

A Framework for ICT Support to Sustainable Mining - An Integral Approach

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Abstract—Motivated by the facts that there is no one-fits-all sustainability assessment framework in mining and that support of information and communications technologies (ICT) to mining is focusing on specific mining process aspects we propose a cutting-edge ICT supported integral framework. The framework relays on multi-objective optimization theory, adaptive control theory, the mining process itself and modern ICT technologies, which position it in line with the concept of the Factory-of-Future. The framework should be able to provide data to all interested parties, e.g. to help top management in mining industry to make optimal decisions, to make available public data, to generate alarms in critical situations.

I. INTRODUCTION

Mining is a fundamental human activity in the process of exploitation of natural ore resources [1]. Since the availability of ore highly affects existence of humans and progress of mankind, mining sustainability is of high importance. As we perceive nowadays, sustainable mining (SM) is leveraged by the five cornerstones [2]: economy, safety, environment pollution, production efficiency, and community.

The cornerstones are usually treated separately, with economy and production efficiency as the most important aspects, especially in developing societies, while safety, community and environment pollution aspects get their importance in high responsible societies mainly in developed countries.

Taking cornerstones for objectives, a multi-objective [3] approach to sustainable mining optimization can be performed, where all the objectives, intrinsically conflicting, are optimized simultaneously. Moreover, optimization of a mining system can be performed continuously to adapt the process to variable circumstances, such as weather conditions, current trading conditions on market regarding the subject ore, hazardous situations when system functionality can be reduced, etc.

Applying cutting-edge Information and Communications Technologies (ICT), including Internet of Things (IoT) [4, 5], Cyber Physical Systems (CPS) [6-8], Wireless Sensor Networks (WSNs) [9, 10], Cloud Computing (CC) [5, 11], Context-Aware Systems (CAS) [12], Data Mining (DM) [13], Machine Learning (ML) [14] and complex mathematical apparatus for multi-objective optimization [3, 15] to geology, mining engineering, machinery engineering, ecology, economy and finance expertise, the aim is to build a complex mining system that can be modelled, simulated or empirically studied in an integral and inter/multi-disciplinary approach with a goal of adaptive multi-objective optimization while satisfying sustainability

condition. Such a system should enable top management of a mine corporation (and other interested sides) to have real-time information [16-18] and to make proper decisions.

Having the previous facts in mind we propose a framework for sustainably mining supported by the cutting-edge ICT that should bring mining to the Factory-of-Future concept, proclaimed by HORIZON 2020 – The European Commission program.

The paper is structured as follows. In section II we review the existing frameworks. In section III, we present the proposed framework with all its components. In section IV, we survey the existing ICT support to mining. In section V, we try to position our framework. Section VI concludes the paper.

II. RELATED WORK

Several ways for describing the term “Sustainability assessment framework” have been recognized. However, descriptions of the term are mostly ad-hoc. In general, “framework is a structure composed of components framed together to support something” [19, p.181]. In the case of sustainability assessment frameworks, these components are indicators/decision variables, conceptual models, principles, criteria, goals, and policies.

The number of frameworks that can be used to assess mining sustainability is on the rise. However, they are based on different approaches and may have different focuses. Moreover, their effectiveness is questionable [20] and requires more research.

Existing sustainability assessment and reporting frameworks primarily can be divided into two large groups [19]:

1. frameworks frequently used by mining companies [21-23]
2. frameworks proposed by analysts and academics, with a number or no implementation results though (e.g., seven questions to sustainability – 7QS [24], innovation and technology driven sustainability performance management framework – ITSPM [25], and Azapagic’s framework [26])

However, frequency of implementation is not a sufficient indicator of the effectiveness of a framework. Rare research studies focused on comparison and categorization of the frameworks (their attributes) confirm this claim [19, 27, 28]. These studies help clarify the positions of selected frameworks in the current theory and practice based on the analyzed variables such as temporal orientation, geographical focus, comprehensiveness / the number of decision variables, etc. As expected, the results of the comparative and other studies [29, 30] show that

there is no one-fits-all solution because of the complexity and variety of mining contexts. Moreover, they reveal some significant limitations of current frameworks that should be overcome by new approaches (e.g., weekly addressed geographical scope, predominantly retrospective temporal orientation, the neglected problem of scarcity of (proven) mineral reserves, etc.).

In an attempt to overcome obvious limitations of leading frameworks, new frameworks are continually being proposed (e.g., a systems-based framework for capturing the flows of materials across the globe [31], an indicator framework for measuring progress towards sustainability in the context of legacy mined land [32], etc.

