World Academy of Science, Engineering and Technology
International Journal of Geological and Environmental Engineering
Vol:17, No:11, 2023

Numerical Modeling of Artisanal and Small-Scale Mining of Coltan in the African Great Lakes Region

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Abstract**—**Findings of a production model of Artisanal and Small-Scale Mining (ASM) of coltan ore by an average Democratic Republic of Congo (DRC) mineworker are presented in this paper. These can be used as a reference for a similar characterization of the daily labor of counterparts from other countries in the Africa's Great Lakes region. To that end, the Fundamental Equation of Mineral Production has been applied in this paper, considering a miner's average daily output of coltan, estimated in the base of gross statistical data gathered from reputable sources. Results indicate daily yields of individual miners in the order of 300 g of coltan ore, with hourly peaks of production in the range of 30 to 40 g of the mineral. Yields are expected to be in the order of 5 g or less during the least productive hours. These outputs are expected to be achieved during the halves of the eight to 10 hours of daily working sessions that these artisanal laborers can attend during the mining season.

Keywords—Coltan, mineral production, Production to Reserve ratio, artisanal mining, small-scale mining, ASM, human work, Great Lakes region, Democratic Republic of Congo.

I. Introduction

ASM is an extractive activity of minerals characterized by the employment of rudimentary processes. Over the past few decades, third-world countries have experienced unprecedented growth in informal work related to minerals and metals [1].

In the case of coltan, this rare ore of the minerals columbite and tantalite, is a minor source of the metal tantalum. The intense need of the high-tech industry for this metallic element has resulted in a worldwide increase in coltan mining. Due to its combination with global demand and a lack of control over production and commerce in the countries (notably Burundi, the DRC, Ethiopia, and Rwanda), ASM has played an essential dominant role in tantalum production in the Great Lakes Region of Africa in recent years [2]. These nations share the Kibaran Belt, a geological province rich in tin, tungsten, and tantalum, which entirely covers Rwanda, and some parts of Burundi, Tanzania, and Uganda on the eastern side of the DRC [3]. The DRC was the world's largest coltan producer in 2021 [4].

Given the economic impact of ASM of coltan in the DRC as well as in global production of the mineral, a characterization of a miner's average daily output of the ore is of particular interest in order to understand the very foundation of the production process. So, this kind of study, is then a relevant subject of research of small scale mining. Coltan production, like many other ores produced by ASM, has so far only been reviewed at the country, provincial, or regional levels [5]-[7]. The current article is concerned with achieving the goal of modeling the average daily output of coltan ore from miners in the Democratic Republic of the Congo in particular, and the African Great Lakes Region in general. In doing so, it will also provide a much-needed reference for attempting to model other ores produced by ASM.

II. Materials and Methods

According to statistics published by the DRC's Ministry of Mines, the country's ASM production of coltan for the first semester of 2022 amounted for 878.66 tonnes (or 864.78 tons) [8]. The total amount of people dedicated every year to coltan or coltan-cassiterite mining in the Great Lakes Region is open to debate. Covering agencies point to figures in the range of 30,000 to 60,0000 active artisanal workers every year [5]. However, estimates of a workforce of up to 80,000 people have been made as well [9]. Although it is variable, the current commodity prices seem to stimulate a participation at the high end without the disregard of the seasonal impact in the production operations. Based on these references, a figure of 50,000 active workers appears as a reasonable endowment for the amount of people engaged every year in the mining of coltan in the Great Lakes Region. Around 65% of these workers are likely to be employed in the DRC, based on the country's relative contribution (700/1,042) to the total volume of coltan produced by African nations in 2021 [4]. For the first half of 2022, a conservative reference of three months of active production out of the six months that the Congo Copper-belt mining season lasts can be used. This mining season typically begins in late April/early May and ends in October [10]. The aforementioned data point to a daily output of ore by worker in the DRC is in the range of:

$$878.66\text{x } 1{,}000/\ (0.65\text{x } 50{,}000\text{x } 3\text{x } 30.5) = 0.3 \text{ kg} = 300 \text{ g} \quad (1)$$

