ZHAOYANG MA[1], NAILIAN HU[1], GUOQING LI[1], DI LIU[1], TAO PAN[2]

Ore value chain modeling and cost analysis based on Petri nets

Introduction

With the increase in production capacity and the promotion of production, the reserves of most mining enterprises under the original industrial indexes are rapidly consumed, and the full use of low-grade resources is receiving increasing attention. If mining enterprises want to simultaneously make full use of low-grade resources and simultaneously obtain good economic benefits they need to strengthen their cost analysis and management. In traditional cost analysis methods, the cost is considered as a whole and is simply split; thus, the cost of different production phases cannot be analyzed. Therefore, considering that the ore value is incrementally added in the production processes, the value chain theory of Michael Porter (Porter 1985) can be applied to the cost analysis of mining enterprises. By constructing the value chain model, the ore value under different engineering controls is evaluated to obtain the staged cost corresponding to the value-added link of the ore and to realize the appropriate cost analysis.

As the value chain theory does not provide an effective computer modeling tool, the related research on the value chain model focuses mainly on the qualitative analysis (Almeida et al. 2016; Badri et al. 2017; Chen and Chiu 2015; Forster et al. 2013; Hamilton-Hart and

✉ Corresponding Author: Guoqing Li; e-mail: qqlee@ustb.edu.cn

[1] University of Science & Technology Beijing, China;
  e-mail: ustbmazhaoyang@163.com; hnl@ustb.edu.cn; qqlee@ustb.edu.cn; ustbliudi@163.com
[2] Shenhua Information Technology Co., LTD, China; e-mail: pantao@shenhua.cc

Stringer 2016; Jaligot et al. 2016; Nahman and de Lange 2013). To carry out quantitative representation of the value chain, a lot of quantitative studies on value chain modelling have been conducted in recent years. Ina Porras et al. used value chain analysis and business model canvas as methodologies to identify and measure the economic relationships along the hilsa fish value chain in Bangladesh (Porras et al. 2017); Brandenburg and Seuring applied benchmarking methodology and a discounted cash flow (DCF) based model for quantifying value contributions (Brandenburg and Seuring 2011); Rubén Elvira Herranz et al. studied financial management performance during 2008–2013 for the Spanish aerospace manufacturing value chain using principal component analysis, data envelopment analysis and an artificial neural network (Herranz et al. 2017).

Despite the fact that these methodologies are expressive enough for describing processes in the value chain, it is difficult to simultaneously implement the quantitative modeling and process simulation of the value chain. To solve this problem, some scholars have recently combined the Petri nets and the value chain theory. U. N. Niranjan et al. presented a novel theoretical model in which the dynamics in a knowledge-based value chain is modeled using Petri nets (Niranjan et al. 2011); Zacek et al. introduced the Object-valued Petri net (OV-PN) modification as a new formalism to create a cyclic model of the value chain (Zacek et al. 2014); C.-D. Li et al. proposed a closed loop medical value chain system model and presented the modeling and simulating method based on Petri nets for a medical value chain system (Li et al. 2017). The introduction of Petri nets can solve the problem of quantitative analysis and process simulation of a value chain model but is mainly applied in manufacturing and related fields and has not been applied in mining enterprises.

Therefore, based on the value chain theory, the value-added links of metal underground mining enterprises (especially gold mining enterprises) were studied, and a value chain model of ore flow with common characteristics was constructed, which can carry out the dynamic evaluation and staged cost analysis of ore value under different engineering controls. In addition, Petri nets are used as a tool for modeling and simulation analysis, and the model is practically applied.

1. Construction of the ore value chain model

For metal ores underground mines, with the gradual implementation of exploration and mining projects, capital investment and labor consumption are dynamic and increase cumulatively by stage. Consequently, in the evaluation of ore value, we proceed from a series of processes, such as: exploration, mining, processing and smelting of geological resources, and then study the increments of the resources in different stages of production and processing. Finally, the main value chain of mining enterprises with ore flow as the carrier is built to achieve the dynamic evaluation of ore value.

1.1. Value-added and non-value-added
activities in mining enterprises

According to the basic view of Potter's value chain theory, not every link in a company's value activities creates value. The value created by an enterprise comes from some specific value activities in the enterprise value chain. These value-added activities, which form the core competence of an enterprise, are the strategic links of the enterprise value chain.

Considering the ore value and surface conditions, the mining methods used in underground gold mines are mostly filling methods. Production activities generally include: geological prospecting, production prospecting, developing, mining preparation, cutting, stoping, ore drawing, backfilling, underground transportation, hoisting, ore processing, concentrate treatment, etc.

Some of these activities, such as: excavating, mining, transporting and hoisting, form the ore flow increments directly by changing the state and position of the ore, which are the main value-added links in ore flow. These activities are interlinked with each other in production procedures and quantities. Other ancillary activities, such as: ventilating, draining and backfilling, neither directly act on the ore itself nor change the state or position of the ore and do not directly result in the increments of ore flow. Although these activities are essential for underground production, they are non-value-added activities in mining enterprises.

According to the different roles in the process of ore production, the activities can be arranged and merged. The production activities of gold mining enterprises can be classified as shown in Figure 1. The value-added activities are the final value-added nodes for the analysis of ore value, which are the key nodes of the ore value chain.
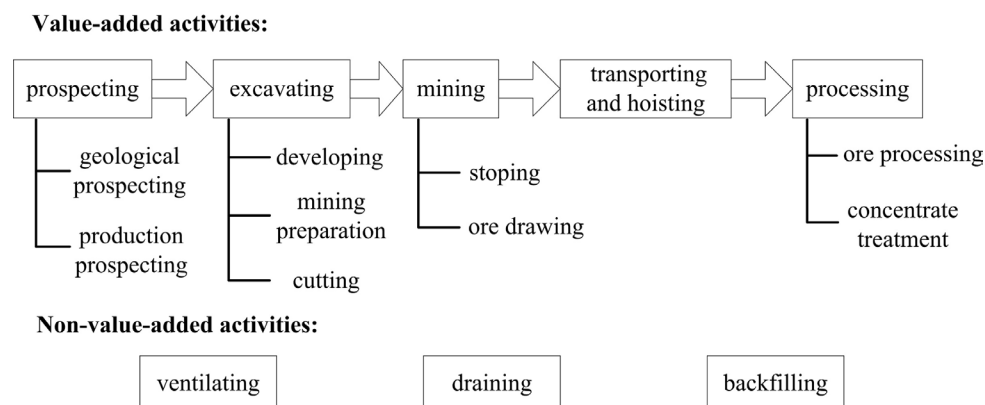

Fig. 1. Classification of value-added and non-value-added activities in mining enterprises

Rys. 1. Klasyfikacja działalności o wartości dodanej i działalności bez wartości dodanej
w przedsiębiorstwach górniczych

1.2. Structure analysis and model construction
of ore value chain

Mine production is a process of staged input. The staged input is transferred to the corresponding stage of the ore, which leads to the different values of mineral resources under different engineering controls. Ore mining and processing is the process of ore value increasing gradually.

