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Optimal pitwall profiles to maximise the overall slope angle of open pit mines: the McLaughlin Mine

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Abstract

The overall slope angle (OSA) of pit walls plays a crucial role in the financial return of open pit mines. The paper showcases a novel design methodology where non-planar geotechnically optimal pit walls with an OSA steeper than what is used in current design practices are employed without compromising mine safety, i.e. the optimal profiles are featured by the same Factor of Safety (FoS) than their traditional design counterparts.

In the current design practice, pit wall profiles are often designed to be planar in cross-section and the profile in between ramps especially tend to be planar and defined by a constant inter-ramp angle. Sometimes rock layers exhibiting different strengths require the inclination of a pitwall to vary with depth, but the inclination across each layer is usually constant. In this study, a new proprietary slope design software, OptimalSlope, is employed to determine geotechnically optimal pitwall profiles of depth varying inclination for the design of each sector of the mine. OptimalSlope seeks the solution of a mathematical optimisation problem where the overall steepness of the pitwall, from crest to toe, is maximised for an assigned lithology, rock properties, and FoS. Bench geometries (bench height, face inclination, minimum berm width) are imposed in the optimisation as constraints that bind the maximum local inclination of the sought optimal profile, together with any other constraints such as geological discontinuities that may influence slope failure. The obtained optimal profiles are always steeper than their planar counterparts (i.e. the planar profiles exhibiting the same FoS) up to 8° depending on rock type and severity of constraints on local inclinations. The adoption of overall steeper profiles leads to a reduction in the amount of waste rock and, consequently, the stripping ratio.

This paper presents the results obtained from the design of three open pit mines, each characterised by different rock types and metal ores (copper and gold). The case study of the McLaughlin Mine, whose block model data are publicly available from the repository MineLib, is presented in detail whereas for the other two case studies already published elsewhere, a brief summary of the results is provided. To quantify the improvement obtained by adopting geotechnically optimal profiles, we performed two designs: one employing planar pit walls and another one adopting the optimal pitwall profiles determined by OptimalSlope. In determining the ultimate pit limit (UPL) and pushbacks, we sought to maximise the net present value (NPV) and achieve an annual production schedule as uniform as possible over the mine lifetime. The FoS adopted for both planar and optimal pitwall is the same, with verifications performed by limit equilibrium method (LEM) analyses (Morgenstein–Price method) run in Rocscience Slide2 and finite difference method analyses with strength reduction technique run in FLAC3D on the 2D UPL sections. Also, a 3D stability analysis of the entire UPL was performed in FLAC3D.

For each mine, we assess both financial gains (in terms of NPV) and environmental gains (measuring the reduction in carbon footprint and energy consumption). It emerges that the adoption of optimal profiles realises gains up to 52.7% NPV and substantial reductions of carbon footprint and energy consumption.

Keywords: *OptimalSlope, open pit mine design, optimal pit walls, NPV optimisation, stripping ratio reduction, carbon footprint reduction*

1 Introduction

In open pit mining there is a clear trend of excavating mines of increasing depths from less than 50 m deep in the 1920s to more than 1 km in recent years (Brown 2004). Owing to the increased efficiency of mining equipment and improved exploration techniques and technology, the orebodies left to be exploited reach depths of even 2,000 km from the ground surface (Randolph 2011). The deeper a mine, the higher the effect of pit wall steepness on the amount of waste rock to be excavated and, therefore, mine profitability (Hustrulid et al. 2013). Hence, designing pit walls to be as steep as feasible has never been more important.

Anecdotal evidence that a slope profile non-linear in cross-section, i.e. a profile whose inclination varies with depth, is better than a linear one, i.e. a planar profile, was reported as far back as 1890 (Newman 1890). The author observed that cuttings of concave shape excavated through homogeneous clay layers tended to be more stable than planar ones with the same OSA, which are more stable than cuttings of convex shape (Figure 1a). Decades later, Hoek & Bray (1977) analysed the stability of some concave circular slopes in cross-section. Assuming the slopes to be excavated in a homogeneous rock layer, and using the Mohr–Coulomb (M–C) failure criterion to characterise its strength, they found a higher Factor of Safety (FoS) for circular profiles than for their planar counterparts, i.e. the planar slopes with the same OSA which share the same toe and crest points. The first systematic theoretical study on the mechanical properties of concave slope profiles for geomaterials exhibiting some cohesion, so applicable to all rocks and clayey soils, appeared in Utili & Nova (2007). In that study, the superior stability of a profile that follows a logarithmic spiral (a spiral curve characterised by a radius of curvature that increases with the depth of excavation), over their planar counterparts was systematically proven. They show that log-spiral profiles exhibit higher FoS than their planar counterparts for any value of cohesive (c) and frictional strength (ϕ) considered. Since then, other researchers (Jeldes et al. 2015; Vahedifard et al. 2016; Vo & Russell 2017) have independently investigated the stability of $c-\phi$ concave profiles, employing different methods, in order: the slip line method, limit equilibrium methods, and finite elements. They all reached the same conclusion concerning the superior stability of non-linear concave profiles.

However, a fundamental limitation of these studies is the assumption of a specific shape, either a circle (Vahedifard et al. 2016), a log-spiral (Utili & Nova 2007), or a curve stemming from the slip line field theory and the associated characteristic equations (Jeldes et al. 2015). Therefore, the shape claimed to be optimal is associated with the highest stability number among curves belonging to a very restricted family. Obviously, these profiles are suboptimal, and their shape could be very different from the truly optimal one. In case of c - ϕ slopes, the optimal shape calculated by OptimalSlope (Utili 2016) turns out to be partly concave and partly convex (Figure 1b), and it is significantly different from the purely concave shapes considered in previous literature. Another perhaps even more critical limitation, which is present in all the methods mentioned above, is the assumption of uniform slope. This simplification prevents the application of these findings to real open pit mines typically featured by complex lithologies involving multiple rock formations of different mechanical strengths and various geological discontinuities.

