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# CONTROL OF LEAD REFINING PROCESS WITH THE USE OF CASE-BASED REASONING APPROACH

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**Abstract**

Presented in this work research concerns pyrometallurgical method of lead refining process. The main objective of the considered lead refining process is to remove impurities of the input lead ore in order to obtain output material of PB985 type. The content of lead in the output material should be at least 99,985%. The considered pyrometallurgical lead refining process consists of 11 subprocesses, which are performed sequentially. The output material of each of the first 10 subprocesses is the input material for the consecutive subprocess. Each of subprocesses is controlled autonomously, however it can influence the control of following subprocesses due to obtained results. The main goal of the work is to design a computer system, which controls the whole lead refining pyrometallurgical process. The essential idea of the control system is to elaborate control advices at every step of the refining process. The proposed computer system should consist of subsystems giving advices according to individual subprocesses, so every subprocess should be controlled by individual control subsystem. Case-Base Reasoning is chosen as the methodology for creation of each control subsystem.

**Key words**: lead refining process, process control, Case-Based Reasoning

## 1. INTRODUCTION

The input material for lead refining process is lead containing impurities, which have to be removed in order to obtain output material of PB985 type – the content of lead in output material should be at least 99,985%. Process of lead refining can be realized with the use of two different methods: either pyrometallurgical or electrolytic refining is used (Habashi, 1997). Presented in this work research concerns the pyrometallurgical method, because this method is used in known industrial plant and real industrial data concerning this method is available to be used in presented next research according the design of control system. The whole pyrometallurgical process of lead refining consists of 11 subprocesses, which are performed sequentially in an industrial plant:

1. Arranging input materials into batches.
2. Drossing (Liquation) – the first stage of decoppering; cooper and other impurities precipitate, when the lead cools.
3. Sulfur decoppering – the second stage of decoppering; selective sulfidizing of cooper by the Colcord process.
4. Initial refining – removal of arsenic, tin and antimony by selective oxidation and the Harris process.
5. Desilvering – removal of noble metals, which involves intermetallic precipitation with zinc by the Parkes process.
6. Dezincing – removal of zinc, which remains after desilvering; this subprocess is achieved by vacuum distillation.
7. Debismuthizing – the removal of bismuth can be achieved by the Kroll-Betterton process, which uses calcium and magnesium.

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8. Final refining I – the first stage of removal of alkali metals and alkaline earth metals remaining after debismuthizing.
9. Removing of thallium (with the use of zinc chloride).
10. Final refining II – the second stage of removal of alkali and alkaline earth metals.
11. Casting – casting temperature is around 400 °C.

The output material of each of first 10 subprocesses is the input material for next subprocess. Each of subprocesses is controlled autonomous, however it influences the control of next subprocesses due to obtained results. Such run of the whole refining process results in the main idea of the computer system that should aid at control of the whole process. The designed computer system should consists of many subsystems giving advices according individual subprocesses, so the purpose of the whole system is to give advices at every one subprocess performed in the industrial plant. Such advices can be a help for the operator of the process in order to find out proper control of the industrial process. This feature can be very important for the operator, that has a little experience according control of the analyzed process. In such case the system will give advices related to experiences of other operators working in the enterprise and will help the inexperienced operator to undertake decisions.

The scientific domain of this paper is the design of an advisory computer system, which should give help for the operator of an industrial process. Advices giving by the designed system are based on experiences gained by the control of the industrial process done in the past, because it is not possible to model the analyzed process in order to simulate physicochemical processes. All experiences being the basis for system functioning concern only results, which in the goal of the whole industrial process was obtained – the output material was of PB985 type, but the specific content of lead in the output material is not know. Such characteristics of the data being the basis for knowledge of the system prevents formulating any objective according optimization of the industrial process performed by the system. The only one functionality providing by the designed system can be giving advices, which