From three dimensions, which are value-added activities, value subjects and value carriers, the analysis framework of the gold mining enterprise value chain system is constructed referring to the computer integrated manufacturing open system architecture (CIMOSA) (Mullane et al. 2010; Chaharsooghi and Ahmadi Achachlouei 2011; Millet 2013). The analysis framework is as shown in Figure 2.

Value-added activities are the processes of creating value, which embody various value-added operations of mining enterprises, including: prospecting, excavating, mining, transporting, hoisting and processing. Value subjects are the main body for performing the
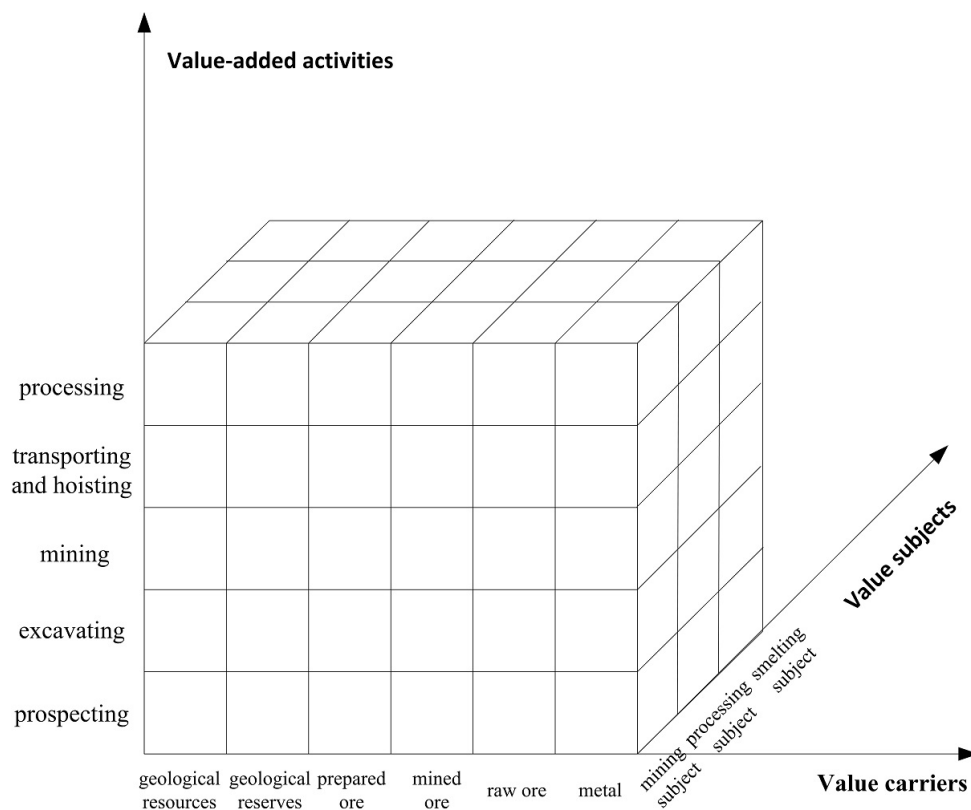

Fig. 2. Analysis framework of gold mining enterprise value chain

Rys. 2. Ramy analityczne łańcucha wartości przedsiębiorstwa górniczego wydobywającego złoto

value-added activities of the value chain and are responsible for the implementation of the value creation process. For mining enterprises, the value subjects include: mining subjects (mining enterprises, mining departments), processing subjects (concentrator), smelting subjects (smelter), etc. Value carriers are the products after each value-added activity and are reflected in the ore flow in mining enterprises, including unexplored geological resources, geological reserves identified by prospecting, prepared ore obtained by excavating, mined ore obtained by mining, raw ore obtained by transporting and hoisting, and final metal obtained by processing.

Based on the analytical framework, the structural model of the value chain system can be abstracted as in Figure 3. Value subjects (S_i) are the executors of value-added activities (A_i), which transform value carrier (C_i) into value carrier (C_{i+1}) by investing capital, materials, power, labor, etc. C_i is the input factor of A_i, and C_{i+1} is the output factor of A_i. From the perspective of value flow, if C_i contains the value of V_i, after the A_i performed by S_i, the obtained C_{i+1} contains the value of V_{i+1}. In this process, the value increment is implemented and is m_i input by S_i.
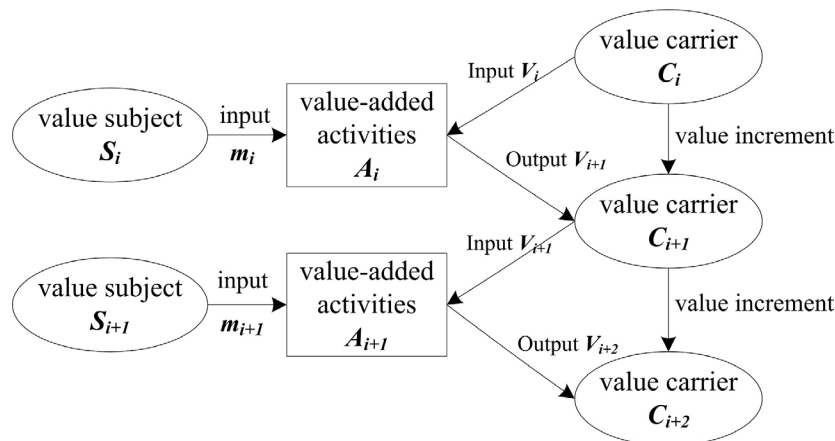

Fig. 3. Structural model of the value chain system of gold mining enterprises

Rys. 3. Model strukturalny systemu łańcucha wartości przedsiębiorstw górniczych wydobywających złoto

Based on a summary of the production process of a gold mine and incremental analysis of the ore flow, the value chain model of a gold mining enterprise is constructed, as shown in Figure 4.
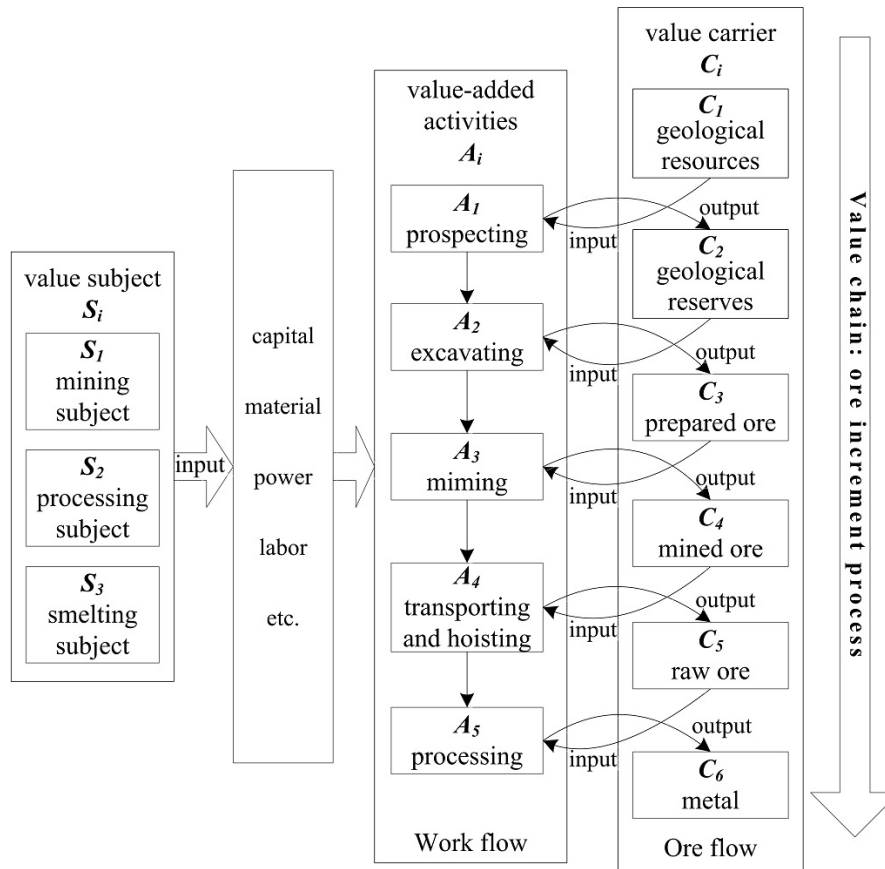
Fig. 4. Value chain model of gold mining enterprises

