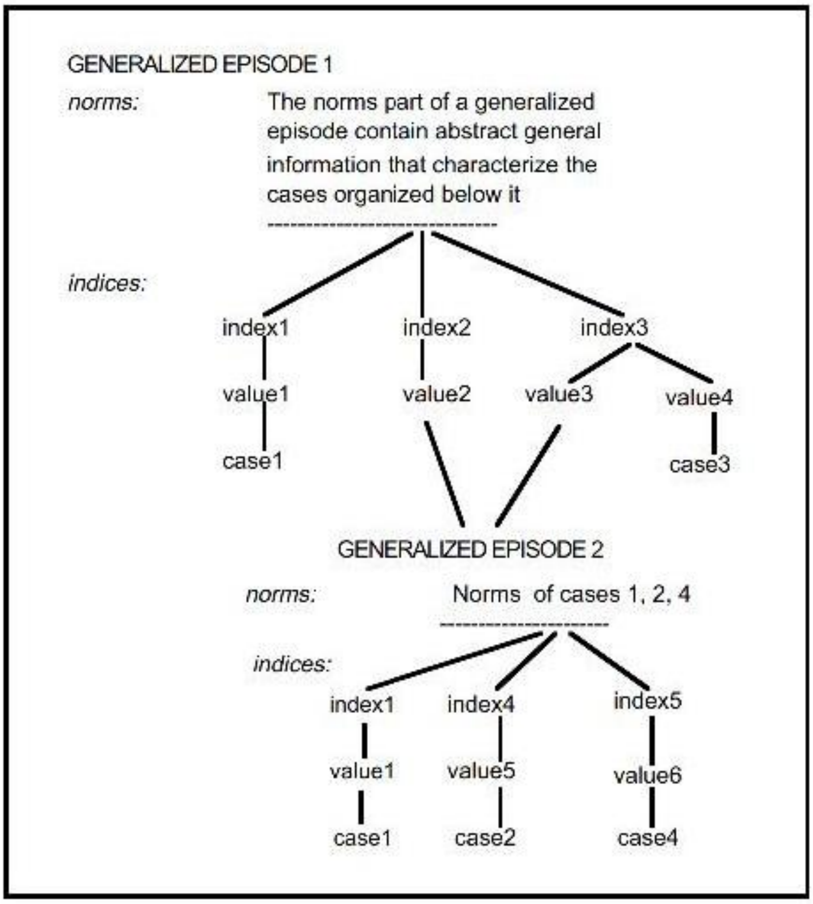

Figure 7.1 Structure of cases and generalized episodes /25/

GE is an indexing structure, primarily intended for storing, searching and retrieval of cases. If during the case storage, feature of new case matches with previous case feature, a new generalized episode is created. Both cases are then discriminated by indexing them under different indices below the new GE (it is assumed that cases are not identical). Thus, similar parts of two cases are dynamically generalized into a new GE and cases being indexed under the GE by their differences; in accordance with this, memory is called dynamic. However, for practical purposes, most CBR systems using this method limit the number of allowed indices to avoid their explosive growth when number of cases is increases. /30/

7.2 The Category-Exemplar Model

Alternative way to organize cases in a case memory was proposed by Ray Bareiss and Bruce Porter in their PROTOS system /41/. This model organizes cases based on the view that the real word should be defined extensionally with cases being referred to as exemplars. The case memory proposed to be a network structure of categories, semantic relations, cases and index pointers. Every case is linked with a category. In describing a case's membership to a category, each feature is assigned its own degree of importance. In this model tree types of indices are provided, which may lead to a case or a category. They are listed below:

- ***Feature links*** pointing from problem descriptors (features) to cases or categories (called remindings);
- ***Case links*** pointing from categories to its associated cases (called exemplar links);
- ***Difference links*** pointing from cases to the neighbour cases that only differs in one or a small number of features. /30/

Usually, a name-value pair describes a feature. Inside the category, a category's exemplars are sorted according to their level of prototypicality. On the Fig. 7.2 a part of memory structure (i.e. links between features, cases and categories) is illustrated.

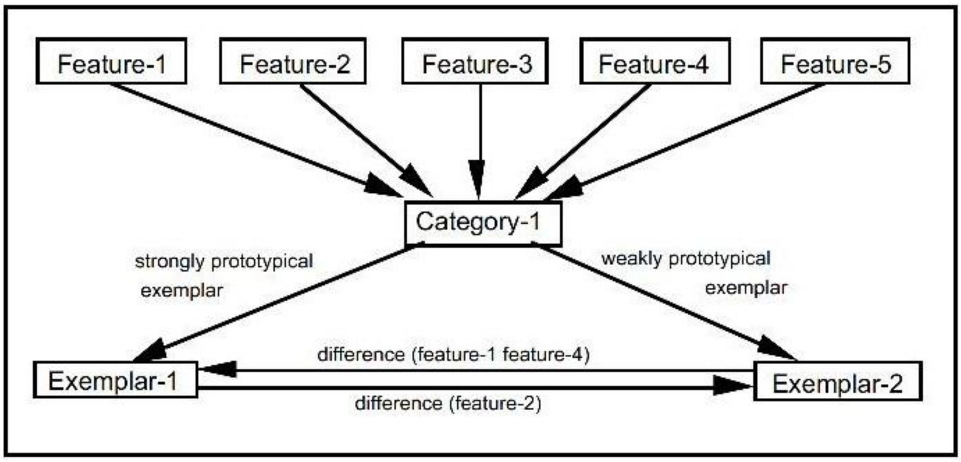

Figure 7.2 The structure of categories, features and exemplars /25/

In this model, the categories are interrelated within a semantic network, which also includes the features and intermediate states (such as subclasses of target concepts) related to by other terms. This network represents a background of general domain knowledge, which enables explanatory support to some of the CBR tasks. For example, a core mechanism of case matching is a method called ‘knowledge based pattern matching’. /30/

Searching for case, which matches an input description, in the case base is done by merging the input features of a problem case into a pointer to the case or category that shares most of the features. If a reminding points directly to a category, the links to its most prototypical cases are traversed, and these cases are returned. In such a way, the general domain knowledge is used to allow matching of features that are semantically similar. A new case is stored be searching for a matching case, and by establishing the corresponding feature indices. If a case is found with only slight differences to the input case, the new one may not be retained or the two cases may be combined by following taxonomic links in the semantic network. /25/

8. CBR CYCLE

8.1 Retrieval in CBR

Retrieval algorithm finds the most similar cases to current situation or problem, given the description of the problem and by using the indices in the case-base memory. Searching for potentially useful cases directly depends on the indices and memory organization. The problem of choosing the “best” cases many times has been the subject of research in the area of analogy. At that time some algorithms were developed, such as: serial search, hierarchical search and simulated parallel search. /40/

The purpose of the conventional database search it is a certain number or record. Unlike a traditional database search, retrieval of cases from case-base should include partial matches, because full coincidence of a new case with old one is practically impossible. And only when the retrieval algorithms will be effective for processing thousands of cases, the CBR system will be ready to solve large-scale problems. /40/

Similarity assessment

Assessment of the similarity of the stored cases can be done by using their surface features (surface features are those which are the part of description and usually are attribute-value pairs). If cases are represented by complex structures (e.g. graphs), retrieval could require an assessment of their structural similarity. By using structural similarity, more relevant cases could be retrieved, but it's computationally expensive. Use of carefully crafted indexing vocabularies to describe cases will help to avoid extra computations. Therefore an explicit description of the case captures the features that determine its relevance. /31/

There are a lot of different ways how to measure a similarity. According to case representation, one or another approach could be selected. For example, if each case is represented as a simple feature vector (or set of attribute-value pairs), *local similarity* measure is determined for every attribute. Global similarity can be calculated as weighted average of the local similarities. Different weights allow various attributes to have different degrees of importance. /25, 31/

Nearest neighbor, induction, knowledge guided induction and template retrieval – are widely known methods for retrieval of cases from case base. They can be used separately or combined into one hybrid strategy /40/. A brief description of these methods will be given further:

- ***Nearest neighbor.*** This technique is perhaps the most common, because it is used in the main part of CBR applications. All algorithms of this group operate approximately the same way. Firstly, the similarity between new problem and case from case based is defined for every case attribute. This value is multiplied by a weighting factor. The similarity between a new case and an old one is calculated by summation of similarity values for all attributes. This technique can be represented by the following equation:

$$Similarity(T,S) = \sum_{i=1}^{n} f(T_i, S_i) \times w_i \qquad (8.1)$$

where T is the target case, S is the source case; n – the number of attributes in each case, i an individual attribute from 1 to n; f is a similarity function for attribute i in case T and S; w – the importance weighting of attribute i. This calculation is repeated for each case in case library, to rank the cases according to their similarity with the target case. Usually, when calculations are already completed, similarities are normalized to fall within a range of zero to one. Where “one” is an exact match and “zero” is totally dissimilar (percentage similarity is also used, where 100% is an exact match). /42/

- ***Template retrieval.*** This method is often used before other methods, to make the first approach and limit the search area to a specific section in case base. In this way, template retrieval returns all cases which match certain parameters. Queries are similar with SQL-queries. /40/

- ***Induction.*** Induction algorithms generate a decision tree type structure in order to organize cases in memory; and determine which features are the most important in discriminating cases. This technique is used when solution is only single case feature and when this feature is dependent from others. There is also *Knowledge guided induction* method, which uses application of knowledge to the process of induction, by manually identifying the parameters of the case, which are known or suspected to affect the primary case features. /43/

Some approaches were also investigated to reduce retrieval time. For example, Stanfill & Waltz /45/ suggested using massive parallel computers. This approach is guaranteed to find the most similar cases, but requires a lot of expensive equipment. Some other researchers, in their attempts to reduce the search time, relied on the organization of cases in memory. Certain of these methods will be considered below:

- ***k - d trees.*** Binary tree is used to separate cases in memory to the groups, so that in one group there will be similar cases, according to a given similarity measure. To verify, that the most similar cases are retrieved, the algorithm computes similarity bounds in order to define, which group of cases should be considered first. The biggest advantage of this approach is the ability to combine CBR techniques and inductive learning methods. Therefore, this process is very suitable for diagnostic tasks. /46/

- ***footprint-based retrieval.*** This method was suggested by Smyth & McKenna /47/. It consists of two stages. Firstly, the first footprint case is identified, which is the most similar with the target case. Secondly, other small subset of cases, which are related to the reference case, is retrieved. Lastly, the final case is selected from retrieved ones. The approach is good, because it is searching for a small proportion of cases in case base and at the same time provides a high level of similarity with the target. This method is related to fish and shrink strategy. /31/

- ***fish and shrink.*** In this model, properties are associated in accordance with specific aspect of similarity. Approach assumes that if the case doesn't satisfy the request, it will lead to a decrease in the usefulness of its neighbors. This assumption allows to eliminate a large number of useless cases during the retrieval. Method could be very useful in areas, where it is necessary to work with highly structured cases (e.g. design). /46/

However side by side with reducing the searching time, some investigators tried to improve the solution quality. It is also important aspect of case retrieval. Methods of quality assessment for founded solutions depend on the type of problem-solving task for which the system is designed, e.g. recommendation, classification or planning. For example, evaluation in terms of classification accuracy is possible only if the outcome classes are represented in the training set. But in such domains like product recommendation, this is not the case, because every outcome class (a unique service or product) is represented by a single case in the case memory. Estimation of classification accuracy is similarity compromised in conversational CBR, where for most cases it's common to have unique solutions. /31/

There are several problems that could affect the solution quality. Here are some of them: using of inappropriate measures of similarity, missing values in cases, noise, unknown values in target problem description, and so-called problem of heterogeneity, which occurs when different features are used to describe different cases. Some possible strategies for handling missing information in similarity assessment were proposed and evaluate by Bogaerts & Leake (2004) /49/. Retrieval based on incomplete information is an important challenge in conversational CBR, where a description of the target problem is incrementally (and often incompletely) elicited in an interactive dialogue with the reasoner.

Aha et al. in their work proposed an incremental query elicitation approach that takes into account the heterogeneity, which is typically found in such areas like fault diagnosis /50/. In his work, McSherry suggested a conversational CBR approach to product recommendation. The method includes a mechanism, which ends the dialogue only if it is known that more similar cases will not be found in the future. /51/

Nowadays, similarity plays an impressive role in case retrieval, but similarity increasingly being combined with other criteria, such as how effectively the solution space is covered by the retrieved cases, how easily old solutions could be adapted to solve target problem, and how easily the proposed solution can be explained /52, 53/. Some alternatives to similarity-based retrieval will be considered below:

- ***Adaptation-guided retrieval.*** I this method, the adaptation requirements of cases are explicitly assessed during retrieval by means of domain-specific adaptation knowledge. Unlike the traditional approaches that relied on heuristics in order to predict how easily a given case could be adapted. To ensure that the best case is selected, adaptation-guided retrieval combines local and global measures of adaptability. This approach can considerably reduce adaptation failures and adaptation costs. /31, 55/

- ***Diversity-conscious retrieval.*** The most similar cases are usually very similar to each other, so that the reasoner is offered a limited choice. Thus, the recommended cases may be lacking in diversity. To solve this problem, some algorithms have been proposed, which combine measures of similarity and diversity in the retrieval process to achieve a better balance between these characteristics. Experiments have shown that by even a small decrease of similarity, significant increase in diversity could be achieved. /56/
- ***Compromise-driven retrieval.*** This approach is based on the assumption that a given case is more acceptable than another, if it is more similar to the user's query and it involves a subset of the compromises that the other case involves. For example, no case is included in the retrieval set, if there is a more similar case that involves a subset of the compromises it involves. /53/
- ***Order-based retrieval.*** This approach offers an expressive query language to define and combine ordering relations. The result of query estimation is partially order of cases in case base. Since the set of retrieved cases is quite diverse, there is no need for an explicit measure of recommendation diversity. /31, 57/
- ***Explanation-oriented retrieval.*** For CBR systems sometimes it is needed to explain their reasoning and justify their solutions. This approach remains precedent-base, but once a classification or diagnosis has been retrieved on the basis of the nearest neighbors, the system performs an additional retrieval step, using an explanation utility metric, to obtain the explanation case. /31, 52/

8.2 Reuse in Case-Based Reasoning

Sometimes, reusing of a retrieved case can be done very easily, and it consists in returning the unchanged retrieved solution as a proposed solution for the new problem. This is often takes place for solving classification tasks. This way, each solution is likely quite often represented in the case base; thus, the most similar retrieved case, if similar enough, is likely to contain a relevant solution. But if there is big difference between the new problem and the retrieved case's problem, reuse becomes much more complicated. Under these conditions, to take the difference into account, it might be required to adapt the old solution to solve new problem. There are some areas, where the process of adaptation is needed: medical decision making, design, configuration, and planning. /31/

Adaptation

As soon as the coincident case is retrieved, the CBR system should adapt an existing solution for new problem needs. Adaptation looks for difference between the current case and retrieved one, and then applies rules of formulas, which can take into account these differences. Basically, there are two types of adaptation in CBR:

- ***Structural adaptation.*** In this approach, adaptation rules are applied directly to the solution, stored in a retrieved case. The most popular technique is to replace a component of the retrieved solution with an alternative value, which may be granted by an additional source of knowledge. CHEF system is a good example of this approach. /43, 58/
- ***Derivational adaptation.*** In this technique, some algorithms, methods, and rules, which generated the original solution, are reused. And it is the way to produce new solution to the current problem. PRODIGY system is a good example of this approach. Derivational adaptation, sometimes referred to a re-instantiation, can only be used for cases that are well understood. /43, 59/

In order to generate complete solutions from scratch, the ideal set of adaptation rules should be strong enough. Sometimes an effective CBR system is able to use both types of adaptation. For example, structural adaptation rules can be used to adapt poorly understood solutions, and derivational method to adapt solutions of cases that are well understood. Several techniques have been used in CBR systems for adaptation, some of them are listed below:

- ***Null adaptation.*** Simple and direct technique, which applies any retrieved solution to the current problem, without adaptation. Suitable for problems with complex reasoning, but quite simple solution.
- ***Parameter adjustment.*** Structural adaptation technique, which compares certain parameters of the current and retrieved cases to change the solution in a particular direction.
- ***Abstraction and re-specialization.*** Complex technology, which uses basic way to obtain an ordinary adaptations and more sophisticated way to create a new, creative solutions.
- ***Critic-based adaptation.*** In this technique, the critic is looking for a combination of parameters, which can lead to problems in the solution. It is also important for critic to know how to solve these problems.
- ***Re-instantiation.*** Technique is used to instantiate features of an old solution with new features.
- ***Derivational reply.*** Method of deriving of an old solution (or just piece of solution) is used to derive a solution in the new situation.
- ***Model-guided repair.*** Casual model is used to guide adaptation.
- ***Case-based substitution.*** Cases are used in this process to suggest solution adaptation. /40/

The purpose of the CBR system is to provide solutions to the new problems. Typically this is achieved by adapting existing solution to satisfy the conditions of new problem. But when it’s impossible to adapt solutions for new problem, there is an alternative way – to adapt the problem situation itself, thus the retrieved case can apply to the new problem without adaptation. The adaptation of context can be done by explaining why the retrieved case is relevant. In such type of systems, ‘bridging’ generates a description of why a case is relevant, showing how the case applies. The ‘bridge’ provided by that explanation makes the retrieved case useful. /26/

8.3 Case revision

When the solution obtained after reuse is incorrect, it becomes possible to learn from failures. This stage is called the revision and comprises two tasks: to evaluate the solution obtained after reuse stage; and if this solution is unsatisfactory, then repair the solution, by using domain-specific knowledge.

Solution evaluation

At this stage, the results of reasoning are tested in the real word. Data about real events that occurred as a result of executing the solution must be received and analyzed. And if the results are not expected, it is necessary to make detailed assessment of reasons of anomalous results. This requires figuring out what caused the anomaly and how to fix and prevent it. Sometimes explanations can be done by case-based reasoning. Solution evaluation is one of the most important steps for a case-based reasoner, because of possibility to get feedback and to learn from experience. Feedback allows to find the consequences of the reasoning process, after that reasoner can easily explain things that didn’t go exactly as it was planned. Thus, the reasoner is able to anticipate and avoid mistakes. It is also possible to notice previously unforeseen opportunities that can be reused in the future. /28/

Evaluation is the process of quality assessment of a proposed solution. It can be based on previous cases, on feedbacks, on the actual or mental simulation. Evaluation includes an explanation of the differences between expected occasion and real event, justification of differences, projecting outcomes, comparison and ranking of alternative possibilities. The result of this process can be an additional adaptation or repairing of the proposed solution. /28/

If the proposed solution is not satisfactory, case repair involves detecting the errors of the current solution and retrieving or generating explanations for them. Good example for this is the CHEF system, where causal knowledge is used to generate an explanation of why certain goals of the solution plan were not achieved. Solution repair task is the part of the revision phase and it uses the failure explanations to modify the solution in such a way that failures do not occur. /25/

8.4 Retention in Case-Based Reasoning process

The purpose of this stage is to decide what will be useful to include in the already existing knowledge from new episode. The learning from success and failures of the proposed solution is triggered by the outcome of the evaluation and possible repair. This stage includes some tasks: which information from the case should be retained and in what form, how to index the case for later retrieval, and how to integrate the new case in the memory structure. /25/

The most important process that takes place at this stage is choosing the way how to 'index' the new case in case base. The index should be chosen in such a way that the new case can be easily recalled from the memory every time it will be useful for solving new problems. In other words, the reasoner has to anticipate the importance of a case for further reasoning. During this step, memory's indexing structure and organization are also adjusted. Thus, it's important to choose appropriate indexes for the new case and at the same time make sure that all other cases still available as we add to the case library's store. /28/

Learning may also take place within the general conceptual knowledge model in some knowledge-intensive approaches to CBR; for example by other machine learning methods or through interaction with the reasoner. Thus, with effective interaction with the user (it could be an expert or a competent user), the CBR system can progressively expand and improve its general knowledge model, as well as its memory of past cases, in the normal mode of problem-solving process. Just learned cases can be easily tested by re-entering the initial problem to make sure that system behaves as it needed. /25/

Early CBR systems simply stored in memory all the cases they created. More recent works examine the effect of design decisions about the maximum size of case library, as well as how to decide which cases must be stored in order to provide the best coverage. Some systems also reason about which cases to try to acquire. /26, 60/

9. ADVANTAGES AND DISADVANTAGES OF CBR

9.1 Benefits

- CBR allows the reasoner to propose solutions to new problem very quickly, because search for solutions made not from scratch. CBR reasoner gets a head start on solving new problems, because it can easily generate new solutions. But like any other reasoner, he still has to evaluate obtained solutions. Also there is no need to redo time-consuming computations and inferences, and this is a significant advantage. This benefit is helpful for almost all reasoning tasks, including problem solving, diagnosis, explanation and planning.
- CBR allows a reasoner to propose solutions in domains that have not been studied completely and in those, which almost impossible to explore fully (for example, those ones, which much depend on unpredictable human behavior). In other words, it is possible to make assumptions and predictions based on what worked in the past and sometimes even without full understanding of the problem.
- When algorithmic methods are not available for evaluation, CBR gives a reasoner a means of evaluating solution. When there are a lot of unknowns, and it is very hard or even impossible to use other methods, using of cases to aid evaluation is particularly useful. Again, the reasoner does evaluation based on what worked in the past and solutions are evaluated in the context of previous similar cases.
- Cases are particularly useful for use in interpreting open-ended and ill-defined concepts.
- Remembering the previous cases is very helpful to avoid future errors. Thus, reasoner can take some actions to avoid repeating of past failures.

Remembered experiences can be failure or successful episodes, i.e. situations in which things did not go as it was planned.

- Cases can indicate the features of the problems, which are the most useful for a reasoner, this way they helps reasoner to focus on really important aspects of the problem. What was important in past issues is likely to be important in the new ones. Thus, if in a previous case, some set of features was implicated in a failure, the reasoner focused on those features to insure that the failure will not be repeated. Similarly, if some features have led to success, they are also worthy of attention. This focus plays a role both in problem solving and in interpretive case-based reasoning. In the interpretative approach, justification and critiques are based on those features that are responsible for success and failures in the past. In problem solving approach, reasoner can adapt the solution, by including more of what was successful in the past and less of what led to mistakes. /28/

9.2 Disadvantages

A case-based reasoner might be tempted to use old cases blindly, relying on previous experience without validating it in the new situation, or cases can bias reasoner too much in solving a new problem. Quite often reasoners, and particularly novices, can forget about the most appropriate sets of cases during the reasoning process. People do find case-based reasoning a natural way to reason, however.

In addition, the case memory technology might allow us to build decision aiding systems that augment human memory by providing the appropriate cases while still allowing the human to reason in a natural and familiar way. In addition, disadvantages of case-based learning include: increased time to design and develop quality cases, particularly technology or multimedia cases; also it is needed to provide reasoners with sufficient resources to understand the case. Complex cases require the collection and storage of a large quantity of resources. /28, 62/

10. CBR SOFTWARE TOOLS

A brief description of the existing case-based reasoning tools and applications will be given in this section. Nowadays a lot of companies are developing and applying CBR technology in industry; some of them are considered in the table below.