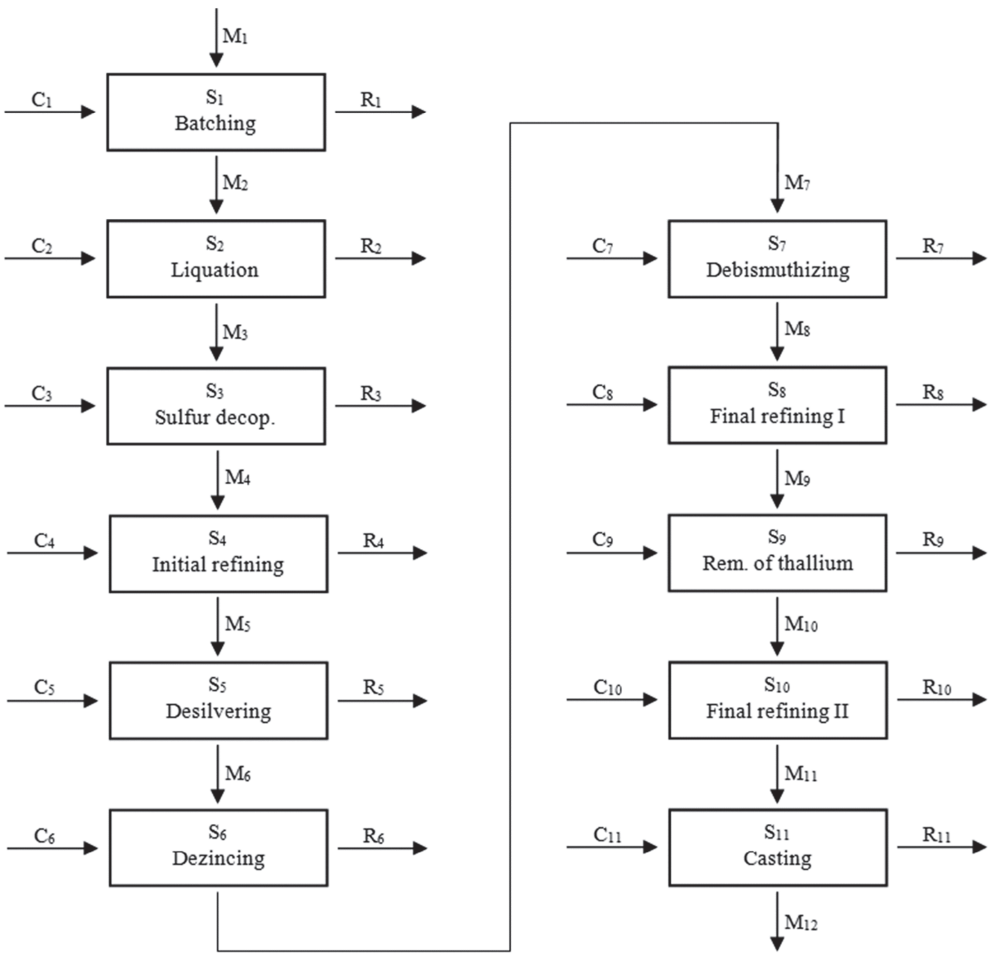


*Fig. 1. Consecutive subprocesses in the whole process of lead refining.*

should help the operator to obtain desirable results, but the optimization of the industrial process is not possible due to inadequate data that are held by the authors.

## 2. CONTROL OF LEAD REFINING PROCESS

As presented in the previous section, the whole lead refining process consists of 11 subprocesses, which are controlled in an autonomous way. The consecutive subprocesses are referenced as $S_1$, $S_2$… $S_{11}$. The schematic view of the whole process control is presented in figure 1.

As presented in figure 1, the input material for a subprocess $S_i$ ($1 \le i \le 11$) is denoted as $M_i$ ($1 \le i \le 11$). The control of a subprocess $S_i$ ($1 \le i \le 11$) is denoted as $C_i$ ($1 \le i \le 11$). The output of a subprocess $S_i$ ($1 \le i \le 11$) is divided into $R_i$ ($1 \le i \le 11$) and $M_{i+1}$ ($1 \le i \le 11$), where $R_i$ means rejectamenta after performing of $S_i$ (materials, which are not used in next subprocesses of the whole analyzed process) and $M_{i+1}$ means materials, which are used in the next subprocess $S_{i+1}$ (in other words, these materials are input materials for a subprocess $S_{i+1}$). $M_{12}$ denotes output materials of the last subprocess (casting) and is output of the whole lead refining process realized with considered pyrometallurgical method.