Rys. 4. Model łańcucha wartości przedsiębiorstw górniczych wydobywających złoto

1.3. Staged cost analysis based on ore value chain model

Every business activity on the enterprise value chain is not only part of the process of creating value but also part of the occupation or the elimination of enterprise resources, which generates a certain cost; thus, there are many cost control opportunities in the enterprise value chain. To solve the problem where the traditional cost analysis methods simply split the cost and do not analyze the cost of different production phases, a staged cost analysis model of mining enterprises is built based on ore flow value-added analysis and the construction of a value chain model, which calculates the cost of each activity and can carry out the quantitative representation of the value chain incremental process.

Through the value-added analysis of ore flow, it can be concluded that some auxiliary activities, such as: ventilation, drainage, and backfilling, are the non-value-added activities of mine production. In the staged cost analysis, according to the "who benefits, who pays" principle, the capital, materials, power, labor, etc. occupied by non-value-added activities are distributed in accordance with the amount of labor consumed by beneficial units, which are included in the related cost and expense items separately. Ventilation and drainage are auxiliary processes serving prospecting, excavating, mining, backfilling and other processes. Considering workload allocation, the input to ventilation by mining subjects is apportioned according to the coefficients of the wind demand in each process, while the input to drainage is equally apportioned to prospecting, excavating, mining and backfilling. Backfilling mainly serves the mining process; thus, backfilling input, which includes the investment apportioned by ventilation and drainage, is allocated to the mining node.

In addition to direct input, the input of the value subjects includes indirect input, which reflects the input in administration, finance, sales, etc. To fully consider the resource consumption of activities and to quantify the value of the ore at all stages, it is necessary to allocate the input, which cannot be directly accounted for, to specific processes in accordance with the appropriate standards and proportions. Since this part of input is not directly related to the production process involved in the value chain of the ore flow, the indirect input is treated as a fixed fee and is equally apportioned to each value-added node of the work flow to reduce the complexity of the calculation.

According to the above analysis, the staged cost analysis model of mining enterprises is constructed, as shown in Figure 5.

In the analysis of the staged cost of mining enterprises, the investment, materials, power and labor input of each value-added node are combined, and then, the total increments of the ore in the value-added nodes are calculated by adding apportioned non-value-added activity
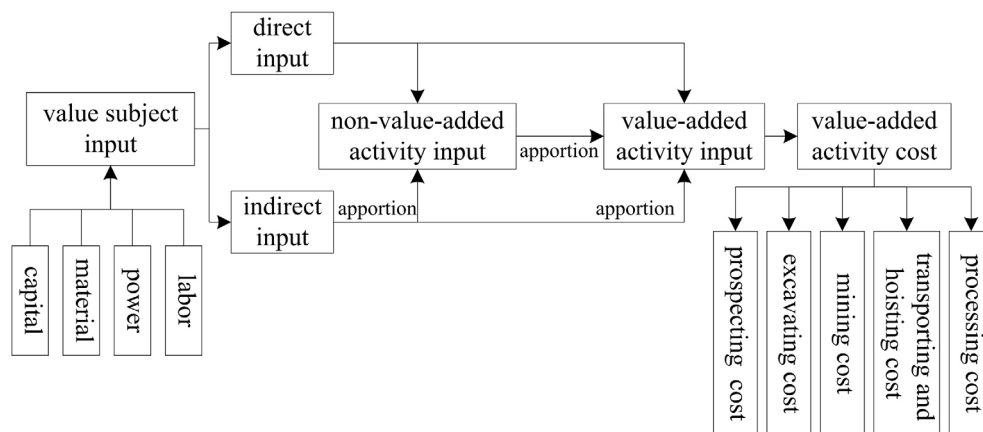

Fig. 5. Staged cost analysis model of mining enterprises

Rys. 5. Model analizy kosztów etapowych przedsiębiorstw górniczych

input and indirect input to the respective direct input. Therefore, costing for each value-added activity is conducted through a quantitative analysis of input by value subject in different value-added nodes to evaluate the ore value dynamically by stage.

2. Simulations of ore value chain model based on Petri nets

Because the value chain theory is mainly qualitative analysis and does not provide an effective computer modeling tool, the Petri nets and the value chain theory are combined to achieve quantitative representation. Petri nets are graphical mathematical modeling tools that describe complex system architectures and are often used in process modeling and simulation analysis (Gusikhin and Klampfl 2010; Tuncel and Alpan 2010; An et al. 2017). Petri nets can describe the value chain model of mining enterprises intuitively and accurately and calculate the related parameter changes of each value-added node. Since there are simulation tools for Petri nets, the operation process of a mining enterprise value chain can be analyzed from reachability, boundedness and flexibility.

2.1. Mapping relationships between value chain model and Petri nets

In a Petri net, a system behavior is represented as a "transition", and a system state is represented as a "place". The specific mapping relationship between the mining enterprise value chain model and the Petri nets is shown in Figure 6.

1. A_i is the process of creating value and is the dynamic factor in the value chain. The role of A_i is equivalent to the "transition" in a Petri net system, through which the system state (the value contained in the value carrier) changes. Thus, A_i's set A is mapped to the transition T, that is,

$$A \rightarrow T_A \tag{1}$$

   where A is the set of value-added activities A_i in the value chain model of mining enterprises, $A = \{A_1, A_2, ..., A_n\}$, and T_A is the set of transitions T_{Ai} in a Petri net, $T_A = \{T_{A1}, T_{A2}, ..., T_{An}\}$.

2. S_i and C_i are the subjects and objects of value-added activities in the value chain, whose sets can be mapped into place P of a Petri net.