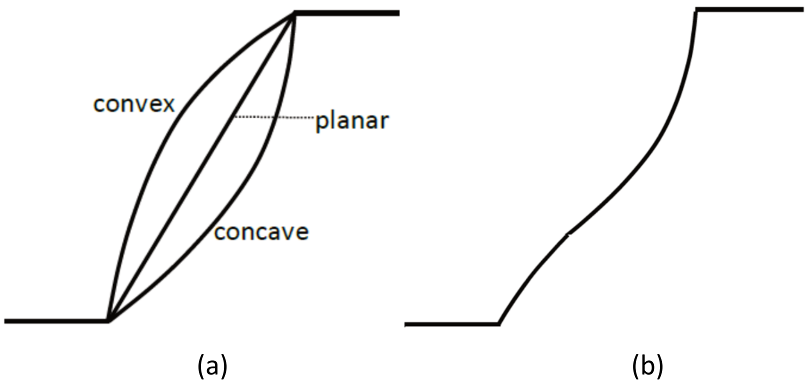


Figure 1 Slopes of different shapes: (a) A concave, planar, and convex slope profile with the same overall slope angle; (b) Optimal profile partly concave and partly convex obtained by OptimalSlope for a uniform layer

OptimalSlope exploits the fact that slope failures occur either as a rotational mechanism (a planar failure being a particular type of rotational failure with an infinite radius of curvature) or mechanisms whose kinematics are dictated by the presence of discontinuities (e.g. the interface between two rock layers, a fault, joints, beddings, etc.). For a homogeneous slope in a c - ϕ geomaterial, the limit analysis upper bound method allows one to find the critical rotational mechanism by determining the minimum of an analytical objective function without requiring any discretisation of the slope into finite elements (Chen 1975). The function is obtained by imposing the energy balance between the external work done by the mass of the candidate failure mechanism and the energy dissipated along its failure surfaces. The equation has been extended to find the critical mechanism for piecewise linear slope profiles in a uniform layer and then to layered slopes. Moreover, the formulation has been extended to slopes in rocks obeying the Generalised Hoek–Brown (G–H–B) failure criterion (Hoek et al. 2002). The minimum of the function stemming from the energy balance equation, and therefore the critical mechanism is found by OptimalSlope using a proprietary optimisation algorithm (Utili 2016).

In the excavation of an open pit, several rock formations of different strengths are usually encountered. OptimalSlope can find the optimal profile for any specified lithological sequence (any number of layers can be specified as input with each layer strength characterised by either M–C or G–H–B parameters) without unduly restricting the search to any predefined family of shapes. The optimal slope profile is found as the solution of a mathematical optimisation problem where the OSA of the slope, i.e. the inclination from slope crest to toe, is maximised for an assigned stratigraphy, rock strength properties and a prescribed FoS. Geometric requirements stemming from bench sizes (bench height, bench face inclination, minimum berm width and road width) are imposed as constraints binding the maximum local inclination of the sought optimal profile together with any other geometric constraint, e.g. constraints to prevent the occurrence of local failure mechanisms due to geological discontinuities such as faults and joints.

In the next section of the paper, we describe a case study of an old but well known mine closed in the early 2000s to demonstrate the financial and environmental benefits of adopting optimal profiles for mine pit walls. A key reason for choosing this mine is the public availability of its block model thanks to the MineLib repository, this means that the calculations reported herein can be easily reproduced by anyone. Then, Section 3 illustrates the methodology employed, followed by results (where we also summarise the benefits of employing OptimalSlope in more complex case studies), and conclusions.

2 Case study: McLaughlin Mine

The deposit employed in this study is available from MineLib (http://mansci-web.uai.cl/minelib/mclaughlin.xhtml), a publicly available library of problem instances for open pit mining (Espinoza et al. 2013). McLaughlin is an abandoned gold mine discovered by Homestake Mining Company in 1978 (Lehrman 1986) located in the northern Coast Ranges of California. Gold was discovered during an exploration program to study gold mineralisation in mercury districts (Sherlock et al. 1995). The mine is under reclamation since 2002. The block model geometry is as follows: blocks of 7.62 × 7.62 × 6.91 m (regular throughout the whole model), total model dimension 1,066.8 × 2,255.5 × 414.5 m, total number of blocks equal to 2,140,342. All the parameters needed to perform the pit design were taken from MineLib except the incremental mining cost per bench and the initial capital cost, which were estimated for this study. Unfortunately, no geotechnical characterisation of the rock properties is available. However, given the available knowledge of the geotechnical setting (Lehrman 1986; Sherlock et al. 1995) and the UPL geometry provided in the 'McLaughlin Limit' dataset from MineLib (http://mansci-web.uai.cl/minelib/mclaughlin_limit.xhtml), we assumed the rock strength parameters (Table 1) to be uniform throughout the entire model. Although the non-linear H–B is a better criterion than M–C to characterise rock strength, it requires the specification of more parameters, hence given the lack of geotechnical tests for the minesite, we felt it was more appropriate to extrapolate the two M–C parameters. The same reasoning led to the assumption of homogeneous slope.

Then a simplified preliminary design was carried out and the geometry of the ultimate pit limit (UPL) was determined. The pit was split into sectors, which will be used to design the pit walls, maximising the OSA of the slope while ensuring the acceptable safety criteria. For the McLaughlin deposit, since the geotechnical properties are uniform, the mine sectors were defined based on the maximum pitwall height resulting from the preliminary pit optimisation with GEOVIA Whittle (Dassault Systèmes 2021). A multi-pit made of two independent pits emerged as a result of the pit optimisation. For each pit, the most critical cross-sections are the ones of maximum height. These cross-sections were selected as representative ones to be employed for the mine design. Finally, we divided the block model into two sectors (N and S) based on the location of the two cross-sections (Figure 2).

The economic parameters, metallurgical recovery values, and discount rate employed are listed in Table 2. The initial capital cost provided in Table 3 was estimated for this study based on the authors' best knowledge and taking into account the main cost items from pre-feasibility studies of similar gold mines (Hardie et al. 2016).

