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Sustainability of switch on-switch off (SOSO) mining: Human resource development tailored to technological solutions

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ABSTRACT

Adaptable, mobile, modularised technical solutions were piloted for switch on-switch off (SOSO) mining at test sites in the west Balkans. Pre-training occurred at the site of module construction and on the mine site in order to transfer knowledge relating to the rapid deployment, commissioning and operation of mining and processing units, in a mature health and safety culture. Translation of extensive documentation, describing operation of the equipment, into local languages and visual aids supported communication. Consideration of the activities required to deploy and operate prototype solutions revealed how characteristics of a SOSO workforce differed from other types of mining. Deployment of modularised plant employed fewer workers than traditional stick-build of a processing plant, but selective mining and processing of complex and variable deposits limited the potential for automation and required operator control. A workforce with mixed levels of experience was most amenable to development of a mature health and safety culture. The total number of employees was small at an individual site and might remain small, even in a multi-deposit, regional business model. However, employment is higher per unit of production than for conventional large-scale mining. The duration of employment is shorter than for large-scale mining but employment can nevertheless be important where there are few alternative opportunities and where it can increase the skills-base to support a more diversified local economy. SOSO mining constitutes a new relationship between society and the mining industry, which needs further consideration for greater resilience in the local community and increased social sustainability.

1. Introduction

The Raw Materials Initiative (European Commission, 2008) set out a strategy for more reliable and secure access to raw materials in Europe, including the creation of a sustainable supply of raw materials within the EU. Many of the raw materials for European manufacturing are used in relatively small quantities and are geologically available in small ore deposits across Europe (Bonnefon et al., 2020; Cassard et al., 2015; European Commission, 2013; Goodenough et al., 2016). The small ore deposits may not be suitable for established mining approaches that rely on the economies of scale in larger mining operations (Moore et al., 2020). However, the minor metals market is subject to price volatility that may rapidly change the economic viability of small ore deposits (Moore, 2020; Renner and Wellmer, 2019). A conceptual switch on-switch off (SOSO) mining paradigm describes the resilient response of the mining sector to changes in demand or supply using adaptable

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small-scale operations. SOSO mining solutions are premised on technologies and frameworks that enable rapid start-up of operations while commodity prices are high, and allow for either the cessation of operations or re-deployment on a different ore deposit when market conditions change. The EU funded IMP@CT project developed whole systems technology-based solutions for SOSO mining, where IMP@CT stands for *Integrated Mobile modularised Plant and Containerised Tools for selective, low-impact mining of small high-grade deposits*.

If the diversification of the mining industry to meet increasing demand includes SOSO approaches, then major transformational changes are required. The ability to deal with geological and geometallurgical uncertainty is paramount for the technological success of rapid 'switch on' mining activities in small or complex deposits but must not negatively impact the economic feasibility of mine start-up. If the efficiency of operations is reduced by complex geological, mineralogical and metallurgical conditions, then this must be offset by a focus on high-grade ore deposits, reduced capital start-up costs and early generation of internal revenue. Increased alternative production capacity can be created by mining of small and/or complex deposits that are known to become economically viable in an advantageous market where: (1) Flexible mining and processing strategies can accommodate diverse geological, mineral and metallurgical challenges; (2) Mining and processing technologies can be rapidly and safely put in place for short-term responses or repeatedly relocated for medium- and long-term mining operations that link multiple small deposits. The safety and efficiency of mining operations requires the input of multiple stakeholders in a whole systems context. In this manuscript, we use two concepts that may underpin the roll-out of a SOSO mining workforce. The first concept is that planned training on the job can cascade the competence required for the institutionalization of organizational change (Jacob and Russ-Eft, 2001). We describe the practical requirements of constructing and operating pilot mining and processing technologies for best practice in responsible mining, with particular reference to communication and rapid training of a proxy SOSO mining workforce with limited automation in a mature safety culture. The second concept we use is that human resource development can facilitate sustainability and ethics in organizations (Garavan and McGuire, 2010). This is important where short duration mining operations, i.e. the withdrawal of industry, impact communities.

In this manuscript, we introduce the technological solutions developed in the IMP@CT project (2016–2020), which straddle the raw materials extraction value chain, from underground mining, through ore sorting and comminution, to minerals processing. European consortium partners developed mobile and modularised equipment, which they containerised at local construction sites. The containerised equipment was transported from the locations of development and deployed at mine sites, in order to validate the SOSO concept in industrially relevant environments. (1) The two main case studies (2018–2020) were located in the west Balkans. The full suite of mining and processing solutions (Fig. 1) were deployed at the fully-licenced Olovo lead (cerussite) mine in the Federation of Bosnia and Herzegovina. The IMP@CT equipment arrived on site shortly after opening of the mine, while the full-size processing plant was under construction. The testwork required that a relatively new workforce at the first test site (Olovo) be rapidly trained to operate the equipment safely and effectively. (2) IMP@CT comminution and processing equipment was also used in the Republic of Serbia in a satellite mining and processing model, according to licencing arrangements. Extraction of antimony ore was licenced at the Zajača mine and processing was licenced at the Veliki Majdan site. There was an experienced workforce at the processing site but the experience gained is significant due to the decommissioning and redeployment activities that are inherent in a SOSO mining approach. IMP@CT demonstrated that it is logistically possible to rapidly design, construct, deploy, refit, and redeploy modularised mining and processing equipment, ideally powered by renewable or hybrid energy (depending on the time-frame of operation) on existing mine sites (Moradi, 2019; Fitzpatrick and

Fig. 1. The containerised technical solutions deployed at the first test site (Olovo) in Bosnia and Herzegovina. Equipment comprises (a) a prototype machine for selective underground mining, (b) XRF ore-sorter unit, (c) comminution unit, and (d) gravity separation plant (throughput 5 ton per hour) in the foreground – the full scale processing plant is under construction in the background. Published with the agreement of Metal Innovations, Extracthive Industry, Rados International, University of Exeter and Mineco.

Moradi, 2019; Paneri et al., 2021; CORDIS, 2020). By describing the training of personnel as a function of the unit processes of IMP@CT equipment, the validation case studies act as a proxy for establishment of a SOSO mining and processing workforce. We discuss how our experience supports the expansion of SOSO mining in a future global extractive industry that has a greater diversity of mining solutions. Ultimately, we aim to understand how employment patterns in SOSO mining influence sustainability, both for the mining practitioners and for communities.

2. IMP@CT technologies and activities in a SOSO mining operation

The deployed modules of the IMP@CT solution (Fig. 1) comprise a selective underground mining tool (Metal Innovations), an X-ray fluorescence sorter for separating ore and waste rock (Rados International), a comminution module for crushing and screening ore (Extracthive Industry), and a gravity-based mineral separation plant (University of Exeter). The enabling characteristics of a SOSO mineral processing circuit are flexibility and mobility, such that it is designed based on flexible flowsheets with adaptable piping and instrumentation (Morrison and Brito-Parada, 2017; Moradi, 2020). Along with the accommodation of additional processing equipment for adaptation to different ore deposits, this differentiates the technological solutions from the customised plug-and-play containerised modules (often for wastewater treatment or specific processes) that are available on the market.