When the system state changes via transition T_{Ai}, C_i is the input element of A_i, and the role is equivalent to the input state of T_{Ai}, which is place P_{Ci}, containing the token color sets of key parameters such as value and price. The value of C_i is increased through A_i, and the output state is C_{i+1} after transition. Similarly, S_i as the executors of value activities can be understood as the enabling element of system transition, which is place P_{Si}, containing a specific type of finite token color sets.
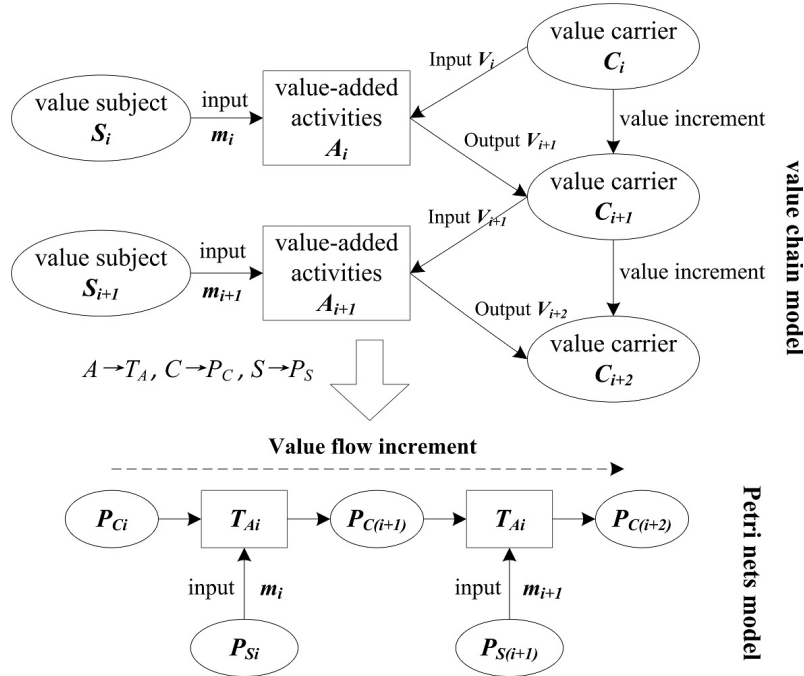
Fig. 6. Mapping relationship between value chain model and Petri nets

Rys. 6. Zależności między modelem łańcucha wartości a sieciami Petriego

$$
\begin{aligned}
C &\rightarrow P_C \\
S &\rightarrow P_S
\end{aligned}
\tag{2}
$$

where C is the set of value carriers C_i in the value chain model of mining enterprises, $C = \{C_1, C_2, ..., C_n\}$; P_C is the set of places P_{Ci} in a Petri net, $P_C = \{P_{C1}, P_{C2}, ..., P_{Cn}\}$; S is the set of value subjects S_i, $S = \{S_1, S_2, ..., S_n\}$; and P_S is the set of places P_{Si}, $P_S = \{P_{S1}, P_{S2}, ..., P_{Sn}\}$.

For the element C_i or S_i, attributes and attribute types can be mapped to the token color sets and token types, as

$$
\begin{aligned}
Attibutes_{Ci} &\rightarrow colset\; p_{Cij}, \quad \forall Type(at_{Cij}) \rightarrow Type(colset\; p_{Cij}) \\
Attibutes_{Si} &\rightarrow colset\; p_{Sij}, \quad \forall Type(at_{Sij}) \rightarrow Type(colset\; p_{Sij})
\end{aligned}
\tag{3}
$$

where $Attributes_{Ci}$ is the set of C_i's attributes at_{Cij}, $Attributes_{Ci} = \{at_{Ci1}, at_{Ci2}, ..., at_{Cin}\}$; $colset\; p_{Cij}$ is the set of all color sets of place P_{Ci} mapped by C_i, $colset\; p_{Cij} = \{colset_{Ci1}, colset_{Ci2}, ..., colset_{Cin}\}$; $Attributes_{Si}$ is the set of S_i's attributes at_{Sij}, $Attributes_{Si} = \{at_{Si1}, at_{Si2}, ..., at_{Sin}\}$; $colset\; p_{Sij}$ is the set of all color sets of place P_{Si} mapped by S_i, $colset\; p_{Sij} = \{colset_{Si1}, colset_{Si2}, ..., colset_{Sin}\}$.

2.2. Petri nets modeling of value chain model

For different application requirements, different types of simulation tools can be used to model a Petri net, while CPN Tools are used in this study to construct a colored Petri net model of the mining enterprise value chain (Mazouzi et al. 2014; Al-Azzoni 2015; Zhu and Wang 2012; Cheng et al. 2013).

As a high-level Petri net, colored Petri nets introduce the concepts of time, color set and hierarchical structure, which are more suitable for the simulation and performance analysis of large complex systems (Tang et al. 2016; Gratie and Gratie 2016; Hui and Berenguer 2015; Zegordi and Davarzani 2012; An et al. 2018; Drakaki and Tzionas 2017; Mahjoub et al. 2017; Guo et al. 2017; Song et al. 2017). As the value chain model and the staged cost analysis model are interrelated, in order to implement the simultaneous modeling of the two, a colored Petri net with hierarchical structure is established, taking the value chain model as a parent page, as in Figure 7, and the cost analysis model as a subpage, as in Figure 8. The parent page
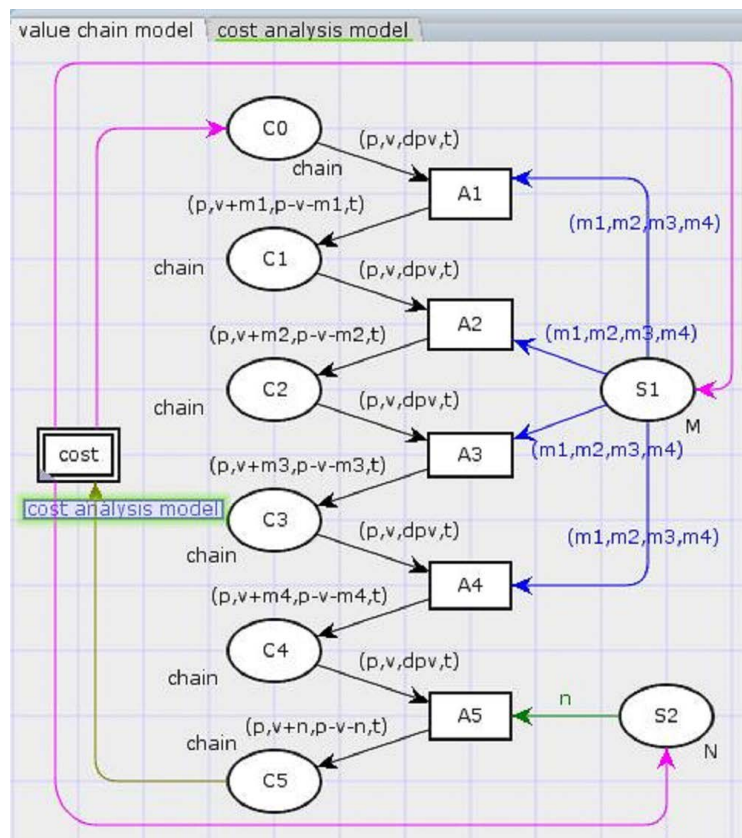

