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A Preliminary Assessment of a Limestone Quarry's Direct and Indirect Carbon Footprint

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Abstract: As a sub-sector of the mining industry, quarrying is also responsible for greenhouse gas emissions. Limestone is one of the most frequently extracted minerals used for construction, building materials and industrial applications. A common way limestone is consumed is for the production of lime, cement, steel, etc. Based on literature review, the amount of carbon emissions per ton of lime and cement was compared to the amount of expected carbon emissions per ton of limestone for a quarrying operation. The carbon emissions for the studied quarry were calculated using the CO_2-equivalent metric in kilograms per ton of limestone, similar to other quarrying operations. A computer script model based on practical theoretic models and rules of thumb was created, aimed to simulate different states of the quarrying operation. A review of literature and modeled results show that the studied quarrying operation is responsible for significantly less carbon emissions, compared to the emissions related to the production of lime and cement. Additionally, based on a non-linear optimization model, different strategies related to the reduction of the carbon footprint for quarrying operations have been established for the design of blast patterns. These practices can serve as a preliminary way of assessing the direct and indirect carbon footprint related to limestone quarrying for future mining operations. Moreover, the effect of the chosen optimization function has also been studied. It resulted in the conclusion that the vector of the optimal solution based on the direct carbon footprint of the quarry can be biased, compared to the one obtained via the indirect and direct emissions approach.

Keywords: Greenhouse gas emissions, Carbon footprint, Limestone quarrying, Blasting, non-linear optimization

Introduction

Climate change is a global problem that has caused many negative impacts on different regions of the world. Regional flooding, reduced dry season rainfall and irreversible ocean temperature rise are causing catastrophic damage to the marine ecosystem. Scientific developments support the theory that the global climate is changing due to human influence, with the Intergovernmental Panel on Climate Change (IPCC) focusing on 4 human-induced greenhouse gases – carbon dioxide, hydrofluorocarbons, nitrous oxide and methane.

Carbon dioxide (CO_2) emissions, resulting primarily from human activities, have global consequences for ecosystems and the atmosphere. The significant increase in carbon dioxide concentration in recent decades has been associated with global warming, changes in climate conditions, rising sea levels and other adverse effects on biodiversity and human health. In addition, excessively increasing emissions of greenhouse gases into the atmosphere are one of the main drivers of global climate change. Jiao (2023) claims that carbon dioxide emissions account for as much as 80% of total greenhouse emissions, and its amounts are increasing significantly. Moreover, according to this research, carbon dioxide emissions have increased rapidly since 1946, concluding that this is due to the increase in the number of countries involved in industrial development (Jiao,

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2023). Despite the efforts of industry and governments, the concentration of carbon dioxide increases with each subsequent year. The trend is correlated with the overall demand for resources and the gradual growing world population. On the one hand, more energy is required to be produced to meet people's needs, which causes more carbon emissions to be released into the air. On the other hand, humans have to pay the penalty as global warming leads to a series of economic threats. Therefore, climate change and the impact of greenhouse gases draw common global challenges across the regimes of many countries. There is a continuous trend where international efforts aim to address this problem through joint action (Lisaria Putri et al., 2023). Most countries are concerned about global warming and are trying to find methods to minimize greenhouse gases to cope with environmental changes. Many governments around the world and environmental organizations are taking measures and actions to reduce emissions of carbon dioxide and other greenhouse gases. The Paris Agreement, signed on December 12, 2015 in Paris, France, reflects these concerns, as carbon disclosure is part of the contribution of businesses to the environment and climate change, exclusively to global warming. The Paris Agreement is one of the foundational international treaties focusing on greenhouse gas emissions adopted at the United Nations conference. More than 160 developing and developed countries established an international agreement to overcome the problem of global warming. In the agreement, each member country commits to limiting the global temperature increase to 2°C above the temperature since the beginning of the industrial revolution era. The agreement provides for commitments to reduce greenhouse gas emissions by all participating countries, emphasizing adaptation to climate change and financial support for developing countries. In addition, the Paris Agreement provides for a review and transparency system to monitor progress towards the targets. This document is essential in global efforts to address climate change and is recognized as an important tool for cooperation between countries on sustainable development.

Limestone and Its Carbon Footprint

With respect to the global effort of reducing greenhouse gas emissions, this paper examines a raw material with extremely wide application, including among the most carbon intensive sectors. As a rock material that consists primarily of the mineral calcite (calcium carbonate – $CaCO_3$), limestone is usually formed by precipitation from aqueous solutions as a result of the evaporation of water. (Koprev et al., 2018) Industrial sources, including lime production and cement production, contribute significantly to global anthropogenic emissions. The process of producing lime, similar to cement, involves heating limestone in a kiln at high temperatures, releasing CO_2 into the atmosphere. This process also indirectly contributes to CO_2 emissions through fossil fuel combustion used for energy. The extensive global production of lime, around 427 Mt in 2020, is primarily used in the chemical industry, environmental treatment, metallurgical industry, and construction industry. The global uptake of CO_2 from lime production processes is reported to have risen from 9.16 million metric tons of carbon per year in 1930 to 34.84 million metric tons of carbon per year in 2020 (Bing et al., 2023). According to Laveglia et al. (2022) in terms of Global Warming Potential (GWP), 0.94 kg CO2 eq/kg hydrated lime are produced. To some extent, cement also has the same magnitude of its carbon footprint. According to Hendriks et al. (2004) and Lei et al. (2011), 0.5-0.9 kg of CO_2 is evolved for every 1 kg of cement produced, which leads to 3.24 billion tons of CO_2 annually. Moreover, Fayomi et al. (2019) point out that these figures do not take into account the emissions from the quarrying and transportation of raw materials and the transport and delivery of produced cement. Apart from its traditional use for cement, limestone is used in steel manufacturing for slag formation, and its demand is influenced by global steel production levels. For the production of 1 t of crude steel, the two key steel production routes using integrated steelmaking and the electric arc furnace require around 270 kg and 88 kg of limestone, respectively. Notably, China, as the largest steel producer, experienced reduced steel production due to policy changes aimed at reducing pollution levels. The United States and Germany also saw changes in steel production. Additionally, limestone is utilized in iron production as a fluxing agent to remove impurities and enhance the efficiency of the blast furnace process.