Coltan ore is mined by hand across the DRC, with methods and conditions similar to those in the 19^{th} Century Californian or Klondike Gold Rush [11]. The ore is produced from open pits, usually in riverbeds where there are ore deposits associated with weathered Pegmatites. With an average daylight duration of 12 hours, mining locations can expect to work eight to 10 hours per day. So, if the working hours are divided into two groups of four to five hours each, an average of 150 g of coltan will be mined in each. Given these working conditions, a half-day journey with a mid-day break will suffice to model production.

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A. The Fundamental Equation of Mineral Production (FEMP)

The FEMP will be used as a theoretical model of ASM of coltan by a miner. This equation is central to the Equations of Mineral Production (EMP), which were developed to satisfy the Law of Conservation of Matter through strong mathematical induction [12], [13]. It has previously been demonstrated to be useful to model ASM of individual miners [14] for what represents a reasonable choice for the intended work. In general, they correspond to the application of the mass-balance principle at specific times using expressions of reserves, production, and Production to Reserves Ratio (P/R).

If the P/R is constant disregarding the time ‘*t*’ ($C(t)= C$), then the FEMP adopt the expression of an exponential function:

$$q(t) = CRo\ (1 - C)^{t-1} \tag{2}$$

where $q(t)$ stands for production at time “*t*”. Time ‘*t*’ is handled in integer numbers. *C* is the P/R (with $C= q(1)/Ro$). *Ro* are the total reserves available at the start of production.

Equation (3) is a proxy expression of (2). It corresponds to a version of the FEMP when the P/R has a lineal rate of change [14], [15].

The linear P/R can be defined by the function $C(t)= at+b$. In this case, the slope of the line is given by “*a*”, while the interception with the vertical axis is given by “*b*”.

$$q(t_i) = C(t_i)\ R(t_i - 1)\ (1 - C(t_{i-1}))^{t-1} = (a\ t_i + b)\ R(t_i - 1)\ (1 - (a\ (t_{i-1}) + b) \tag{3}$$

To proceed with the modeling of production, (3) is applied in a piecewise manner. Two successive points in time (t_i and t_{i+1}, with $t_{i+1} = 1 + t_i$, and $i = 1$ or 2) define the segments describing the modeled intervals of production. $R(t_{i-1})$ and $R(t_{i+1}-1)$ are constant for these intervals. This constant matches the reserves present at the time $t_{i-1.}$ in (3). For example, being *Ro* the total reserves at the initial time, then from $t_1 = 1$ to $t_2 = 2$:

$$Ro= R(t_1-1) = R(1 -1) = R(0) =R (t_2- 1) = R(2 - 1) = R(1).$$

Furthermore, from $t_1= 3$ to $t_2= 4$:

$$R(t_1- 1) = R(t_2- 1), \text{ with } Ro - q(0) - q(1) - q(2) = R(3 - 1) = R(2) = R(4 - 1) = R(3).$$

Calculations for the next points in time follow the afore-explained formulation, (3).

III. Results

The halves of each mineworker's daily production of coltan ore, distributed over a four-hour time span, were modelled in (3) and resulted in (4). The linear rate of change of the P/R has been set with a slope of 0.10 and a *t*-intercept of 0.05. Details of the sequence of coltan production following the aforementioned trend can be inspected in Fig. 1.

$$q(t_i)=(0.1\ t_i+0.05)\ R(t_i-1)\ (1-(0.1(t_i-1)+0.05))^{i-1} \tag{4}$$

This equation corresponds to the expression of the general proxy equation (3) for the variant of the FEMP when the P/R has a linear rate of change given by $a = 0.1$, and a *t*-intersect given by $b = 0.05$. For this case, *Ro* would be 150 g. In this formulation, a change of the independent variable “working time” (time in half hour fractions from zero to four) is made as *2x* “working time” = *t*. In doing so, every half hour “*t*” is assimilated to an integer between zero and eight.