Fig. 7. Petri nets modeling of value chain model

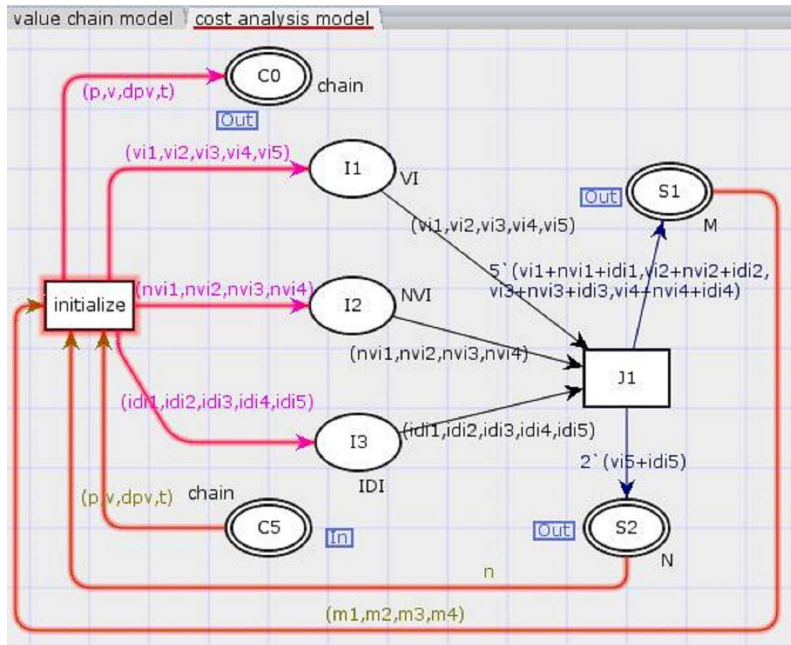Rys. 7. Modelowanie łańcucha wartości za pomocą sieci Petriego

Fig. 8. Petri nets modeling of the staged cost analysis model

Rys. 8. Modelowanie analizy kosztów etapowych za pomocą sieci Petriego

and the subpage are associated by a substitution transition "*cost*", and the cycle simulation of the model is implemented by adding an initializing transition.

In the established value chain Petri nets model, the transition "*cost*" is the substitution transition, and the transitions $A1$ to $A5$ represent the value-added activities in the mining enterprise value chain model, which are prospecting, excavating, mining, transporting and hoisting, and processing. Places $C0$ to $C5$ represent the value carriers, which are geological resources, geological reserves, prepared ore, mined ore, raw ore and metal, and the color set that describes their state is

$$colset \ p_{Ci} = \{colset \ P, \ colset \ V, \ colset \ DPV, \ colset \ T\} \tag{4}$$

where P represents the metal price and is a real variable, V represents the value contained by value carrier P_{Ci} and is a real variable, DPV is the difference between price and value and is a real variable, and T is the cycle count and is an integer variable. The type of the color set of value carrier place can be expressed as a product color set *chain,*

$$colset \ chain = product \ P \cdot V \cdot DPV \cdot T \tag{5}$$

Places $S1$ and $S2$ represent the value subjects in the value chain model, which are the mining subject and processing and smelting subject, respectively. The types of the color sets that describe the state of $S1$ and $S2$ are product color set M and real number color set N.

$$colset\ M = product\ M1 \cdot M2 \cdot M3 \cdot M4$$
$$colset\ N = real$$

 (6)

where the elements in $M1$ to $M4$ represent the total inputs provided to prospecting, excavating, mining, transporting and hoisting, respectively, by the mining subject and are all real variables; the elements in color set N represent the total inputs provided to processing by the processing and smelting subject.

In the cost analysis Petri nets model, the transition $J1$ represents the cost analysis process, and the "*initialize*" transition is the initializing transition, which can carry out the cycle simulation and parameter initialization of the model. Places $I1$ to $I3$ are inputs by value subjects. Place $I1$ represents direct input to value-added activities, and the color set type is product color set VI,

$$colset\ VI = product\ VI1 \cdot VI2 \cdot VI3 \cdot VI4 \cdot VI5$$

 (7)

Place $I2$ represents direct input to non-value-added activities, and the color set type is product color set NVI,

$$colset\ NVI = product\ NVI1 \cdot NVI2 \cdot NVI3 \cdot NVI4$$

 (8)

Place $I3$ represents indirect input, and the color set type is product color set IDI,

$$colset\ IDI = product\ IDI1 \cdot IDI2 \cdot IDI3 \cdot IDI4 \cdot IDI5$$

 (9)

Furthermore, $C0$, $S1$ and $S2$ are output port places of a subpage, while $C5$ is an input port place. They are associated with port places of the same name in the parent page. The tokens in $S1$ and $S2$ are the costs of value-added activities.

It should be noted that, since the Petri nets model here is only the basic model and has no specific data, it does not pass syntax checking.

3. Results and Discussion

3.1. Case background and calculation of value subject input

A large gold mining enterprise in China is used as an example for this study. After decades of mining, the reserves of the mine are consumed rapidly, and the ore grade has a significant negative trend; thus, a fine assessment of ore value must be carried out, and cost analysis and management need to be strengthened to ensure the maximum production and operation efficiency of the enterprise.

Using the enterprise cost statements in 2016 as basic data, the inputs of value subjects are collected and arranged. For ease of calculation, the inputs are all in metal units. The results are shown in Table 1.

Table 1.   Calculation results of inputs of value subjects (Unit: yuan·g^{-1})

Tabela 1.   Wyniki obliczeń wartości wejściowych podmiotów (jednostka: yuan·g^{-1})

A_i Value-added activities	A_1 Prospecting	A_2 Excavating	A_3 Mining	A_4 Transporting and hoisting	A_5 Processing
Direct input to value-added activities	0.98	6.53	17.96	27.09	16.79
Direct input to non-value-added activities	1.07	1.95	15.77	0.24	–
Indirect input	18.29	18.29	18.29	18.29	20.76

3.2. Model simulation and result analysis

Using the inputs of the value subjects in Table 1 as the initial tokens of places, CPN Tools are used to model the staged cost analysis model, as shown in Figure 9. The metal price is the enterprise's internal accounting price of 240 yuan/gram.

After passing syntax checking, the model is simulated, and the results are shown in Figure 10 and 11. In the model simulation, the cost of value-added activity and the value of carrier place at each stage can be obtained. The cost analysis results and the specific increments of the ore flow are shown in Table 2.