III. FRAMEWORK

The proposed framework relies on multi-objective optimization theory, adaptive control theory, the mining process itself and modern ICT technologies.

A. Multi-Objective Optimization (MOO) Fundamentals

Let $\mathbf{z} = (z_1, \dots, z_n)$, $\mathbf{z} \in \mathbf{Z}$, where \mathbf{Z} is the set of all feasible objectives' values, be the vector of objectives. Let $\mathbf{x} = (x_1, \dots, x_m)$, $\mathbf{x} \in \mathbf{X}$, where \mathbf{X} is the set of all possible decision vector values, be the vector of decision (design) variables. Let $\mathbf{p} = (p_1, \dots, p_k)$, $\mathbf{p} \in \mathbf{P}$, where \mathbf{P} is the set of all possible parameter vector values, be the vector of given parameters. Let $\mathbf{F}: (\mathbf{X}, \mathbf{P}) \rightarrow \mathbf{Z}$ be the mapping function from \mathbf{X} and \mathbf{P} spaces to \mathbf{Z} space. Then $\mathbf{F} = (F_1, \dots, F_n)$, $\mathbf{z} = \mathbf{F}(\mathbf{x}, \mathbf{p})$, $z_1 = F_1(\mathbf{x}, \mathbf{p})$, ..., $z_n = F_n(\mathbf{x}, \mathbf{p})$. Let $\mathbf{G}(\mathbf{x}, \mathbf{p}) = \mathbf{G}^*$ and $\mathbf{H}(\mathbf{x}, \mathbf{p}) \leq \mathbf{H}^*$ be the constraints given in equality and inequality forms, respectively.

For $\mathbf{p} = \mathbf{p}^*$, a point $\mathbf{x}^* \in \mathbf{X}$, is Pareto optimal (PO) iff there does not exist another point $\mathbf{x} \in \mathbf{X}$, such that $\mathbf{F}(\mathbf{x}, \mathbf{p}^*) \leq \mathbf{F}(\mathbf{x}^*, \mathbf{p}^*)$, and $F_i(\mathbf{x}, \mathbf{p}^*) \leq F_i(\mathbf{x}^*, \mathbf{p}^*)$, $1 \leq i \leq n$, for at least one function.

For $\mathbf{p} = \mathbf{p}^*$, a point $\mathbf{x}^* \in \mathbf{X}$, is weakly Pareto optimal (WPO) iff there does not exist another point $\mathbf{x} \in \mathbf{X}$, such that $\mathbf{F}(\mathbf{x}, \mathbf{p}^*) \leq \mathbf{F}(\mathbf{x}^*, \mathbf{p}^*)$.

In other words, a point is WPO if there is no other point that improves all of the objectives simultaneously. In contrast, a point is PO if there is no other point that improves at least one objective without detriment to another. PO points are also WPO, while WPO points are not PO.

The set of all PO points is called Pareto optimal set, Pareto front or Pareto frontier.

The task of MOO is to find all

$$\mathbf{x}^* = \operatorname{argmax}_{\substack{\mathbf{G}(\mathbf{x}, \mathbf{p}^*) = \mathbf{G}^* \\ \mathbf{H}(\mathbf{x}, \mathbf{p}^*) \leq \mathbf{H}^*}} \mathbf{F}(\mathbf{x}, \mathbf{p}^*).$$

B. Adaptive Control Theory Fundamentals

Control theory is a useful tool for control of system dynamics, another way around, for control of system transition from some state to the desired state. In addition, adaptive control should help system keep desired state, in the case of variable system parameters change, where the desired system state can also vary with the parameters change. Basics of the adaptive control are given in Fig. 1, e.g. see [33, 34].

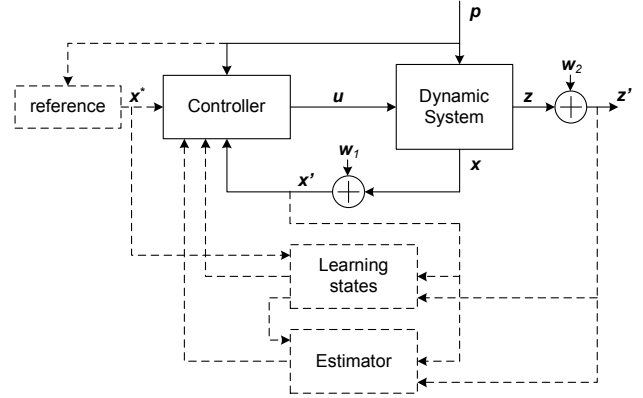


Figure 1. Adaptive control - basic diagram

The system state \mathbf{x} and output \mathbf{z} can be obtained by some measurement that introduces measurement errors \mathbf{w}_1 , \mathbf{w}_2 , respectively. Controller calculates optimal control vector \mathbf{u} , using all available data. Dashed lines mean optional. The way information regarding desired system state is obtained and specific adaptive control system architecture is chosen, depends on a particular controlled dynamic system.