The control $C_i$ ($1 \le i \le 11$) of a subprocess $S_i$ relates to temperatures (temperature at the process start and temperature at the process end), duration time and amount of technological additives, which are added (e.g. S, PbS, NaOH, $NaNO_3$, $ZnCl_2$, sawdust). As it is earlier mentioned, the control $C_i$ ($1 \le i \le 11$) is autonomously performed in the subprocess $S_i$. The control $C_i$ should be adjusted to the input materials $M_i$ of the subprocess $S_i$ in order to obtain the output materials $M_{i+1}$, which are desired materials for the next subprocess $S_{i+1}$. The rejectamenta $R_i$ relates to amount of rejected materials after performing of the subprocess $S_i$ (e.g. amount of dross after the $P_2$ subprocess).

## 3. DESIGN OF THE CONTROL SYSTEM

The control of the whole lead refining process is realized by autonomous controls of every subprocess $S_1$, $S_2$ … $S_{11}$, what is the basis for the main idea of the control system design as many control systems giving advices at each subprocess. The whole control system should consists of 11 units related to 11 subprocesses, the control unit $CU_i$ is related to the subprocess $S_i$ ($1 \le i \le 11$), what is presented in figure 2.

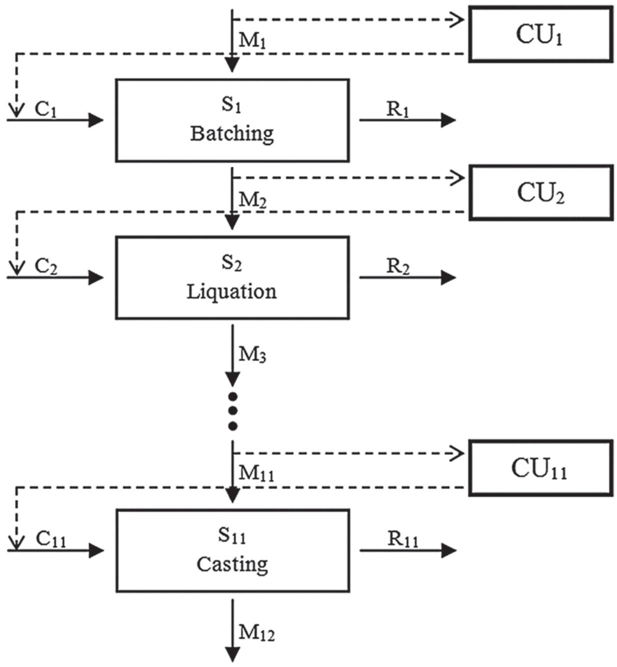


***Fig. 2.*** *Control units related to consecutive subprocesses of the whole lead refining process.*

The main functionality of the control unit $CU_i$ ($1 \le i \le 11$) is giving advices at control of the subprocess $S_i$ ($1 \le i \le 11$). The control unit $CU_i$ should indicate proper control $C_i$ of the subprocess $S_i$ according to the current specification of used input material $M_i$. Because any rules according proper control realized by control units are not possible to formulate, every control unit should use available industrial data according past made actions. The available industrial data concerns several runs of the whole lead refining process and can be source of knowledge according proper control advices giving by all control unites related to consecutive subprocesses.

Analyzing the possibilities of design of the control unit $CU_i$ ($1 \le i \le 11$) related to the subprocess $S_i$ ($1 \le i \le 11$) the basic remark is, that analytical model of any subprocess $S_i$ ($1 \le i \le 11$) is not possible to formulate due to complexity and not completely known nature of the physico-chemical processes. This remark is the reason for searching of solutions concerning design of the control units in the domain of Artificial Intelligence (AI). One of wide used approaches related to AI in the domain of control of industrial processes consists of building the model of the industrial process with the use of Artificial Neural Network (ANN) and using this model by an optimization procedure. In Sztangret et al. (2009) ANN model is based on the architecture of Multi-Layer Perceptron (MLP) and particle swarm optimization (PSO) is used as the optimization procedure. This approach requires enough amount of data in order to train the ANN, which should predict outcomes of a hypothetical control. Presented further remarks on system functioning indicate, that the available amount of data (for presented here research) seems to be not sufficient in order to use the approach, which uses ANN as the model of the analyzed process. Another approach related to AI, which is applied to control of industrial process, relies on Case-Based Reasoning (CBR). In Kusiak et al. (2013) the CBR system is presented, which is applied to the oxidizing roasting process of sulphide zinc concentrates. In Sun (2008) the CBR methodology is used to control of combustion control of blast furnace stoves. Another application of CBR in the domain of industrial production is presented in Michael and Khemani (2002). The CBR methodology enables to construct an advisory system even the amount of the available data is very scant, so this methodology is chosen for creation of each control unit $CU_i$ ($1 \le i \le 11$).