Table 10.1 Companies developing and applying CBR technology /64/

Company name	**Works**
brox	Together with *empolis* they support the SMILA an extensible framework for building search solutions to access unstructured information in the enterprise. Well-known in Germany, as a software and services provider for enterprise-wide information management and data governance.
caseBank	The most well-known technology is *SpotLight* – a decision support system that contains solutions built from field experience events. The main activity is the creation of diagnostic software solutions, effective support of technical specialists in maintenance and repair of equipment, processes and systems.
CDM Technologies, Inc.	The company specializes in the developing of integrated decision-support software, as well as in the developing of advanced technologies for military industries and commercial customers. The most commonly known applications related to reference mapping to support database interoperability and to concerning transportation planning.

empolis	Organization creates knowledge management solutions for information logistics in whole company and solutions for business processes improving.
Enkia	In order to solve various business problems, the possibilities of human cognition and algorithms of CBR are used in Enkia's products. The company produces intelligent software for solving problems of information analysis and particularly in text analytics area.
Industrial Artificial Intelligence Lab at GE Global Research	The major areas of company activities are: optimization, decision support, condition based maintenance; also condition based maintenance and the development and application of computational algorithms, including neural networks, genetic algorithms and CBR.
Kaidara	The company has developed the Advisor system, a conversational case-based system for help desks management.
Knexus Research Corporation	Develops intelligent software to automate and simplify the knowledge-intensive tasks. Systems learn from their mistakes and adapt to unexpected situations, by going beyond conventional systems.
Stottler Henke	This company is investigating various methods of simulation of human thinking and reasoning, such as case-based reasoning and model-based reasoning. Specialized in artificial intelligence products and solutions for education and training, decision support, knowledge management,

	planning and scheduling, computer security and reliability.
Strands	The company helps people to open new items, by developing of recommendation and personalization technologies.
Verdande Technology	This company's technology combines the principles of the case-based reasoning with knowledge modeling and data interpretation. Designed products and services are used to automatically capture and reuse the business-essential knowledge.

11. RESULTS

To develop a decision support system for slurry viscosity determination, software application MS Office Excel was used. Designed system consists of three parts: workspace, the case base, and section for calculating the viscosity of Newtonian slurries. First and second sections are supposed to work with Newtonian and Bingham fluids. In the last section, apparent viscosity can be calculated only for Newtonian slurries. Results of several laboratory studies of slurries were taken from several sources /1, 14, 18/ and were used to fill the case base with cases. The case base consists of 112 cases. At any moment, reasoner can add new cases, which he considers to be useful for further work.

The Fig. 11.1 shows Workspace part of system. For each new case it is possible to enter 6 initial data, i.e. density, solid volume fraction, solid weight fraction, viscosity yield stress, particles size. The system is flexible and the number of parameters can be further increased. The data availability coefficient is entered for correct calculations of the degree of difference. Thus, if the value is unknown, it does not contribute to the degree of difference calculations.

Decision support system for slurry viscosity determination

(with the use of CBR methodology)

Enter the details of a new case:

	Density	Solid volume fraction	Solid weight fraction	Viscosity	Yield stress	Particles size (≈ 50% of volume)
	kg/l	%	%	mPa·s	Pa	µm
New slurry	1,58	37,3	60,4	7,26	2,318	30
Data availability coefficient	1	1	1	1	1	1

The coefficient is required for correct calculations !

0	Select 0 from the list, if parameter's value is unknown
1	Select 1 from the list, if parameter's value is known

Figure 11.1 Workspace section of decision support system

As a result of search for most similar cases, 15 less different cases are retrieved. This amount was chosen because of the small size of the case base and can be easily increased.

The second part of system is a Slurry Case Base. In addition to main data about slurries, it contains some helpful calculations (i.e. normalized values of parameters of target case and previous cases, max and min values, degree of difference). One of the main tasks of the reasoner is to add new cases in the case base. Record for new slurry can contain all the features or just some known ones. But the type of liquid should always be known for each case in case base, based on the objectives of the developed system. The degree of difference in this case base is the primary search criteria for appropriate cases; the smaller the value, the more appropriate case will be retrieved.

Calculation section allows user to calculate the viscosity of Newtonian slurry, on the basis of absolute viscosity of liquid phase and total solid volume fraction. The equations for these calculations were discussed earlier in the Section 3.3 of the literature review. The system is able to calculate the apparent viscosity for very diluted slurries with solids concentration less that 1%; for slurries with solids concentration less that 20%; and for very concentrated liquids.

To check the efficiency of the system, some tests were performed. For this purpose, record (case) was removed from case base and then was used as new slurry to find matches.

Table 11.1 The results of system test

№	Name	Type	Density	Solid volume fraction	Solid weight fraction	Viscosity	Yield stress	Particles size
			kg/l	%	%	mPa·s	Pa	μm
Test 1								
Target case								
23	Cromite 1	Newtonian	1,10	3,1	12,1	1,47	0	40
Retrieved case (Degree of difference = 0,0457)								
59	Sulphide 1	Newtonian	1,08	4,3	11,5	1,29	0	40

Test 2								
Target case								
57	Phlogopite 4	Bingham	1,45	24,5	48	4,46	0,309	35
Retrieved case (Degree of difference = 0,0295)								
77	Fine coal	Bingham			49		1	40
Test 3								
Target case								
107	Fine liminite	Bingham	2,44		52,4		30,0	50
Retrieved case (Degree of difference = 0,1091)								
93	Red Mud	Bingham			50		33,2	30
Test 4								
Target case								
76	Sulphide 3	Bingham	1,63	33,4	59,2	8,18	2,318	30
Retrieved case (Degree of difference = 0,0456)								
88	Uranium Tails	Bingham			58		4	38
Test 5								
Target case								
7	Quartz 2	Newtonian	1,21	13,6	28,7	1,73	0	35
Retrieved case (Degree of difference = 0,0353)								
3	Quartz 1	Newtonian	1,22	14,2	29,8	1,76	0	40

From the presented results it can be seen, that system correctly finds the instances of the appropriate type of fluids, which is its main objective. You can also note that the search is much more efficient if all the features of target and previous cases are known. Thus, the quality of the system in general is highly dependent on the quality of the case base. And the more full and complex cases will fill the case base, the more similar cases will be retrieved.

All three parts of the system are presented in Appendixes.

Some recommendations how to improve the system:

- Improve the case base. The best option is to look for a large industrial database for slurries. Also it is possible to continue the search in various scientific papers.

- Add new features for the slurries. It will make the process of search more efficient.
- Add weights to calculate the similarity/dissimilarity. With appropriate weights, important parameters will have a significant impact on the assessment of similarity and the less significant vice versa.
- Modify the system interface to a more convenient and comprehensible form. Also it is possible to implement the algorithm in on of programming languages to get an independent software application.
- Use new techniques and methodologies to store and retrieve the cases.
- Include to the system the ability to work with different non-Newtonian slurries and thereby expand the area of its use.

12. CONCLUSION

This work has shown that CBR can be an effective problem-solving method in complex, real-world tasks, and in domains where more traditional approaches are difficult to apply. However it is very important to assess the quality of the data base (case base) before investing significant resources in developing sophisticated algorithms; thereby the quality of the case base is the determining factor for the efficiency of whole CBR system. According to this, for the further development of designed system it is necessary to make a more thorough search for comprehensive and complete cases for case base.

Being able to retrieve appropriate cases, based on partial information (if one or more features of case are unknown), is also a fundamental problem for CBR systems. Alternative strategies and ways to address this problem should be investigated.

The objective of the developed system is to support the decision making process. The system helps to select the type of fluid for current slurry. After that it becomes possible to choose correct model and make needed calculations. Also some data from the most similar retrieved case can be used as initial approximations for some calculations. For Newtonian fluids, if it is necessary for further reasoning, the viscosity value can be calculated in system. According to the tests results, the system works effectively, even despite the small and rather poor case base with some amount of incomplete cases. This once again proves the effectiveness of the CBR methods for various industrial applications.

