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SMART, ERGONOMIC AND SUSTAINABLE MINING MACHINERY WORKPLACES: AN OVERVIEW OF THE SMARTMINER PROJECT

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Abstract: Despite being the oldest, the mining industry continues to be a major source of pollution, with more people killed or injured than in all other industries. Additionally, social tension related to this sector is widespread around the world, since mining businesses continue to have a significant negative influence on land, water, air, biota, and people through direct and indirect mechanisms. The mining machinery workplaces, which are in the focus of this study have the largest environmental footprint. The dominance of technology-centered design in present research streams is most likely the explanation for the lack of advancement in the mining industry. The SmartMiner project creates shift from technology-centered design and its concept creates solutions for improving the standard of environmental quality in complex systems and suggests a paradigm change to a Human and Data-Centric Engineering. By aligning advanced operator I4.0&5.0 and society S5.0 standards, the SmartMiner project develops solutions for raising the level of environmental quality in complex interactions between physical, behavioural, and organizational processes field. Proposed paradigm can be easily transferred to other industries. The safety of mining machinery operators in their immediate surroundings and their regular alignment with value chain stakeholders are the first steps in our original idea approval process. Research moves to the operator macro-environment, which is determined by organizational contextual factors, and is encompassed by the development of intelligent, ergonomic, non-invasive, and dependable operator aid systems for regulating physical environment job stressors - noise, human vibration, lighting, temperature, air quality, workplace layout issues, etc., with high potential to solve environmental and human health issues and to influence overall performance.
Keywords: mining machinery, workplace, ergonomics, industry 4.0, sustainability

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1. INTRODUCTION

Mining industry today has numerous challenges, problems, and issues, recognized in recent publications, which need urgent solutions. Accordingly, numerous green digital and sustainability transformation solutions are needed, and the SmartMiner project aim to enable step towards smart, ergonomic and sustainable mining machinery workplaces, as in Table 1.

Table 1. Current mining industry challenges and possible solutions

Current Mining Industry Challenges/Problems/Issues	**Proposed Solutions**
Conservative & risky adverse industry which employs 413000 people in EU and 349947 in USA, with more people are killed, injured or with long term health effects than in any other industry, because air pollution increases the risk of having an accident at work (National Institute for Occupational Safety and Health, 2018; Sovacool et al., 2020; Vega-Calderón et al., 2021; Business economy by sector - Mining and quarrying statistics-NACE Rev.2, 2021; Perišić et al., 2022).	Make the oldest industry in the world modern, sustainable and compatible with I4.0&5.0, but mitigate its risks (S5.0), by science & industry & stakeholders /beneficiaries' cooperation, with aim to significantly influence the further development of society and the economy as a whole.
It accounts for 6% of the world's energy demand and 22% of global industrial emissions and seriously causes the destruction of land, water bodies, the atmosphere, vegetation resources and new geological problems that perilously impact human civilization and life (Wang et al., 2021).	
Despite a proliferation of mining industry standards, there is no comprehensive environmental standard and mining machinery is late nearly two generations in comparison to their on-road counterparts (Blengini et al., 2017).	
In 17500 EU mining companies is 5 times less labor productivity then in gas and petroleum sector (Business economy by sector - Mining and quarrying statistics-NACE Rev.2, 2021).	Improve labor productivity to numbers close to similar sectors.
The health cost of the mining activities outweighs its benefits - since 1995 number of employees with cancers, respiratory illnesses (silicosis, asbestosis, and pneumoconiosis…), musculoskeletal injuries, hearing loss, etc. raises (National Institute for Occupational Safety and Health, 2018).	Improve employee's health – reduce employees' illness and health risks of other people living within the surrounding region.
77% of all accidents resulting in a fatality have occurred involved mining machinery with human error as the most frequent cause (ICMM, 2021).	Focus on mining machinery and human error which implies prevention based on interdisciplinary, applied research.
Low level of safety culture as possible cause of high pollution levels, accidents and incidents (Zhang et al., 2020, ICMM, 2021; Tetzlaff et al., 2021).	Analyze safety culture constructs and dimensions (human and organizational factors) to prevent hazards leading to climate changes, pollution, loss of biodiversity and unsustainable use of natural resources.
Mining operations, except mining waste, are regulated at the national level. Serbia has 300 mines; mining sector contributes with share of 2% in the country's GDP, with increase of 6% in the last few years; that inverse is visible in increase of number of companies (+6%), GDP (+25%), innovation potential (41,9%) and employment (+0,5%) (National Qualifications Framework, 2016, Serbian Government, Smart Specialization Strategy, 2020).	Focus primarily on current issues in Serbian mines – on national level.
Novel EU policy documents related to sustainability are particularly important for the mining sector - European Green Deal, EU Climate Law and Pact, New Industrial Strategy for Europe and Circular Economy Action Plan (Blengini et al., 2017; Zhu & Lin, 2021; Puška et al., 2022).	Towards green and digital transition to enable better monitoring, reporting and prevention of air, water and soil pollution and extends mining machine lifetime.
Application of sustainability principles to mining is inherently challenging, as mining is the act of removing and consuming a limited resource. Agenda 2030 (Colglazier, 2015; Blengini et al., 2017; Moomen et al., 2019) and the desired goal of climate neutrality by 2050 is a long way off - sustainable mining is woefully hard to realize, especially in mineral resource-rich developing countries and regarding Sustainable Development Goals 3 and 6.	Field requires an urgent attention from excellent and young scientists, stakeholders and policy makers to fully embrace and pursue the 2030 Sustainable Development Goals (SDGs) agenda, especially in the direction of the progress to decarbonation challenge.