Table 1 Rock strength parameters

Rock formation	c (kPa)	Φ (deg)	γ (kN/m³)
Coast range ophiolites	469	31	29

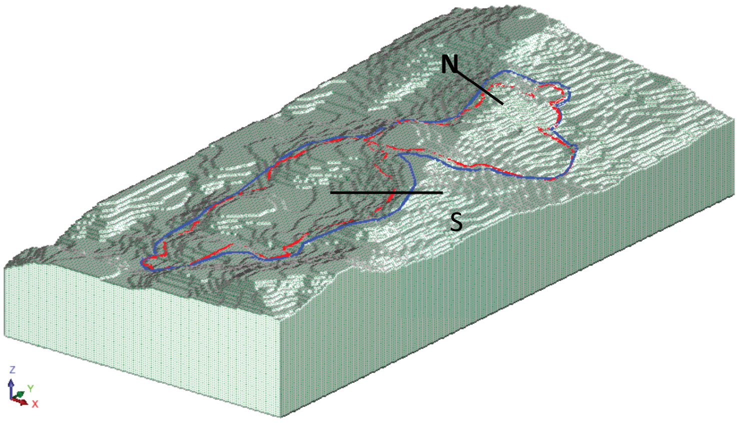


Figure 2 3D view of the block model. The UPL crest boundary is denoted by the coloured closed curves (in blue for the design with planar pit walls, in red for the design with optimal pit walls). A straight black line denotes the representative cross-sections (N and S) for each pit sector

Table 2 Economic parameters and metallurgical recovery

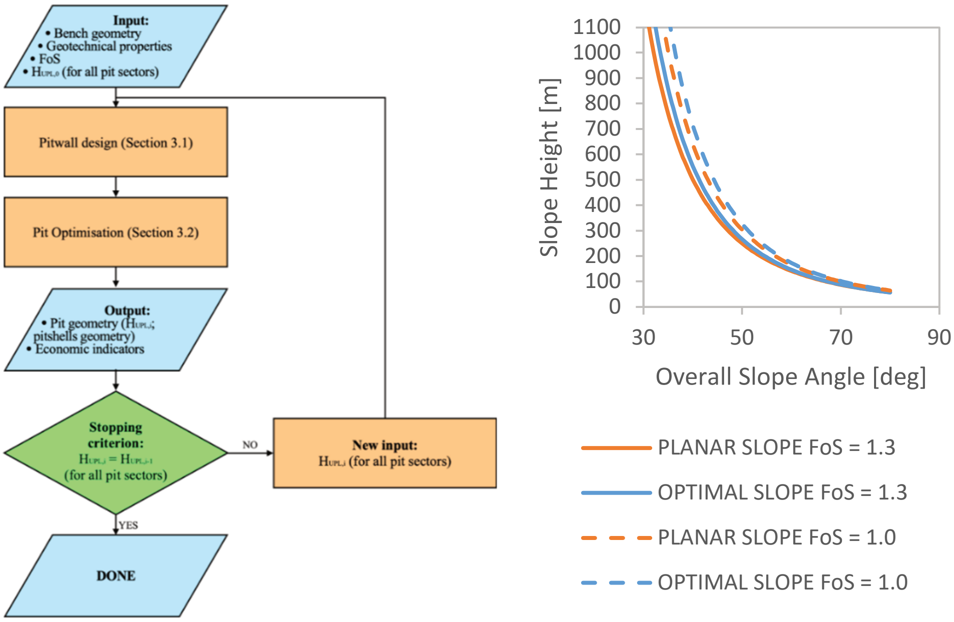
Gold price (USD/oz)	900
Selling cost (USD/oz)	10
Reference mining cost (USD/tonne)	1.32
Processing cost (USD/tonne)	19
Metallurgical recovery (%)	90
MCAF (USD/tonne/bench)	0.025
Annual discounting (%)	15
Processing method limit (Mtonne/year)	3.3

Table 3 Breakdown of the capital costs considered

Cost item	Cost (million USD)
Mine equipment	92
Mine development	77
Process facilities	237
Infrastructure	241
Owner costs	53
Total	**700**

3 Methodology

The iterative procedure we followed to calculate the UPL is the same one employed in Utili et al. (2021) and Agosti et al. (2021). The procedure, illustrated in Figure 3, is the same irrespective of the shape of the pitwall profile adopted, i.e. planar or optimal profile. The procedure is herein described. Initially, a reference pit depth ($H_{UPL,0}$) was assumed equal to the depth of the orebody from the surface. Note the presence of two pit sectors (see Figure 2) implies two independent values of pitwall heights, one for each sector, but for the first preliminary iteration, these two values were taken as equal. Later, we calculated the pitwall profile for each sector given the specified height: for the case of planar pit walls by finding, by trial and error, the maximum OSA compatible with the target FoS (with the FoS of each trial profile calculated by Slide2), whereas for optimal pit walls we used OptimalSlope (see Section 3.1). Then we assigned the calculated pitwall profiles together with the relevant economic and metallurgical parameters for the mine as an input into the pit optimiser (GEOVIA Whittle) and ran it to produce the UPL and the pushbacks (the steps entailed are described in Section 3.2). Finally, the UPL depth obtained as an output of the strategic pit optimisation, $H_{UPL,1}$, was compared to the one prescribed as input in the slope design process, $H_{UPL,0}$. If it turned out to be different, a second iteration would need to be performed with $H_{UPL,1}$ to be used as input for a second slope design process followed by a second run of the pit optimiser. A total of three iterations were necessary for the planar pit walls case, while only one was needed for the case with optimal pit walls because the final heights of the planar pit walls were used as $H_{UPL,0}$ in the optimal pitwall design procedure. The iteration performed and the values of the pit wall height and OSA for each sector are reported in Section 4.



(a) (b)

Figure 3 Pit design process. (a) Flow chart illustrating the iterative process used to determine the ultimate pit limit and pushbacks. Note that the process is the same irrespective of the shape of the adopted pitwall profiles; (b) Slope (pitwall) height versus overall slope angle for different Factor of Safety (FoS) values and profile shapes (planar profiles in orange and optimal profiles in blue). Note that the curves were derived for the specific geotechnical parameters of the case study mine. A different set of strength parameters would produce different curves, however, the qualitative trend of the curves is valid irrespective of the rock strength values

3.1 Optimal pitwall design

In the design of pit walls, we followed the standard practice of starting with the design of benches and then move to the overall pitwall profiles (Read & Stacey 2010). The height of the benches adopted for the whole mine is 12.19 m (equal to 40 ft since the block model units are imperial). We computed the minimum berm width, b_w, using the Modified Ritchie Criteria, published in the SME Mine Engineering Handbook (Hartman et al. 1992) which has been demonstrated to be effective in field tests in several benched mine slopes (Ryan & Pryor 2001):

$$b_w[m] = 4.5[m] + 0.2 * H_{bench} \tag{1}$$

Note that containment of fragments generated by bench excavation and local wedge failure are not necessarily captured by the modified Ritchie formula and may dictate larger b_w values. Also, rockfall modelling by bespoke software packages is increasingly performed by mining practitioners and this may in some cases dictate b_w values different from the Ritchie formula. The maximum inclination of each bench face angle was taken as steep as possible, i.e. 90°. The stability of the benches was verified via Slide2 (Rocscience Inc. 2021) using the Morgenstern–Price LEM. The minimum acceptability criteria are listed in Table 4.