Limestone in the context of quarrying operations' carbon emissions is not sufficiently studied in the scientific literature, which further strengthened the interest of the authors. One reason behind this, is that limestone as a product from the aggregate industry is associated with substantially less greenhouse gas emissions, compared to its use as a raw material for cement, lime or steel manufacturing. (Hristova, 2022) Multiple reports of the environmental impact of quarrying sites show that the overall GHG emissions range roughly between 1.5 to 5 kg of CO_2-equivalent (Environmental Product Declaration for limestone aggregates Xirorema Quarry; Winstone Aggregates Environmental Product Declaration For Aggregate and Sand Products, 2022; Eigenrieden Quarry: Climate neutrality in the extraction of raw material; EVA025 –Final Report: Aggregates Industry Life Cycle Assessment Model: Modelling Tools and Case Studies, 2009; Environmental Product Declaration for aggregates from Nyrand gravel pit – Svebølle, 2021). Regardless of the small relative impact of a single quarry, the problem regarding the carbon footprint of the quarrying industry itself also needs to be formalized as global limestone exports are forecast to reach 1.04 billion tons by 2029 (Limestone Market Size & Share Analysis - Growth Trends & Forecasts (2024 - 2029)). Since 2019, the market was negatively affected by the COVID-19 pandemic due to disruptions in manufacturing and supply chains, but it has been recovering with increasing demand from industries like construction, steel production, agriculture, and water treatment. Short-term market drivers include rising demand from the construction industry and increasing global steel production, while health risks associated with limestone consumption and high carbon dioxide emissions may hinder market growth. The Asia-Pacific region is expected to lead the market, and upcoming global wastewater treatment projects are likely to create growth opportunities. India possesses abundant and high-quality limestone reserves across its area, which has positioned India as the second-largest producer of cement in the global market. Due to population growth and the central government's liberalization policies, there has been a significant increase in the mining of limestone rocks to meet social demands (Somayajula et al., 2021). Based on the established literature review, an overview of the key technological processes which influence the production of limestone and their direct or indirect relationship with GHG emissions is provided in Fig. 1.

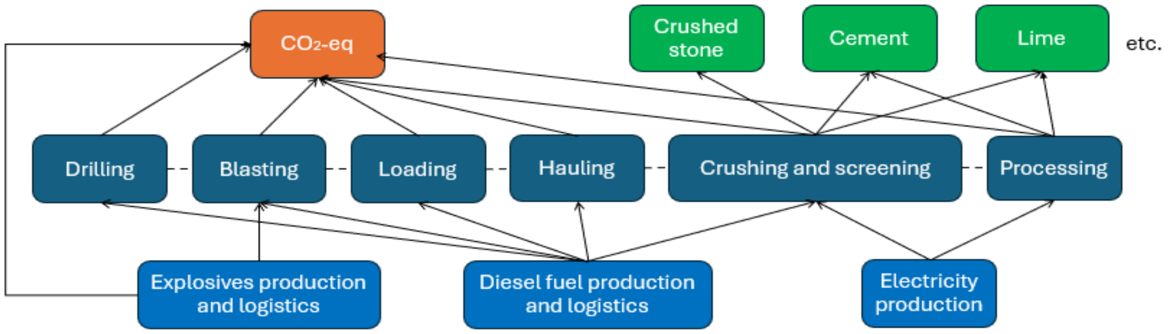

Figure. 1. A network model of the direct and indirect GHG emissions related to limestone quarrying and processing

Certain site-specific details such as selected mining technology, energy sources, equipment used, stages of crushing and screening and end-product designation are all factors which affect the overall carbon footprint for each quarrying operation. If coal is used as an energy source for the provision of electrical power for limestone processing, the emissions from this process will be significant. Alternatively, using cleaner energy sources such as gas or renewables can reduce the carbon impact. Taking into consideration the end-product's designation, applying more efficient and cleaner extraction technologies can reduce carbon emissions, for example during the production of cement or lime. Last but not least, effective treatment and management of waste from limestone mining can have a significant impact on emissions. Study by Yankova (2020) highlight the key issues related to mining and mineral processing waste, particularly focusing on tailing storage, reducing the amount of mining waste, and ensuring safe storage practices. If the process includes waste reduction methods or the use of waste storage or processing technologies, this can contribute to reducing the negative impact on the environment. Mining and mineral processing general significant quantities of waste that pose environmental and health risks if not properly managed. Therefore, effective waste management is essential for sustainable development in the mining industry (Tomova & Kisyov, 2023). At the same time, if more sophisticated ways of reclaiming depleted deposits are being applied, this could temporarily increase the amount of GHG emissions due to the more extensive use of diesel-powered equipment for earthwork operations and land reclamation. Despite that in due time this effect can be negated. Hence, the process of providing a generalized model for the evaluation of the carbon footprint of a quarrying operation is a highly complex task and can be dependent on a large set of decision variables. However, given that certain initial assumptions are made, a preliminary assessment of the GHG emissions based on their typical sources can be provided.

