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Author	Family Name	**Toporov**
	Particle	
	Given Name	**Viktor**
	Prefix	
	Suffix	
	Division	
	Organization	Systemotechnika Company
	Address	Manila, Philippines
	Email	viktor.toporov@gmail.com
Author	Family Name	**Axelrod**
	Particle	
	Given Name	**Valery**
	Prefix	
	Suffix	
	Division	
	Organization	TST-16 Company
	Address	Amangeldy Str. 40/112, 050000, Almaty, Kazakhstan
	Email	gsns2016com.va@gmail.com
Corresponding Author	Family Name	**Tukeyev**
	Particle	
	Given Name	**Ualsher**
	Prefix	
	Suffix	
	Division	Information Systems Department
	Organization	Al-Farabi Kazakh National University
	Address	Al-Farabi Av., 71, 050040, Almaty, Kazakhstan
	Email	ualsher.tukeyev@gmail.com
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Keywords (separated by '-')	Online - Monitoring - System - Ore - Flow - Enrichment - Factory - Temporal - Model	

Online Monitoring System of the Enrichment Factory Input Ore Flows Quality on the Base of Temporal Model

Viktor Toporov[1], Valery Axelrod[2], and Ualsher Tukeyev[3](✉)

[1] Systemotechnika Company, Manila, Philippines
viktor.toporov@gmail.com
[2] TST-16 Company, Amangeldy Str. 40/112, 050000 Almaty, Kazakhstan
gsns2016com.va@gmail.com
[3] Information Systems Department, Al-Farabi Kazakh National University,
Al-Farabi Av., 71, 050040 Almaty, Kazakhstan
ualsher.tukeyev@gmail.com

Abstract. This article describes the solution of the problem of determining the ore belonging to a particular quarry in the multi-flow technological process of ore crushing at the ore enrichment fabric of a mining and processing plant. The paper proposes a new temporal model for solving this problem and describes its implementation in the form of an online monitoring system of ore quality and it belonging to a concrete quarry.

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Keywords: Online · Monitoring · System · Ore · Flow · Enrichment Factory · Temporal · Model

1 Introduction

The technology for processing of ore raw materials entering to enrichment factory (EF) of the ore mining and processing plant (MPP) starts with its unloading from the railway wagons to the receiving bunkers of the enrichment factory and crushing to a consistency acceptable for the enrichment process. At this stage of ore preparation, one of the most important production and analytical tasks that determine the efficiency of the follow technological parts is an on-line assessment of the volume and quality of the ore delivered by rail transport in real time from each particular quarry.

It should be emphasized that obtaining such estimates on-line in the context of an appropriate diagnostic input control system is not an easy task. This is due, first of all, to the difficulties of conducting reliable and credible measurements in real time of quality indices and volume-weight characteristics of a large-lump ore mass flow (the size of a piece up to 1200 mm) at the time it enters the enrichment factory. The use of laboratory data and surveying measurements made in a quarry is also of little use because of the large intervals between measurements and differences in assessments of the quality of ore from mining and enrichment factories [1].

Thus, the existing arsenals of methodology, software and hardware does not allow reliable measurements of the qualitative and quantitative characteristics of the input ore

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flows of the multi-flow enrichment factories in real time. In this connection, within the framework of this article, the possibility of determining the qualitative-quantitative characteristics of the input streams from the corresponding measurements of the output flow of ore crushing using the paradigm of temporal logic was investigated. Temporal logics are a powerful means of describing events and have great expressive capabilities in representing real time structures. The main elements of such logics are considered in [2–4].

With regard to the assessment of the volume and quality of ore pit flows, taking into account the temporal features of the process of entering and processing the ore mass for large crushing, it is possible to restore the characteristics of these ore-streams on the basis of the chronology of the unloading process of mobile units, and also on the basis of chronology and measurements of qualitative and quantitative indices of the resulting ore flow after a large crushing. Moreover, the temporal model takes into account the peculiarities of the solution of such a task within the framework of the corresponding monitoring system, namely:

- the need to obtain a solution in conditions of time constraints determined by a real controlled process;
- the need to take into account the time factor (dependencies) in describing the problem situation and in the process of finding a solution;
- impossibility of obtaining all objective information necessary for the decision, and, in this connection, the use of subjective, expert information;
- the need to use a significant amount of data that changes with time (sensor readings, values of control parameters performed by operators of actions, etc.).