Table 4 Acceptability criteria for Factor of Safety

$FoS_{min,bench}$	1.1
$FoS_{min,UPL}$	1.3

Then we computed the geotechnically optimal slope profiles for the two representative cross-sections of the mine (Figure 2) using the proprietary software OptimalSlope (Utili 2016). OptimalSlope requires bench height, bench face inclination, and road width (in our case, 30.5 m) as input from the user since these geometric data will act as constraints in the search for the optimal profile. A detailed explanation of how OptimalSlope works can be found in Utili et al. (2021). Therefore, it will not be repeated for this paper.

3.2 Pit optimisation

To assign the pitwall profiles in GEOVIA Whittle, we split the block model into horizontal 'slope zones' (according to the Whittle terminology) and assigned a slope angle to each 'zone'. Then, to derive the UPL and pushbacks, we ran Whittle to produce the pit-by-pit graph. The specified case scenario curve was computed using the Milawa NPV algorithm and specifying an initial set of pushbacks chosen in correspondence of sharp increases exhibited by the best-case scenario curve. Next, to maximise the NPV, we recomputed the specified case scenario curve a few times, exploring the choice of different pit shells as pushbacks nearby the ones initially selected. As UPL, we selected the pit in correspondence of the highest point of the specified case scenario curve. Finally, having found the combination of pushbacks that maximises the NPV of the UPL, we plotted the annual scheduled ore production, as illustrated in Section 4.4.

4 Results

The OSAs and the UPL height resulting from the pit design process are reported in Table 5.

Table 5 Results of the pit design process showing traditional mine design and design based on optimal pitwall profiles

Iteration planar pit walls	$H_{UPL,i-1}$ (m)		OSA (deg)		$H_{UPL,i}$ (m)	
	N	S	N	S	N	S
1	414.5	414.5	38.2	38.2	207.3	231.6
2	207.3	231.6	50.3	47.8	207.3	268.2
3	207.3	268.2	50.3	44.9	207.3	268.2
Iteration optimal pit walls	**$H_{UPL,i-1}$ (m)**		**OSA (deg)**		**$H_{UPL,i}$ (m)**	
	N	**S**	**N**	**S**	**N**	**S**
1	207.3	268.2	54.1	49.1	207.3	231.6

4.1 Pitwall profiles

In Figures 4 and 5, the final planar and optimal pitwall profiles for pit sectors S and N respectively are plotted. Figure 4a and Figure 5a provide a visual comparison between the planar pitwall profile of a traditional design, demarcated by blue lines, and the optimal pitwall profile, demarcated by red lines. The optimal profiles are consistently steeper than the planar ones. The hatched area in the figures indicates the difference in rock volume excavated between the two pitwall designs: it is evident that the optimal profiles are characterised by a significantly lower amount of rock to be excavated.