Assumed Methodology for Calculating the Variable GHG Emissions

Blasting is one of the key processes related to the extraction of limestone as the level of fragmentation can lead to a substantial increase in the time, energy and fuel consumption for the down-stream operations. (Georgiev et al, 2018) Hence, its planning has a crucial role not only for optimizing the cost model of the quarrying operation, but also for the reduction of its carbon footprint. In the context of this paper, the fundamental mining and processing operations related to a limestone quarry were considered, including drilling, blasting, loading, hauling, crushing and screening. To evaluate the correspondence between variable costs and variable GHG emissions, a typical small-scale quarrying operation with an annual output rate of 200 000 t of mined limestone was analyzed. It should be noted that this methodology can be considered as a preliminary one, as it relies primarily on theoretical calculations, well-established empirical models and other site-specific empirical formulae, which provide additional ways to take into account the non-linear relationship between certain variables. A table denoting the assumed methods for estimating different technological parameters with respect to the applied methodology for preliminary assessment is provided (Table 1).

Table 1. Assumed methodology for estimating key modelled parameters

Parameter	Estimation method	Reference
Drilling rate	$Drilling\ rate = \frac{0.1759 \times B_c^2 - 5.8579 \times B_c + 48.86}{\left[\pi \times (D/1000)^2\right]/4}$ B_c – blasting coefficient, $B_c = \sigma_c / T_s$ σ_c – uniaxial compressive strength, MPa T_s – tensile strength, MPa D – blasthole diameter, mm **Note: Drilling rate formula is adjusted from m³/h to m/h**	Shehu et al., 2019
Bucket fill factor	$Bucket\ fill\ factor = 0.9833 - 0.00022 \times X_{50}$ **Note: Formula is adjusted for X_{50} measured in mm**	Ozdemir and Kumral, 2019
Bucket swell factor	$Bucket\ swell\ factor = -1.1776 \times Bucket\ fill\ factor + 2.4564$ **Note: Formula is transformed from original paper to use *Fill factor* as argument**	Kujundžić et al., 2021
Dig time	$Dig\ time = a - b \times X_{50} \times n$ a = 8.9942 b = -0.06.8706E-2	Doktan, 2001
Crushing energy	$W = 10.W_i \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}} \right)$ W – specific energy, kWh/t W*i* – Bond work index, kWh/t P – 80% passing sizes in the product of the crusher, μm F – 80% passing sizes in the feed of the crusher, μm	Bond, 1952
Equipment fuel consumption	$q_d = P \times k_o \times s_d$ P – rated engine power, kW k_o – engine load factor, s_d – specific fuel consumption, kg/(kWh)	Stefanović, 1980; Klanfar et al., 2016
Blasted rock fragmentation distribution	$X_{50} = 10 \times A \times \left(\frac{V_o}{Q_e} \right)^{0.8} \times Q_e^{1/6} \times \left(\frac{S_e}{115} \right)^{-19/30}$ $n = \left[2.2 - 14 \left(\frac{B}{D} \right) \right] \times \left[\frac{1 + \left(S/B \right)}{2} \right]^{0.5} \times \left[\left(1 - \frac{W}{B} \right) \times \left(\frac{L}{H} \right) \right]$ $P = 100 \times \left[1 - e^{-0.693 \left(X/X_{50} \right)^n} \right]$ X_{50} – mean fragment size, mm n – uniformity index of rock fragments granular size distribution A – rock factor P – rock fragments percentage passing an X-sized mesh sieve, % V_o – volume of the rock per blast hole, m³ Q_e – explosive charge mass per blast hole, kg S_e – relative weight strength of the explosive compared to ANFO B – burden, m S – spacing, m W – drilling standard deviation, m L – drillhole length, m H – bench height, m	Kuznetsov, 1973; Cunningham, 1999; Rosin and Rammler, 1933

Indeed, some models can be improved with site-specific formulations. However, for the purpose of preliminary estimation they can be considered sufficient. Nonetheless, these methods were implemented as a computer script, based on the Python programming language for the purpose of investigating different scenarios. Table 2 shows the utilized mining equipment for the quarry. Other site-specific key input parameters used for the scripted model are shown in Table 3.

Table 2. Input parameters for the equipment used for the studied quarry

Equipment	**Model**	**Engine power, kW**	**Load-specific fuel consumption, l/kWh**
Production drill rig	Atlas Copco ROC F9	224	0.20
Excavator	Caterpillar 330D L	200	0.14
Haul truck	Man 41.403	179	0.06

Table 3. Site-specific input parameters for the model

Parameter group	**Parameter**	**Value**
Overall conversion factors	Diesel price, EUR/l	1.65
	Carbon emission conversion factor for diesel fuel, kg CO_2-eq./l	2.67
	Carbon emission conversion factor for diesel fuel (including production and logistics), kg CO_2-eq./l	3.31
Explosive properties	Explosive type	ANFO
	Explosive density, g/cm³	0.80
	Direct GHG emissions from explosive detonation, kg CO_2-eq./kg	0.20
	Indirect GHG emissions from the production of bulk explosives, kg CO_2-eq./kg	1.60
	Indirect GHG emissions from the logistics of bulk explosives, kg CO_2-eq./kg	0.10
Rock mass and rock properties	Rock factor (A)	8.04
	Limestone density, t/m³	2.64
	Bond work index	13.00
Blast panel geometry	Blast panel length, m	50
	Blast panel width, m	15
	Slope height, m	10
	Slope angle, °	70
Drilling	Blasthole diameter, mm	110
Excavator	Bucket capacity, m³	2.07
Haul truck	Average truck speed, km/h	20
	Haul distance, km	0.6
	Haul truck capacity, m³	6
	Haul truck payload, t	15
Crushing and Screening	Oversize threshold value, mm	600
	Product 80% passing size, mm	20
	Material output rate, t/h	200