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APPENDICES

Appendix 1. Workspace part of system

Appendix 2. Case Base part of system

Appendix 3. Working interface for viscosity calculations

Appendix 1.Workspace part of system

Decision support system for slurry viscosity determination

(with the use of CBR methodology)

Enter the details of a new case:

	Density	Solid volume fraction	Solid weight fraction	Viscosity	Yield stress	Particles size (≈ 50% of volume)
	kg/l	%	%	mPa·s	Pa	µm
New slurry	1,58	37,3	60,4	7,26	2,318	30
Data availability coefficient	1	1	1	1	1	1

The coefficient is required for correct calculations !	
0	Select 0 from the list, if parameter's value is unknown
1	Select 1 from the list, if parameter's value is known

Results: (15 the most similar cases)

№ in case-base	Name	Type	Density	Solid volume fraction	Solid weight fraction	Viscosity	Yield stress	Particles size (≈ 50% of volume)	Additional notes	Degree of difference
			kg/l	%	%	mPa·s	Pa	µm		
10	Quartz 2	Newtonian	1,58	37,3	60,4	7,26	0	35	Shear stress = Shear rate * 0,00726	0,0306
6	Quartz 1	Newtonian	1,58	37,3	60,4	7,27	0	40	Shear stress = Shear rate * 0,00727	0,0532
86	Copper Concentrate	Bingham	0	0	64	0	0,45	0	0	0,0544
88	Uranium Tails	Bingham	0	0	58	0	4	38	0	0,0548
95	Cement	Bingham	1,52	0	55	0	3,8	0	0	0,0905
16	Quartz 3	Newtonian	1,57	35,9	59,3	7,81	0	20	Shear stress = Shear rate * 0,00781	0,1036
78	Fine coal	Bingham	0	0	68	0	8,3	40	0	0,1299
64	Sulphide 1	Bingham	1,64	33,6	59,6	7,72	1,127	40	Shear stress = Shear rate * 0,00772 + 1,127	0,1411
101	Clay suspension	Bingham	1,36	0	0	0	6,65	0	0	0,1611
100	Clay suspension	Bingham	1,44	0	0	0	20	0	0	0,1674
77	Fine coal	Bingham	0	0	49	0	1	40	0	0,1741
22	Quartz 4	Newtonian	1,56	35,7	58,9	6,3	0	11	Shear stress = Shear rate * 0,00630	0,1745
76	Sulphide 3	Bingham	1,63	33,4	59,2	8,18	2,318	30	Shear stress = Shear rate * 0,00818 + 2,318	0,1753
89	Gold Tails	Bingham	0	0	50	0	5	50	0	0,1832
81	Kaolin+Sod.Silicate	Bingham	0	0	53	0	6	0,8	0	0,1842

Comment:

Zero values in the table indicate the unknown parameters. Except of "Shear stress" column, where zero value corresponds to the Newtonian fluid

Appendix 2. Case Base part of system

Decision support system for slurry viscosity determination

(with the use of CBR methodology)

Slurry Case Base

№	Name	Type	Density	Solid volume fraction	Solid weight fraction	Viscosity	Yield stress	Particles size (≈ 50% of volume)	Additional notes
			kg/l	%	%	mPa·s	Pa	µm	
1	Quartz 1	Newtonian	1,04	2,7	6,6	1,17	0,000	40	Shear stress = Shear rate * 0,00117
2	Quartz 1	Newtonian	1,12	7,8	17,8	1,41	0,000	40	Shear stress = Shear rate * 0,00141
3	Quartz 1	Newtonian	1,22	14,2	29,8	1,76	0,000	40	Shear stress = Shear rate * 0,00176
4	Quartz 1	Newtonian	1,31	20,0	39,0	2,21	0,000	40	Shear stress = Shear rate * 0,00221
5	Quartz 1	Newtonian	1,45	28,9	51,1	3,57	0,000	40	Shear stress = Shear rate * 0,00357
6	Quartz 1	Newtonian	1,58	37,3	60,4	7,27	0,000	40	Shear stress = Shear rate * 0,00727
7	Quartz 2	Newtonian	1,21	13,6	28,7	1,73	0,000	35	Shear stress = Shear rate * 0,00173
8	Quartz 2	Newtonian	1,31	20,0	39,0	2,17	0,000	35	Shear stress = Shear rate * 0,00217
9	Quartz 2	Newtonian	1,44	28,3	50,3	3,38	0,000	35	Shear stress = Shear rate * 0,00338
10	Quartz 2	Newtonian	1,58	37,3	60,4	7,26	0,000	35	Shear stress = Shear rate * 0,00726
11	Quartz 3	Newtonian	1,04	2,6	6,5	1,18	0,000	20	Shear stress = Shear rate * 0,00118
12	Quartz 3	Newtonian	1,12	7,6	17,7	1,34	0,000	20	Shear stress = Shear rate * 0,00134
13	Quartz 3	Newtonian	1,21	13,3	28,5	1,65	0,000	20	Shear stress = Shear rate * 0,00165
14	Quartz 3	Newtonian	1,30	19,0	37,8	2,29	0,000	20	Shear stress = Shear rate * 0,00229
15	Quartz 3	Newtonian	1,43	27,1	49,1	3,41	0,000	20	Shear stress = Shear rate * 0,00341
16	Quartz 3	Newtonian	1,57	35,9	59,3	7,81	0,000	20	Shear stress = Shear rate * 0,00781
17	Quartz 4	Newtonian	1,04	2,7	6,6	1,28	0,000	11	Shear stress = Shear rate * 0,00128
18	Quartz 4	Newtonian	1,11	7,1	16,5	1,41	0,000	11	Shear stress = Shear rate * 0,00141
19	Quartz 4	Newtonian	1,20	12,8	27,5	1,61	0,000	11	Shear stress = Shear rate * 0,00161
20	Quartz 4	Newtonian	1,30	19,2	38,0	2,05	0,000	11	Shear stress = Shear rate * 0,00205
21	Quartz 4	Newtonian	1,43	27,5	49,4	3,19	0,000	11	Shear stress = Shear rate * 0,00319
22	Quartz 4	Newtonian	1,56	35,7	58,9	6,30	0,000	11	Shear stress = Shear rate * 0,00630
23	Cromite 1	Newtonian	1,10	3,1	12,1	1,47	0,000	40	Shear stress = Shear rate * 0,00147
24	Cromite 1	Newtonian	1,21	6,5	22,9	1,75	0,000	40	Shear stress = Shear rate * 0,00175
25	Cromite 1	Newtonian	1,35	10,8	34,0	2,20	0,000	40	Shear stress = Shear rate * 0,00220
26	Cromite 1	Newtonian	1,50	15,4	43,7	2,37	0,000	40	Shear stress = Shear rate * 0,00237
27	Cromite 1	Bingham	1,67	20,6	52,5	2,66	0,294	40	Shear stress = Shear rate * 0,00266 + 0,294
28	Cromite 1	Bingham	1,89	27,3	61,6	3,58	0,688	40	Shear stress = Shear rate * 0,00358 + 0,688
29	Cromite 2	Newtonian	1,07	2,2	8,8	1,30	0,000	27	Shear stress = Shear rate * 0,00130
30	Cromite 2	Newtonian	1,17	5,3	19,2	1,48	0,000	27	Shear stress = Shear rate * 0,00148
31	Cromite 2	Newtonian	1,31	9,6	31,1	1,80	0,000	27	Shear stress = Shear rate * 0,00180
32	Cromite 2	Bingham	1,45	13,9	40,7	2,16	0,236	27	Shear stress = Shear rate * 0,00216 + 0,236
33	Cromite 2	Bingham	1,62	19,1	50,1	2,81	0,494	27	Shear stress = Shear rate * 0,00281 + 0,494
34	Cromite 2	Bingham	1,85	26,1	60,1	3,96	1,691	27	Shear stress = Shear rate * 0,00396 + 1,691
35	Cromite 3	Newtonian	1,17	5,2	19,2	1,45	0,000	18	Shear stress = Shear rate * 0,00145
36	Cromite 3	Bingham	1,29	8,9	29,5	1,56	0,241	18	Shear stress = Shear rate * 0,00156 + 0,241
37	Cromite 3	Bingham	1,43	13,2	39,4	2,10	0,307	18	Shear stress = Shear rate * 0,00210 + 0,307
38	Cromite 3	Bingham	1,60	18,4	49,1	2,60	0,836	18	Shear stress = Shear rate * 0,00260 + 0,836
39	Cromite 3	Bingham	1,83	25,4	59,3	3,64	2,528	18	Shear stress = Shear rate * 0,00364 + 2,528
40	Phlogopite 1	Newtonian	1,06	3,4	9,0	1,34	0,000	40	Shear stress = Shear rate * 0,00134

