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A 3D brute-force algorithm for the optimum cutting pattern of dimension stone quarries

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Abstract

This paper presents a 3D algorithm for finding the optimum cutting direction in ornamental stone quarries aiming at maximizing the recovery ratio of blocks through tackling the fracture problem that causes material and economic losses. The presented algorithm is based on 3D deterministic fracture modeling or mapping data and considers new parameters: i) displacement of the cutting grid; (ii) material lost by quarrying; (iii) irregularity of the tested area; (iv) and subdivision of large quarrying area. The algorithm searches for the optimum cutting direction and displacement of the cutting grid that maximizes the number of non-fractured blocks. The algorithm was coded in a software package named BlockCutOpt. This paper presents BlockCutOpt results applied in two case studies of different characteristics. The first case study was a limestone bench where fractures were modeled deterministically using Ground Penetrating Radar (GPR) survey. The second case study was in a very large area of granite quarrying zone where the regional fractures were mapped using the aerial photogrammetry method (literature data). BlockCutOpt was found as a fast tool for finding the optimum cutting pattern in the presented case studies. The results showed that the optimum cutting direction of blocks can vertically (within different strata) and horizontally (within very large scale area) vary, giving geometric information about the cutting grid design that optimizes the number of non-fractured blocks.

Keywords

Sustainable quarrying; 3D optimization algorithm; Dimension stone; Recovery maximization; Waste minimization

1. Introduction and review

Dimension stones are natural non-renewable resources that have to be quarried sustainably for environmental and economic reasons (Carvalho et al., 2018). Stone quarrying industry should satisfy the fundamental values of geoethics which include sustainability, environmental impact, economic development (Careddu et al., 2019). Several works have studied the economic and environmental sustainability of the dimension stone sector (Careddu, 2019; Careddu et al., 2013; Careddu and Siotto, 2011; Macedo et al., 2017). Commercially, ornamental stones are considered as main economic resources for many countries overall the world (Montani, 2008). However, about two-thirds of the ornamental stone exploited material is waste whilst one-third goes to the market (Montani, 2003).

Natural rock discontinuities play a significant role in the profitability of ornamental stone quarries. The exploitability of an ornamental stone deposit refers to the possibility of cutting non-fractured commercial-size blocks from quarries (Carvalho et al., 2008). Among the others, discontinuities are one of the main causes of waste production in the quarrying industry. Discontinuities occur in different geologic forms, classes and dimensions as given in detail in (Gillespie et al., 2011). The profitability of ornamental stone quarry can be optimized by minimizing waste production and maximizing the bulk extraction volume of non-fractured commercial-size blocks (production optimization).

Fractures and discontinuities are natural rock-break surfaces that form natural rock blocks or can be named in-situ blocks (Lu and Latham, 1999) whose size depends on spacing and number of discontinuities (ISRM, 1979). Geo-structurally speaking, the spacing of fractures is the most critical parameter affecting quarrying. Generally, a larger fracture set spacing exhibits a larger amount and volume of extracted non-fractured commercial-size blocks.

Several literature works presented geometric or stochastic methods to identify the geometry and quantify the volume of natural blocks for mining and geoengineering purposes (e.g. Cho et al., 2012; Elmouttie and Poropat, 2012; Turanboy, 2010; Turanboy and Ülker, 2008; Yarahmadi et al., 2015, 2014). The majority of these previous works were based on the traditional manual method of fracture survey which has well-known drawbacks (Assali et al., 2014; Kemeny and Post, 2003).

The estimation of natural rock blocks size and shape can be used for preliminary reserves estimation and quantification in quarries, especially when the calculation of the maximum largest cuboid (Ülker and Turanboy, 2009) or of the marketable block size (Mutlutürk, 2007) inside natural rock block can be accomplished. Mosch et al., 2011, developed a software package, named 3D-BlockExpert, that can identify and compute the volumes of the natural-formed blocks. 3D-BlockExpert can generate a derived 2D section inside the rock body, from two selected parallel sections, to visualize the natural blocks' geometry. This helps the user operator of the program to optically determines the most suitable arrangement of different block sizes inside a derived 2D section (Mosch et al., 2011; Sousa et al., 2017). For the bench scale quarrying, the approaches of natural blocks identification cannot be adopted to the quarrying logic, since the orientation of the quantified/identified natural blocks may or may not be consistent with the typical cutting strategy (continuous cutting direction for the same size of blocks quarried) in benches which is practically non-changeable for quite large areas. Moreover, these approaches model fractures as planes with finite persistence based on the data of the main fracture sets surveyed by the manual method which may entail errors in identifying the actual natural blocks geometry.