As it can be observed, the indirect variable GHG emissions are taking into account the production of diesel fuel and bulk explosive, both used as consumables over the life of mine. However, the GHG emissions provided by the explosives used for initiation were not used for this case study as they are practically negligible compared to the scale of the other emissions. It should be noted that hauling of crushed limestone and processing to a final product are not included in the analysis as they are site-specific. Moreover, costs and GHG emissions related to them can be assumed to be non-variable as they are independent of the selected mining technology. (Dimov et al, 2020) Indeed, the choice of belt conveyer, mineral and chemical processing methods for the crushed limestone can also significantly impact the amount of GHG emissions. However, this requires an additional study, as this paper primarily focuses on the quarrying operation. Hence, considering all provided input variables and all assumed empirical methods, the optimization problem can be defined as follows:

Objective function:

Alternative 1 - Minimize the Total variable costs OR
Alternative 2 - Minimize the *Direct total variable CO_2-eq. emissions* OR
Alternative 3 - Minimize the *Direct and Indirect total variable CO_2-eq. emissions* OR
Alternative 4 - Minimize the *Total use of bulk explosive*

Decision variables:

1) Burden
2) Spacing
3) Subdrilling
4) Stemming

Constraints:
1) Fly rock radius ≤ Designated area of effect radius AND
2) Airblast radius ≤ Designated area of effect radius AND
3) $Burden_{min} \leq \underline{Burden} \leq Burden_{max}$ AND
4) $Spacing_{min} \leq \underline{Spacing} \leq Spacing_{max}$ AND
5) $Subdrilling_{min} \leq \underline{Subdrilling} \leq Subdrilling_{max}$ AND
6) $Stemming_{min} \leq \underline{Stemming} \leq Stemming_{max}$ AND
7) $KB_{min} \leq \underline{KB} \leq KB_{max}$ AND
8) $KH_{min} \leq \underline{KH} \leq KB_{max}$ AND
9) $KS_{min} \leq \underline{KS} \leq KS_{max}$ AND
10) $KJ_{min} \leq \underline{KJ} \leq KJ_{max}$ AND
11) $KT_{min} \leq \underline{KT} \leq KT_{max}$ AND
12) $0 \leq \underline{Oversize} \leq 5\ \%$

Notation:
KB – Burden to Blasthole Diameter ratio
KH –Bench height to burden ratio (Stiffness ratio)
KS – Spacing to Burden ratio
KJ – Subdrilling to Blasthole Diameter ratio
KT – Subdrilling to Burden ratio

Traditionally, the KJ coefficient is used for denoting the ratio between the Subdrilling and Burden (Konya and Konya, 2019). However, for this case study the ratio related to the blasthole diameter is taken into consideration, following one of the rules of thumb, provided by Dyno Nobel (Blasting and Explosives Quick Reference Guide, 2010). Table 4 shows the assumed values for the upper and lower bound of each of the constraints and decision variables.

Table 4. Assumed constraints for the decision variables and their respective domain

Constraint	Measure	Min	Max
Fly rock hazard radius	m	0	450
Airblast hazard radius	m	0	450
KB	-	20.00	40.00
KH	-	1.50	4.00
KS	-	1.00	2.00
KJ	-	3.00	15.00
KT	-	0.75	1.00
Burden	m	2.00	6.00
Spacing	m	2.00	6.00
Subdrilling	m	0.40	0.70
Stemming	m	2.00	5.00
Oversize	%	0.00	5.00

The set of constraints for the objective function can include additional limitations considering different economic, ecological, social or safety concerns. For example, if the seismic effect of blasting requires to be reduced, an additional constraint regarding the quantity of the charge mass for a single or multiple blastholes can also be included. Another constraint for the model can include the rock fragment size for the 80th percentile (X_{80} or D_{80}) of the rock fragmentation distribution or the total amount of gas products for the blast. In addition, some of the assumed constraints can be adjusted, depending on the specific quarrying conditions and the applied rules of thumb and empirical considerations. One such example is the set of constraints regarding the calculation of blast design parameters and the respective intervals of the k-factors. Alternatively, other parameters can also be used for the objective function for the sake of simplicity and depending on data availability. However, they should be analyzed in terms of their capability of addressing the actual carbon footprint in an indirect way. The total amount of explosive used is an integral parameter which bins the GHG gas emission volume, measured by the mass of CO_2-equivalent emissions (kg CO_2-eq.), with the total volume of toxic gases, measured by the carbon monoxide (CO) toxicity equivalent. Essentially both parameters are dependent on the amount of explosive used in the blast, however, each gas product has a different weight in either of the two formulations. Hence, the objective function based on the total amount of explosive is expected to have a certain amount of bias compared to the ecological or safety interpretation of the parameter.

Results

The applied algorithm for solving the optimization problem was grid search, as it also provides a way to sample the solution space for estimating other non-apparent dependencies between the input parameters. The assumed grid for the algorithm allowed for reaching a precision of 0.05 m for each decision variable (Burden, Spacing, Subdrilling and Stemming). For this current iteration of the problem, the solutions yielded by the grid search algorithm based on the four alternatives of the objective function are shown in Table 5.