Combining MOO and adaptive control, in the case the given parameters are not fixed, if they change independently of our control, for any change of \mathbf{p} , from \mathbf{p}_1^* to \mathbf{p}_2^* or some hazardous situation or any other system change reason, dynamic MOO [35] control mechanism, whichever the dynamism origins are [36], should adapt moving optimal point from \mathbf{x}_1^* to \mathbf{x}_2^* , keeping transition slight, without running system out of function region or through the undesirable states.

Once having system state data and observed objectives, it is easy to generate alarms on critical system states and present data to interested parties.

C. Objective Space Analysis

Objective space can be qualitatively defined based on the five SM cornerstones [2], assigning, at least one, objective to each cornerstone.

Economy shows the difference of revenue and cost and the goal is to maximize benefit to all stakeholders [37]. Economy depends on many things and it is usually seen as the ultimate goal. Profitability analysis in mining starts from estimation of total ore amount in a mine region and target minerals' concentration in ore by geologists. Economy answers sustainability problem in mining by introduction of circular economy [38].

Production efficiency [39, 40] gives the ratio of produced goods (tones of target mineral or ore) and consumed resources (machinery, fuel, employees, etc.) in production process.

Safety [41, 42] can be expressed as the number of injuries in time unit, relatively to the number of employees or per the amount of produced goods or absolutely. Depending on consequences the injuries range from light, resulting in lost work time [43] to fatal, when human lives are lost.

Environment including air, water and soil is inevitably polluted in mining process [44-48]. Pollution can be expressed as the concentration distribution of pollutant. A decision support system for environmental reclamation of an open-pit mine is presented in [49]. Regulations,

monitoring and control of dust in mineral industries are surveyed in [50].

Community (local, state level, regional or even global) relates to mining twofold [51-53]. The first relation is directed from community to the mine corporation: does the mine corporation sufficiently attract individuals to keep the mining process and is the community sufficiently strong (numerous) to support the mining process? The second relation concerns how the mining contributes to the community wellbeing. The contribution is direct through the investments of the mine corporation to the community budget [54] and indirect, through the attracted investments to the community due to the mine existence. Contribution can be expressed as the fraction of the community GDP.

D. MOO Constraints

Having five objectives, sustainability [55, cf. ch. I, sec. B-I] can be expressed as the integral condition that all or some (the more the better) objective functions are non-decreasing¹ in time [19] or, having in mind that man is the measure of all things (Protagoras), it can be expressed as the non-decreasing contribution to the development of the universal human rights [48, 56] in community, in terms of health, education and living standards.

E. Design Space Analysis

We use two levels process identification to define decision space. At the first level, we consider a life cycle of a mine through all its phases. At the second level, we focus on the phase of ore exploitation as the main phase in mining and consider all the sub-phases in general, without details regarding specific ore exploitation or type of a mine.

The main phases in life cycle of a mine are shown in Fig. 2. In strategic level land exploration and ore detection phase analysis of spatial ore distribution within ground as well as evaluation of ore fraction are performed. Mine establishment phase relates to all activities needed for physical placement of a mine. Ore exploitation is the main phase and more details are given in the next section. After the exploitation phase, the mine should be closed while all the equipment and accompanying facilities should be removed. Finally, ground should be rehabilitated and the state before mine restored to keep environmental balance.

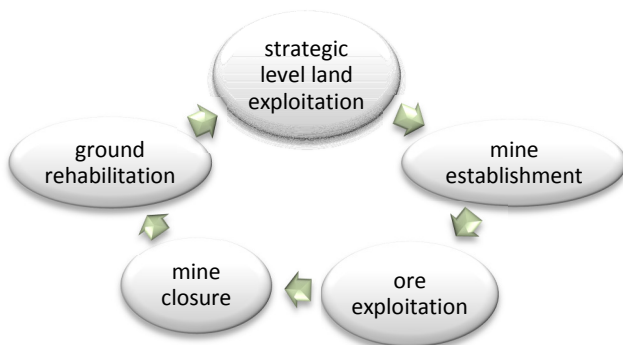


Figure 2. Lifecycle of a mine

¹ For mathematical clarity pollution and safety should be considered as the inverse functions

Ore exploitation phase consists of several sub-phases including the first and the second phases at tactical level. The phases are:

3. Tactical level land exploration and ore detection
4. Ore extraction method selection and the technique parameters setting, extraction schedule and location plan
5. Ore transportation technique selection and the technique parameters setting
6. Storage type of equipment selection
7. Equipment maintenance
8. Market, proper time and ore amount to be traded selection (trading)
9. Revenue management
10. Safety methods selection and safety plan (safety provision)
11. Environment protection methods selection and protection plan establishment

Ore exploitation sub-phases can be grouped into three groups: economy related, background processes and ore obtaining processes. Diagram of grouped sub-phases are shown in Fig. 3.