The SOSO activities comprised deployment, installation, commissioning, operation and mobilisation of the equipment (Fitzpatrick and Moradi, 2019). Test equipment was built using the concept of safety by design and it was deployed in a mature safety culture (Doyle, 2020). However, the effective job creation effort on-site started significantly in advance of SOSO mining using the IMP@CT equipment. The number of local employees, their required skill set and respective competencies are determined when any new site is selected for future mining work. The planned workforce might vary significantly with project location, since the technical processes, and, therefore, number of adaptable modules required, depend on the deposit and ore characteristics. Fig. 1 illustrates the equipment at Olovo, the first test site, and Table 1 describes the technical job roles that are required as a function of the corresponding unit processes. Semi-skilled workers who may be new to working on mine sites dominate the workforce profile. Since the SOSO mining testwork at Olovo operated on a larger mine site that was under construction, there was additional support available beyond that cited as necessary in Table 1, including sample testing in the on-site laboratory. The lead site engineer in an independent SOSO operation would require the competencies to maintain equipment across the mine and processing plant, as well as site management skills and health and safety management experience.

Early on-site activities involved site preparation, deployment of engineering solutions and hot commissioning of equipment. Fig. 1d depicts the difference between the typical construction phase of a stick-build processing plant (background) and the containerised processing modules for SOSO mining (foreground). Ordinarily, the design of processing plants results in optimized minerals processing flowsheets such that bespoke solutions are deployed in a construction phase that, depending on supply chains, can be a protracted process. SOSO mining solutions were constructed and pre-commissioned off the mine site, in that cold commissioning was completed prior to deployment. This accelerated on-site installation under the supervision of equipment providers and experienced engineers. The IMP@CT selective mining tool and the comminution module were deployed (installed and hot commissioned) in half-days by Metal Innovations, Extracthive Industry and GEOMET/Mineco. The larger and adaptable minerals processing test facility was deployed in two days by UNEXE and GEOMET/Mineco. The modules have a small footprint and require minimal site preparation. The comminution and processing modules were installed on pre-cast concrete blocks (to dampen vibration in the comminution module) or small, levelled concrete pads (gravity separation unit at the second test site (Veliki Majdan)). Consequently, the installation of SOSO solutions was not labour-intensive, but the rapid transfer of knowledge from providers was critical, since the small throughput of material required specific operating conditions.

The SOSO pilot testwork was automated, where automation is described as the intelligent management of a mining and processing operation using appropriate technology and computer-based systems for partial or complete control (Lynas and Horberry, 2011). However, during the development phase of the selective mining tool, Metal Innovations established that operator control was required to respond to inconsistent properties in the rock face of a complex, narrow-vein ore deposit. The design of the selective mining tool thus proceeded to incorporate health and safety for an underground operator. Similarly, inconsistent feed into the processing plant necessitated that the processing test facility was built with manual over-ride safety controls. Moreover, advanced and costly controllers for automation of a flexible processing circuit (Powell and Bye, 2009) were not viable within the business model of the project, and the cost may also be prohibitive for a SOSO mining operation.

The comminution and processing equipment was decommissioned at the second test site (Veliki Majdan) during the Covid-19 pandemic. The lead IMP@CT engineer was located in the UK and connected remotely to the experienced mine and process engineers in Serbia, whose time was split between tasks. This was a more lengthy process (six part-time work days) than at the first test site (Olovo) where an experienced team of engineers was dedicated to the decommissioning and packing process over two full-time working days. The differences in the efficiency of decommissioning highlight that remote supervision requires a pre-designed communication and training plan.

3. Health and safety in SOSO mining

The training of mobile SOSO mining workforces needs to ensure that all skilled, semi-skilled and unskilled employees will be equally well prepared to conduct their work on-site in a safe manner. Due to the rapid deployment and commissioning that underpins this mining paradigm, employees and management must initiate operations with suitable

Table 1
The projected number of operators required for the IMP@CT circuit, per shift of continuous operation, for the unit processes included in Fig. 1 (sample testing and tailings management omitted).

Unit Processes	Operator	Truck Driver	Geologist	Loader driver	Telehandler driver	Lead site engineer
Continuous mining	1	1	1	0	0	1, all unit processes
Sizing & stockpiling	0	0	0	1	0	
Primary crushing	1	0	0	0	0	
Ore sorting	1	0	0	0	0	
Sizing & secondary crushing	2	0	0	0	1	
Gravity separation plant[a]	3	0	0	0	0	
Total	8	1	1	1	1	1

[a] Using a feed hopper.

health & safety standards and culture. Fig. 2 shows the principles of safety culture maturity that can be incorporated into training for SOSO mining. Investigations of health and safety culture perspectives (Doyle, 2020) identified that: (a) mature and experienced operators contribute the experience needed to rapidly start operations in a new location and to impart knowledge to new recruits, and (b) incomers to the mining workforce may not have worked in a suitable pre-existing health and safety environment so that they are more likely to adopt best practice as a consequence of training. Thus, a workforce with different levels of experience with good communication channels and training has the potential to operate in a mature safety culture.

The innovative nature of the containerised equipment developed for the small-scale SOSO paradigm presents particular risks and challenges with regards to occupational health and safety, which must be mitigated with effective training methods and materials. The key aspects of health and safety training for SOSO mining are: (a) teaching new & experienced employees the skills and mindset to identify hazards; (b) empowering employees to communicate problems to supervisors and managers; and (c) giving them the confidence to effectively manage their own risks while underground or at surface, using the 'Plan-Do-Check-Act' process (Haight et al., 2014). Specifically for the operator-controlled mining tool, workers need to be taught the health and safety risks associated with poor ergonomics (strain injuries, musculoskeletal complications, etc.), and how to identify and report issues to supervisors for review and potential retrofitting.

The optimal approach is to ensure that all workers undergo general induction, COSHH (Control of Substances Hazardous to Health) and task-specific training prior to commencement of mining/processing operations. If workers are employed after operations begin, then formal inductions and on-the-job training shall be delivered for the individual or group of workers. Training sessions in the project were conducted by the health and safety manager/lead officer, with contributions from the lead engineer for each specific area of the SOSO operation (selective miner, mobile modularised plant, comminution, sorting) to ensure workers understood the main procedures associated with operation of the equipment. Following this, site supervisors observed normal operations, to ensure that workers put procedural knowledge into practice safely. Supervisors ensured and documented that workers had read all relevant RAMS (Risk Assessment and Method Statements) specific to their task(s) before starting work.

Health and safety by design is more important in a SOSO paradigm relative to traditional large-scale operations due to the rapid deployment of mobile modularised equipment. During the initial concept design phase, health and safety was considered using 8 design philosophies developed by the Earth Moving Equipment Safety Round Table, encompassing features such as access & egress, controls, manual handling and confined spaces (EMESRT, 2018). Ensuring that the modularised solutions are designed with safety as the first priority can reduce the training requirements for operators as many of the prevailing occupational and/or ergonomic hazards are either eliminated or reduced to an acceptable level. The provision of specialist pre-training at the site of fabrication of the modularised solutions, particularly plant operation, is a safer approach than pre-training on a mine site. Training of personnel while the fabricated equipment is undergoing cold-commissioning and comprehensive testing in a safe, controlled environment has a lower risk of harm that training in plant operation during the extensive construction phase on a mine-site. Moreover, transfer of knowledge from equipment providers or a trained team at the point of installation ensures that there is consistent messaging in relation to operational best practice. Subsequently, the small workforce and footprint of mining and processing operations aid inspection and monitoring of safe practice in a controlled environment.