Table 5. Solutions from the considered objective function alternatives

Parameter	**Objective function alternative 1**	**Objective function alternative 2**	**Objective function alternative 3**	**Objective function alternative 4**
Burden, m	3.05	3.05	3.05	2.55
Spacing, m	3.15	3.15	3.05	4.55
Subdrilling, m	0.70	0.70	0.60	0.45
Stemming, m	2.30	2.30	2.30	2.05
X_{50}, mm	243.48	243.48	239.08	283.15
X_{80}, mm	407.97	407.97	404.83	434.81
Oversize, %	4.88	4.88	4.88	4.83
Powder factor, kg/m³	0.665	0.665	0.678	0.550
Carbon footprint, kg CO_2-eq./t	1.8908	1.8908	1.2500	1.9373

The sampled points from the solution space grid from the Direct GHG emissions was analyzed for the purpose of providing an explanation for the difference between both solutions. A comparison of the results of the Direct GHG emissions model with the Indirect and Direct GHG emissions model can be seen on Fig. 2.

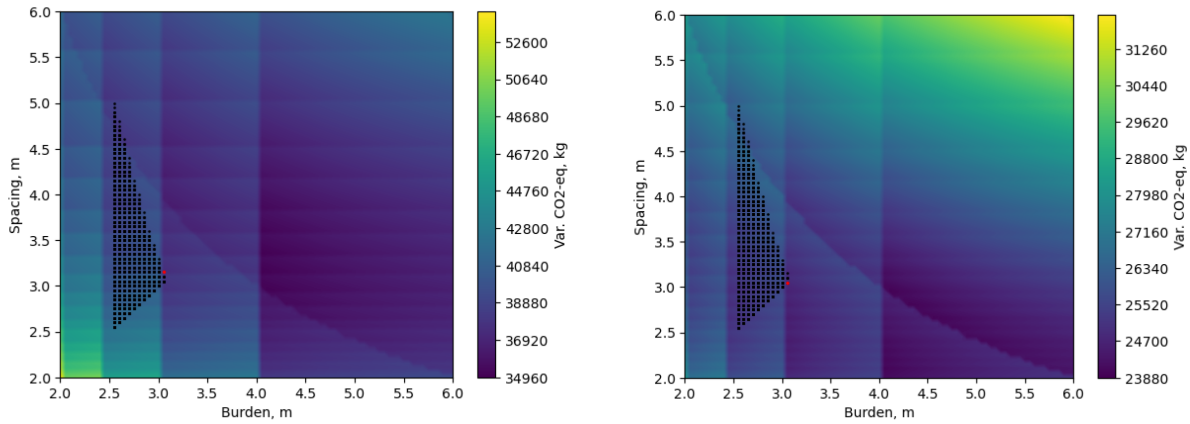

Figure. 2. Obtained solution from the set of feasible solutions and their indirect and direct GHG emissions (left-hand graph) and direct GHG emissions (right-hand graph)

It should be noted that both graphs assume that the Subdrilling has a constant value of 0.70 m, while the Stemming has a constant value of 2.30 m. As it can be observed, the objective function in both cases is piecewise with multiple local extrema. In addition, the objective function for the Direct GHG emissions model signifies that scarce blasting patterns lead to an increased carbon footprint due to the increase of the operational time for loading and hauling, resulting from the increased mean fragment size. However, this affect is dampened severely when the indirect GHG emissions are considered. This is a direct result from the decreased carbon footprint from the manufacturing of ANFO as a scarce blasting pattern is associated with less consumption and demand of bulk explosive. As a direct result of this crucial difference, both objective functions have different solutions with respect to the set of constraints. Moreover, the global extrema in both cases are conditional, as they lie in either of the boundaries from the set of constraints. Hence, sensitivity analysis can prove to be crucial in order to see whether certain constraints can be relaxed for the purpose of obtaining a better solution. A correlation matrix is provided for the approach considering both Indirect and direct GHG emissions, as shown in Fig. 3.