For production optimization, the characterization of the deposit quality needs to be assessed. Geostatistical methods give indices estimation for ornamental stone deposits (e.g. Taboada et al., 1999, 1997; Tercan and Özçelik, 2000), however, the geostatistical methods are still far from the production optimization point of view in this paper. Production optimization of ornamental stone deposits, in this paper, concerns finding the optimum cutting direction of equal-sized blocks from benches of quarries, based on 3D deterministic fracture modeling or fracture mapping as well, aiming at maximizing the production recovery ratio and/or revenue when economic data are available. The approach in this paper is different than those which find the optimal cutting direction based on geo-mechanical parameters of the deposit (Deliormanli and Maerz, 2016; Yarahmadi et al., 2017).

Optimization of ornamental stone production recovery was introduced in 2D, for the first time, graphically, by (Tomasic, 1994) who illustrated that the production recovery is controlled by the block size, the spacing of fractures, and the orientation of blocks. However, the graphical 2D application in the work of (Tomasic, 1994) was on an orthogonal vertical profile along a working bench and with considering different block sizes, which is not coherent with the actual quarrying applicability.

The most noticeable contributions in 3D production optimization of ornamental stone deposits are the work done by (Fernández-de Arriba et al., 2013) and (Yarahmadi et al., 2018). Fernández-de Arriba et al., 2013, developed a numerical optimization algorithm programmed in a software package using the C# programming language and named CUTROCK. The CUTROCK method is based on using the data (dip angle, dip direction, and spacing) of three fracture families, assumed persistent and continuous planes, to identify the volume of the maximum block bounded in the natural block inside the spatial data of the three fractures families. A mesh of blocks with the desired dimensions is then generated in a parallelepiped form and inside the maximum block. The final aim of this method was to find the optimum cutting orientation within the mesh generated to maximize the yield. Field studies of several works have shown that fracture families often occur in two or three prominent families and one or more minor families; in addition random joints may be present (Palmström, 1995). This may cause errors in the optimization result of this method, with a limitation of non-workability in case of the presence of a fracture set greater of the main three fracture families.

Yarahmadi et al., 2018, improved the previous methods within two directions: (i) natural blocks identification and classification numerically and (ii) production optimization. This work was coded in a software package, using the MATLAB environment, and named 3D-QuarryOptimizer. Firstly, natural block identification was improved by assuming random discontinuities with finite persistence and fracture families while considering block shape factor. The block shape factor is a classification measure of the shape quality and was defined as the ratio of the surface area of a representative rectangular block (with the same volume as the given natural block) to the surface area of the natural block. The block shape factor shows how much an irregularly shaped block is similar to an equal volume rectangular block and does not provide information about the 3D orientation of the block, but it is an important aspect of the quarrying suitability.

Regarding the optimization, 3D-QuarryOptimizer performs optimization within two scales: analysis of quarrying direction on a large scale, based on the main fracture families' data, and cutting the interval in a face on a small scale Large Volume Blocks (LVB): LVB (named in Italian language: *bancata*), loosened by means of primary cuts, from which commercial sizes of blocks are cut. At small-scale optimization, a genetic algorithm was used to find the best variable cutting intervals to cut blocks from a LVB. This is theoretically an innovative optimization method; however, practically the cutting interval in large-scale benches usually occurs with fixed distances and often occurs as well in large blocks.

On the other hand, the objective of the large-scale optimization algorithm, in 3D-QuarryOptimizer, was to maximize the volume of the extracted blocks bounded in a mesh of blocks. Accordingly, several blocks' classes of different volumes and shapes can be assessed to compute the economic value of each class. The optimization algorithm presented in this paper can find the optimum commercial-size of the block, that can be extracted from a bench, which maximizes the recovery ratio when several sizes are tested.

As given by (Reina and Loi, 2015), the blocks are classified into three classes, based on the rock material and the geometric shape: (i) first class blocks have commercial size with six regularly-shaped sides (known as blocks); (ii) second class blocks whose one or more faces are not regular (called "half blocks"), (iii) and third class blocks which do not have a regular shape (known as "unformed"). Hereby, in this paper, the optimization targets only to the first class blocks and the method can be applied following the current quarrying routine.

The presented quarrying optimization algorithm, in this paper, decreases the gap between the previous methods and improves the optimization concepts considering the practical aspects. The main features of the presented optimization algorithm are listed as follows:

- The algorithm can work using any source of fracture data. Fracture surveys are usually performed with the classical manual method, GPR, laser scanner, aerial and terrestrial photogrammetry. The modeled fractures must be encoded in the Polygon File Format files (PLY) (Bourke P., 2011). The results uncertainty may be minimized when using a 3D deterministic fracture model (Elkarmoty et al., 2018b, 2017a).
- No natural block identification algorithms are required and there are no restrictions on the number of fracture sets.
- The algorithm can work for a large scale bench or for a face on a small scale (LVB).
- The wasted material caused by the cutting method is newly considered in the algorithm.
- Providing a new option of dividing the tested area into several sub-divisions of quarrying zones.
- Introducing the horizontal displacements of the cutting grid of blocks as an optimization parameter.