The main scientific contribution in this paper is the new temporal description of ore preparation in the multi-flow technological process of ore crushing. That new approach allows to decide the problem of defining ore quality in real-time and increase the management quality in chain “quarry - enrichment fabric - plant”.

Below, in Sect. 2 is described new approach for formal description of the ore preparation, in Sect. 3 is presented the implementation of proposed approach as a real-time monitoring system, in Sect. 4 is described results of experimental studies.

2 Temporal Description of Ore Preparation

2.1 Set of Temporary Model Primitives

As it was noted, it is quite problematic to perform direct reliable measurements of the qualitative and quantitative characteristics of the input ore flows of the EF in real time and with the accuracy necessary for practice. In this connection, we consider the possibility of obtaining these characteristics by calculating them by the corresponding measurements of the output flow. It is clear that without the additional information on the moments of initiation of the flows at the input of the concentrating redistribution, the dynamics of their motion along the crushing complex, and the chronology of the measurements of the integral output flow after crushing, this problem does not have a unique solution.

The composition of such temporal information ensuring uniqueness of the solution of the task of the incoming control of the volume and quality of the ore mass entering the concentrator is determined by the technological scheme of crushing. In accordance with this scheme, the ore of gross production with the size of pieces of not more than 1200 mm, arriving by rail (dump trucks with a lifting capacity of 105 tons) from various quarries is fed to the receiving bunkers of the large crushing body.

The ore from each receiving bunker is crushed to the size of 350-400 mm, and then fed to the second stage of crushing (not shown in the diagram), where it is crushed to a fineness of not more than 22 mm. The product of the second stage of crushing is fed to belt conveyors for further processing. Thus, for a time interval ΔT, the discrete flows of wagons with ore from different quarries after large crushing are transformed into an integrated continuous ore stream for which instantaneous weight and quality parameters can be measured with sufficient accuracy and reliability. The time interval ΔT includes various events characterizing the rate of advance of the ore mass to the place of measurement of its qualitative and quantitative characteristics, over which, in the final analysis, a correspondence can be established between the real discrete units of the input streams of the formatting object and the virtual segments of the output integral stream.

2.2 Temporal Model of the Ore Preparation

To construct a temporal model of ore preparation and to determine on its basis the ore segment of the output stream belonging to a particular wagon of one of the input discrete ore streams at the input of the EF, we use the Timed Interval Calculus (TIC) apparatus [2, 3].

The main elements of the TIC, used further in the formalization of the temporal model of ore preparation, define the following concepts:

- The time domain (T) is a non-negative real number and the interval is a sequence of time points, for example, the time interval [x…y] is defined as:

$$\forall x, y: R * [x \ldots y] = \{z: T \mid x \leq z \leq y\}$$

- Constants. For example, the maximum weight (MaxWeight) can be described as a real number (MaxWeight; R, where R is the real number).
- Timestamp (trace) is a function of the time domain of the variable definition. For example, the weight of the ore on the conveyor can be represented by the time dynamics (Weight) of the variable real-world range. So, Weight: T → R.
- Interval operators. There are three primitives of interval operators: α, ω, σ having type I → T, where I denotes all intervals and they return the starting point, end point and length of the interval.
- Interval brackets. A pair of interval brackets returns all the intervals that are defined by the predicate inside the parentheses. A predicate is usually a first-order predicate. For example, for the following TIC expression, $[Weight(\alpha) \leq \mathrm{Weight}]$, indicating that the value of the variable Weight is not less than the value obtained at the beginning of the interval.
- Rules. Rules define the time properties of intervals and their connections.

All listed elements of the TIC-model, except the last one, are intuitively understandable and can be numerically identified for the technological object of ore preparation at the input of a specific formatting object. The rules of the TIC-model of the ore segment belonging to the output stream segment to the concrete wagon of one of the input discrete flows, and hence the determination of the ore belonging to the career, will be considered in more detail.