The value change of carrier places can be seen from the simulation results; that is, the value of the ore flow is accumulated in stages with the progress of production and operation. The value of carriers will increase at each value-added node, and the added value is the total input by the value subject in the corresponding value-added node.
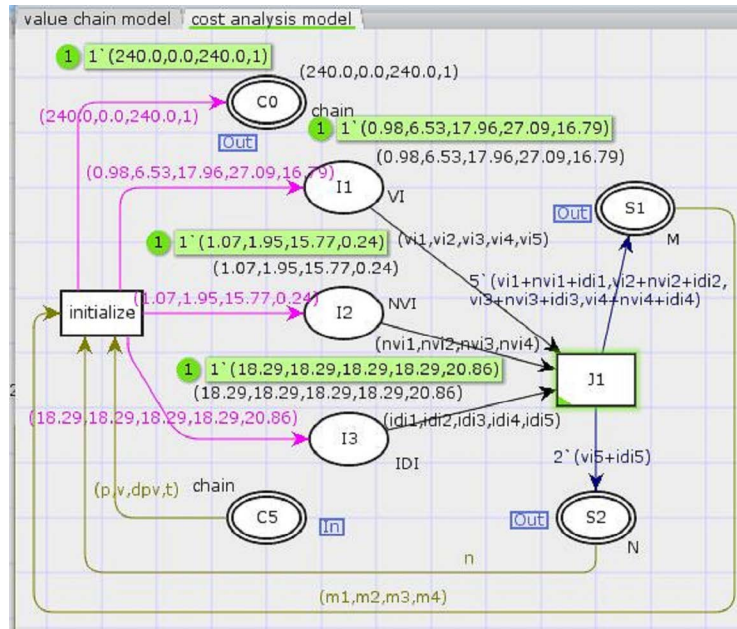
Fig. 9. Petri nets modeling of the cost analysis model in practical application

Rys. 9. Modelowanie analizy kosztów w praktyce za pomocą sieci Petriego
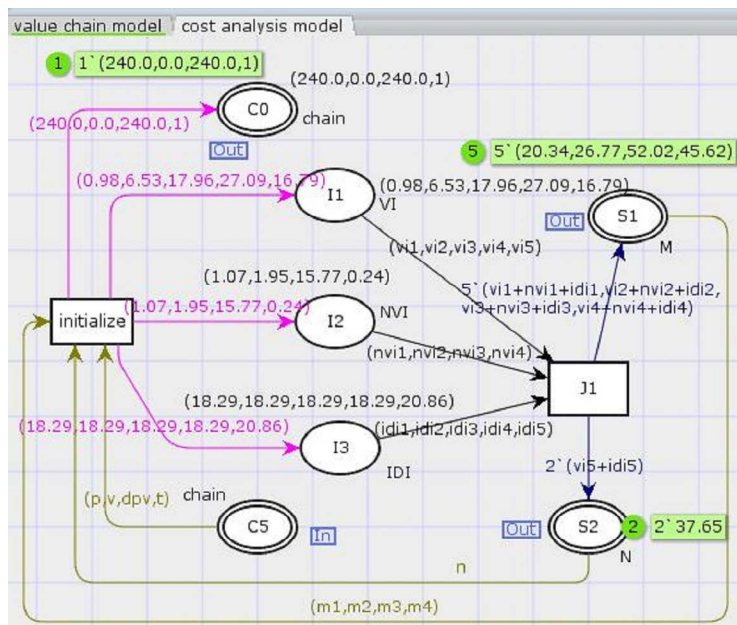

Fig. 10. Simulation results of the cost analysis model based on Petri nets

Rys. 10. Wyniki symulacji modelu analizy kosztów w oparciu o sieci Petriego
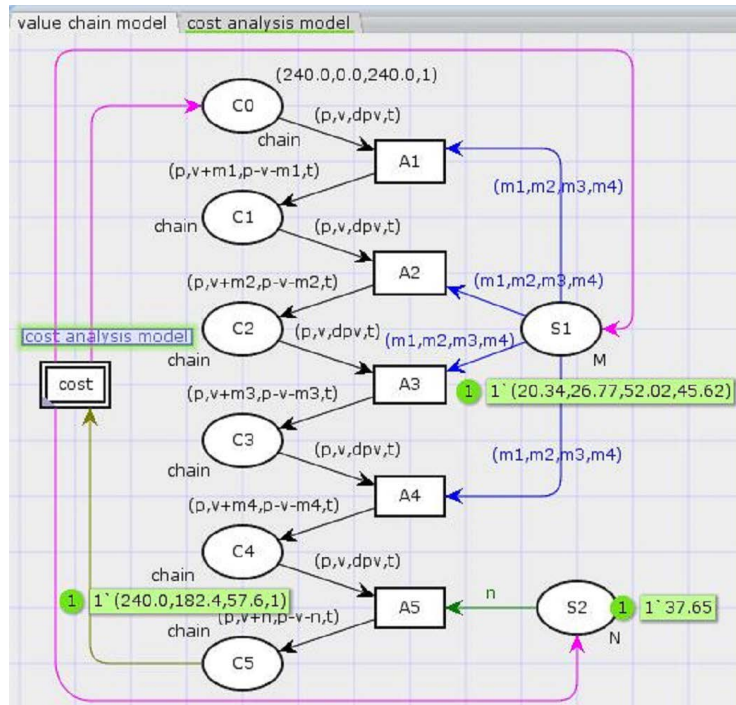
Fig. 11. Simulation results of the value chain model based on Petri nets

Rys. 11. Wyniki symulacji modelu łańcucha wartości w oparciu o sieci Petriego

Table 2.   Model simulation results (Unit: yuan·g^{-1})

Tabela 2.   Wyniki symulacji modelu (jednostka: yuan·g^{-1})

A_i Value-added activities	A_1 Prospecting	A_2 Excavating	A_3 Mining	A_4 Transporting and hoisting	A_5 Processing
Cost	20.34	26.77	52.02	45.62	37.55
Value carrier	geological reserves	prepared ore	mined ore	raw ore	metal
Value of carrier	20.34	47.12	99.14	144.76	182.31

Cost analysis using a traditional method is also carried out with the same basic data, and the results are shown in Table 3.

Table 3.   Cost and expense under traditional cost analysis method (Unit: yuan·g^{-1})

Tabela 3.   Koszty i wydatki w tradycyjnej metodzie analizy kosztów (jednostka: yuan·g^{-1})

Items	Prospecting	Excavating	Mining	Transporting and hoisting	Processing	Ventilation	Drainage
Cost	0.98	6.53	17.96	27.09	16.79	2.99	4.28
Items	Backfilling	Manufacturing expenses of mining	Manufacturing expenses of processing and smelting	Management expenses	Financial expenses	Sales expense	Total
Cost	7.15	34.13	9.85	52.55	1.46	0.55	182.31

As seen from the comparison between Table 2 and Table 3, the traditional cost analysis method divides cost according to activity, which can neither reflect the value of the ore under different engineering controls nor meet the requirement of refined cost analysis for low-grade resource utilization. Comparatively, the value chain model constructed by Petri nets can quantitatively analyze the value of ore flow at different stages during the mine production process; this model can calculate the cost of each value-added activity and provide the basis for targeted cost control and full the utilization of resources.

3.3. Discussion

In this paper, the Petri net was introduced into mining science as a tool for modeling and simulation analysis to solve the problem of quantitative analysis and process simulation of the value chain model of mine enterprises, and a case study of a large gold mining enterprise in China was conducted. The research extends the application of the value chain theory and Petri net tools, and also enriches the method of phased cost analysis for mining enterprises.