41	Phlogopite 1	Newtonian	1,15	8,4	20,5	1,62	0,000	40	Shear stress = Shear rate * 0,00162
42	Phlogopite 1	Newtonian	1,25	13,9	31,2	2,44	0,000	40	Shear stress = Shear rate * 0,00244
43	Phlogopite 1	Newtonian	1,35	19,4	40,4	3,07	0,000	40	Shear stress = Shear rate * 0,00307
44	Phlogopite 1	Newtonian	1,47	26,0	49,8	5,97	0,000	40	Shear stress = Shear rate * 0,00597
45	Phlogopite 2	Newtonian	1,06	3,3	9,0	1,42	0,000	40	Shear stress = Shear rate * 0,00142
46	Phlogopite 2	Newtonian	1,14	7,7	19,1	1,62	0,000	40	Shear stress = Shear rate * 0,00162
47	Phlogopite 2	Newtonian	1,23	12,5	29,0	2,01	0,000	40	Shear stress = Shear rate * 0,00201
48	Phlogopite 2	Newtonian	1,33	17,9	38,4	2,82	0,000	40	Shear stress = Shear rate * 0,00282
49	Phlogopite 2	Bingham	1,46	24,9	48,7	5,07	0,321	40	Shear stress = Shear rate * 0,00507 + 0,321
50	Phlogopite 2	Bingham	1,49	26,6	50,8	5,95	0,573	40	Shear stress = Shear rate * 0,00595 + 0,573
51	Phlogopite 3	Newtonian	1,05	2,8	7,6	1,34	0,000	37	Shear stress = Shear rate * 0,00134
52	Phlogopite 3	Newtonian	1,13	7,2	18,0	1,57	0,000	37	Shear stress = Shear rate * 0,00157
53	Phlogopite 3	Newtonian	1,22	12,1	28,1	1,91	0,000	37	Shear stress = Shear rate * 0,00191
54	Phlogopite 3	Newtonian	1,33	18,1	38,5	2,72	0,000	37	Shear stress = Shear rate * 0,00272
55	Phlogopite 4	Newtonian	1,23	12,6	29,1	1,89	0,000	35	Shear stress = Shear rate * 0,00189
56	Phlogopite 4	Newtonian	1,33	18,0	38,5	2,59	0,000	35	Shear stress = Shear rate * 0,00259
57	Phlogopite 4	Bingham	1,45	24,5	48,0	4,46	0,309	35	Shear stress = Shear rate * 0,00446 + 0,309
58	Phlogopite 4	Bingham	1,50	27,2	51,6	5,10	0,900	35	Shear stress = Shear rate * 0,00510 + 0,900
59	Sulphide 1	Newtonian	1,08	4,3	11,5	1,29	0,000	40	Shear stress = Shear rate * 0,00129
60	Sulphide 1	Newtonian	1,16	8,5	21,2	1,56	0,000	40	Shear stress = Shear rate * 0,00156
61	Sulphide 1	Newtonian	1,26	13,7	31,6	1,90	0,000	40	Shear stress = Shear rate * 0,00190
62	Sulphide 1	Newtonian	1,37	19,4	41,3	2,81	0,000	40	Shear stress = Shear rate * 0,00281
63	Sulphide 1	Bingham	1,50	26,2	50,9	3,72	0,367	40	Shear stress = Shear rate * 0,00372 + 0,367
64	Sulphide 1	Bingham	1,64	33,6	59,6	7,72	1,127	40	Shear stress = Shear rate * 0,00772 + 1,127
65	Sulphide 2	Newtonian	1,06	3,2	8,9	1,26	0,000	40	Shear stress = Shear rate * 0,00126
66	Sulphide 2	Newtonian	1,15	8,0	20,1	1,60	0,000	40	Shear stress = Shear rate * 0,00160
67	Sulphide 2	Newtonian	1,24	12,7	29,7	1,96	0,000	40	Shear stress = Shear rate * 0,00196
68	Sulphide 2	Newtonian	1,36	19,0	40,6	2,92	0,000	40	Shear stress = Shear rate * 0,00292
69	Sulphide 2	Bingham	1,48	25,3	49,6	4,09	0,337	40	Shear stress = Shear rate * 0,00409 + 0,337
70	Sulphide 2	Bingham	1,64	33,7	59,7	8,27	1,662	40	Shear stress = Shear rate * 0,00827 + 1,662
71	Sulphide 3	Newtonian	1,05	2,7	7,5	1,26	0,000	30	Shear stress = Shear rate * 0,00126
72	Sulphide 3	Newtonian	1,14	7,5	19,0	1,51	0,000	30	Shear stress = Shear rate * 0,00151
73	Sulphide 3	Newtonian	1,23	12,3	28,8	1,95	0,000	30	Shear stress = Shear rate * 0,00195
74	Sulphide 3	Newtonian	1,33	17,5	38,1	2,81	0,000	30	Shear stress = Shear rate * 0,00281
75	Sulphide 3	Bingham	1,47	24,9	49,0	3,86	0,476	30	Shear stress = Shear rate * 0,00386 + 0,476
76	Sulphide 3	Bingham	1,63	33,4	59,2	8,18	2,318	30	Shear stress = Shear rate * 0,00818 + 2,318
77	Fine coal	Bingham			49,0		1,000	40	
78	Fine coal	Bingham			68,0		8,300	40	
79	Fly ash	Bingham			64,0		8,840	70	
80	Kaolin Clay	Bingham			32,0		20,000	0,8	
81	Kaolin+Sod.Silicate	Bingham			53,0		6,000	0,8	
82	Kimberlite Tails	Bingham			37,0		11,600	15	
83	Kimberlite Tails	Bingham			69,0		132,000		
84	Phosphte Tails	Bingham			37,0		28,500		
85	Copper Concentrate	Bingham			48,0		19,000	35	
86	Copper Concentrate	Bingham			64,0		0,450		
87	Zinc Concentrate	Bingham			75,0		12,000	20	
88	Uranium Tails	Bingham			58,0		4,000	38	
89	Gold Tails	Bingham			50,0		5,000	50	
90	Minerals Sands Tails	Bingham			55,0		30,000	160	

91	Coal Tails	Bingham		31,0	2,000	70
92	Red Mud	Bingham		39,0	23,000	
93	Red Mud	Bingham		50,0	33,200	30
94	Red Mud	Bingham		53,0	80,000	3
95	Cement	Bingham	1,52	55,0	3,800	
96	Clay suspension	Bingham	1,28		59,000	
97	Clay suspension	Bingham	1,21		25,000	
98	Clay suspension	Bingham	1,15		7,800	
99	Clay suspension	Bingham	1,52		34,500	
100	Clay suspension	Bingham	1,44		20,000	
101	Clay suspension	Bingham	1,36		6,650	
102	Bauxite	Bingham	1,16	21,4	8,500	200
103	Gold Tails	Bingham		31,0	5,000	50
104	Iron oxide	Bingham	1,17	18,0	0,780	50
105	Kaoline clay	Bingham	1,10	7,5	7,500	
106	Limestone	Bingham	1,53	58,0	2,500	160
107	Fine liminite	Bingham	2,44	52,4	30,000	50
108	Minerals Sands Tails	Bingham		58,0	30,000	160
109	Milicz clay	Bingham		13,9	2,300	70
110	Milicz clay	Bingham		16,8	5,300	70
111	Milicz clay	Bingham		19,6	13,000	70
112	Sewage sludge	Bingham	1,06	14,0	3,100	
113						