Rule 1. Binding events to the timeline.

if $S_i^{dw} = \text{true}$ then $T_i^{dw} = t$,

where: S_i^{dw} is the sign of the dump of the i-th wagon, T_i^{dw} is the time of the i-wagon's dump, t is the current time.

This rule means that if an accident occurred as the wagon dump, the time for the wagon dump is the same as the current time.

Rule 2. Determination of the time interval for crushing ore in a bunker.

if $[\![W_i^{ew} - P^b \neq 0]\!] = \{x, y: T \mid \forall t: [x \ldots y] * (W_i(\alpha([x \ldots y])) = W_i^{ew} \wedge W_i(\omega([x \ldots y])) = 0 \wedge W_i = W_i - P^b)\}$

then $t^b = \sigma([x \ldots y])$,

where: W_i^{ew} is the estimated weight of the ore of the i-th wagon; P^b - bunker capacity per second; W_i - the current weight of the ore of the i-th wagon, t^b - time interval of crushing of the ore of the bunker.

This rule means that in each cycle (1 s) of the total weight of the ore in the hopper, the quantity equal to the capacity of the hopper per second is subtracted. This rule allows to calculate the time spent by the bunker on crushing the dumped wagon and fix the expected moment of the end of the wagon ore exit from the bunker.

Rule 3. Determination of the time interval from the moment of appearance of the ore of the wagon on the conveyor until the moment of measurement on the conveyor scales.

$$t_i^c = L^c / V^c,$$

where L^c is the length of the conveyor to the conveyor scales (meters); V^c - the speed of the conveyor (meters/second).

Rule 4. Determination of the expected time of the beginning of the flow of ore in the wagon through the scales.

$$T_i^{etb} = T_i^{dw} + t^b + t_i^c.$$

This rule means that the expected time for the beginning of the flow of the wagon ore through the scale is determined by the sum of the time of the wagon dump with the time interval for crushing the ore of the bunker and the time interval for the appearance of the wagon ore on the conveyor.

Rule 5. Calculation of the length of the time interval of the wagon's flow.