Testing and commissioning of the SOSO mining solution in the Balkans demonstrated how the occupational safety and health of equipment

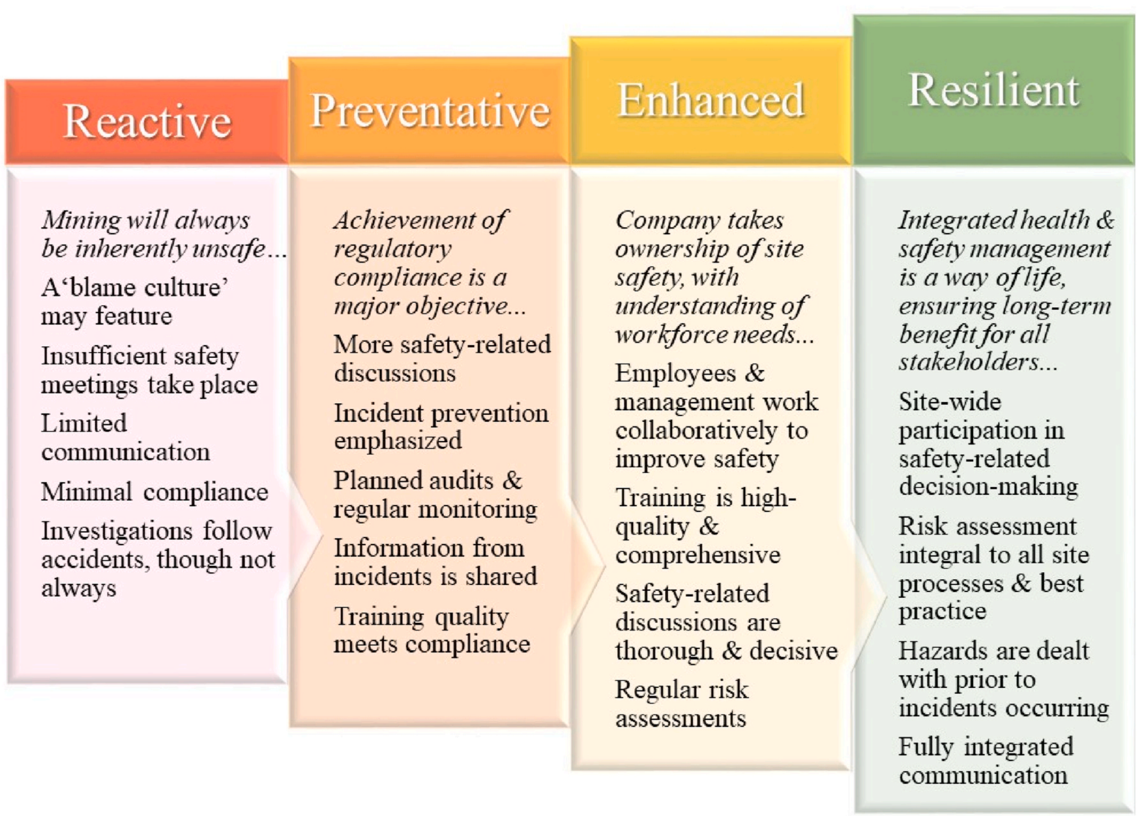

Fig. 2. The safety culture maturity model applied to mining, comprising 4 stages of increasing maturity with associated criteria that contribute to the overall occupational safety culture. Edited from Anglo American Plc (2010); Foster and Hoult (2011, 2013); The University of Queensland (2008).

operators is significantly improved compared with traditional mining. Workers received specialist training and skills using the modularised solutions prior to commencing work in the full-scale operations with reduced risk of harm. In the minerals processing unit, plant workers were more sheltered from intense weather conditions than plant workers on the full-scale facility. In high ambient summer temperatures, workers were better protected in the modularised containers from serious health impacts such as heat stress and exhaustion and less work time was lost to rest breaks. In the Balkans, there are also potential health effects during extreme winter cold, which may also be mitigated by the increased shelter provided in modularised containers. Workers do not operate within the SOSO comminution unit, which is fed externally. This is advantageous from a safety perspective to prevent exposure to dust particles. The container remains closed during crushing and milling operations to prevent the escape of excess dust which would cause harm to nearby workers. The ambient noise and vibration produced by the SOSO processing solutions is also minimised relative to traditional operations, primarily attributed to the reduced scale of the modularised plant and ore sorter.

4. Access to pre-training

The training of operators on-site comprised pre-training and training on-the-job. The operator knowledge pre-training required meetings, presentation of 3D models and review of drawings to communicate: the basis of process and module design; the stages, priority and validity of the work. The operator practical training on-the-job provided the learning relating to, and validation of, actual operations. Table 1 states the expertise that was required for the IMP@CT testwork as a function of unit process (Fig. 1). In brief, it shows that a small workforce with skilled and highly-skilled workers were needed to operate and service automated equipment for SOSO mining operations. Experienced mine managers and mine engineers had already been appointed to the full Olovo operations, from outside the local area. Many of the newly appointed, rural, workforce had no prior technical qualification to work on a mine site, except licenced loader and forklift drivers. In Bosnia and Herzegovina, there is a national requirement for personnel to have attended a mining high school to ensure they are suitably qualified to work in certain positions on a mine site. The education is provided through the state education system and can be completed in post, which ensures that there is oversight of minimum training standards by the state. Additional personnel that assisted IMP@CT activities included those with training outside the sphere of mining, including a part-time journalist. The skills, and particularly language skills, of the support team were extremely important for communications. With the assistance of personnel with language skills, a common language quickly developed between the onsite team and the IMP@CT team, comprising signs and a combination of Bosnian and English words, to reinforce training in safe and effective operation.

There were no pre-existing SOSO mining operations to visit for training purposes. Instead, the European equipment manufacturers exchanged knowledge within the IMP@CT consortium during the pre-commissioning activities. The intentions were to facilitate planning of testwork and to support a cascade of knowledge on site. Chemical engineers appointed to the GEOMET mine workforce received training in minerals processing techniques through industry-academia collaboration (2017–2018) to transfer knowledge into the mining company. The mining practitioners provided the materials used for processing, which subsequently supported student research at academic institutions into ore sorting, crushing and grinding, flotation testwork, and flotation reagents for SOSO mining. In addition, students were involved in on-site testwork using the ore sorter, as part of an endeavour to train a future mining generation. The teams that designed equipment managed hot commissioning and transferred knowledge to the local workforce. In the context of a SOSO mining trial, the teams developing the modularised solutions acted as a proxy for a set of core employees, moving with the mobile modularised plant to a new project site.