The presented methodology, which is applicable to universal underground metal mines, can be extended to other mining enterprises by analyzing different activities and is scientific and extensible. Compared with traditional cost analysis methods and value chain modeling methods, the value chain model constructed by Petri net can carry out quantitative modeling and process simulation of the value chain, thus quantitatively analyze the value of ore flow at different stages during the mine production process, and calculate the cost of each value--added activity.

However, the research results also have certain limitations. The analysis of the mine production process is not sufficiently detailed, and the specific steps of ore processing and concentrate processing are not taken into account. The modeling process is complex, and the value chain structure needs to be analyzed again when expanding to other types of enterprises. During further research, we need to further improve the production process analysis, simplify the modeling process and study the construction of a general model.

This study provides a theoretical basis for the dynamic evaluation and optimal utilization of low grade resources, and makes the evaluation of ore value from static, single and extensive to dynamic, phased and refined. It provides a new idea and a basic model for the full utilization of geological resources. It is of great theoretical significance and practical implication for fully recycling and utilizing mineral resources, increasing the reserve of mine resources and improving the comprehensive utilization of resources.

Conclusions

1. Based on the value chain theory, the value chain model of mining enterprises is constructed using Petri nets, and the simulation of the formation, flow, transfer and realization of ore value is completed using available computer simulation tools. Through the research on the value-added links of mining enterprises, the analysis and dynamic evaluation of ore value under different engineering controls are carried out.
2. A simulation example based on a gold mining enterprise is provided. Through staged cost analysis and Petri nets calculation, the ore value is finely evaluated in stages.
3. The value chain Petri nets model and simulation analysis method proposed in this study can solve the problem that traditional cost analysis methods cannot-the analysis of the stage cost of different production links, which can carry out the quantitative description of the value chain model of mining enterprises and provide a theoretical and practical reference for the stage value evaluation and cost analysis of the ore. This study will help to improve the strategic management of mining enterprises, to promote the application of computer modeling and simulation technology in mine engineering, and to evaluate the economic feasibility of ore utilization more accurately to provide the basis for the value evaluation and effective utilization of low-grade ores. Further, the model and simulation method, which can also be applied to other similar enterprises in value chain modeling, are scientific and extensible.

REFERENCES

Al-Azzoni, I. 2015. Server consolidation for heterogeneous computer clusters using Colored Petri Nets and CPN Tools. *Journal of King Saud University – Computer and Information Sciences* 27, pp. 376–385.
Almeida et al. 2016 – Almeida, J., De Meyer, A., Cattrysse, D., Van Orshoven, J., Achten, W.M.J. and Muys, B. 2016. Spatial optimization of Jatropha based electricity value chains including the effect of emissions from land use change. *Biomass and Bioenergy* 90, pp. 218–229.
An et al. 2017 – An, Y., Wu, N., Hon, C. T. and Li, Z. 2017. Scheduling of Crude Oil Operations in Refinery without Sufficient Charging Tanks Using Petri Nets. *Applied Sciences* 7.

An et al. 2018 – An, Y., Wu, N., Zhao, X., Li, X. and Chen, P. 2018. Hierarchical Colored Petri Nets for Modeling and Analysis of Transit Signal Priority Control Systems. *Applied Sciences* 8, p. 141.

Badri, H., Ghomi, S. M. T. F. And Hejazi, T.-H. 2017. A two-stage stochastic programming approach for value-based closed-loop supply chain network design. *Transportation Research Part E-Logistics and Transportation Review* 105, pp. 1–17.

Brandenburg, M. and Seuring, S. 2011. Impacts of supply chain management on company value: benchmarking companies from the fast moving consumer goods industry. *Logistics Research* 3, pp. 233–248.

Chaharsooghi, K. and Ahmadi Achachlouei, M. 2011. Developing life-cycle phases for the DoDAF using ISO15704 Annex A (GERAM). *Computers in Industry* 62, pp. 253–259.

Chen, Y.-T. and Chiu, M.-C. 2015. A case-based method for service-oriented value chain and sustainable network design. *Advanced Engineering Informatics* 29, pp. 269–294.

Cheng et al. 2013 – Cheng, F., Li, H., Wang, Y.W., Skitmore, M. and Forsythe, P. 2013. Modeling resource management in the building design process by information constraint Petri nets. *Automation in Construction* 29, pp. 92–99.

Drakaki, M. and Tzionas, P. 2017. Manufacturing Scheduling Using Colored Petri Nets and Reinforcement Learning. *Applied Sciences,* 7.

Forster et al. 2013 – Forster, C., Zapp, M., Aelker, J., Westkämper, E. and Bauernhansl, T. 2013. Collaborative Value Chain Management between Automotive and Semiconductor Industry: An Analysis of Differences and Improvement Measures. *Procedia CIRP* 12, pp. 312–317.

Gratie, D.-E. and Gratie, C. 2016. Composition Colored Petri Nets for the Refinement of Reaction-based Models. *Electronic Notes in Theoretical Computer Science* 326, pp. 51–72.

Guo et al. 2017 – Guo, Z., Zhang, Y., Zhao, X. and Song, X. 2017. A Timed Colored Petri Net Simulation-Based Self-Adaptive Collaboration Method for Production-Logistics Systems. *Applied Sciences* 7.

Gusikhin, O. and Klampfl, E. 2010. Integrated Process Planning and Supply Chain Configuration for Commodity Assemblies Using Petri Nets [In:] Lilius, J. and Penczek, W. (eds.) *Applications and Theory of Petri Nets, Proceedings.*

Hamilton-Hart, N. and Stringer, C. 2016. Upgrading and exploitation in the fishing industry: Contributions of value chain analysis. *Marine Policy* 63, pp. 166–171.

Herranz et al. 2017 – Herranz, R.E., Estévez, P.G., Oliva, M.A.D.V.Y. and Dé, R. 2017. Leveraging financial management performance of the Spanish aerospace manufacturing value chain. *Journal of Business Economics and Management* 18, pp. 1005–1022.

Hui, S. and Berenguer, C. 2015. Delayed maintenance model for deteriorating track using colored Petri Nets. *IFAC – Papers Online* 48, pp. 464–469.

Jaligot et al. 2016 – Jaligot, R., Wilson, D.C., Cheeseman, C.R., Shaker, B. and Stretz, J. 2016. Applying value chain analysis to informal sector recycling: A case study of the Zabaleen. *Resources, Conservation and Recycling* 114, pp. 80–91.

Li et al. 2017 – Li, C., Chen, H. and Xie, T. 2017. Modeling and simulating method for the medical closed loop––value chain system. *Computer Integrated Manufacturing Systems* 23, 19.

Mahjoub et al. 2017 – Mahjoub, Y.I., El-Alaoui, E.H.C. and Nait-Sidi-Moh, A. 2017. Modeling a bus network for passengers transportation management using colored Petri nets and (max, plus) algebra [In:] Shakshuki, E. ed. *8th International Conference on Ambient Systems, Networks and Technologies.*

Mazouzi et al. 2014 – Mazouzi, M., Kallel, O., Mbarek, I.B., Hasnaoui, S. and Abid, M. 2014. SCPN modeling and comparative performance evaluation of bussed and crossbar-based switched fabric CAN. *Computer Standards & Interfaces* 36, pp. 953–962.