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if $[\![S_i^{dw} = true \,\&\, t \ge T_i^{etb}]\!] = \{x, y: T \mid \forall t: [x \dots y] * (S_i^{dw} = true \wedge t \ge T_i^{etb})\}$
then $\{W_i^{sum} = 0;$
        while $(W_i^{sum} \le W_i^{ew})$
        $W_i^{sum} = W_i^{sum} + W_i;$
        $t = t + 1;$
        end
        $\{T_i^{int} = t - T_i^{etb}; T_i^{ete} = T_i^{etb} + T_i^{int}\}$
    $\},$
```

where T_i^{int} - the time interval of the wagon's flow, T_i^{etb} – the beginning of the wagon's flow, T_i^{ete} – the ending of the wagon's flow.

This rule means that if the wagon event occurred and the current time is greater than or equal to the time of the expected start of the wagon unloading, then the condition is checked whether the total weight of the wagon is less than the expected weight of the wagon and, as soon as this condition is not fulfilled, wagon and time of the end of the wagon flow.

Rule 6. Correction rule for the beginning of the wagon flow.

If $[\![W(t) - W(\alpha) \ge 0{,}05W(\alpha) = \{x, y: T \mid \forall t: [x \dots y] * (W(t) - W(\alpha([x \dots y]))) \ge 0.05\, W(\alpha([x \dots y])) \wedge \sigma[x \dots y] \ge 5\}$
then $t_i^{etb} = \alpha([x \dots y])$.

This rule means that as the start time of the flow, the system captures a significant (more than 5 s) and stable (more than 5%) increase in the signal from the weight sensor.

Rule 7. Correction rule for the end of the wagon's flow.

If $[\![W(t) - W(\alpha) \le 0{,}03W(\alpha)]\!] = \{x, y: T \mid \forall t: [x \dots y] * (W(t) - W(\alpha([x \dots y]))) \le 0{,}03W(\alpha([x \dots y])) \wedge \sigma[x \dots y] \ge 5\}$
then $t_i^{ete} = w([x \dots y])$.

This rule means that as the end-of-flow time, the system records a stable (more than 5 s), close to zero (not more than 3%) value of the signal from the weight sensor.

3 Implementation of a Monitoring System

Practical use of the above rules of temporal logic was carried out in the development of a system for monitoring ore flows at the input of iron ore of EF. The monitoring system was implemented taking into account the canons of hard real-time systems on a duplicated Siemens controller in the form of functionally complete program blocks united by a common algorithm of operating environment of the controller. The functional description of these blocks is given further in the text.

3.1 Fixing the Time of Entry/Exit of Wagons

The ore enters the crushing site on the railway tracks. To fix the time of entry and exit of unloaded wagons on the tracks, track occupancy sensors are installed. When the signal from the occupancy sensor comes in, the system records the time for entering the train's composition on the crushing site. The fixation takes into account the stability of the signal. If the signal appears for a short time and disappears, the system identifies the event as a false signal and does not fix the input of the train composition. The exit time is fixed when the busy signal is removed.

3.2 Determination of the Number of Dumped Wagons

The task is to identify the moment of dumping the wagon into the bunker and counting such scores for the composition of wagons on the tracks. To identify the moment of a dumping, the system uses the following discrete signals: occupation of the paths, movement of the train along the way, the operator's command to dump the wagon, signal of the wagon dump,

The signal of the wagon's dump should most accurately reflect the moment of the wagon's dump. But because of the highly noisy environment (dust), the sensor does not always provide accurate information. Therefore, the system provides additional algorithmic processing, which allows filtering the appearance of false alarms of the sensor, as well as identify the dump even in the absence of the signal "Dump".

3.3 Accounting of the Ore Weight and Quality

Conveyors feeding ore from bunkers on the queue are equipped with conveyor scales and sensors of magnetic susceptibility of ore. The iron content in the ore is calculated on the basis of the signal from the magnetic susceptibility sensor according to the formula:

$$\mathrm{Fe} = \mathrm{A} * \mathrm{X} + \mathrm{B},$$

where: Fe is the iron content, X is the magnetic susceptibility of the ore; A, B - coefficients of the regression model for the quarry, from which the ore came.

The coefficients A and B are obtained as a result of statistical processing of samples of ore taken from the mine. Obtaining these coefficients is not included in the tasks that the system solves. The system provides interfaces for entering them and uses the entered values in the calculations. Ore comes for redistribution from several mines. The coefficients are given for each of them. In order to calculate the iron content in the ore as precisely as possible, the system identifies the ore that goes through the conveyor to belong to a particular mine and uses the corresponding coefficients.

3.4 Identification of the Ore Passing Through the Conveyor for Belonging to the Mine

Unloading into the bunker can be conducted in parallel with two paths. Obviously, the unloaded trains could come from different warehouses. Therefore, the solution of this problem is reduced to determining whether ore belonging to the conveyor is belonging to one of the dumped wagons. The task becomes nontrivial if unloading is conducted in a dense mode and the ore is conveyed by a continuous flow. The system determines the time limits of the wagons in the flow relative to the scales. That is, the system determines the ore from which wagon, passed at a certain point in time by scales. Knowing the magnitude of the transport lag between the weights and the magnetic susceptibility sensor, the system determines the time boundaries of the wagons in the flow relative to the magnetic susceptibility sensor. The determination of the time bounders of the wagons in the flow relative to the weights is carried out in four stages:

1. determination of the time of the beginning of passing the wagon through the scales;
2. determination of the end time of passing the wagon through the scales,
3. correction of the wagon boundaries in the flow, taking into account the total weight of the ore in the flow;
4. secondary adjustment of the wagon boundaries in the flow, taking into account the extremes of the signal from the weight sensor.

3.5 Determination of the Start Time of the Passing of the Wagon Through the Scales

At this stage, the system determines the expected time of occurrence of ore from the unloaded wagon on the scales. This time is calculated according to rule 4.

The calculated T_i^{etb} is adopted by the system as the first (rough) approximation of the border of the wagon and in the future is subject to refinement taking into account the actual situation at the facility. If, when T_i^{etb} comes on, there is no ore flow (lumen) on the scales, then the nearest occurrence of ore flow on the scales will be accepted as the beginning of the wagon. Other cases of correction of the moment of the beginning of the car are closely connected with the moment of determining the end of the previous wagon.

3.6 Determination of the End Time of Passing the Wagon Through the Scales

When determining the moment of the end of passage of the wagon through the scales, the system relies on the expected (known a priori) weight of the wagon. The algorithm for determining the end time of the passage of the wagon through the scales is carried out according to rule 5. The algorithm sums the weight of the ore passed on the scales from the moment of the beginning of the wagon and, when the expected weight of the wagon is reached, fixes the moment of the end of the passage of the wagon.

If the expected weight for the wagon is already summarized, but for the next wagon, the inequality is not valid:

$$T_i^{etb} \leq t,$$

where t is the current moment, then the system continues to count the weight for the current wagon until the following condition is satisfied for the next wagon. In this case, T_i^{etb} of the next car will be adopted as the end of the wagon.

If the expected weight of the wagon is not reached, but the end of ore flow on the conveyor (lumen) is observed, the system fixes the end of the wagon, but additional analysis is performed. If the collected weight is much less than expected (less than 70%), then the system analyzes the moment of the end of the exit from the bunker of the previous wagon and the moment of the beginning of the current one. If the difference between these moments makes up a time interval sufficient for the appearance of a lumen on the scales, then the end of the flow is fixed as the moment of the end of the passage through the scales of the previous wagon. If the time interval is too small or absent, the end of the flow is fixed as the end of the current wagon.

3.7 Correction of the Wagon Boundaries in the Flow

Under the flow is understood the time interval from the moment of occurrence of ore flow on the scales until the moment of its termination. Determination of the boundaries of wagons in the flow is carried out according to rule 6. When fixing the end of the flow, the system corrects the boundaries of wagons inside the flow defined at the previous stages. The system determines the total weight of the ore in the flow and the number of wagons in it. Next, for each wagon in the stream, the system summarizes its expected weight. The result of this operation is the expected weight of the stream. Further, the expected flow weight is compared with the actual one and the discrepancy coefficient is determined:

$$k_{disc.} = \frac{W_{exp.} - W_{act.}}{W_{act.}},$$

where: $k_{disc.}$ is the discrepancy coefficient, $W_{exp.}$ - expected flow weight, $W_{act.}$ is the actual weight of the stream.

For each wagon in the flow, the actual weight is calculated by the formula:

$$W_{wag.act.} = W_{wag.exp.} * (1 - k_{disc.}),$$

where:

$W_{wag.act.}$ – the actual weight of the wagon,

$W_{wag.exp.}$ – the expected weight of the wagon.

Then the system arranges the wagon boundaries in the stream in such way that the weight of each wagon corresponds to the $W_{wag.act.}$ received for it.

3.8 Secondary Adjustment of the Wagon Boundaries in the Flow

The appearance of ore flow on the scales is not characterized by an instantaneous abrupt change in the signal from the weight sensor. The signal has some inertia. This is due to the inertia of the crusher, which, when it enters the ore, goes to full capacity with a little delay, and also damping the signal itself in order to suppress noise. A similar inertia is observed at the end of the flow.

With a certain porosity of sites, this leads to situations where the flow of ore for the wagon has already begun to decline and at that time the ore begins to come on the scales from the next wagon. This situation is characterized by the presence of an extremum in the signal from the weight sensor.

The processing of such extremes allows more accurate determination of the wagon boundaries in the flow. The algorithm of secondary correction searches for extremums in the analyzed flow. In finding those, the system analyzes the extremum for proximity to the wagon boundaries obtained at the previous stage. If the extremum found is near one of the boundaries, the system adjusts the boundary, taking the extremum moment as the new boundary. If the extremum is at a considerable distance from the boundaries obtained at the previous stage, it is accepted by the system for changing the amount of ore on the conveyor, possibly related to the interruption of ore feed from the crusher, and is ignored.