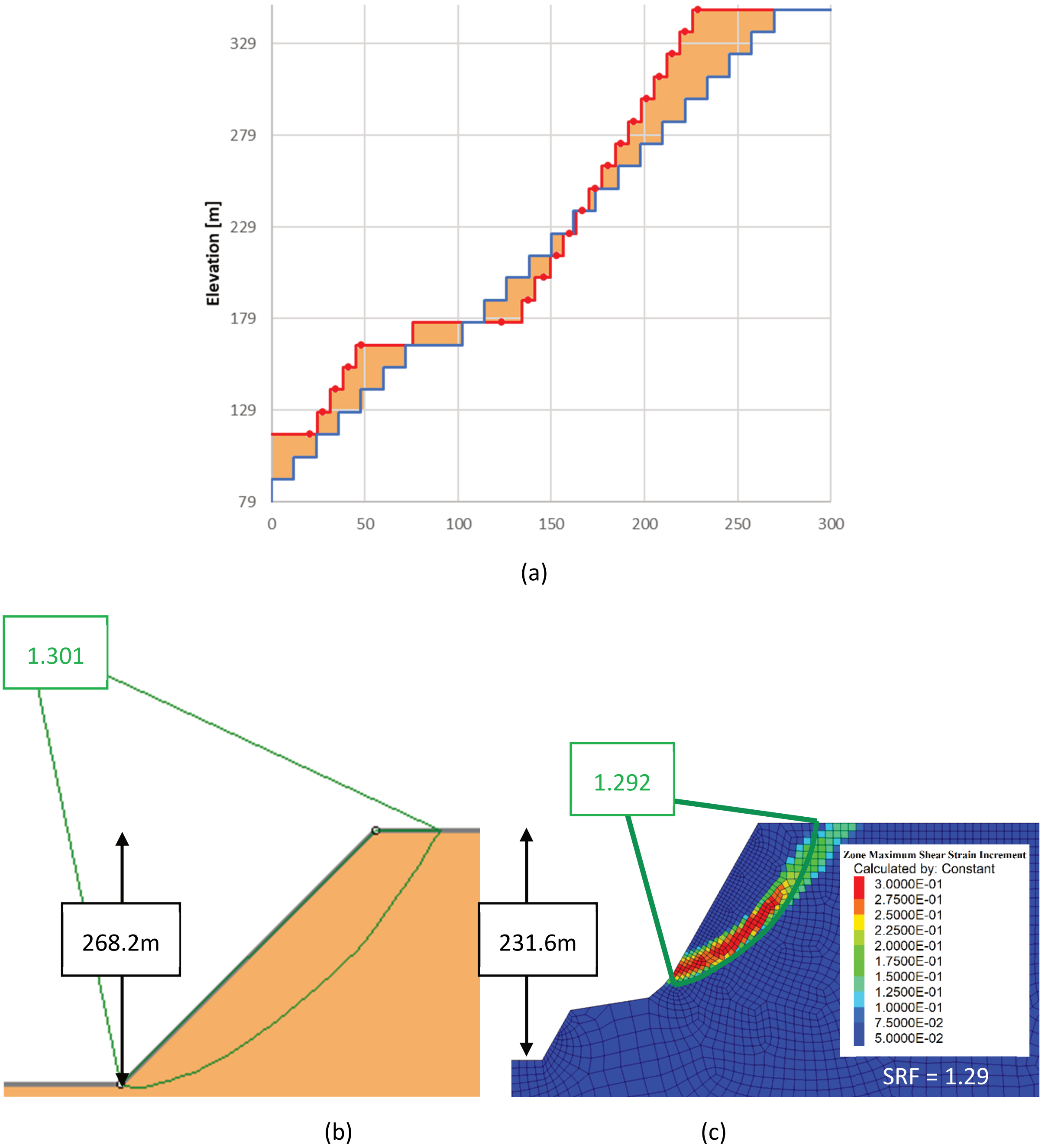
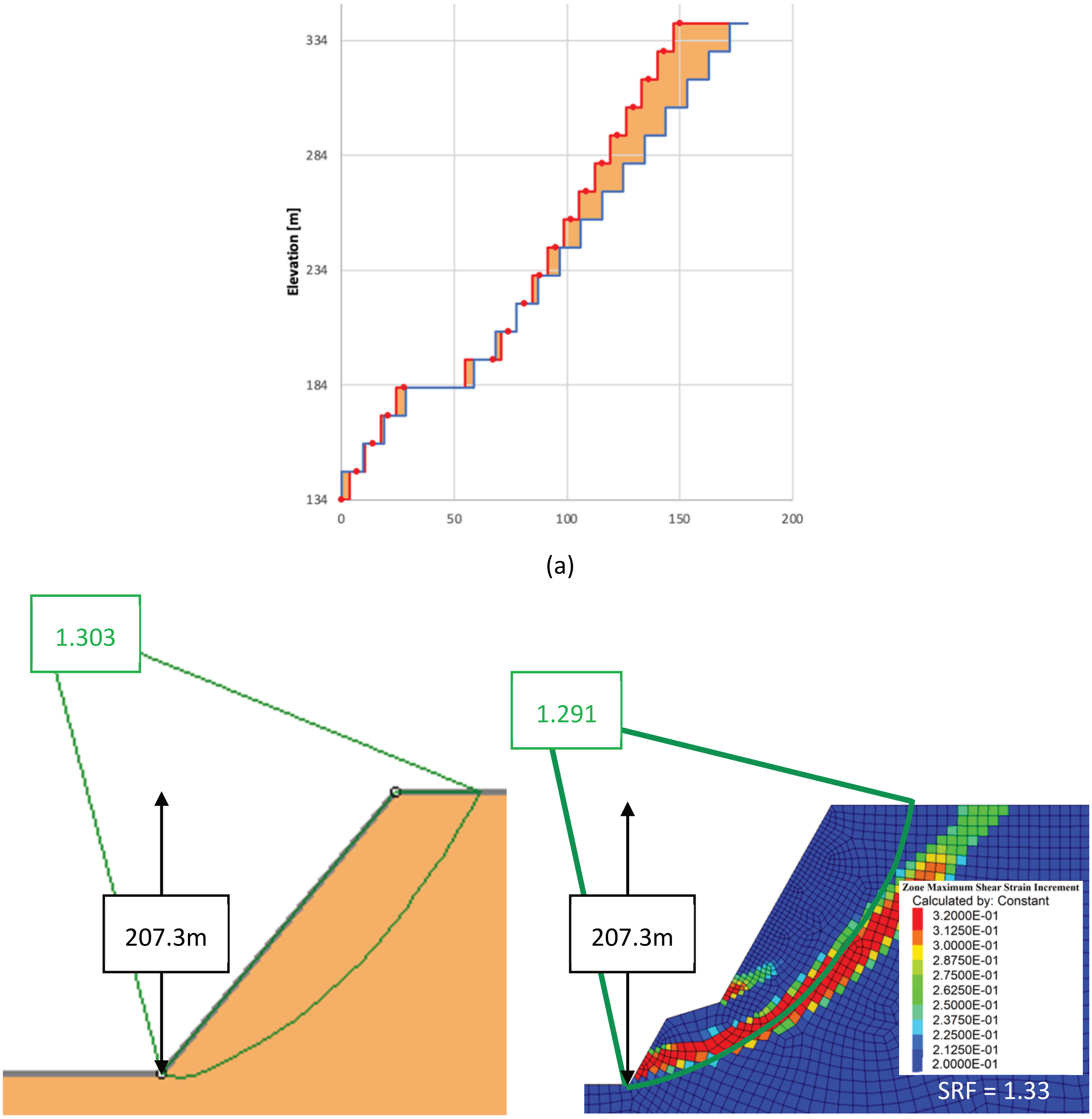


Figure 4 Ultimate pit limit pit walls for sector S: (a) Comparison between the pitwall profile for traditional design (planar pitwall in blue) and the optimal design (optimal pitwall in red, the dots represent the x_i, z_i coordinates obtained as output from OptimalSlope): the hatched area in orange denotes the difference between the two profiles; (b) Failure mechanism and Factor of Safety (FoS) determined by limit equilibrium method (LEM) analysis of Slide2 for the planar profile; (c) Failure mechanism and FoS determined by LEM analysis of Slide2 (in green) and maximum shear strain increment determined by finite difference method analysis of FLAC3D for the optimal profile

The FoS of all the pitwall profiles was verified by performing a LEM analysis with the Morgenstern–Price method using Slide2 (Rocscience Inc. 2021). Additional stability analyses on the optimal slope profiles were run by the finite difference method with shear strength reduction technique (FDMSSR) employing FLAC3D 7.0 (Itasca International Inc. 2021), having assigned a unit length in the out-of-plane direction. The critical failure mechanisms identified by Slide2 and FLAC3D and the associated FoS for each is reported in Figures 4c and 5c. In both mine sectors, the FoSs found are less than 2.3% from the target value of 1.30. This is a key verification by two independent geotechnical softwares that confirms the pitwall profiles found by OptimalSlope are as safe as the planar ones.