Density norm	% vol norm	% mass norm	Viscosity norm	Yield stress norm	Size norm
0,00	0,01	0,00	0,00	0,00	0,20
0,06	0,16	0,16	0,03	0,00	0,20
0,13	0,34	0,34	0,08	0,00	0,20
0,19	0,51	0,47	0,15	0,00	0,20
0,29	0,76	0,65	0,34	0,00	0,20
0,39	1,00	0,79	0,86	0,00	0,20
0,12	0,32	0,32	0,08	0,00	0,17
0,19	0,51	0,47	0,14	0,00	0,17
0,29	0,74	0,64	0,31	0,00	0,17
0,39	1,00	0,79	0,86	0,00	0,17
0,00	0,01	0,00	0,00	0,00	0,10
0,06	0,15	0,16	0,02	0,00	0,10
0,12	0,32	0,32	0,07	0,00	0,10
0,19	0,48	0,46	0,16	0,00	0,10
0,28	0,71	0,62	0,32	0,00	0,10
0,38	0,96	0,77	0,94	0,00	0,10
0,00	0,01	0,00	0,02	0,00	0,05
0,05	0,14	0,15	0,03	0,00	0,05
0,11	0,30	0,31	0,06	0,00	0,05
0,19	0,48	0,46	0,12	0,00	0,05
0,28	0,72	0,63	0,28	0,00	0,05
0,37	0,95	0,76	0,72	0,00	0,05
0,04	0,03	0,08	0,04	0,00	0,20
0,12	0,12	0,24	0,08	0,00	0,20
0,22	0,25	0,40	0,15	0,00	0,20
0,33	0,38	0,54	0,17	0,00	0,20
0,45	0,52	0,67	0,21	0,00	0,20
0,61	0,72	0,80	0,34	0,01	0,20
0,02	0,00	0,03	0,02	0,00	0,13
0,09	0,09	0,19	0,04	0,00	0,13
0,19	0,21	0,36	0,09	0,00	0,13
0,29	0,33	0,50	0,14	0,00	0,13
0,42	0,48	0,64	0,23	0,00	0,13
0,58	0,68	0,78	0,39	0,01	0,13
0,09	0,09	0,19	0,04	0,00	0,09
0,18	0,19	0,34	0,05	0,00	0,09
0,28	0,31	0,48	0,13	0,00	0,09
0,40	0,46	0,62	0,20	0,01	0,09
0,57	0,66	0,77	0,35	0,02	0,09
0,01	0,03	0,04	0,02	0,00	0,20
0,08	0,18	0,20	0,06	0,00	0,20
0,15	0,33	0,36	0,18	0,00	0,20
0,22	0,49	0,49	0,27	0,00	0,20
0,31	0,68	0,63	0,68	0,00	0,20
0,01	0,03	0,04	0,04	0,00	0,20
0,07	0,16	0,18	0,06	0,00	0,20

Density diff	% vol diff	% mass diff	Viscosity diff	Yield stress diff	Size diff	**Degree of difference**
0,15	0,97	0,62	0,74	0,00	0,00	1,5738
0,11	0,71	0,39	0,68	0,00	0,00	1,3724
0,07	0,43	0,20	0,60	0,00	0,00	1,1411
0,04	0,24	0,10	0,51	0,00	0,00	0,9417
0,01	0,06	0,02	0,27	0,00	0,00	0,5978
0,00	0,00	0,00	0,00	0,00	0,00	0,0532
0,07	0,46	0,21	0,61	0,00	0,00	1,1610
0,04	0,24	0,10	0,51	0,00	0,00	0,9449
0,01	0,07	0,02	0,30	0,00	0,00	0,6302
0,00	0,00	0,00	0,00	0,00	0,00	0,0306
0,15	0,98	0,62	0,73	0,00	0,00	1,5756
0,11	0,72	0,39	0,70	0,00	0,00	1,3825
0,07	0,47	0,22	0,62	0,00	0,00	1,1755
0,04	0,27	0,11	0,49	0,00	0,00	0,9559
0,01	0,08	0,03	0,29	0,00	0,00	0,6481
0,00	0,00	0,00	0,01	0,00	0,00	0,1036
0,15	0,97	0,62	0,71	0,00	0,01	1,5675
0,11	0,74	0,41	0,68	0,00	0,01	1,3974
0,07	0,49	0,23	0,63	0,00	0,01	1,1978
0,04	0,27	0,11	0,54	0,00	0,01	0,9803
0,01	0,08	0,03	0,33	0,00	0,01	0,6733
0,00	0,00	0,00	0,02	0,00	0,01	0,1745
0,12	0,95	0,50	0,67	0,00	0,00	1,4943
0,07	0,77	0,30	0,60	0,00	0,00	1,3210
0,03	0,57	0,15	0,51	0,00	0,00	1,1209
0,00	0,39	0,06	0,47	0,00	0,00	0,9639
0,00	0,23	0,01	0,42	0,00	0,00	0,8163
0,05	0,08	0,00	0,27	0,00	0,00	0,6342
0,13	1,00	0,57	0,70	0,00	0,00	1,5512
0,09	0,83	0,36	0,66	0,00	0,00	1,3938
0,04	0,62	0,18	0,59	0,00	0,00	1,1980
0,01	0,44	0,08	0,52	0,00	0,00	1,0258
0,00	0,27	0,02	0,39	0,00	0,00	0,8280
0,04	0,10	0,00	0,22	0,00	0,00	0,5963
0,09	0,84	0,36	0,67	0,00	0,00	1,3993
0,04	0,65	0,20	0,64	0,00	0,00	1,2449
0,01	0,47	0,09	0,53	0,00	0,00	1,0531
0,00	0,29	0,03	0,43	0,00	0,00	0,8671
0,03	0,11	0,00	0,26	0,00	0,00	0,6410
0,14	0,93	0,56	0,70	0,00	0,00	1,5274
0,10	0,68	0,34	0,63	0,00	0,00	1,3214
0,06	0,44	0,18	0,46	0,00	0,00	1,0704
0,03	0,26	0,09	0,35	0,00	0,00	0,8506
0,01	0,10	0,02	0,03	0,00	0,00	0,4119
0,14	0,94	0,56	0,68	0,00	0,00	1,5231
0,10	0,71	0,36	0,63	0,00	0,00	1,3446

0,14	0,29	0,33	0,12	0,00	0,20
0,21	0,45	0,47	0,23	0,00	0,20
0,30	0,65	0,62	0,55	0,00	0,20
0,32	0,70	0,65	0,67	0,00	0,20
0,01	0,02	0,02	0,02	0,00	0,18
0,06	0,14	0,17	0,06	0,00	0,18
0,13	0,28	0,32	0,10	0,00	0,18
0,21	0,45	0,47	0,22	0,00	0,18
0,14	0,30	0,33	0,10	0,00	0,17
0,21	0,45	0,47	0,20	0,00	0,17
0,29	0,64	0,61	0,46	0,00	0,17
0,33	0,71	0,66	0,55	0,01	0,17
0,03	0,06	0,07	0,02	0,00	0,20
0,09	0,18	0,21	0,05	0,00	0,20
0,16	0,33	0,37	0,10	0,00	0,20
0,24	0,49	0,51	0,23	0,00	0,20
0,33	0,68	0,65	0,36	0,00	0,20
0,43	0,89	0,78	0,92	0,01	0,20
0,01	0,03	0,04	0,01	0,00	0,20
0,08	0,17	0,20	0,06	0,00	0,20
0,14	0,30	0,34	0,11	0,00	0,20
0,23	0,48	0,50	0,25	0,00	0,20
0,32	0,66	0,63	0,41	0,00	0,20
0,43	0,90	0,78	1,00	0,01	0,20
0,01	0,01	0,01	0,01	0,00	0,15
0,07	0,15	0,18	0,05	0,00	0,15
0,14	0,29	0,33	0,11	0,00	0,15
0,21	0,44	0,46	0,23	0,00	0,15
0,31	0,65	0,62	0,38	0,00	0,15
0,42	0,89	0,77	0,99	0,02	0,15
		0,62		0,01	0,20
		0,90		0,06	0,20
		0,84		0,07	0,35
		0,37		0,15	0,00
		0,68		0,05	0,00
		0,45		0,09	0,07
		0,91		1,00	
		0,45		0,22	
		0,61		0,14	0,17
		0,84		0,00	
		1,00		0,09	0,10
		0,75		0,03	0,19
		0,64		0,04	0,25
		0,71		0,23	0,80
		0,36		0,02	0,35
		0,47		0,17	
		0,64		0,25	0,15
		0,68		0,61	0,01
0,34		0,71		0,03	
0,17				0,45	