3.9 Combining Wagon Compositions

The system provides the operator with an interface for performing the operation of combining the two consecutive trains of wagons into one train. The need for such an operation can occur when a failure occurs in the workload sensor of the path, as a result of which the signal disappears for a while. The system, when the busy signal disappears, fixes the output of the composition, and the next time it appears, it fixes the input of the new composition. If, at the time, there was only one composition on the way, the operator performs the unification operation for the compositions recorded by the system. To combine, the operator specifies the number of the first and the following composition and confirms the operation. As a result, the system assigns the wagons fixed to the second train to the first train and removes the second train. For reconnected wagons, the iron content is recalculated taking into account the parameters of the warehouse of the first composition.

3.10 Separation of the Wagons Composition

Similarly, the composition combining operation allows the system to perform a composition separation operation. The need for such an operation can occur when a failure occurs in the workload sensor of the path, as a result of which the work path sensor does not respond to the output of the train and the busy signal remains unchanged. In this case, the system does not fix the output of the train and the entrance to the unloading of the next one, as a result of which the cars unloaded from the second train are tied to the first train by the system. To correct this erroneous situation, the operator performs a splitting operation. To perform the operation, the operator enters the number of the segregated structure, the number of wagons that should be left in it, and the time to enter the unloading of the next convoy. As a result of the operation, the system fixes the input of the new composition with the entry time entered by the operator and re-ties the wagons indicated by the operator to it. For reconnected wagons, the content of iron is recalculated taking into account the parameters of the warehouse of the second composition.

4 Results of Experimental Studies

The results of experimental studies carried out in real time on the industrial site showed that the proposed scientific and technical solutions make it possible to improve the efficiency of monitoring the qualitative and quantitative characteristics of the ore at the entrance of the large crushing body and to ensure the formation of objective data for effective operational management of the ore preparation and enrichment processes.

The process of approbation of the pilot online monitoring system of the characteristics of the input ore at the mine processing plants was carried out at the industrial plant in Kazakhstan. At the same time, both direct measurements of the characteristics of the ore were carried out, and their analytical evaluation was carried out on the basis of the developed online monitoring system (OMS).

The average values of the characteristics of the ore in the wagons coming from different mines to the crushing department is given in Table 1.

Table 1. The average values of the ore characteristics from different quarries defined by developed online monitoring system and direct laboratory measurement.

Number of quarry	OMS, the average weight of ore in wagon (tons)	The average weight of ore in wagon. Direct measurement.	OMS, weight measurement error (deviation/%)	OMS, average Fe% content in the wagon	Average Fe% content in the wagon. Direct measurement.	OMS, the error in the content of Fe% measurements (deviations)/%)
1	94.3	98.8	−4.5/4.5%	32.4	32.0	0.4/1.25%
2	95.0	100.0	−5.0/5.0%	27.9	29.3	−1.4/4.77%
3	91.8	89.1	2.7/3.0%	37.7	40.2	−2.5/6.2%
4	90.5	91.0	−0.5/0.5%	27.9	29.7	−1.8/6.0%
5	102.5	99.6	2.9/2.9%	38.5	39.7	−1.2/3.0%

It can be seen from Table 1 that the relative error in monitoring of the input characteristics of the ore at the input of the enrichment factory does not exceed 6.2%, which will allow the effective use of the results obtained for the operational management of the mine processing plant technological processes.

Comparing proposed approach with other existing techniques. Above proposed approach was compared with traditional laboratory direct measurement. The accuracy of measurement within the permissible range, but traditional laboratory direct measurement is not real-time. Existing technologies for assessing the quality of ores in real-time for shallow-fractions ore flows uses ore-controlling station (OCS), which is commonly used for a single-flow ore crushing process [5]. For a multi-flowed ore crushing process an OCS is required in terms of the number of flows. Since the cost of an OCS is quite high (several hundred thousand dollars), the cost of the ore quality assessment system is proportional to the number of flows. For comparison, the technology proposed in this paper assumes the use of only one OCS for a multi-flowed process. Accordingly, there is a significant benefit in the cost of the proposed technology for real-time assessment of the quality of ores.

5 Conclusion and Future Works

In this paper is proposed to use the temporal model to determine the ore belonging to a quarry in the multi-flow technological process of ore crushing in the mining and processing plant. The proposed temporal model and online monitoring system allows the real-time control of the enrichment fabric input ore flows quality and the effective management of the beneficiation process, providing feedback to the quarries supplying the ore.

As a future works are planed the investigation of proposed approach on other mining plants and on production of building materials.

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