According to the cumulative production (green points in Fig. 1), approximately 36% of the coltan would have been picked within the first hour. By then, the cumulative production amounted slightly below 55 g. The peak of coltan production (33 g, red point on blue line) would occur within the next half hour, when the cumulative yield reaches a total shy of 90 g. Following that, the production rate tends to slow down, as does the cumulative production. This is despite the P/R's linear increase over time, because it is operating over even smaller remaining reserves, which are already significantly less than half of the initial volume. As a result, the cumulative production only increases by 29 g (from 116 g to 145 g) between the second and third hour. The final hour of production yields a total yield of 5 g, completing the total of 150 g of coltan expected after half a day of work.

IV. Discussion

Traditionally, studies of numerical modeling of coltan production in the Great Lakes region have focused on the characterization of mining activities with volumes of production ranging from regional to mining locations [5]-[8]. In this regard, the proposal regarding the characterization of individual miners' work in small-scale coltan mining provides much-needed insight into this critical aspect of the process. The findings could aid in the resolution of many outstanding issues concerning ASM, not the least of which is the development of strategies for the formalization of its operations, a priority for many governments in Africa and elsewhere [16].

Considering the large context of ASM of the Great Lakes, the results found regarding individual mineworker's daily output of coltan ore in the DRC (300 g) seem reasonable. A quick calculation shows that individual mineworkers from a population of 30,000 to 80,000 should produce an estimated daily average output of 760 g to 285 g during the six-to-seven-month long mining seasons. This is to account for the total conservative yield of 4,536 tonnes (5 MM tons) of coltan reportedly produced each year by the Great Lakes region's collection of countries [5], [9].

References to mineworkers' daily wages could be used as another indirect way of cross validating their estimated daily output. Although wages at mine sites vary by province in the Great Lakes region, a range of 22 USD to 35 USD per kg appears to be adequate for Congolese coltan ore volumes [4], [7]. So, a daily production of 0.3 kg of coltan ore could represent earnings to miners ranging from 6.6 USD to 10.5 USD (198 USD to 315 USD per month). This earning range indicates that 0.3 kg as a reference for daily production of coltan ore appears to be at the high end of productivity for mineworkers, if their monthly earnings, which are reportedly in the order of

200 USD, are considered [4], [17].

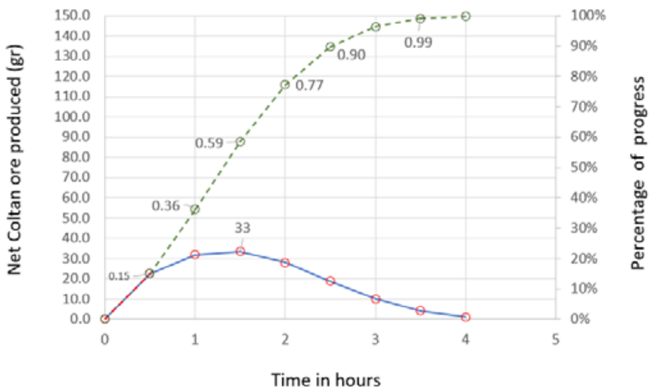

Fig. 1 Half day coltan production model of a miner in the DRC (FEMP based)