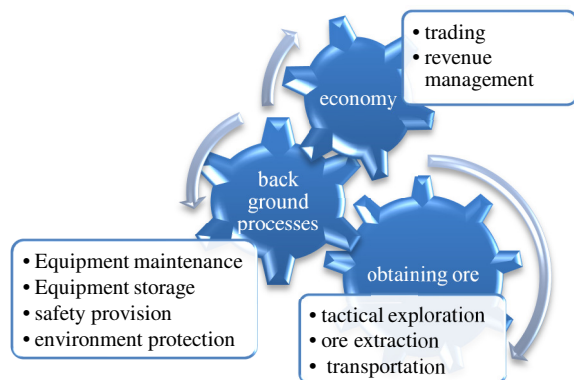


Figure 3. A mine in exploitation phase

We give some qualitative examples of decision variables arising from exploitation sub-phases:

1. Machinery fuel consumption
2. The set of engaged machines
3. The engagement schedule
4. The preventive maintenance schedule
5. Geographical plan of mining
6. The set of employees
7. Water-curtain air-clean system activation conditions and schedule
8. Blasting [57] or drilling schedule and space distribution
9. Design parameters of water-jet slotting system [58]

IV. EXISTING ICT SUPPORT TO MINING

There are a number of existing applications of ICT in mining. Here we list some examples following the states of control cycle given in Fig. 4.

For *data collection* in mining ICT provides several concepts with IoT, WSN, and CPS the most promising. IoT as a concept for information and control systems that are employed by mining industries is introduced in [4].

In [5] IoT and CC based system is employed to improve mine tailings dam safety. It is accomplished with the abilities of real-time monitoring of the saturated line, impounded water level and the dam deformation with the objective to provide pre-alarm information automatically and remotely in all weather conditions.

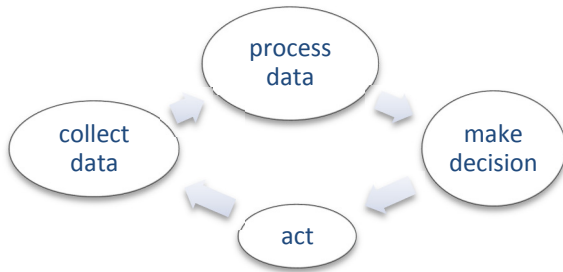


Figure 4. Control cycle

Locata [18] is the CPS for reliable positioning and navigation, invented by Locata Corporation, a Canberra-based company. Locata is a terrestrial high accuracy positioning system that can augment Global Navigation Satellite System (GNSS) with extra-terrestrial signals to permit cm-level positioning accuracy even when there are insufficient GNSS satellite signals.

A CPS targeting safety and accident rescue occurred in underground coal mine is proposed in [6]. The CPS senses surrounding, estimates environment parameters and based on personnel location generates warnings.

A CPS for unconfined compressive strength of rocks surrounding access tunnels in long-wall coal mining estimation can be designed based on Mamdani fuzzy model, proposed in [7]. The CPS should use Schmidt hardness, density, or porosity as the input parameters.

WSN based CPS for fire detection, location and spreading direction determination in a Bord-and-Pillar underground coal mine with capability to stop fire spreading is proposed in [9].

Structure-Aware Self-Adaptive WSN system able to rapidly detect structure variations caused by underground collapses and robust mechanism for efficiently handling queries under the instable circumstances is proposed in [10].

Data processing in mining can be efficiently supported by ICT through CC, DM and ML services. Some existing applications follow.

A new approach to implementation of a geo-information environment for the mining geo-information science problem solution using CC technologies is analyzed in [11].

A new emission model namely computer model for the construction of model-ready emission inventories (MOSESS) which is being used to compile high-resolution emission inventories or improve existing ones, utilizing complex GIS techniques is proposed in [13]. MOSESS, as well as the other similar models, such as AERMOD [59], can be efficiently realized using CC and DM technologies.

A remote sensing-based methodology for quantifying the impact of surface mining activity and reclamation from a watershed to local scale is proposed in [14]. The method is based on a Support Vector Machines (SVMs)

classifier combined with multi-temporal change detection of Landsat Thematic Mapper imagery.