Millet, P.-A. 2013. Toward a model-driven, alignment-oriented ERP methodology. *Computers in Industry* 64, pp. 402–411.

Mullane et al. 2010 – Mullane, S.L., Justham, L.M., West, A.A. and Conway, P.P. 2010. Design of an end-user centric information interface from data-rich performance analysis tools in elite swimming. *Procedia Engineering* 2, pp. 2713–2719.

Nahman, A. and De Lange, W. 2013. Costs of food waste along the value chain: evidence from South Africa. *Waste Manag* 33, pp. 2493–500.

Niranjan et al. 2011 – Niranjan, U.N., Itagi, S. and Mohan, B.R. 2011. Petri Net Model for Knowledge-Based Value Chain [In:] Shah, K., Gorty, V. R. L. and Phirke, A. eds. *Technology Systems and Management.* Berlin: Springer--Verlag Berlin.

Porras et al. 2017 – Porras, I., Mohammed, E.Y., Ali, L., Ali, M.S. and Hossain, M.B. 2017. Power, profits and payments for ecosystem services in Hilsa fisheries in Bangladesh: A value chain analysis. *Marine Policy* 84, pp. 60–68.

Porter, M.E. 1985. *Competitive advantage,* New York, Free Press.

Song et al. 2017 – Song, H., Liu, J. and Schnieder, E. 2017. Validation, verification and evaluation of a Train to Train Distance Measurement System by means of Colored Petri Nets. *Reliability Engineering & System Safety* 164, pp. 10–23.

Tang et al. 2016 – Tang, J., Piera, M.A. and Guasch, T. 2016. Coloured Petri net-based traffic collision avoidance system encounter model for the analysis of potential induced collisions. *Transportation Research Part C: Emerging Technologies* 67, pp. 357–377.

Tuncel, G. and Alpan, G. 2010. Risk assessment and management for supply chain networks: A case study. *Computers in Industry* 61, pp. 250–259.

Zacek et al. 2014 – Zacek, J., Melis, Z. and Hunka, F. 2014. Modeling the Value Chain with Object-Valued Petri Nets. *Lecture Notes in Electrical Engineering* 307, 12.

Zegordi, S.H. and Davarzani, H. 2012. Developing a supply chain disruption analysis model: Application of colored Petri-nets. *Expert Systems with Applications* 39, pp. 2102–2111.

Zhu, L. and Wang, W. 2012. UML Diagrams to Hierarchical Colored Petri Nets: An Automatic Software Performance Tool. *Procedia Engineering* 29, pp. 2687–2692.

ORE VALUE CHAIN MODELING AND COST ANALYSIS BASED ON PETRI NETS

Abstract

At present, with the increase of production capacity and the promotion of production, the reserves of most mining enterprises under the original industrial indexes are rapidly consumed, and the full use of low-grade resources is getting more and more attention. If mining enterprises want to make full use of low-grade resources simultaneously and obtain good economic benefits to strengthening the analysis and management of costs is necessary. For metal underground mines, with the gradual implementation of exploration and mining projects, capital investment and labor consumption are dynamic and increase cumulatively in stages. Consequently, in the evaluation of ore value, we should proceed from a series of processes such as: exploration, mining, processing and the smelting of geological resources, and then study the resources increment in different stages of production and the processing. To achieve a phased assessment of the ore value and fine evaluation of the cost, based on the value chain theory and referring to the modeling method of computer integrated manufacturing open system architecture (CIMOSA), the analysis framework of gold mining enterprise value chain is established based on the value chain theory from the three dimensions of value-added activities, value subjects and value carriers. A value chain model using ore flow as the carrying body is built based on Petri nets. With the CPN Tools emulation tool, the cycle simulation of the model is carry out by the colored Petri nets, which contain a hierarchical structure. Taking a large-scale gold mining enterprise as an example, the value chain model is quantified to simulate the ore value formation, flow, transmission and implementation process. By analyzing the results of the simulation, the ore value at different production stages is evaluated dynamically, and the cost is similarly analyzed in stages, which

can improve mining enterprise cost management, promote the application of computer modeling and simulation technology in mine engineering, more accurately evaluate the economic feasibility of ore utilization, and provide the basis for the value evaluation and effective utilization of low-grade ores.

K e y w o r d s: value chain, Petri net, cost analysis, gold mine, ore flow

MODELOWANIE ŁAŃCUCHA WARTOŚCI RUDY I ANALIZA KOSZTÓW W OPARCIU O SIECI PETRIEGO

S t r e s z c z e n i e

Obecnie wraz ze wzrostem zapotrzebowania na surowce mineralne, zasoby większości tych surowców podlegają bardzo szybkiemu sczerpaniu, a wykorzystanie zasobów o niskiej jakości jest brane pod uwagę coraz powszechniej. Jeśli przedsiębiorstwa wydobywcze chcą w pełni wykorzystać zasoby surowców mineralnych niskiej jakości i jednocześnie uzyskać dobre wyniki ekonomiczne, niezbędna jest szeroka analiza i zarządzanie kosztami. W przypadku podziemnych kopalń rud metali, przy stopniowej realizacji projektów poszukiwawczo-wydobywczych, nakłady inwestycyjne i nakłady pracy są dynamiczne i wzrastają stopniowo w realizowanych procesach. W związku z tym, w ocenie wartości rudy powinno się uwzględniać szereg procesów, takich jak: poszukiwanie, wydobycie, przeróbkę i hutnictwo, a następnie rozpatrywać przyrosty wartości i kosztów na poszczególnych etapach produkcji i przetwarzania. Aby osiągnąć etapową ocenę wartości rudy i dokładną ocenę kosztów, w oparciu o teorię łańcucha wartości, należy zastosować metodę komputerowego modelowania zintegrowanej produkcji otwartej architektury systemu (CIMOSA). Ramy analizy łańcucha wartości przedsiębiorstwa wydobywczego złota są ustalane z trzech ocen: wartości dodanej, wartości podmiotów i wartości nośników. Model łańcucha wartości wykorzystujący przepływ rudy zbudowany jest w oparciu o sieci Petriego. Symulacja cyklu modelu jest realizowana przez kolorowe sieci Petriego, które zawierają hierarchiczną strukturę. Przykładem jest wielkoskalowe przedsiębiorstwo wydobywcze złota, w którym model łańcucha wartości jest określany ilościowo w celu symulacji procesów tworzenia, przepływu, przeniesienia i realizacji. Analizując wyniki symulacji, wartość rudy na poszczególnych etapach produkcji jest oceniana dynamicznie, a koszty są również analizowane etapami, co może: poprawić zarządzanie kosztami przedsiębiorstw górniczych, promować zastosowanie modelowania komputerowego i technologii symulacji w inżynierii górniczej, bardziej dokładnie ocenić ekonomiczną wykonalność wykorzystania rudy i zapewnić podstawę do oceny wartości i efektywnego wykorzystania rud niskiej jakości.

S ł o w a k l u c z o w e: łańcuch wartości, sieć Petriego, analiza kosztów, kopalnia złota, przepływ rudy