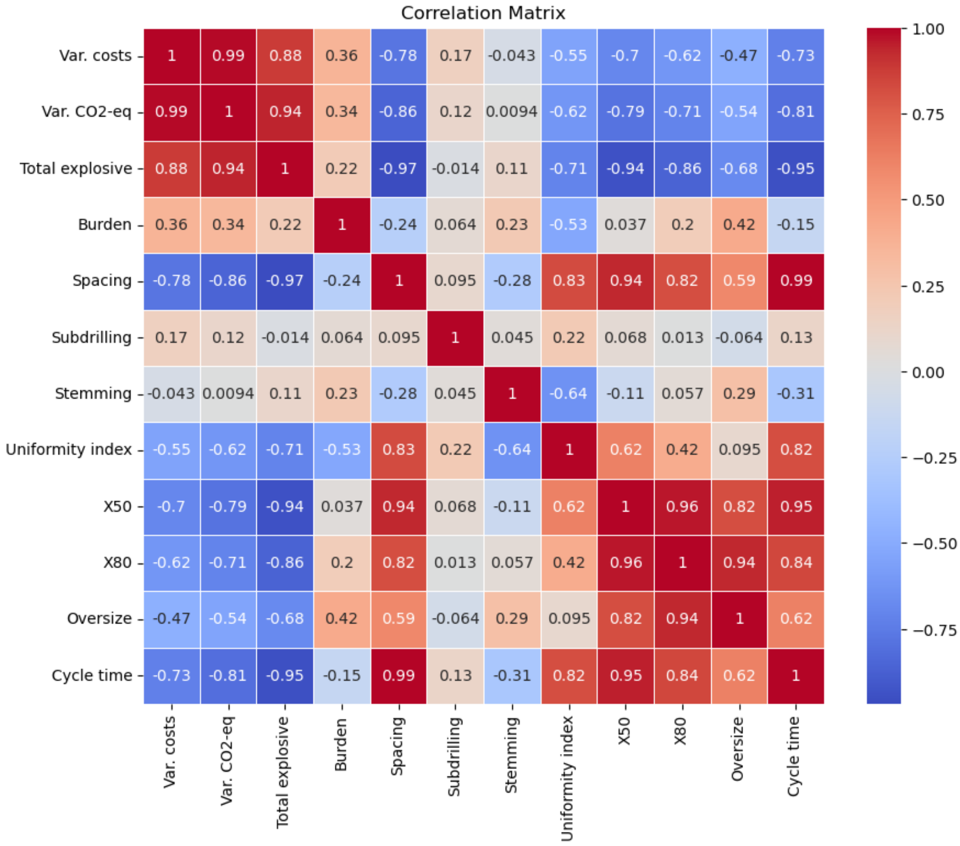

Figure. 3. Spearman correlation matrix based on Indirect and direct GHG emissions from the quarrying model

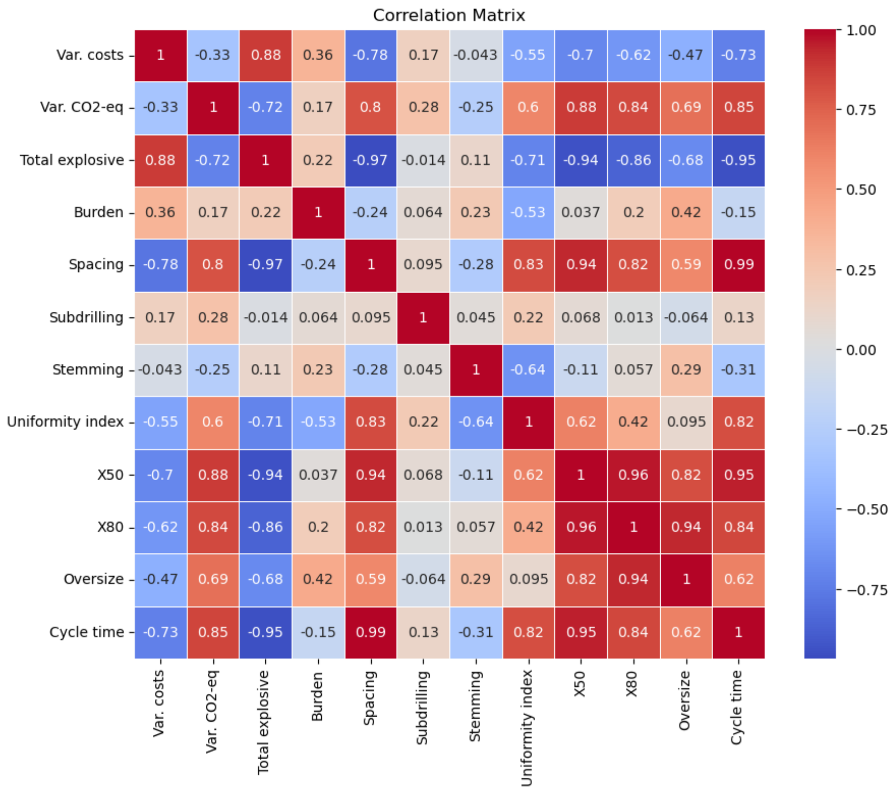

Figure. 4. Spearman correlation matrix based on direct GHG emissions from the quarrying model

Based on the established theoretical model, it can be observed that the Total mass of bulk explosive, the Variable costs and the variable GHG emissions in CO_2-equivalent are strongly correlated. Hence, minimizing one objective can lead to the minimization of the other two objectives as well. However, it should be investigated whether the same optimal solution is reached in all cases and whether using one objective as a substitute for another would be robust. The reason behind this approach is for the sake of simplifying the objective function to a less complex one. A further observation worth mentioning regards the Mean fragment size (X_{50}) estimated via the Kuz-Ram model. As seen from the correlation matrix, it can be assumed to be a good predictor for the Indirect and Direct variable CO_2-equivalent GHG emissions and vice versa. Hence, its potential needs to be further investigated in real-life scenarios based on empirical data. It should also be noted that the correlation coefficient values are sensitive to the assumed economic model. This also implies that the correlation values between the objective function can vary depending on the assumed mining technology for the quarrying operation, as well as the available equipment. Contrary to the Indirect and Direct emissions approach, the Mean fragment size for the Direct emissions approach is positively correlated with the variable GHG emissions (Fig. 4).

Hence the estimation of the direct carbon footprint of the quarry shows that the GHG emissions which predominantly constitute the Direct GHG emissions are related to downstream activities following the primary fragmentation of rocks. Similarly, the variable GHG emissions tend to be negatively correlated with the total variable costs in this case. Therefore, this can serve as a solid proof of the inherent bias behind the Direct emissions approach, given that the amount of GHG emissions from the production of diesel fuel and explosives are not taken into account. This conclusion that the indirect GHG emissions can affect the choice of drilling pattern is further supported by the pie charts, as shown in Fig. 5.