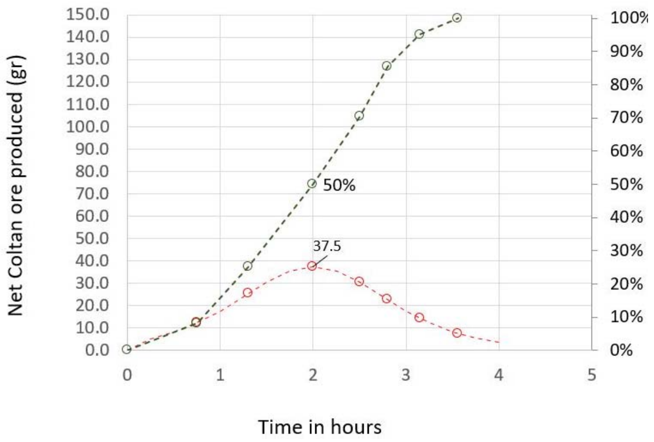

Fig. 2 Half day coltan production model of a miner in the DRC (based on Hubbert linearization)

In terms of optimal yielding, known features of human productivity by working hours support the existence of production peak intervals rather than a constant flat yield around an average [18], [19]. Furthermore, the FEMP-estimated peak of production (33 g) appears to be comparable (by defect) to the Hubbert-calculated peak value. When half of the initial reserves are depleted, the application of this model predicts a production plateau of the order of a quarter of the total volume of production [20]. This would occur at the halfway point of the half-day working journey. In Fig. 2, this is represented by the 50% point in the green segmented cumulative production curve, when half (75 g) of the initial reserves (150 g) are depleted. In our case, this plateau would be in the order of 38 g (or 150 g x 0.25, apex of the red segmented curve in Fig. 2). Using the reference values from the models examined, the peak hour production of coltan ore by a mineworker could be estimated to be in the 30 g to 40 g range. Because of the symmetry and configuration of the Hubbert model, the lowest yields are thought to be in the order of 18 g or less (first and last hours of production). This is three and a half times the lowest hourly yield estimated by the FEMP (5 g). In this regard, the FEMP model's output appears more realistic than Hubbert's, given the well-known fact that workers' stamina is likely to decrease with sustained labor over hours [21]-[23].

The reviewed models can be considered as a first trial in replicating the total yield of coltan expected to be produced as a result of mineworker's artisanal labor. However, more field data are required to address outstanding questions such as the fair to highest P/R workers can afford given their working conditions and the rudimentary means at their disposal. In this regard, evidence should be gathered to determine whether mineral production could be regulated by an underlying principle in which there is a maximum P/R, related to ore tonnage and other factors, beyond which it is not physically feasible to increase the rate of resource depletion via ASM [24], [25].

Future Directions

The study focused on modeling mineral production as a result of an individual worker, which is a vital component of artisanal work. The FEMP-modeled coeval addition of many components of a productive system beyond artisanal means (workers and even machines) could allow to recreate the global collective output of ASM cases at scales larger than that of an individual worker. Among these, the daily output of mine sites appears to be the most obvious choice for further research, with the number of miners present to work each day being one of the models' key elements. This kind of additive models could be made in a similar fashion that multi-Hubbert cycles are applied to model complex cases of large-scale mineral production [26]. In this sense, the proposed methodology offers a numerical framework that could support the assessment and evaluation of interrelationships between small and larger scale mining operations [27].

V. Conclusions

The production model of ASM of coltan ore by an average mineworker in the DRC, based on applying the FEMP, indicate daily yields of individual miners in the order of 300 g of coltan ore, with hourly peaks of production in the range of 30 to 40 g of the mineral. Yields during the least productive hours are expected to be in the order of 5 g or less, although a comparative analysis with a Hubbert-based model points to significantly higher yields during such hours of declining production. These yields result from the study of the job the artisanal sloggers can make during the halves of the eight to 10 hours of daily work sessions allowed by the setting of the mining season.

The proposed methodology provides for a numerical framework that could support the assessment of an integrated model of small and larger scale mining operations at mine sites in the region under study. The results presented are suggested to be a fair reference for a similar characterization of the daily labor of counterparts of the DRC from other countries in the African Great Lakes region.

Data Availability Statement

The data used for the research came from public sources, notably from cited [4], [5], [8]-[10].

Conflicts of Interest

The authors declare no conflict of interest.

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