The firm communication of safety culture was a core aspect to both recruitment and pre-training of new staff on the mine site. Pre-training of the assembled initial workforce commenced with induction materials that break down the essence of the relevant technical processes (Fig. 1), and adherence to mining and safety regulations (Fig. 2). The mining company Mineco/GEOMET therefore ensured adherence to international best practice and local regulations, including those relating to the experience and training levels required to fulfil key posts. Tailoring of training materials to role and required level of complexity assisted the transfer of knowledge from the equipment providers, through engineers, to the operators. Moreover, quick learners were identified and deeper training undertaken with these individuals who became more confident with making operational decisions, and were subsequently able to cascade best practice. A set of recommendations arose from the practical requirements of testing the SOSO mining approach:

1. A mobile team should establish operations and rapidly train a local workforce;
2. The requirements for the training material, programmes and schedules should be communicated in advance of deployment;
3. There should be opportunity for trainers or employees to examine mobile and modularised plant in an operational environment, which would significantly enhance training efforts;
4. Ideally, staff at a new location can be involved in the mobilisation of equipment from a previous site, such that they are trained and inducted prior to the commencement of operations.

5. Communication and training by operational stage

A project communication (management) plan for the site activities established how the team engaged in IMP@CT testwork would interface with the larger mine team at the first test site (Olovo). The management communications involved logs of activities and adherence to safety requirement, records of lessons learned and daily progress picture updates, communication and feedback to IMP@CT consortium partners. This applied to all the modules within the testwork but, to demonstrate the communication activities by stage, we now focus on the largest module. The gravity separation unit comprised processing equipment configured in a four-container assembly with external apparatus (spirals and feed hopper for jigs). The definitions of stage of operation (Table 2) were essential elements of communicating with contractors for construction of equipment, in order to avoid engineering delays. Technical operations on site fell into three main categories that required different approaches to communication and visualisation of tasks for practical training prior to or on-the-job: assembly (and commissioning); operations; decommissioning. The mine owner took responsibility for the selection and management of the competent operations personnel and site contractors to carry out on-site assembly, commissioning and decommissioning operations, where the decommissioning phase of the work was a reversal of the assembly step.

The pre-training documentation for on-site assembly included the full set of RAMS (Risk Assessment and Method Statement). It was compiled by the competent IMP@CT engineers, approved by the site managers and IMP@CT management team, translated into Bosnian and Serbian, reviewed and signed by all people involved in their preparation. The RAMS documents were readily accessible to all operations personnel and visitors, and were modified when circumstances dictated. Engineering documents were communicated to, reviewed and confirmed by operations personnel prior to commencement of the assembly operations.

The site managers had responsibility for training of personnel prior to operations, in multiple factors as described in Table 2. As previously described, the qualified and competent IMP@CT engineers who managed on-site assembly and decommissioning also had responsibility for the development, implementation, and supervision of personnel

Table 2
Summary definition of the stages of SOSO mining activities, described in terms of the requirements for, and management of training. Competent IMP@CT engineers and local site managers were key trainers, with management supporting the training program as a high priority. The training methods were circular and repeated for ongoing compliance with safety standards: Prepare, approval loop, present, try-out performance, follow-up, signed completion, and report. HAZOP: Hazard and operability review. SOP: Standard operating procedures. PFD: Process flow diagram. P&ID: Piping and instrumentation diagram. COSHH: Control of substances harmful to health. PPE: Personal protection equipment. LOLER: Lifting operations and lifting equipment regulations.

Stages of operations	On-site work planning	Assembly & commissioning	Operations	Decommissioning
Definition	1. Permitting 2. Site development 3. Organizational chart 4. Pre-training	1. Positioning the containers 2. Mechanical Completion 3. Motor rotation check and a run-in 4. Introducing mineral ores & sub-systems check 5. HAZOP 6. Full plant operation	1. Initial operation – optimization 2. Stabilising the plant 3. Validating the plant performance 4. Troubleshooting 5. Ready to produce saleable concentrates	1. Refurbishment and retrofitting 2. Spare parts & consumables 3. Optimal dismantling 4. Packing containers 5. Timber packing of feed/product conveyors
Technical training requirement	• 3D models • visual aids of factory assembly • testing plant • plant descriptions • civil engineering drawings	• 3D models • mechanical & electrical drawings • Equipment maintenance & operating manuals • SOP • PFD • P&IDs • performance checklists • visual aids	• SOPs • performance checklists • step-by-step and valve-by-valve visual aids.	• 3D packing models • performance checklists • step-by-step visual aids
H&S training Requirements *Note Risk assessment and method statements (RAMS) for all tasks*	1. Site H&S induction 2. Working at height awareness 3. Manual handling 4. First aid 5. Fire awareness 6. Slips, trips & falls 7. Explain potential site hazards 8. Agreed PPE	1. Safe operation of mobile access towers 2. COSHH 3. HAZOP 4. Demonstrate safe assembly & commissioning procedures 5. Identifying moving parts & pinch points 6. Explaining potential hazards of the plant 7. Alarm acknowledge, and emergency shut down. 8. Electrical safety	1. COSHH 2. Demonstrating safe operating procedures 3. Alarm acknowledge, and emergency shut down	1. Safe operation of mobile access towers 2. Demonstrating safe decommissioning and packing procedures 3. Explaining the potential hazards of decommissioning and packing 4. Electrical safety
Training for required competencies		1. Licence for electrical maintenance 2. LOLER		1. Licence for electrical maintenance 2. LOLER
	Site management safety training scheme (SMSTS) for safe site management across all stages of operation			