### 3.1. General view of Case-Based Reasoning

The CBR methodology involves reuse of previously collected data by solving of a current problem. After the current problem is solved, the data related to this problem and its solution is saved in order to be used at next system functioning, what enables learning on the basis of performed by system actions (Bergmann et al., 2009). In Rojek and Kusiak (2012) application of Case-Based Reasoning to a generic industrial process is presented, however it is assumed, that a generic process does not consist of subprocesses. The main notion of CBR is a case, which represents a past event (referenced also as an episode or an experience item). A case is represented usually as an ordered pair (*problem*, *solution*), where *problem* describes a specific situation and *solution* describes actions, parameters and any other data related to the performed solution to this specific problem. One case represents one event, that took place in the past. Because a CBR system uses data according many past events, notion of a case base is used. The case base is collection of all cases representing all registered past events.

A system developed with Case-Based Reasoning performs the CBR cycle, that consists of four phases. The CBR cycle start, when a new problem (called the current problem) has to be solved Aamodt and Plaza (1994):

1. Retrieve phase – select in the case base a case, which is similar to the current problem; the selected case is referenced next as the retrieved case.
2. Reuse phase – use the information and knowledge in the retrieved case in order to solve the current problem; the solution in the retrieved case is returned as the solution to the current problem (with possible adaptation).
3. Revise phase – the proposed in the previous step solution is revised by e.g. being applied to the real environment of the CBR system.
4. Retain phase – the information concerning the current problem and its revised solution is saved in order to be useful for future problem solving; this step usually happens by adding a new case to the case base.

### 3.2. Definition of a case of a control unit

Because a control unit $CU_i$ should give advices at control of the subprocess $S_i$ ($1 \le i \le 11$), a case is denoted as $case_i$ equal to a pair ($problem_i$, $solution_i$) concerning the subprocess $S_i$. It means, the control unit $CU_i$ has its own case base, which consists of cases related to control of the subprocess $S_i$. The problem in the domain of subprocess control relates to particular input materials. The solution relates to done control and its results, so finally it is proposed to define a case as a pair ($M_i$, ($C_i$, $M_{i+1}$, $R_i$)), where:

- $M_i$ denotes problem in the form of the specific materials, used as the input materials for the subprocess $S_i$,
- $C_i$ denotes control of the subprocess $S_i$,
- $M_{i+1}$ denotes the output materials of the subprocess $S_i$ after performing of the control $C_i$ and using input materials $M_i$,
- $R_i$ denotes the rejectamenta of the subprocess $S_i$ after performing of the control $C_i$ and using input materials $M_i$ (the rejectamenta are materials not used in next subprocess of the whole industrial process).

### 3.3. The CBR cycle of a control unit

As it was mentioned before, a control unit $CU_i$ gives advices at control of the subprocess $S_i$. The control unit $CU_i$ has its own case base, which contains cases according past runs of the subprocess $S_i$. When a need is to give an advice of control of the subprocess $S_i$, the control unit $CU_i$ creates the representation of the current problem (by contents of individual elements: Ag, Cu, Zn etc.) and performs the CBR cycle:

1. Retrieve phase: selects in the case base a case ($M_i^R$, ($C_i^R$, $M^R_{i+1}$, $R_i^R$)), which is most similar to the current problem related to the specified input materials $M_i^C$.
2. Reuse phase: presents the control $C_i^R$, the specification of the output material $M^R_{i+1}$ and the rejectamenta $R_i^R$ as the solution to the current problem.
3. Revise phase: enables the user to change the data presented in the previous step according to the real control and its results made in the industrial environment – the control $C_i^C$, the specification of the output material $M^C_{i+1}$ and the rejectamenta $R_i^C$ can be inputted by the user.
4. Retain phase: creates a new past case ($M_i^C$, ($C_i^C$, $M^C_{i+1}$, $R_i^C$)), which relates to the current problem $M^C_i$ with its solution ($C_i^C$, $M^C_{i+1}$, $R_i^C$) and adds this case to the case base.