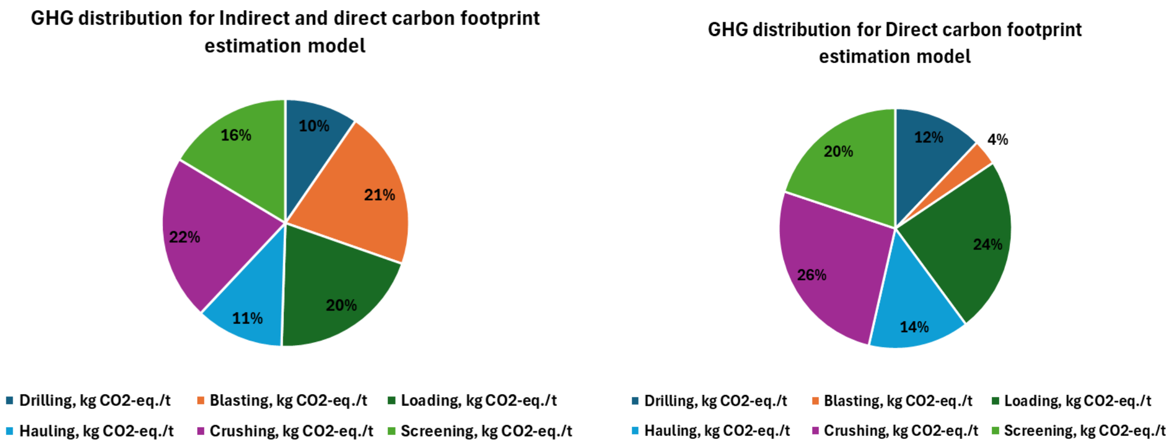

Figure. 5. Pie charts of different operations constituting the Indirect and direct GHG emissions (left-hand graph) and the direct GHG emissions (right-hand graph) from the quarrying model

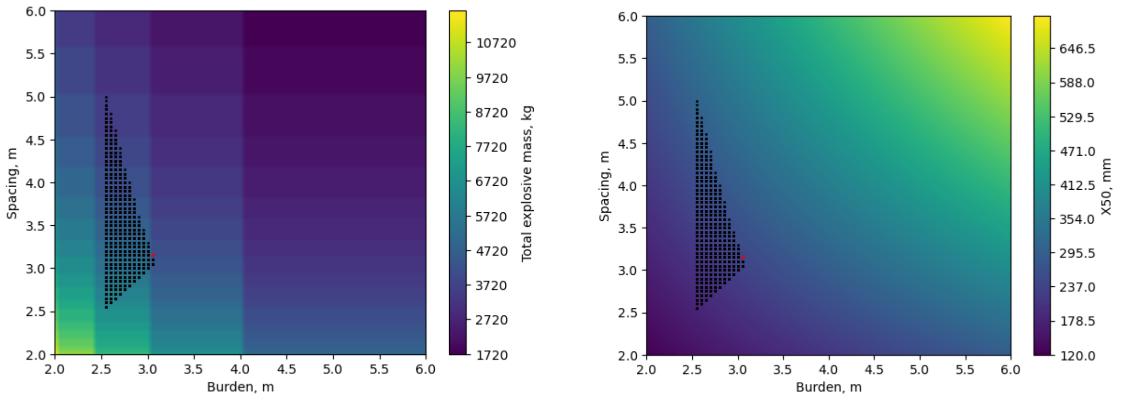

Figure. 6. Obtained solution from the set of feasible solutions and their respective Total explosive mass (left-hand graph) and mean fragment size – X_{50} (right-hand graph)

As charging rules for the blastholes are less prone to change due to safety and practical concerns, the Burden and Spacing parameters are less constrained than them. Therefore, a viable strategy for optimizing the results yielded by the quarrying operation would lead to the adjustment of the drilling pattern, be that to a denser one, depending on the goal of the engineer. Fig. 6 shows the obtained solutions with the Total explosive mass (in kilograms) and Mean rock fragment size (X_{50}), based on different drill pattern designs allowed by the set of constraints. It should be noted that the red point for both graphs denotes the optimal solution for objective functions 1 and 2. Once more, it is assumed that the Subdrilling has a constant value of 0.70 m, while the Stemming has a constant value of 2.30 m for the graphs.

Regardless of the high correlation coefficient value between the Total explosive mass and the Mean fragment size with the Direct and indirect GHG emissions, they cannot be efficiently exploited as parameters for the objective function. The reason behind this conclusion is that the optimal solution from objective function 1 and 2 does not coincide with the minimum value in both respective solution spaces. Hence, their application in a real-life environment remains only to serve as a potentially good predictor of the GHG emissions or vice versa after the introduction of a noise component to their relation. A comparison of the carbon footprint of the quarrying operation in terms of both approaches can be seen on Fig. 7.