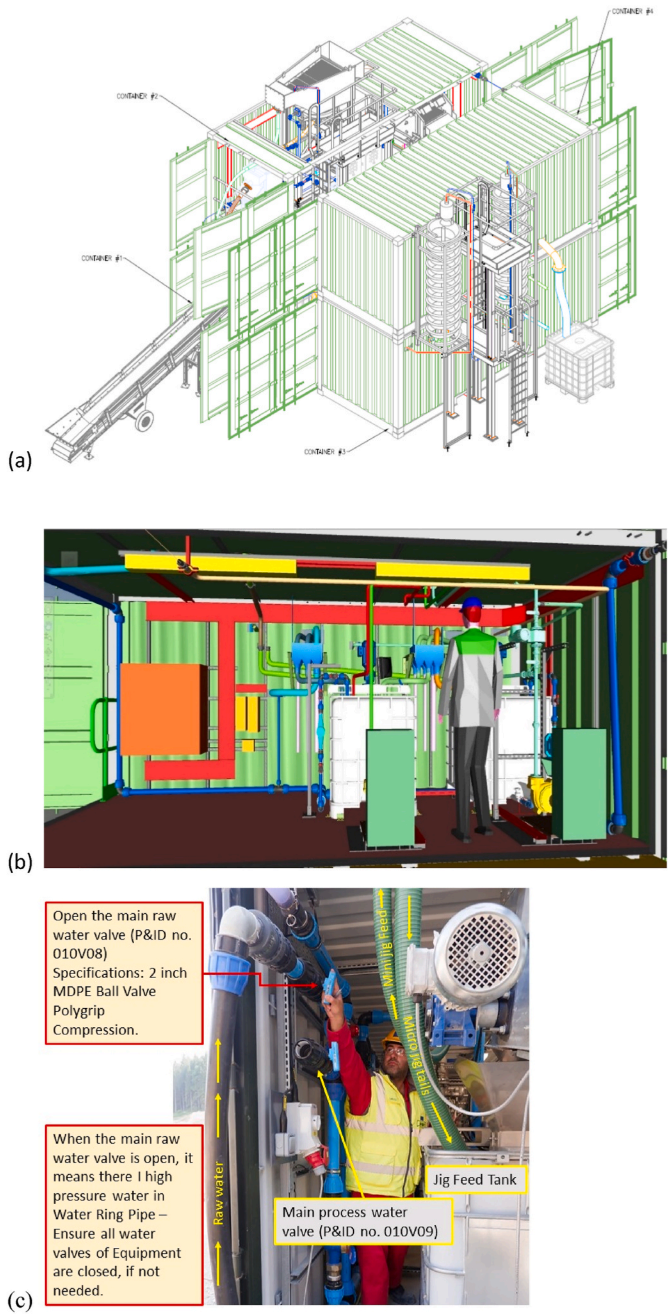

Figure 3. Visualisation of IMP@CT gravity separation plant: (a) isometric view; (b) Navis model of container 3; (c) Example of the visual aids in the step-by-step and valve-by-valve guidance, for safe start-up, operation and shut-down, retained in all containers to ensure consistent standards of operation. Engineering visualisation (a) and (b) were particularly useful during installation. The visual aids (c) were used to communicate to all types of learner, and when language barriers created challenges, since the labelling on the visual aids matched the labelling on equipment and piping in the containers.

training programs at both test sites. They considered who needed to be trained and the level of training appropriate to different individuals and groups. They used the most up-to-date reference material and covered all key aspects of the work. With experience and feedback, they further developed the training materials.

The engineering documents that were utilised as additional training aids prior to commencement of mechanical installation operations included the civil layout requirement of IMP@CT containers, isometric views of IMP@CT containers (Figure 3a), IMP@CT container assembly sections and the IMP@CT container assembly plan. An interactive 3D model (in Navisworks 3D viewer, Figure 3b) for the gravity separation module was used to explain installation of walkways, ship ladder, spiral support brackets and spiral assemblies, spiral access platform and all pipes & hoses. Piping & Instrumentation Diagrams (P&IDs) were used to train operations personnel about the interconnection of process equipment. Visual training aids were most useful when equipment and valves in the mobile modularised plant were labelled with numbers. The supplier of conveyors (Conveya Ltd.) provided assembly procedures, step-by-step instructions, electrical and safety documentation, and training for IMP@CT engineers.

Commissioning was framed in the context of converting IMP@CT equipment containers into a fully-operational processing circuit for SOSO mining and processing. Items of plant equipment and their purpose were described using vendor manuals, standard operating procedures (SOP), visual guides and 3D model review (Fig. 3). The scope of commissioning checks and the operator knowledge required prior to commencement of commissioning activities are detailed in Table 2. All IMP@CT operatives had a good awareness and understanding of material safety data (including COSHH) for mineral feed material, intermediates, concentrates, tailings and effluent prior to commencement of commissioning.

Practical training for operators on the job started with an induction to the delineated IMP@CT area of the mine (or processing) site, detailed description of the IMP@CT processing circuit, process hazards (the Hazard and Operability Study (HAZOP)), plant safety, and location of safety equipment. All operators signed the briefing record at completion of this stage of training, prior to further activity. The roles and responsibilities of individuals involved in IMP@CT plant operations were defined and the detailed theory of equipment operation presented. Operators were provided with training on pre-start checks, valve positions for start-up, initial start-up and how to complete a start-up. A step-by-step (e.g. Figure 3c) and valve-by-valve procedure, describing how the total IMP@CT circuit is brought into normal operation supported training and coaching of the operations teams. The guidance included standard operational values, which were written into P&IDs and left in IMP@CT containers for operators to use for reference. Equipment drawings, engineering documents and fault-finding guides were reviewed by operations personnel for dry commissioning and maintenance, including housekeeping and clean-up at the end of shifts.

The first primary requirement of SOSO mining is that operations can be stopped and solutions moved to another location. The operators were trained in normal, safe shut-down procedures, which are a reversal of the starting-up process. A step-by-step and valve-by-valve description also accompanied this training. In line with safe operating practice, very direct instructions were also provided to operators in how to conduct an emergency shut-down using the red emergency stop push-buttons that were installed on all control/distribution panels. The operations personnel learned how to manage tank alarms, where level probes alerted of high and low levels in jig and rougher spirals feed tanks.

The second primary requirement of SOSO mining and processing solutions is that they are adaptable to complex materials in small deposits. Operations personnel learned monitoring and recording of key process variables in the plant log, and how and when to take laboratory samples from sampling points, such as raw material, intermediates, concentrates and effluent. They learned how to optimise the operation and process variables such as: feed rate determination and quality; concentrate quality determination; entrainment of oversized/undersized particles; and change in process configuration or process operating conditions.

The duration of testwork within the project (weeks to months at a single site) was short relative to activities at a SOSO mine (1 or more years at a site) or traditional mine (operation over decades). In an active SOSO mining operation with a mature health and safety culture, training would be reinforced every 3–4 months to prevent the latent failures that might result in accident. Principles would also be reinforced through frequent assessments and unannounced audits from regional operations managers. Regular open discussions around preventative measures and opportunities for improvement should be encouraged and scheduled as part of regular operations. Training records for each member of staff, which document progress and abilities, are a crucial part of legacy skills development and may underpin transfer of skills to other workplaces beyond the operational time of the IMP@CT system.

6. Cascade training in a community of SOSO mining practice

The training model that emerged from the practicalities of implementing testwork on an operating mine site comprised the cascade of knowledge from the core development engineers to line managers on site, who then cascaded it to shift workers. The *cascade*, or multiplier, training model is a useful means of rapidly educating a large number of workers, when there are deficiencies in time and budget, and informal learning activities are appropriate (Karalis, 2016). This applies to mine-sites where skilled labour is costly to recruit and retain, and new workers must receive immediate on-the-ground training. Kennedy (2005) argues that the cascade model supports a technicist view of teaching, where skills and knowledge are given priority over attitudes and values, in a collaborative approach to continuing professional development that supports transmission of knowledge. Kennedy (2005) further suggests that continuing professional development can become transformative if due consideration is given to underlying influences, expectations and possibilities, and when the trainers are both the subjects and the agents of change acting as 'shapers, promoters and well-informed critics of reforms'. The development of a mature safety culture in mining requires that attitudes are addressed within training programmes as well as the technical aspects of operations, and that attitudes are shared between management, supervisors and workers.

Learning in a *community of practice* model requires evolving forms of mutual engagement, understanding and a range of discourses, such that learning happens as a result of that community and its interactions, and not merely as a result of planned learning episodes, such as courses. In contrast with the characteristics of a typical cascade model (Karalis, 2016), participants at all phases of the cascade model during the SOSO mining testwork did not have the same educational level; such that diverse participatory learning activities were appropriate. The purpose of the mining testwork was the creation of knowledge in industry-academia collaboration to underpin a transformation of mining practice. It requires both transmission of knowledge and development of new frameworks for the dissemination of a diversified mining paradigm, created through collective experience and reflection.