(b) (c)

Figure 5 Ultimate pit limit pit walls for sector N: (a) Comparison between the pitwall profile for traditional design (planar pitwall in blue) and the optimal design (optimal pitwall in red, the dots represent the x_i, z_i coordinates obtained as output from OptimalSlope): the hatched area in orange denotes the difference between the two profiles; (b) Failure mechanism and Factor of Safety (FoS) determined by limit equilibrium method (LEM) analysis of Slide2 for the planar profile; (c) Failure mechanism and FoS determined by LEM analysis of Slide2 (in green) and maximum shear strain increment determined by finite difference method analysis of FLAC3D for the optimal profile

4.2 3D slope stability analysis

In Figure 6, the 3D view of the UPLs computed with the pit optimisation process for the planar and optimal pitwall profile are plotted. The FoS of the entire UPL was verified by performing a 3D FDMSSR analysis (Itasca

International Inc. 2021). Note that the numerical settings adopted in the 3D stability analysis were the same as those employed for the 2D analyses reported in Section 4.1 for sake of consistency. The critical failure mechanism identified by the software and the distribution of FoS are plotted in Figure 7. Throughout the entire mine, the minimum FoS found is 1.74, which is significantly higher than the FoS values obtained by the 2D FLAC analyses of Section 4.1. This increase in stability is caused by the presence of lateral confinement, created by the very pronounced concavity of the UPL that acts to constrain movement (Hoek & Bray 1977; Lorig & Varona 2001). However, this effect is not taken into account by 2D analyses, which consequently are conservative (i.e. lower FoS).

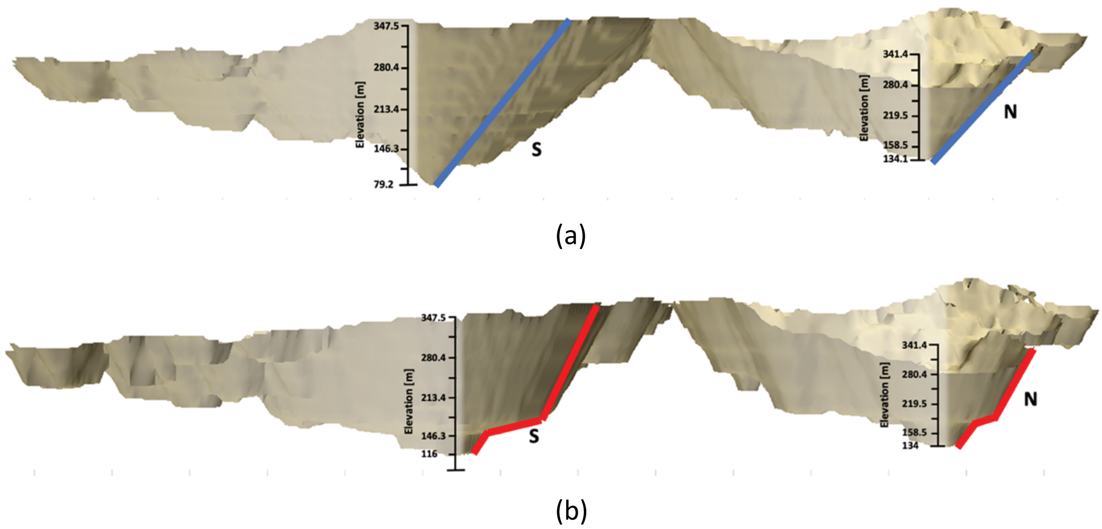


Figure 6 Ultimate pit limit of (a) case of traditional design and (b) case of optimal profile

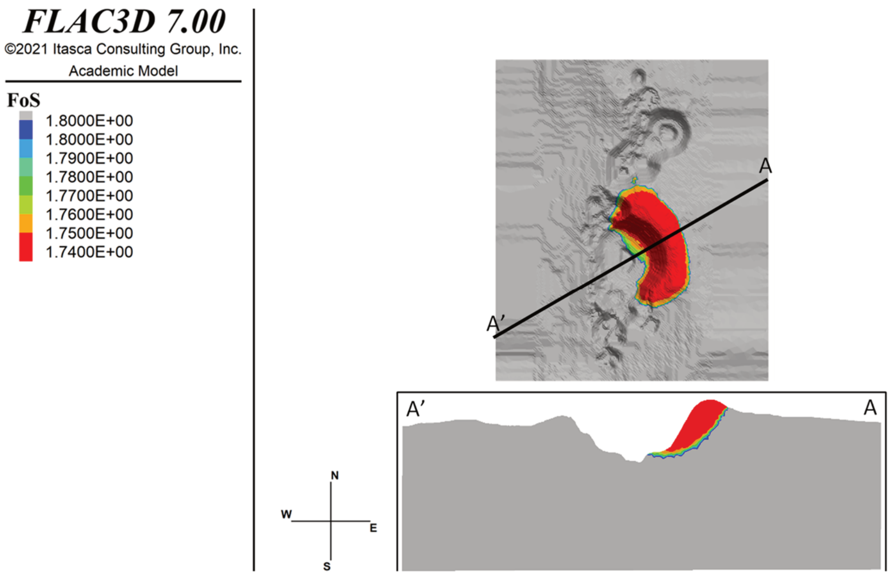


Figure 7 Map of the Factor of Safety (FoS) computed by FLAC3D for the ultimate pit limit with optimal pit walls (plan view and vertical cross-section A-A'). The zones of the pit in grey are all featured by FoS > 1.80