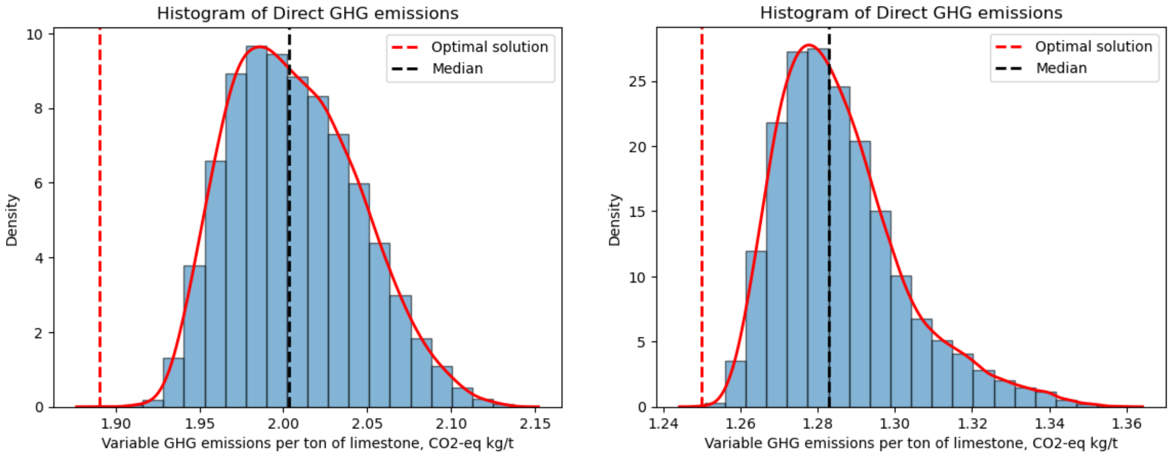

Figure. 7. Estimated indirect and direct GHG emissions (left-hand graph) and direct GHG emissions (right-hand graph) related to the theoretical model

Based on the theoretical model, a reduction of 5.61% (0.1124 kg CO_2-eq. per ton of limestone) can be expected from the median emissions from the set of all possible drillhole patterns, constrained by the assumed set of parameters. The median value was used as a measure of the central tendency of possible GHG emissions per ton of limestone for a single blast, given that no optimization is applied. Hence, an optimization approach is crucial for reducing the carbon impact of quarrying operations. The maximum estimated reduction from the model is 11.52% (0.2463 kg CO_2-eq./t) for the Indirect and Direct GHG emissions approach. It should also be pointed out that there is a substantial difference in the distribution of the GHG emissions' distribution for both approaches. This can be interpreted that regardless of what drilling pattern is applied for the quarry, there is a small likelihood of increasing the direct carbon footprint of the quarry. However, should the indirect emissions be taken into considerations, the likelihood of notably increasing the carbon footprint increases. Once more, this signifies the inherent bias for the Direct GHG emissions approach. Furthermore, each design decision regarding the quarrying operation, such as the case for the choice of drilling pattern, magnifies its effect in the domain of the overall GHG emissions model.

Discussion and Future Work

First and foremost, it should be noted that the optimization function is highly sensitive to the assumed economic model and GHG emissions model. Hence, a robust theoretic background and empirical data is mandatory for its correct definition. Although the proposed model establishes the non-linear dependency of the variable costs and variable GHG emissions with rock fragmentation, further adjustments are required for a more precise approximation of their actual relation. Moreover, a data-driven approach can provide to be a crucial tool for establishing certain individualities of the conditions for each quarry, which can be further implemented in the objective function. Nonetheless, using well-established theoretic or empirical formulae, based on similar mining sites, can be a starting point for building such models for a preliminary assessment, which can be further adjusted and built-on during the life of mine or quarrying operation. Regarding the choice of optimization function, there are certain cases, where the optimal solution vector is invariant to the application of a simpler or more complex model, taking into account the direct and indirect impact of the quarry. However, this was not the case in this paper. Hence, it is recommended that a sensitivity analysis is performed before using a more sophisticated model in order to gain an initial understanding of which parameters tend to be invariant to changes in a certain set of inputs. Last but not least, based on the results yielded by this case study, it can be established that the optimization problem is a non-convex one. Moreover, the objective function is piecewise with multiple local extrema. Hence, this would require the use of other non-linear optimization algorithms for improving the computation time compared to the grid search method. Therefore, the performance and reliability of different non-linear optimization algorithms should be investigated, as this would allow for the optimization problem to be solved automatically for different alternative scenarios in the context of a more complex optimization problem. Furthermore, as the optimal solution tends to be a conditional extremum, a more robust analysis should be made regarding the set of applied constraints for ranking them depending on their impact on the overall solution. Last but not least, additional environmental criteria can be adopted to the model for a more generalized approach regarding the quarrying operation's impact.

Conclusions

Results from this case study show that limestone quarrying has a significantly lower GHG emissions per ton of product, compared to the production of lime or cement. This is further supported by actual reports of quarrying sites, which yield similar values in terms of their overall carbon footprint to the ones obtained from the model used for preliminary assessment. However, due to the large number of quarrying sites and the substantial worldwide demand of limestone, quarrying operations also require attention for the purpose of reducing the overall carbon footprint, related to limestone. Moreover, taking into account and evaluating the impact of indirect CO_2-equivalent GHG emissions proved to be crucial for estimating the actual reduction of the quarrying carbon footprint from blasting activities. The results from the preliminary estimations lead to the conclusion that optimizing the blast pattern and charging rules for each drillhole can lead to the reduction of the carbon footprint of the quarry by up to 11.52%. Should the median of the GHG emissions (measured in kg CO_2-eq.) per ton of crushed limestone from the set of constrained solutions be taken as a reference, the carbon footprint can be estimated to be 5.61% lower. Hence, an optimization approach is crucial for quarrying operations. Apart from the reduced GHG emissions, a decrease in the variable operational costs is also expected, as they are strongly correlated with the variable GHG emissions. Last but not least, using a more simplified formulation of the objective function, which takes into account only the direct GHG emissions, can lead to a biased solution compared to the one obtained from the overall (direct and indirect) GHG emissions. Hence, it is essential that each quarry should indeed be considered both as a producer and a consumer for obtaining a more robust assessment of its carbon footprint.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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