The requirement for engineers to act in a training capacity requires skills that individuals may not necessarily have utilised prior to working in SOSO mining. The additional skills relate to the techniques and methods of communication, which were supported in the project by visualisation materials, and the appreciation of the social and cultural contexts of training a peer group. Bax (2002) describes the impediments to cascade training in an educational context. He emphasises that there is a change in role and status of a newly selected trainer within a peer group that is challenging to navigate: new trainers needed to establish credibility and to persuade key stakeholders of the value of training. The translation of this experience to a mining operation is not straightforward for several reasons. (1) It cannot be assumed that the workforce at a mine is more or less likely than other professions to accept new trainers from within their ranks, when the consequences of failure to engage with training are high. (2) There is an absolute requirement for regularly reinforced procedural training (with health and safety by design) at an operational mine that has the backing of, and oversight by, mine management. (3) Where there are limits to remote operation, underground workers have continued dependence upon one another for safety, which reinforces group identity. Indeed, Somerville and Abrahamsson (2003) found that trainers and mine workers co-participated in the construction of a community of practice that reinforced safety through the experience of working. In other professions where historic influences permeate contemporary practices, managers that develop and foster transformational leadership in local trainers can surmount negative traditions (Murphy, 2005).

The cascade model is implemented where there is a lack of trainers (Karalis, 2016). This automatically applies to the trial of SOSO mining because the technical knowledge resided in the developers of prototypes and test facilities. The number of end recipients at any SOSO mining site is relatively small, but the widespread adoption of SOSO mining may equate to a large regional workforce. The potential exists for messages (and knowledge) to diminish as they cascade (Turner et al., 2017; Karalis, 2016; Bax, 2002; Jacob and Russ-Eft, 2001) and the misrepresentation of crucial information in an active mining operation has potentially fatal consequences. Karalis (2016) promotes, initially, an analysis of the educational needs of participants at all phases of the cascade model and, subsequently, quality assurance and formative evaluation in all phases to mitigate against decrepitude in the last phase of training. Turner et al. (2017) proposed that in-service development of trainers by mentors, coupled with knowledge in practice, facilitates successful knowledge transfer throughout the system. The inclusion of in-service development of trainers would improve the business plan for a company supplying SOSO mining solutions. Since in-service mentoring requires personalisation of training according to local situation, the resulting dialogues may inform the further roll-out of SOSO mining.

The mining company supporting the IMP@CT project has a policy of repatriating the skills of experienced geologists and miners into the Balkans coupled with employment amongst the local population of Olovo and Veliki Majdan. Some of the respondents interviewed by Sydd et al. (2020) recognised the possible incompatibility of the locals' skills and the expertise needed for working in the mine, as well as the lack of education opportunities in the field of mining. The combination of experienced workers and incomers to mining for the dissemination of established safety practice and adoption of updated safety practice (Doyle, 2020), respectively, highlights a particular social dynamic. Bax (2002) describes the challenging propensity of senior workers to show what they know when they are surrounded by junior colleagues in a training scenario. The collective wisdom of dominant members of the group shapes other individuals' understanding of the community and its roles (Kennedy, 2005), particularly where there is past experience of unstructured on-the-job training (Orser, 2001). Thus, the senior workers need to be brought closer to engagement and accept the trainer and new learning, such that the cumulative knowledge can support transformation (Kennedy, 2005; Bax, 2002). The cited traits of a good trainer are confidence at the outset, flexibility and adaptability to the stakeholder group, spontaneity and inclusion of all levels of experience as equals, such that the social and cultural dimension of training is as important as the technical knowledge (Bax, 2002). For maximum impact and transformation, the training provided to trainers will require inclusion of communication and cultural elements, in addition to technical knowledge. For the incomers to the short-duration mining operations from the local area, the trainers may highlight the transferable nature of acquired skills. The community in practice approach to cascade training in the IMP@CT project bears the traits of all of the 'types' of cascade plans of Jacobs and Russ-Efts (2001), such that information and learning cascades downwards in a hierarchical fashion, learning informs planning, and the process of creating the frameworks for SOSO mining are developed.

7. Jobs, automation and skills in a SOSO mining workforce

Key characteristics of SOSO mining, to improve economic feasibility, are a reduction in start-up time, a reduction in CAPEX (capital expenditure), transfer of both of these 'costs' into OPEX (operating expenditure) per ton of throughput, and rapid offset of development costs by early production of high-grade ore. Establishment of large, fully automated mining equipment is CAPEX-intensive and it must be efficient

(Elevli and Elevli, 2010). Subsequently, larger capacity mines are expected to have lower OPEX and can be run with less employment due to the high degree of automation, offsetting the high CAPEX cost in feasibility analysis of mineral projects. The limits to automation in the pilot SOSO project included a reliance on the driver/operator to 'read the rock' for selective removal of complex ore and manual or semi-skilled labour to manage stockpiles and the variable Run of Mine (RoM) into comminution and processing streams. The work undertaken within the framing of the project thus corresponds to the *mid-level automation* category of Lynas and Horberry (2011). Advanced and costly controllers to manage complex and variable RoM by increased automation do not transfer costs from CAPEX to OPEX. Where SOSO mining approaches are used to minimize economic risk in large ore deposits (Quirke et al., 2019), there is greater potential for automation and the use of real-time information to make the mining process more precise and predictable. The geological and business context of SOSO mining therefore controls the extent of automation, the proportion of the workforce that comprises operators and the final size of the workforce. The characteristics of a mobile SOSO mining operation place it within the category of small-scale mining, where scale applies to the impacts of mining as well as the level of technology adopted (Sidorenko et al., 2020a). Technological small-scale mining operations are already used globally for reprocessing of gold tailings and operations are mobile and modular. The economic case for such small-scale gold operations is based on reduced energy consumption because feed into processing facilities is already crushed and ground and, to some extent, homogenized. Where there is one commodity of interest, there is no need for the adaptable and flexible electrical and piping circuits used in SOSO mining. However, adaptable, mobile and modular solutions could help offset development costs by temporary use at larger mines, for the purpose of project staging and early revenue generation (Quirke et al., 2019). In this case, SOSO mining would be replaced with optimized and extensively automated solutions further along the life cycle of a mine with repercussions for community, since the economies of scale reduce employment needs (Lockie et al., 2009; Paredes and Fleming-Muñoz, 2021).