The goal of the retrieve phase is to select a case $case^R_i$ = ($M_i^R$, ($C_i^R$, $M^R_{i+1}$, $R_i^R$)), which is most similar to the current problem related to the specified input materials $M^C_i$. This involves use of a similarity measure, which is usually formalized as a function $sim : P \times P \rightarrow [0, 1]$, which compares descriptions of two problems from $P$ and produces a similarity assessment as a real value from [0, 1]. Taking into consideration the analyzed industrial process and the subprocess $S_i$, the similarity function is proposed to be equal to the inverse Euclidean distance:

$$sim\left(case_i^x, M_i^C\right) = \frac{1}{1+\sqrt{\left(m_i^{x,1}-m_i^{C,1}\right)^2+\left(m_i^{x,2}-m_i^{C,2}\right)^2+\ldots+\left(m_i^{x,N}-m_i^{C,N}\right)^2}} \quad (1)$$

where: $case^x_i$ = ($M_i^x$, ($C_i^x$, $M^x_{i+1}$, $R_i^x$)), $M_i^x = [m_i^{x,1}, m_i^{x,2}, \ldots, m_i^{x,N}]$ and $M^C_i = [m_i^{C,1}, m_i^{C,2}, \ldots, m_i^{C,N}]$.

The reuse phase is very simple in presented here application of CBR methodology – the system presents the control $C^R_i$, the specification of the output material $M^R_{i+1}$ and the rejectamenta $R^R_i$, which are directly copied from the retrieved case $case^R_i$. Adaption is not made in the reuse phase due to the lack of knowledge related to physicochemical nature of the analyzed process. The available industrial data is also to scant for the use of any statistical methods at adaptation of the retrieved case $case^R_i$ to the current problem related to the specified input materials $M^C_i$.

The revise phase requires implementation of the system to the real environment of its functioning. The system enables only to input the real control and its results made in the industrial environment – the control $C^C_i$, the specification of the output material $M^C_{i+1}$ and the rejectamenta $R^C_i$ have to be inputted by the user. The insertion of this data is the basis for the last – the retain phase, which enables to enlarge the case base with currently made experience. In the retain phase a case ($M^C_i$, ($C^C_i$, $M^C_{i+1}$, $R^C_i$)) is created and added to the case base. During the next system functioning this case is treated equally with other past cases – is processed in the retrieved phase and can be chosen as the retrieve case being the basis for future problem solving.

## 4. REMARKS ON SYSTEM IMPLEMENTATION AND FUNCTIONING

The control system is implemented according to previously presented remarks. By implementation jCOLIBRI framework is used as the code library for classes related to operations performed during the CBR cycle. Functioning of the system is presented on the base of the $P_7$ subprocess (debismuthizing). The available industrial data enables to create 9 cases according the debismuthizing done in the past. An example of a case can be given as:

```
1. ( case 5
2. (Ag:4, Cu:5, Zn:2, Bi:553, As:3, Sn:3, Sb:33,
Cd:2, Ni:1, Tl:360, Fe:12, S:7, Al:1, Te:18)
3. (
4. (duration_time: 12.5, temperature_at_start: 325,
temperature_at_end: 460, MgCa: 320)
5. (Ag:6, Cu:4, Zn:8, Bi:64, As:3, Sn:3, Sb:21,
Cd:2, Ni:1, Tl:360, Fe:17, S:20, Al:6, Te:21)
6. (Bi_foam: 4000)
7. ))
```

The second line in the above given example specifies the problem $M^5_7$, the fourth line specifies the control $C^5_7$, the fifth line specifies the output material $M^5_8$ and the sixth line specifies the rejectamenta $R^5_7$. The main influence on the system functioning has the similarity measure, which is presented by equation (1) and which operates on descriptions of problems. The results of system functioning depend on the similarity measure and input data, which characteristic according description of problem is presented in table 1.