4.3 Key financial indicators

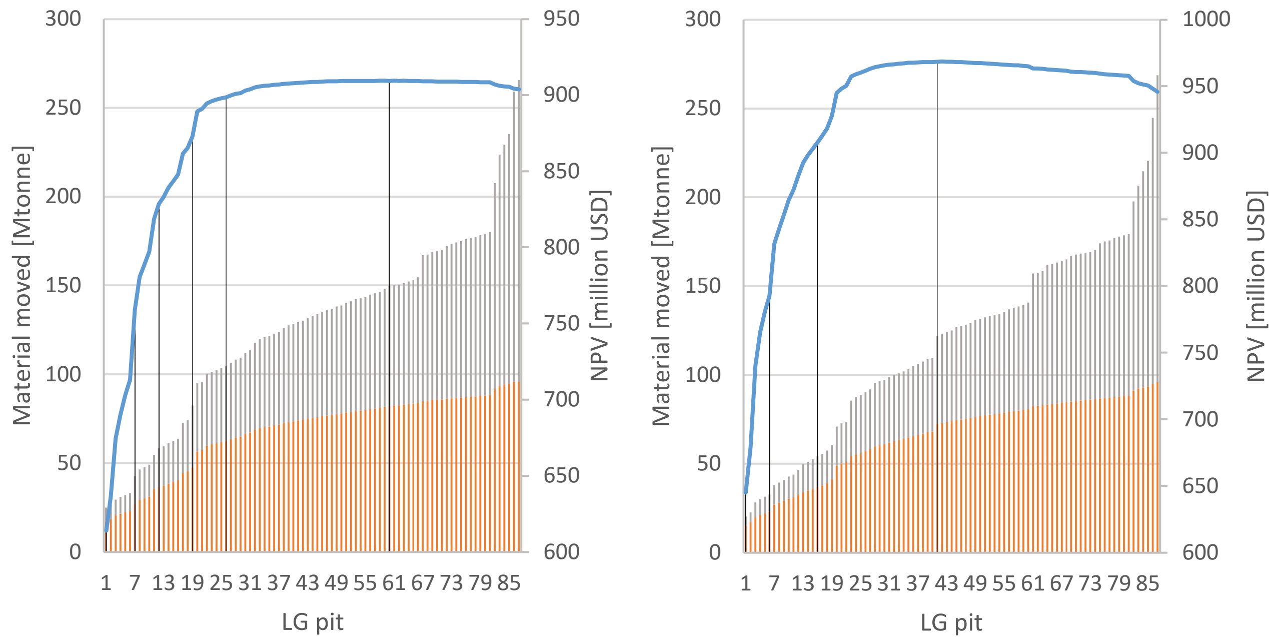
In Table 6, the main output data for the two design cases are provided. The NPV for the design based on optimal pit walls is approximately USD 60 million higher than the NPV of the design based on planar pit walls. Therefore, the adoption of the optimal profiles would lead to an increase of NPV of 28.3%. This increase is because of a 27% reduction of waste rock volume, from 67.6 Mtonne to 49.3 Mtonne. This change in volume excavated can also be measured as a reduction of the stripping ratio from 0.82 to 0.68. Another important metric measuring the financial return of a mine is the internal rate of return (IRR). Adopting the optimal profiles leads to an IRR of 23% instead of the 21% obtained from the design with planar pit walls.

Table 6 Pit optimisation results, economics and material movement

UPL output	Optimal pit walls	Planar pit walls
Ore (Mtonne)	72.405	82.154
Waste (Mtonne)	49.311	67.559
Stripping ratio (-)	0.68	0.82
NPV (USD)	268,562,363	209,359,372
NPV increase (%)	28.3%	

4.4 Production schedule

The ‘pit-by-pit graph’ (according to the Whittle terminology) of the mine is plotted in Figure 8 for the traditional design based on planar pit walls (Figure 8a) and for the design based on optimal pit walls (Figure 8b). The vertical black lines indicate the pit shells selected as pushbacks. In both cases, the UPL has been selected as the pushback corresponding to the peak of the specified case NPV curve. The fact that the NPV curves exhibit a plateau implies that the choice of UPL provides a robust NPV. In Figure 9, the amount of tonnage is plotted against the life of the mine in years. It can be seen that an almost uniform quantity of ore is to be processed year after year for both designs. A constant production over time is a highly desirable feature from a logistical point of view.



(a) (b)

Figure 8 Pit-by-pit graph showing net present value specified case scenario in USD (blue line) and tonnage of mined ore (orange bars) and waste rock (grey bars) plotted against nested pit shell number. (a) Traditional mine design; (b) Design based on optimal pitwall profiles. The vertical black lines show the pit shell selected as pushbacks

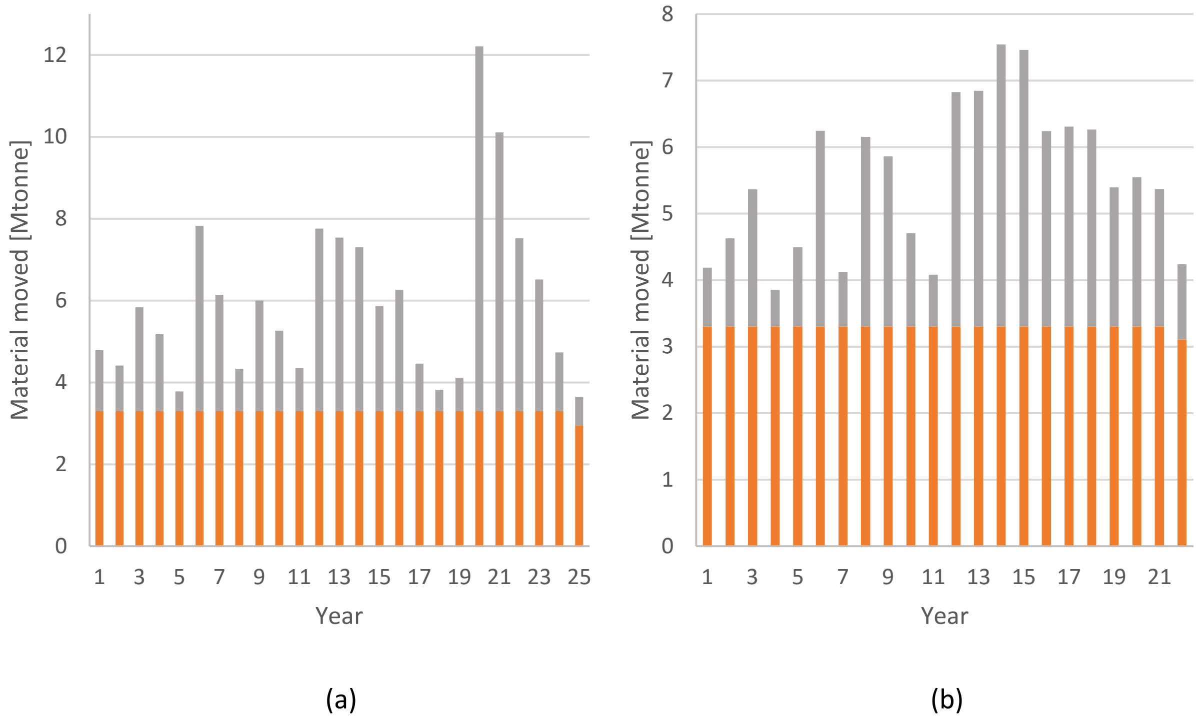


Figure 9 **Ore (orange) and rock waste (grey) tonnage (vertical axis) plotted against time in years. (a) Traditional mine design; (b) Design based on optimal pitwall profiles**