Jobs creation is routinely considered as one of the main positive outcomes of mining activities for local communities. The IMP@CT workforce detailed in Table 1 represents a minimum workforce operating at test-scale per shift (13 staff total), but it usefully provides some context for a minimum employment estimate. (The geologist and lead-site engineer are unlikely to be employed locally but are offset in the calculation by employees required to provide cover for absence). The SOSO mining and processing operation worked alongside conventional mining/processing workforces at Olovo and Veliki Majdan. Through establishment of mining and processing activities to 2020, the workforce rose to 220 at Olovo. 288 people are employed at Veliki Majdan (Mineco, 2021). Thus the employment level of a single-shift, single-locality SOSO operation is very small by comparison. Since small-deposit mining could usefully provide multiple metal commodities (Moore et al., 2020), it is worth considering the contribution to local employment from a mining business model of multiple SOSO mining operations. In a business running SOSO operations at 3 mines, with 3 shifts in a 24-h period, a simple scaling calculation indicates that the technical workforce would number 117. With inclusion of administrative and support staff, the workforce is comparable to that for a single medium-to long-term mine site. For continuous operation (3 shifts in a 24 h period) of 3 mines with processing plant running at 5 tonnes per hour, the minimum technical workforce is less than 1% of total population, including all age groups (Census data). Table 3 gives further information on the dependency and employment profiles of the hosting municipalities. Age dependency ratio is the ratio of people younger than 15 or older than 64 (dependents) to the working-age population between 15 and 64 years, as a national proportion of dependents per 100 working-age population (World Bank, 2019). From this we extrapolate the proportion of the total population that are working age and calculate the number of unemployed workers using the census data. We therefore estimate that, in the communities where a quarter or a third of the adult working population is unemployed, the contribution of technical jobs created by SOSO mining could reduce unemployment by up to 9%. There are assumptions in this calculation that no jobs are sourced from outside the region, or if they are then there are balanced by an equivalent number of support jobs (or jobs in an onsite analytical laboratory or tailings management), and that the national age dependency ratio applies to the municipalities hosting the test sites. Increasing both the number of operations and the throughput of operations will require up-scaling of the workforce.

The SOSO workforce calculations above relate to the operational phase of mining, in which salaries vary as a function of the unit processes in the mining solution. Because of the challenges in recruitment for roles perceived as more dangerous, salaries for underground work on the main Olovo mine are higher than for equivalent semi-skilled roles above ground. All technical (skilled or unskilled) salaries at test sites provided higher incomes than local agrarian activities. Furthermore, local respondents to social surveys talked positively about salaries being reliable and paid on time (Sydd et al., 2021a,b). Lockie et al. (2009) found that the construction phase of conventional mining life cycles is linked to a peak in community development, the operational phase is linked to a period of maturity in community development, and labour recruitment and social infrastructure policies mediate the resource community cycle. In contrast to the construction of a bespoke stick-build processing plant (background, Fig. 1d), the construction phase of SOSO mining operations is off-site and deployment is fast, under the management of external consultants (foreground, Fig. 1d). Thus, there is low capital expenditure to minimize the investment required and ensure that early returns from processing of high-grade ores support larger mine developments. The main tasks in the SOSO construction phase are establishment of a safe underground environment, and training by technology providers and consultants. The possibilities for local employment may depend on the professional capacity of the community and prior experience of mining. However, local employment was strengthened at the test sites through training and education of locals, in co-operation with state education, and by emphasizing local service procurement and sub-contracting when possible. Such social infrastructure policies can also apply in SOSO mining, particularly for multi-operation business models that require a regional value chain. For short-duration mining operations, local workers may face the challenges of unpredictable employment and unemployment periods according to whether mining is active or whether mines are under care and maintenance. It should be noted that the care and maintenance phase of activities requires a very minimal or part-time workforce and that a 'bust' phase following a SOSO or other mining 'boom' may significantly impact regional value chains and communities (Marchand, 2012). This is observed throughout the extractive industries (Marais et al., 2018; Shandro et al., 2011; Törmä et al., 2015), but it may be more acute for

Table 3
Potential impact of SOSO mining operations on unemployment in the municipalities hosting test sites. Calculated using the IMP@CT workforce of Table 1 scaled for 24 h continuous operation with cover, with three small mines operating in a single municipality (workforce = 117). Population and unemployment rate according to Census of Population. % working age population = 100 minus the national age dependency ratio (World Bank, 2019).

Deployment site	Municipality	Population	% working age population	% unemployment	% reduction in unemployment
Olovo	Olovo	10,175	53.2	24.5	8.8
Veliki Majdan	Ljubovija	12,800	47.8	36.6	5.2

SOSO mining of ore deposits very close to economic feasibility.

The similarities between large automated mines and SOSO mining operations may seem limited but the fundamental economic requirement of profitability, the issues surrounding the health and safety of mining workforces, best environmental practice to or beyond local regulations, and the reputation of organizations for acceptance of mining apply. Where automation is established, it provides a steady low-labour, low-cost, optimal operation for economic sustainability (Bellamy and Pravica, 2011; Gumede, 2018). It is promoted as a safe mining solution since it removes workers from potentially hazardous environments, but Lynas and Horberry (2011) emphasise that system failures in automated mining can have catastrophic consequences and impact the reputation of mining companies. Highly- or fully-automated mining can also have a negative impact on social sustainability, as it relates to employment (Bellamy and Pravica, 2011), since workforces change away from manual and semi-skilled employees, towards high-skilled and trained operators. The fact that low-wage, less-skilled job roles are more likely to become automated relative to that of highly qualified employees increases inequality, since the availability of retraining does not prevent non-employment or employment in worse jobs (Arntz et al., 2016; Lordan and Neumark, 2018; Holcombe and Kempe, 2019; Paredes and Fleming-Muñoz, 2021). However, the new competencies and knowledge required for remote control from above ground (of mining machinery at the working face) correlates with an increasingly diverse workforce in terms of identity and gender (Abrahamsson and Johansson, 2006), though the location away from mine sites increases rural-urban inequality (Paredes and Fleming-Muñoz, 2021). For social acceptance of automation, Leeuw and Mtegha (2018) examined the opportunities for reskilling of inadvertently redundant miners to earn a living beyond mining, by analysis of the linkages between supply and value chains in mining regions. The limits to the extent of automation in SOSO mining raise interesting questions about whether it has a role to play in a just transition programme (Paredes and Fleming-Muñoz, 2021) but this might be challenging where operations are of short duration. Recently trained semi-skilled workers can rapidly face loss of occupation, unless they chose to move to alternative mine sites. Thus, SOSO mining can usefully learn from the issues around redundancy and workforce turnover at large-scale mines, and the geography of labour processes (Leeuw and Mtegha, 2018; Beach et al., 2003; Ellem, 2016).

8. Local employment and sustainability?

We use the Brundtlant (1987) definition of sustainability as '*meeting the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs*'. We place this in the context of decoupling the impacts of natural resource production from human well-being (Oberle et al., 2019). Harvey (2019) recommends decoupling of economic growth from environmental degradation by incentivising minimally invasive automated mining and abandoning fossil fuels. SOSO mining is linked to small-scale mining, which has a challenging relationship with social, environmental and economic sustainability, primarily as a function of the small size of operations, and their resultant short duration of operations and modest possibilities for economic development (Sidorenko et al., 2020a, 2020b, 2020b; Sydd et al., 2021a). We note that small-scale operations are amenable to renewable energy provision (Paneri et al., 2021) and have a smaller physical footprint and dramatically reduced mining wastes, relative to large-scale operations, despite lower automation. We note that Beylot et al. (2021) have completed environmental life cycle assessment of the pilot work at Olovo, and identified the environmental hotspots of SOSO mining. We thus maintain our focus on workforce and training, where employees are assets with situated knowledge and social identity, who can work collaboratively for the promotion of long-term sustainability, even by short-term mining operations.