0,06	0,50	0,21	0,55	0,00	0,00	1,1497
0,03	0,31	0,10	0,39	0,00	0,00	0,9136
0,01	0,12	0,03	0,10	0,00	0,00	0,5092
0,00	0,09	0,02	0,03	0,00	0,00	0,3918
0,14	0,97	0,59	0,70	0,00	0,00	1,5496
0,10	0,74	0,38	0,64	0,00	0,00	1,3662
0,07	0,52	0,22	0,57	0,00	0,00	1,1721
0,03	0,30	0,10	0,41	0,00	0,00	0,9187
0,06	0,50	0,21	0,57	0,00	0,00	1,1576
0,03	0,30	0,10	0,43	0,00	0,00	0,9329
0,01	0,13	0,03	0,16	0,00	0,00	0,5752
0,00	0,08	0,02	0,09	0,00	0,00	0,4426
0,13	0,88	0,51	0,71	0,00	0,00	1,4939
0,09	0,67	0,33	0,64	0,00	0,00	1,3186
0,05	0,45	0,18	0,57	0,00	0,00	1,1199
0,02	0,26	0,08	0,39	0,00	0,00	0,8696
0,00	0,10	0,02	0,25	0,00	0,00	0,6114
0,00	0,01	0,00	0,00	0,00	0,00	0,1411
0,14	0,94	0,57	0,71	0,00	0,00	1,5379
0,10	0,70	0,35	0,64	0,00	0,00	1,3328
0,06	0,49	0,20	0,56	0,00	0,00	1,1452
0,02	0,27	0,08	0,37	0,00	0,00	0,8699
0,01	0,12	0,02	0,20	0,00	0,00	0,5907
0,00	0,01	0,00	0,02	0,00	0,00	0,1878
0,14	0,97	0,60	0,71	0,00	0,00	1,5579
0,10	0,72	0,37	0,66	0,00	0,00	1,3571
0,06	0,51	0,21	0,56	0,00	0,00	1,1588
0,03	0,32	0,11	0,39	0,00	0,00	0,9217
0,01	0,12	0,03	0,23	0,00	0,00	0,6231
0,00	0,01	0,00	0,02	0,00	0,00	0,1753
		0,03		0,00	0,00	0,1741
		0,01		0,00	0,00	0,1299
		0,00		0,00	0,04	0,2134
		0,17		0,02	0,02	0,4597
		0,01		0,00	0,02	0,1842
		0,12		0,00	0,01	0,3568
		0,02		0,97		0,9904
		0,12		0,04		0,3950
		0,03		0,02	0,00	0,2222
		0,00		0,00		0,0544
		0,05		0,01	0,00	0,2309
		0,00		0,00	0,00	0,0548
		0,02		0,00	0,01	0,1832
		0,01		0,04	0,43	0,6900
		0,18		0,00	0,04	0,4739
		0,10		0,02		0,3495
		0,02		0,05	0,00	0,2789
		0,01		0,35	0,02	0,6135
0,00		0,01		0,00		0,0905
0,05				0,18		0,4803

0,12		0,19		0,07		0,03		0,3178
0,08		0,06		0,10		0,00		0,3117
0,34		0,26		0,00		0,06		0,2476
0,29		0,15		0,01		0,02		0,1674
0,23		0,05		0,02		0,00		0,1611
0,09	0,22	0,06	1,00	0,09	0,32	0,00	0,73	1,0696
	0,36	0,04	0,25		0,18	0,00	0,01	0,4413
0,09	0,17	0,01	0,25	0,09	0,38	0,00	0,01	0,6926
0,05	0,01	0,06		0,12	0,60	0,00		0,8455
0,35	0,75	0,02	0,80	0,00	0,00	0,00	0,43	0,6545
1,00	0,67	0,23	0,25	0,38	0,01	0,04	0,01	0,6658
	0,75	0,23	0,80		0,00	0,04	0,43	0,6864
	0,11	0,02	0,35		0,46	0,00	0,04	0,7079
	0,15	0,04	0,35		0,41	0,00	0,04	0,6678
	0,19	0,10	0,35		0,35	0,01	0,04	0,6337
0,01	0,11	0,02		0,14	0,46	0,00		0,7732

New case parameters:	Density norm	% vol norm	% mass norm	Viscosity norm	Yield stress norm	Size norm
	0,39	1,00	0,79	0,86	0,02	0,15

	Density	Solid volume fraction	Solid weight fraction	Viscosity	Yield stress	Particles size
Max	2,44	37,30	75,00	8,27	132,00	200,00
Min	1,04	2,20	6,50	1,17	0,00	0,80

№ in case-base	Name	Type	Density	Solid volume fraction	Solid weight fraction	Viscosity	Yield stress	Particles size (≈ 50% of volume)	Additional notes	**Degree of difference**
			kg/l	%	%	mPa·s	Pa	µm		
10	Quartz 2	Newtonian	1,58	37,3	60,4	7,26	0	35	Shear stress = Shear rate * 0,00726	0,0306
6	Quartz 1	Newtonian	1,58	37,3	60,4	7,27	0	40	Shear stress = Shear rate * 0,00727	0,0532
86	Copper Concentrate	Bingham	0	0	64	0	0,45	0	0	0,0544
88	Uranium Tails	Bingham	0	0	58	0	4	38	0	0,0548
95	Cement	Bingham	1,52	0	55	0	3,8	0	0	0,0905
16	Quartz 3	Newtonian	1,57	35,9	59,3	7,81	0	20	Shear stress = Shear rate * 0,00781	0,1036
78	Fine coal	Bingham	0	0	68	0	8,3	40	0	0,1299
64	Sulphide 1	Bingham	1,64	33,6	59,6	7,72	1,127	40	Shear stress = Shear rate * 0,00772 + 1,127	0,1411
101	Clay suspension	Bingham	1,36	0	0	0	6,65	0	0	0,1611
100	Clay suspension	Bingham	1,44	0	0	0	20	0	0	0,1674
77	Fine coal	Bingham	0	0	49	0	1	40	0	0,1741
22	Quartz 4	Newtonian	1,56	35,7	58,9	6,3	0	11	Shear stress = Shear rate * 0,00630	0,1745
76	Sulphide 3	Bingham	1,63	33,4	59,2	8,18	2,318	30	Shear stress = Shear rate * 0,00818 + 2,318	0,1753
89	Gold Tails	Bingham	0	0	50	0	5	50	0	0,1832
81	Kaolin+Sod.Silicate	Bingham	0	0	53	0	6	0,8	0	0,1842

Appendix 3. Working interface for viscosity calculations

Decision support system for slurry viscosity determination

(with the use of CBR methodology)

Calculation section for viscosity of Newtonian slurries

Absolute viscosity of mixtures with volume concentration smaller than 1%

Initial data		Result
Absolute viscosity of a liquid phase	Total solid volume fraction	Absolute viscosity
mPa·s	%	mPa·s
1,60	0,10	2,00

Absolute viscosity of mixtures with volume concentration smaller than 20%

Initial data		Result
Absolute viscosity of a liquid phase	Total solid volume fraction	Absolute viscosity
mPa·s	%	mPa·s
1,60	15,00	2,71

Absolute viscosity of mixtures with high volume concentration of solids

Initial data		Result
Absolute viscosity of a liquid phase	Total solid volume fraction	Absolute viscosity
mPa·s	%	mPa·s
1,60	15,00	2,61