Actions needed to solve current mining industry challenges must deploy Human Factors and Ergonomics (HF/E) solutions offered in digital transformation era. But, according to recent literature research on HF/E in a frame of Industry 4.0 is very scarce in all types of industry

(Reiman et al., 2021; Neumann et al., 2021). A very few HF/E researchers' publications on HF/E in Industry 4.0 are available, however without empirical evidence to support theories and developed models, without any connection to mining industry and without focusing on all organizational levels in mining companies – operational, tactical and strategic. HF/E field is even without mention in the vision of forthcoming Industry 5.0. EU document: *Industry 5.0, a transformative vision for Europe : governing systemic transformations towards a sustainable industry* enumerates and considers projects which deal with workplace conditions, psychosocial factors and stress, but HF/E solutions are not foreseen there (European Commission, Directorate-General for Research and Innovation, 2021). Therefore, The Smartminer project aims to address all above-mentioned challenges, problems and issues recognized in I4.0 concept and I5.0 vision through development of novel, advanced supporting systems based on 1) applied research scientific methods based on experimental measurements and monitoring and 2) economy pushed and society-driven innovation which integrates smart and ergonomic solutions into sustainable mining machinery workplaces.

2. THEORETICAL FRAMEWORK

Most of the research on mining machinery is focused to dynamic modeling of structure and mechanisms and aimed to extend machinery exploitation life (it is over 40 years, which only increases pollution) and reliability and maintenance procedures improvement (Brkić et al., 2014; Rusiński et al., 2017; Tanasijevic et al., 2019), since downtime/stoppage time leads to losses close to 10000EUR/hour (Pantelić et al., 2020). Research in sustainability fields are very rare, although level of greenhouse gases and energy consumption in mining is far from accordance with reduction plans and safety is far from desired (Mirzaei Aliabadi et al., 2018; Ma et al., 2019; Helmers et al., 2020). Safety and pollution are positively correlated and adverse events are dominantly affected by human errors (Vega-Calderón et al., 2021; Mirzaei Aliabadi et al., 2018), while possible future avenues such as exoskeletons and body-worn sensors bring new risks and privacy, perception and acceptance issues (Spasojević-Brkić et al., 2015; Gorgey, 2018; Ghamari et al., 2022). Human errors are caused by numerous unsolved ergonomic issues and it is evident that mining machinery operators and shift/site managers are not satisfied at work (Dempsey et al., 2018; Lööw et al., 2018). As logical consequence there is lower productivity due to operator fatigue and discrepancies between behavioral characteristics and company's organizational culture (Parker et al., 2019; Han et al., 2020). Also, it is noticeable that management practices in the mining sector are under-researched (Street et al., 2019; Balogun et al., 2020) and that corporate governance and social responsibility issues need more scholar attention (Saenz & Romero, 2020; Stojanovic et al., 2020). Similarly, in I4.0 research focus are technical deployments and it is necessary to expand the knowledge to organizational aspects and human-machine interaction – HF/E and management disciplines, with special attention towards avoiding possible superintelligence dangers (Lodgaard & Dransfeld, 2020). Accordingly, our concept goes beyond I5.0 which focuses only human without orientation towards HF/E and organizational context (European Commission, Directorate-General for Research and Innovation, 2021; Maddikunta et al., 2022).