At the mine test sites of Olovo and Veliki Majdan, the recruitment of citizens from nearby villages by the mining company was considered fair because 'local' natural resources are being exploited and locals will feel the possible environmental impacts the most (Sydd et al., 2020). Although the number of citizens employed in SOSO mining operations will be modest (Tables 1 and 3), this may yet be a very positive impact for regions with small population and high unemployment rates (Sidorenko et al., 2020a, 2020b; Sydd et al., 2021b). Interviews with local communities showed that any number of new jobs were considered very important not only for individual citizens and households but also for the whole village or municipality. Small-scale mining was perceived as important for the viability of the small community, as the industry may provide conditions that make it possible to continue living in the area (Sydd et al., 2020). The Olovo community suffered from out-migration of working age citizens prior to the onset of mining. The mining company policy of recruitment supported the return of local workers, and the longer–term operation has provided the conditions for continuing occupation in the region. The need for a more educated workforce due to the level of automation in the larger and long-lived Olovo mining operation may have further positive implications for the development of rural working populations, since the professional capacity of the local population is increased through training and education of mine employees. Indeed, local respondents cited lack of education opportunities in the field of mining as potential barriers to their employment (Sydd et al., 2020, 2021a).

The study of social impacts conducted in Olovo and Veliki Majdan revealed that employment in SOSO small-scale mining is additionally limited by the potential mobility of work forces deployed with mining solutions between mine sites Sydd et al., 2021a,b. Critical questions for socially sustainable small-scale mining include whether it can contribute to local economic development and employment to the extent that the locals hope for and whether a company has adequate resources to meet local community expectations (ibid). Stakeholder engagement within the IMP@CT project (Finland, May 2019) highlighted that local workforces do not necessarily migrate with mining operations (Sidorenko et al., 2020b) unlike the highly-skilled equipment engineers and service providers. For that portion of the local workforce that may move within a region of SOSO mining operations connected within a single business model, some level of transformative continuing professional development is required to apply SOSO technologies to different deposits and situational contexts. The portion of the workforce that move out of the mining industry will have gained transferable skills. These will include safe operations and industrial practice, and also modern requirements for businesses to communicate and act ethically in relation to the environment and society. While employees may focus on corporate social responsibility activities to assess the extent to which their employer values the community, strategic Human Resource Development (HRD) by the employer can contribute to community sustainability in terms of providing leaders with the skills to drive positive change for greater, sustainable economic diversity (Garavan and McGuire, 2010). Development of transferable skills may be coupled with reskilling activities based on analysis of local situation (Leeuw and Mtegha, 2018; Harvey, 2019; Paredes and Fleming-Muñoz, 2021) to foster local activities that stimulate and diversify the economy, where short duration of mining operations may fail to meet community expectations for employment.

HRD is critical to achieving successful performance and profitability outcomes, and also to creating a culture of best practice behaviours for health and safety, adherence to environmental protection regulations, and the standing of the mining company in society (Garavan and McGuire, 2010). Thus, HRD plays a facilitative role in sustainability and ethics in organizations, but it also operates within the wider cultural and ethical attitudes of the society from which the workforce is drawn (Garavan and McGuire, 2010; Soltani and Joneghani, 2012; Peppoloni et al., 2019; Allington and Fernandez-Fuentes, 2014; (Arvanitidis et al., 2017)). There is a critical need to consider how human resource development can contribute to the sustainability of SOSO mining and particularly to the sustainability of post-SOSO mining communities, in a culture of ethical and social awareness. Discussions around knowledge and skills transfer as a means to economic and thereby social sustainability, and the implementation of sound health and safety principles, within training programmes may disseminate through both formal and informal pathways to penetrate other workplaces. There is not currently enough evidence to comment on whether the mobility of SOSO mining solutions limits the creation of local supply chains and service industries, even though a focus on mutually beneficial improvements to infrastructure, supplier capacity and human resources can create shared value (Cosbey et al., 2019). However, the social dimensions of the circular economy (Schröder et al., 2020) may provide a framework for further consideration of the issue.

9. Conclusions

The practical requirements of undertaking a short testwork programme on an active mine site required the very rapid transfer of knowledge to ensure that project and mine site employees operated in a mature safety culture. A cascade training plan was enacted that centred around: (a) the transfer of technical knowledge from the developers of mining and processing solutions to operators (drawn both from within the research team and the mine workforce); (b) the important stages of operations appropriate to switch-on switch off (SOSO) mining; (c) amendment of training approaches using a community in practice approach. The SOSO mining testwork occurred simultaneously with the establishment of a full-scale processing plant. The new mine workforce spent time training on the SOSO mining equipment and a small team worked more closely with the equipment. The advanced training in a modular mining and processing environment contributed to an accelerated process plant ramp-up to full capacity at the Olovo mine site. Since SOSO or other small-scale operations could be used to manage uncertainty by project staging for larger ore deposits (Quirke et al., 2019), the SOSO training helped to very early build, and subsequently cascade, a mature safety and sustainability-oriented culture to a wider workforce.

Where SOSO operations are redeployed to a different ore deposit, and workforces do not migrate with the mining, then the social sustainability of mining falls into question. A new workforce will be diverse and require skilled, semi-skilled and manual labour. New employees will need training tailored to job role and responsibility at each new site, and additional skills for new trainers in the cascade of information. A core mobile team of trainers to start the cascade of knowledge, behaviours and attitudes would usefully comprise specialists in safe SOSO mining technologies, effective leadership and communication, the wider requirements of modern responsible mining, and reskilling to prepare for the withdrawal of mining. Training and reskilling at mining operations can catalyse economic diversification for community resilience to the mutual benefit of mining organization and community, when mining is placed in situational contexts, local supply and service contexts, and value chains.

The SOSO approach requires retention of some of the old physical and tacit knowledge and skills that are described as obsolete for large modern mines (Abrahamsson and Johansson, 2006), but with an expanded remit for training and mid-level automation, such that attitudes and operating philosophies can be more closely aligned with the concerns of the present day. The evolution of mining workforces away from arduous physical work under dangerous conditions, to an increasing culture of technological superiority and control distal to the mine face is somewhat reversed in SOSO mining, where some of the work is proximal to the mine face and processing equipment, but with the highest possible safety controls. Ultimately, SOSO mining can contribute to a diversified mining paradigm by focussing on high-grade deposits for early financial returns that support subsequent mine development. In doing so, it will: (1) contribute to social sustainability by changing the paradigm of large mining operations to create a new balance between workforces and automation; (2) create a new dialogue through which local populations may benefit from mining of amenable small, high-grade ore deposits; and (3) decrease risks of supply shortages to regional (e.g. European) manufacturing sectors. Consideration of social sustainability is essential from the outset of SOSO mining, since the short duration of operations dictates that planning and costs for mine closure are significant features throughout the operating life of mine.

CReDiT author statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interestsIn the event that small-scale mining becomes more widely adopted, the equipment providers and mining practitioners that were involved in the pilot test work may be in a position to make financial gain by commercializing their technologies. Since our aim is to facilitate responsible best practice in small-scale mining for the diversification of mining practice, we consider this a complimentary interest rather than a competing interest. Nevertheless we state that the companies involved are as follows. Mining practitioners: Mineco Ltd was the mining company involved in testwork. Equipment providers: The companies involved are Rados International, Metal Innovations and Extracthive International. The University of Exeter holds the IP for the design of the minerals processing test facility but does not currently have a direct route to commercialization.

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