Decision making in mining can be supported by ICT in almost all phases and sub-phases. Several existing examples follow.

Context-aware intelligent service system that can be used to provide the most appropriate information services to miners according to their real-time situation, enabling self-safety control is proposed in [12]. The system address questions regarding modeling the served miners' context, provision of the information service that meets miners' customized demands and verification of service invocation availability.

A framework for modeling interaction between a CPS and its environment is proposed in [60]. The lack of the interaction modeling can result in invalid worst-case estimation of system's safety and reliability. The framework supports simulation-based risk analysis of an initiating event such as equipment failure or flooding.

The decision support for optimal reclamation method using an AHP-based model for coal production in an open-pit coal mine located at Seyitomer region in Turkey is proposed in [49].

To help decision makers to optimally achieve objectives such as production lines reliability, maintaining costs, and system failure and downtime, employing preventive maintenance scheduling of complex manufacturing equipment the multi-objective optimal approaches are proposed in [61, 62].

An example showing how ICT can support action state of control cycle is a CPS for utilizing optimal switching control and a variable speed drive based optimal control. The CPS is proposed in [8] with the objective to improve the energy efficiency of belt conveyor systems at the operational level, under the constraints of time-of-use tariff, ramp rate of belt speed and other system parameters.

The need for an integral concept such as the proposed framework is validated by the previous examples, which tackle the framework just in some particular aspects.

V. POSITIONING OUR FRAMEWORK

We used the main attributes of sustainability assessment and reporting frameworks proposed in [19] to position our framework in the framework design space. The corresponding attributes are: temporal orientation, spatial or geographical focus, comprehensiveness, integration, scale and scope considerations. We also included ICT considerations in the set of attributes, as we find this attribute very important and unjustifiably neglected for comparing and positioning sustainability assessment frameworks. The proposed framework was described based on the given attributes in Table 1.

TABLE 1. POSITIONING THE FRAMEWORK IN THE FRAMEWORK DESIGN SPACE

Attribute	Position
Temporal orientation	The framework is aimed to be both retrospective and prospective. Past year data and indicators based on them are necessary for considering the future implications of mining operations to sustainability. The mine life cycle is taken into consideration as explained in Section III-E.

<i>Geographical focus</i>	The framework should enable clear specification of spatial boundaries and criteria for aggregating data from multiple sites, if necessary. This would allow for broader corporation, i.e. organizational-centered perspective.
<i>Comprehensiveness</i>	The framework is conceptualized as adaptive to change of parameters. Moreover, it should be scalable to SME and large companies, to private and public companies. Consequently, the proposed framework will incorporate a wider set of decision variables from which a subset adequate for a particular domain could be selected. The decision variables are focused on the defined cornerstones, but not limited to.
<i>Integration</i>	The framework especially targets the decision variables that have conflicted impact on the objectives. These include both integrated and non-integrated variables (see Section III-C).
<i>Scale and scope considerations</i>	Scale considerations (i.e. how performance varies across local, regional, national and global scales) are largely overlooked by current frameworks. Since this is an attribute hard to achieve in target economy, it is not in focus of the proposed framework. Scope considerations stem from the five cornerstones [2]. However, specific decision variables, protocols, policies and principles are expected to be drawn from different bodies of literature.
<i>ICT considerations</i>	The framework seeks to improve decision management thanks to historical, real-time and simulation information. To be able to achieve this goal, ICT support is of crucial importance (as explained in Section I). However, specific ICT support in an implementation environment should depend on needs and interests of a mine corporation.

In this light, we believe that what particularly distinguishes the proposed framework is scalability (comprehensiveness), importance given to prospective temporal orientation, as well as strong focus on decision management that requires modern ICT support.

VI. CONCLUSION

We propose an integral framework for sustainable mining taking into account the five SM cornerstones: economy, safety, environment pollution, production efficiency, and community. It relies on multi-objective optimization theory, adaptive control theory, the mining process itself and modern ICT technologies.

Following multi-objective optimization concept and using the mining process, we try to qualify objective space, decision/design space and constraints. Using adaptive control theory we introduce dynamic component of the mining process and try to adapt the system to any system disturbance. We evaluate how the current mining employs ICT and show that an ample space for ICT support exists.

Compared with the other sustainability frameworks we find that scalability (comprehensiveness), importance given to prospective temporal orientation, as well as strong focus on decision management that requires cutting-edge ICT support distinguishes it from the rest.

Moreover, further development of the proposed framework could bring mining to the Factory-of-Future concept.

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