Since there is evidenced obvious lack of addressing human and organizational factors level completely novel The SmartMiner idea goes beyond the state-of-the-art by giving answers to the following questions:

- Is mining machinery downtime caused primarily by technical/technological causes and is there any hidden potential in human and/or organizational factors for solving pollution and accidents issues?

- How to improve productivity of mining machines through higher user (operator) satisfaction, wellbeing, high motivation, and improved workload/organization?
- How to further improve safety in mining machinery operations and prevent environmental degradation, displaced populations, inequality and increased conflict?
- How to further lower mining machinery costs? How to solve challenges connected to extended mining machinery exploitation life such as environmental and health impacts, achieve energy efficiencies, etc.?
- How to make the mining industry a trusted partner for the development of wealth and prosperity in the society? Can all those measures make local communities happier?

Therefore, The SmartMiner aims to involve contextual, systematic approach and integrate human, organizational and technical factors in order to offer, to domestic (and international) industry, technological readiness for innovative, smart mining machinery cabins` concept, which provides comfortable, well organized, unpolluted and safe work for operator and shift/site manager, high business performances for company management, and cleaner and healthier environment for society.

The concept of The SmartMiner is based on a paradigm shift from existing to novel, flexible and scalable solutions based on combination of Human and Data Centric Engineering, matching advanced operator (4.0&5.0) (Gladysz et al., 2023; Bechinie et al., 2024) and society (5.0) (Yao et al., 2024) standards. Our concept, sketched in Figure 1, combines the stakeholder requirements and, at the same time, put the operator wellbeing satisfaction and his sustainable workplace in the center. Operator and his environment represent a set of complex interactions between physical, psychosocial, and organizational factors and processes, which, if mastered could lead to sustainable company performance and people-centric smarter society. Namely, concept starts with operator environmental quality/ wellbeing issues solved by a combination of cyber-physical system, ergonomics and real data analytics. Finally, data analytics and maintenance algorithms should give an input towards society 5.0 by preventing/alarming potential health issues or threats on individual and local community level.

When posting The SmartMiner concept, we had in mind an observation published in (Crawford & Calo, 2016; Janković et al., 2021; Većkalov et al., 2023; Bozkurt & Gursoy, 2023; Yampolskiy, 2024) in sense that "Machines and robots that outperform humans across the board could self-improve beyond our control — and their interests might not align with ours". Broad popular and scientific discourses concern massive use of Artificial Intelligence and Machine Learning appeared. Some could argue that after the learning phase the production process could continue without human intervention (European Commission, Directorate-General for Research and Innovation, 2021; Maddikunta et al., 2022; Chinchane & Mutreja, 2023). This is true but only for stable and repetitive processes, which for sure are not the case in mining industry for now, which is in growing dynamics and uncertainty (European Commission, Directorate-General for Research and Innovation, 2021; Maddikunta et al., 2022). Accordingly, the learning should be employed as a continuous process (emphasized with red circles in Figure 2)! Therefore, the SmartMiner concept is original, novel and based on slogan “Human will be always in center, and we should keep it so”. In a nutshell, we will analyze complex interactions between physical, psychosocial/behavioral aspects of operator and organizational factors and processes. Since concept focuses on environmental quality, we start the analyze by determining operator’s micro and macro Human Factors and Ergonomics – HF/E environment. This is a part of human centric engineering field. The collected data will be analyzed by data centric engineering disciplines. Finally, by means of interdisciplinary human and data centric approaches we will draw significant and applicable conclusions.