4.5 Environmental indicators

Recently, several methods have been proposed in the literature to calculate the life cycle assessment for open pit mines. Here, we have computed the energy required to mine both ore and waste rock together with the associated carbon footprint for both design types (design with planar pit walls and with optimal pit walls) based on Pell et al. (2019). The approach uses equations to translate properties of the block such as grade, mass, load factor, and block distance to a reference point on the surface to estimate the energy required to produce one tonne of mined ore. The energy requirement per tonne can be translated into carbon footprint by using characterisation factors and includes scope 1, 2 and 3 emissions associated with drilling, blasting, extraction, loading, and hauling. In this scenario, the background energy was assumed to be the electricity production mix for the country where the mine is located (Wernet et al. 2016). The results are provided in Table 7.

Table 7 **Energy consumption and carbon footprint for the two design options considered**

	Design based on planar pit walls	Design based on optimal pit walls	Difference optimal – planar	Difference optimal – planar (%)
Energy (MJ)	3.694×10^9	3.002×10^9	-6.916×10^8	-18.7%
Carbon footprint (kg CO_2 eq)	7.945×10^9	6.458×10^9	-1.486×10^9	

It emerges that the adoption of optimal pit walls leads to reductions of carbon footprint and energy consumption of 1.5 billion kg CO_2 eq and 691.6 million MJ, respectively, over the life of the mine. To provide some context, a reduction of 1.5 billion kg CO_2 eq is equivalent to the carbon sequestered by 24.6 million tree seedlings grown for 10 years and the greenhouse gas emissions avoided by 309 wind turbines producing electricity for a year, as calculated using Environmental Protection Agency (2021). Both carbon footprint and energy savings are achieved by mainly reducing waste rock excavation, around 27% in volume (Table 6).

5 Other case studies

The methodology described in this paper has already been applied to two other case studies of contemporary metalliferous open pit mines: a copper (Utili et al. 2021) and a gold mine (Agosti et al. 2021). In Utili et al. (2021), OptimalSlope was applied to a multi-pit (two sectors) copper mine with rock strength characterised by the G–H–B failure criterion. In Agosti et al. (2021), OptimalSlope was employed in a more complex geological context with several rock formations of different M–C strength which required the design of five different pit sectors and a significant overburden which required the inclusion of uniform surcharges to be applied on the upper topography of the pit walls. Table 8 summarises the main results obtained in those two studies. For both cases, employing optimal pitwall profiles in the mine design leads to significant increases of NPV and decreases of energy consumption and carbon footprint, both a result of the decrease in mine stripping ratios due to the adoption of geotechnically optimal profiles.

Table 8 Pit optimisation results

UPL output	Cooper mine (Utili et al. 2021)		Gold mine (Agosti et al. 2021)	
	Optimal pit walls	Planar pit walls	Optimal pit walls	Planar pit walls
Ore [tonne]	20,651,462	23,707,500	22,104,813	21,419,848
Waste [tonne]	59,232,285	59,314,446	64,490,746	66,853,379
Stripping ratio [–]	0.35	0.40	2.92	3.12
NPV [USD]	46,231,284	34,561,747	39,761,671	26,045,669
NPV increase [%]	33.8		52.7	
Energy: Opt – Pln [MJ]	-8.25×10^7		-3.13×10^7	
Carbon footprint: Opt – Pln [kg CO_2 eq]	-1.696×10^8		-6.13×10^7	

6 Conclusions

In current design practices, mines tend to be designed on the basis of planar pitwalls, i.e. with a constant inter-ramp angle (IRA) in each sector of the mine. However, looking at the final geometry of any pit cross-section, this is anything but planar due to the need to accommodate for benches, step-outs and roads, therefore the assumption of constant IRA adopted at the design stage is a simplification which can and should be removed if a better design can be achieved as result. It seems only natural to wonder whether pitwalls of non-linear shape could be used instead of planar ones. The OptimalSlope software has been developed to find geotechnically optimal shapes for non-uniform slopes accepting any number of layers as input and geomaterials whose strength is described by either the Mohr–Coulomb criterion or the Generalised Hoek–Brown criterion. In this paper, we employed the optimal pitwall profiles determined by OptimalSlope to systematically maximise the OSA of the pit walls of the McLaughlin deposit, an abandoned gold mine located in California, the United States. A key advantage of the mine that is considered is the public availability of the block model that can be freely downloaded from the MineLib repository (Espinoza et al. 2013) so that the calculations reported here can be replicated by anyone. The design of the mine was carried out employing GEOVIA Whittle, however, several other commercial pit optimisers, e.g. Datamine, Maptek, Hexagon, etc., could have been employed to perform the design procedure that has been discussed (Utili 2021).

Adopting geotechnically optimal profiles to the McLaughlin case study led to a 28.3% higher net present value and reductions in carbon footprint and energy consumption of 1.5 billion kg CO_2 eq and 691.6 million MJ, due to a 27% reduction of waste rock volume in comparison with the traditional design based on planar pitwalls. The FoS of all the pit walls were checked by the two most popular geotechnical software packages, namely Rocscience Slide2 to perform limit equilibrium method analyses with the Morgenstern–Price method and FLAC3D to perform finite difference method analyses with the shear strength reduction technique, verifying that all the pit walls adopted in the mine design, planar, and optimal alike, exhibited the same minimum FoS against overall slope failure (see Section 4.1). A 3D finite difference method analysis of the optimal profile UPL was also performed by FLAC3D (see Section 4.2), demonstrating that the non-linear shapes computed by OptimalSlope do not negatively affect the stability of the 3D UPL.

The McLaughlin Mine presents a rather shallow UPL. The economic impact of pit wall steepness increases with pit depth (Hustrulid et al. 2013) and therefore, we believe that the financial and environmental gains obtained for large and deep pits can be even higher. Finally, irrespective of the size of the open pit mine, because a planar slope is a particular case of a curve (obtained by setting the radius of curvature to infinity along the entire slope), there is a theoretical argument to say that adopting a planar slope is a suboptimal choice for most rock and soil types.

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