At the start of the functioning of the subsystem $CU_7$ giving advices for the debismuthizing subprocess the user inputs description of the current problem e.g.: (Ag:4, Cu:4, Zn:1, Bi:545, As:3, Sn:3, Sb:34, Cd:1, Ni:1, Tl:360, Fe:10, S:8, Al:1, Te:18). The subsystem moves to the retrieve phase and computes the similarity measure for all cases: 0.016, 0.017, 0.012, 0.014, 0.105, 0.008, 0.019, 0.011, 0.025. The most similar is case 5, so case 5 (presented in the example at the beginning of this section) is selected as the retrieved case and the subsystem moves to the reuse phase – presents the control, the specification of the output material and the rejectamenta, which are directly copied from the retrieved case 5. Next subsystem moves to the revise phase, which in the user can change presented data according to performed control in the real environment. Data revised by the user are saved in the case base as a new past case in the last retain phase.

***Table 1.*** *Characteristics of data related to description of problem.*

| parameter | min | max | average | median | variance |
|---|---|---|---|---|---|
| Ag | 1 | 4 | 2.22 | 2 | 1.44 |
| Cu | 1 | 7 | 3.33 | 2 | 4.50 |
| Zn | 1 | 9 | 2.67 | 1 | 9.50 |
| Bi | 480 | 668 | 584.78 | 591 | 3150.69 |
| As | 3 | 8 | 3.78 | 3 | 2.69 |
| Sn | 3 | 5 | 3.33 | 3 | 0.50 |
| Sb | 1 | 33 | 13.56 | 13 | 91.78 |
| Cd | 1 | 2 | 1.44 | 1 | 0.28 |
| Ni | 1 | 2 | 1.22 | 1 | 0.19 |
| Tl | 340 | 380 | 360.00 | 360 | 100.00 |
| Fe | 12 | 27 | 18.44 | 18 | 29.78 |
| S | 6 | 15 | 8.22 | 7 | 10.19 |
| Al | 1 | 2 | 1.22 | 1 | 0.19 |
| Te | 6 | 36 | 20.56 | 21 | 72.28 |

## 5. CONCLUSION

The problem of building the computer advisory system, which helps at control of the industrial lead refining process can be resolved using Case-Based Reasoning (CBR). Presented in this work design of such computer system is adjusted to the specific of the analyzed process that consists of 11 subprocesses, which are performed sequentially in the industrial plant. The efficiency of presented solution due to specific of CBR cannot be evaluated without full deployment of the system to the real environment, which is the industrial plant in the case of the analyzed process. Influence on the system efficiency has amount of data related to operations done in the past, because this data collected in the case base of CBR system are source for advices giving by the system. Future evaluation of the system should be done in long period of time – half a year or even longer in order to make possible use of data that is add to the case base by functioning of the system.

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### STEROWANIE PROCESEM RAFINACJI OŁOWIU Z WYKORZYSTANIEM PODEJŚCIA OPARTEGO O WNIOSKOWANIE EPIZODYCZNE

Streszczenie

Przedstawione w pracy badania dotyczą pirometalurgicznej metody rafinacji ołowiu. Głównym celem procesu rafinacji ołowiu jest usunięcie zanieczyszczeń z materiału wejściowego w celu otrzymania materiału wyjściowego typu PB985, w którym zawartość ołowiu wynosi co najmniej 99,985%. Rozważany pirometalurgiczny proces rafinacji ołowiu jest złożony z 11 podprocesów, które są wykonywane w sposób sekwencyjny. Materiał wyjściowy każdego z pierwszych dziesięciu podprocesów stanowi materiał wejściowy do następującego po nim podprocesu. Każdy podproces jest sterowany autonomicznie, jednakże może wpływać na następujący po nim podproces poprzez osiągnięte rezultaty. Głównym celem niniejszej pracy jest projekt systemu komputerowego, który pozwala na sterownie całym procesem rafinacji. System ten powinien prezentować wskazówki odnośnie sterowania na każdym z etapów rafinacji. Proponowane rozwiązanie jest w postaci systemu komputerowego, który składa się wielu pod-

systemów sterowania przyporządkowanych do odpowiednich podprocesów rafinacji, więc każdy podproces jest sterowany poprzez indywidualny podsystem. Przy projektowaniu każdego z podsystemów sterowania użyto podejścia opartego o wnioskowanie epizodyczne (ang. Case-Based Reasoning).

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