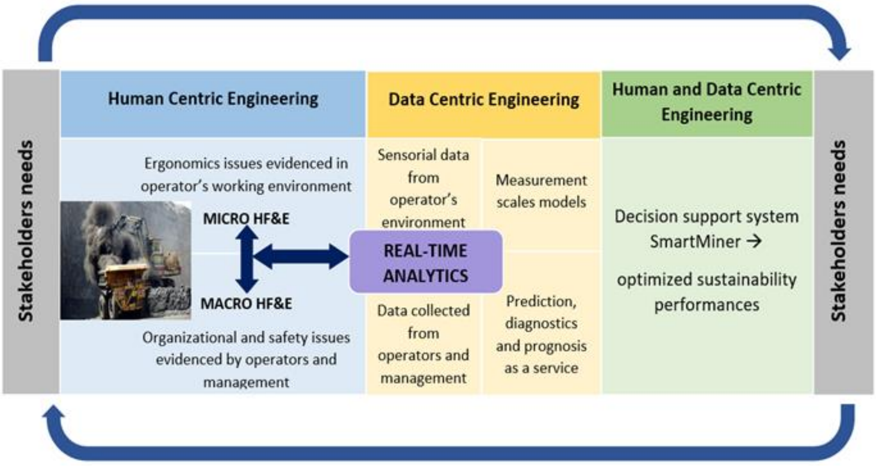

Figure 1. The SmartMiner concept in a nutshell

3. RESEARCH METHODOLOGY

The SmartMiner methodology implied combines multiple design-based research (DBR) cycles and design-based science (DBS), as shown in Figure 2, based on the following hypothesis:

H0: Necessary step between operator 4.0&5.0 and society 5.0 is "management 4.0", which means human (and his environment) in the center and raising environmental quality through micro (physical environment) and macro environment levels (organizational environment).

H1: Level of necessary digitalization and automation of mining machinery workplace depends on contextual factors – primarily on human and organizational factors.

H2: It is possible to prototype innovative support systems: 1. Operator's ergonomic seating adjustment system, serving to solve human factors issues and 2. Smart multi-sensorial operator aid system and software system structural description model as constituent, serving to solve both human and organizational factors issues. Both prototypes are prerequisite parts of commercial Decision Support System.

H3: If level of HF/E, digitalization and automation and contextual factors are aligned, high value of sustainability index must be achieved.

3.1. Research Design

Operator's MICRO environment is represented by his physical environment - noise, human vibration, lighting, temperature, air quality, workplace layout. Its solutions lie in the field of physical and cognitive ergonomics. Job stressors load, if sustained over time, produces adverse effects such as health and safety problems and lack of performance. Operator's MACRO environment is determined by organizational contextual factors - safety awareness, competence and communication on operational and managerial level, organizational environment dimensions, management support, risk judgment and management reaction, safety precautions, accident prevention. This can be overcome by safety trainings and similar and those solutions may lay in the fields of organizational ergonomics and job design. All those factors impair and deteriorate employees' results and sustainability.

Micro and micro levels as physical processes layers are to be connected and balanced by real time analytics - digital processes layers to fit high sustainability performance indicators (economic, social, environmental etc.). Namely, stakeholders' needs satisfaction starts with data collection. Sensorial network data (although with low failure probability) will be controlled and extended with organizational context and sustainability performance data collected by questionnaires, filled by operators and managers. On micro HF/E level, operator's ergonomic support accessorize for anthropometric adjustment and sensors, which guarantee the necessary comfort in usage, without any invasiveness, and high reliability will be used to improve, measure and control operator's physical environment job stressors (noise, lighting, temperature, vibration, air quality, work place layout etc.), as they represent the first layer of a learning loop and tool to improve overall performance (higher productivity and lower workplace stressors and pollution). It is also important to point out that there are neither privacy nor acceptance issues since sensors are not directed to operator such as in wearable devices but to operator's working environment, while other macro level data will be collected on voluntary, weekly basis by questionnaires. Also, it is important to have in mind that the size of the sensors is of insignificant dimensions in relation to the volume of the cabin of haulage trucks, bulldozers and excavators in mining sector (ISO standard 3411:2010; ISO standard 2860:2010; ISO standard 2867:2013) and they will be placed in accordance to work envelopes. After collection, data are to be undergone to descriptive, predictive and prescriptive analytics to obtain measurement scales and to get prediction, diagnostics and prognosis (preventive alarm function) as a service and as a base of decision support system, which will optimize sustainability performance in the second learning loop ("learning about learning"). Namely, "feedback loops where physical processes affect computations and vice versa", so human stand in the center and cooperate. In that manner both operators' and operations management – productivity, safety, environmental and dispatching issues will be solved through optimized relationship between environment, strategy and structure which leads to both economic results and solutions to environmental and social problems in parallel. The cycle again reaches stakeholders needs and after receiving a positive/negative feedback loop can continue towards sustainability and performance improvement, as in Figure 2.

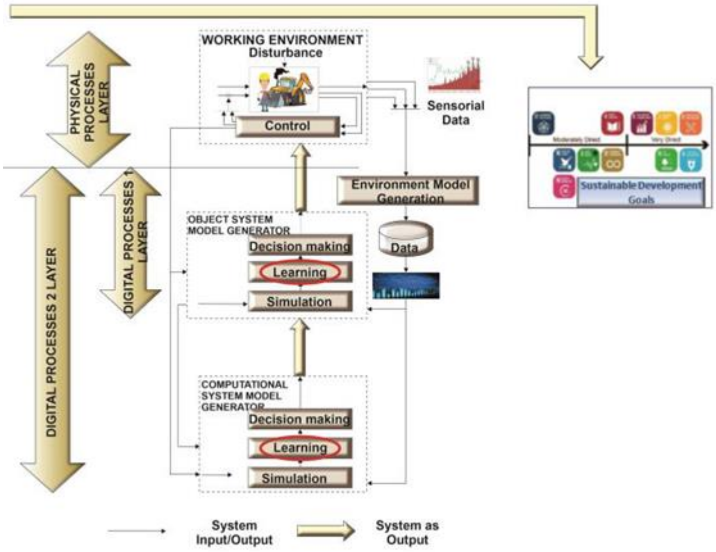

Figure 2. The SmartMiner project methodology paradigm

4. CONCLUSION

The progress beyond the state-of-the art is seen in the "main SmartMiner break-through", by expressing paradigm shift as following:

- The new decision system concept for mining industry, based on machinery characteristics, ergonomic workplace design, smart resources for workplace conditions control, improved work planning procedures and company organization (the SmartMiner paradigm), which is transferable to other industries such as agriculture, logistics, construction, maritime, etc.
- Operator's ergonomic adjustment system as a novel technical solution.
- Multi sensorial aid system (as modular, but integrated tool), which enables the implementation of the paradigm consisting in a unified set of methods for risk management analysis on machine operator workplace through chains sensors-data acquisition-data processing and analysis-improvement of a workplace-increase of productivity.
- Software system structural description model, which covers planning and results on 4 levels – operator, shift/site manager, top management and society and enables strategic or annual work plans realization through real-time measurement system with final aim to improve sustainability indicators (Techno-Economic, Environmental, Societal, Stakeholders and Voluntariness dimensions).

Accordingly, it is expected to increase productivity and wellbeing, based on optimal operators' workplace and proper management decision, as practice today suffers from lack of real-data input in real-time which is crucial for decision makers!

Mining projects have direct and indirect environmental impacts and seriously affect land, water, air, biota, and people, while mining equipment focused in this project has the highest footprint (ISO standard 3411:2010; ISO standard 2860:2010; ISO standard 2867:2013). Beside the fact that mines are visible and can be heard, smelled and felt with all senses, since modern societies need the products of mining, the global mining equipment market size was valued at $125,274 million in 2020, and is expected to reach $165,827.8 million by 2027, growing at a CAGR of 5.7% from 2020 to 2027. Surface mining equipment is expected to be the most lucrative segment, Europe to have the highest - 10% CAGR and metal mining segment to dominate the global mining equipment market throughout 2023-2032 (Chinchane & Mutreja, 2023). In the SmartMiner post-project phase from 2026 much steeper growth is expected, due to paradigm shift resulting in high sustainability index achievement by this project.

The main global benefit and the main positive impact is software system structural description model helpful in decision making on different organizational levels, based on ergonomics and smart support systems in this novel, specific scientific field. It enables improvement and optimization of techno-economic, environmental, societal, aspects of a workplace, stakeholders and voluntariness sustainability indicators while maintaining the highest standards of safety.

Other key impacts of this project for the stakeholders are:

- Solutions and practices considering operator and society 5.0 concepts.
- Environmentally and socially sustainable workplaces.
- Test sites for the benchmarking and the analysis of public acceptance and awareness.
- Change of the stakeholders' mindset: introducing a new way of thinking from the collection of user requirements, to the iterative development and validation of the system's technical specifications, through a pilot demonstration and tests,

through often involvement of different user groups – machinery operators, shift/site manager, top management, crisis managers, resource/infrastructure managers, and public agencies.

- Invigorated key players and investors by diminishing administrative and financial costs which will boost exploration and increase the attractiveness of mining sector, which is of special importance in Serbia.
- Promotion of customized solutions in similar workplaces in other sectors such as agriculture, logistics, construction etc. and easily commercialized.
- Improvement in education and engagement of practitioners, policy-makers and wider society with respect to the mining machinery and sustainability.

Aforementioned facts have direct global impact on the mining, environment, healthcare, safety and economy. Similar industries and indirect impact can be envisioned on climate change, healthcare, research, education, and other aspects of social development.

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