2. Methodology

Accurate design and production plan of the cutting areas of non-fractured blocks can decrease the amount of waste, improving quarrying sustainability. As fractures are generally modeled as three-dimensional planes, there will be a potential risk of inaccuracy and, consequently, forming of waste material during quarrying operation. While modelling fractures deterministically as irregular 3D surfaces as close as possible to reality may lead to the optimal minimization of waste (Elkarmoty et al., 2018a, 2017a, 2017b). The optimum cutting direction can be determined by an optimization algorithm through finding orientation, interval, and other cutting parameters allowing to maximize the number of non-fractured blocks.

The authors of this paper have recently developed an algorithm for an optimized slab cutting from ornamental stone blocks, named SlabCutOpt (Elkarmoty et al., 2020). The SlabCutOpt software was coded in the C++ programming language. In this paper, it is presented a modification to the SlabCutOpt algorithm, having adapted it to the quarrying logic to optimize the cutting of blocks from quarry benches. The adapted algorithm in this paper was named "BlockCutOpt" referring to Block Cutting Optimization.

BlockCutOpt, similarly to SlabCutOpt, searches for the intersection between fractures and blocks defined in a 3D cutting grid, initiated from the geometric center of the tested area. The 3D cutting grid of blocks is then rotated, with a fixed given step of the cutting direction. For each simulated cutting direction, the 3D cutting grid is displaced horizontally (dx and dy), within a given domain, to test several designs of cutting grids as well, outputting the number of non-intersected blocks with full dimension inside the tested area. Following, the recovery ration can be calculated by Eq. 1. The optimum revenue can be estimated as well when the selling prices of several tested sizes of blocks are available, following the work presented in (Elkarmoty et al., 2020).

$$recovery\ (\%) = \frac{volume\ of\ non{-}intersected\ blocks\ with\ full\ dimension\ inside\ the\ rock\ body\ studied\ x\ 100}{total\ volume\ of\ the\ rock\ body\ studied} \qquad (1)$$

Hence, the presented method uses a developed brute-force algorithm, searching for not only the possible cutting directions but also for the corresponding possible designs of the cutting grid. A simplified graph in Fig. 1 illustrates the used method in 2D.

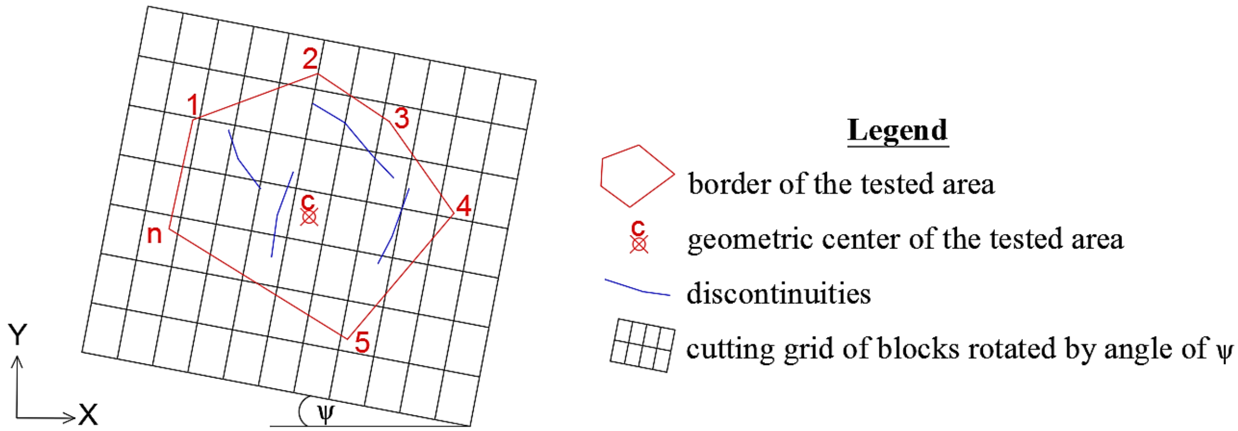

Fig. 1. A 2D illustrative sketch for the used method.

BlockCutOpt contains the same concept of the 3D cutting grid domain in SlabCutOpt. The dimensions of slabs were replaced by the dimensions of blocks and the surveyed block body was replaced by the surveyed bench body. The thickness of the saw was replaced by the thickness of lost material due to quarrying, named in the algorithm “material-lost-by-quarrying”. The main adaptions or modifications done in BlockCutOpt are listed below:

- Only the horizontal rotation is considered (ψ) which is the cutting/quarrying direction ranging from 0.0° to 180°.
- No vertical displacement (dz) of the 3D cutting grid of blocks is considered.
- The tested quarrying area can be in any geometric shape: a regular shape or a concave/convex polygon.
- Optionally, in case of large area computation, the tested area can be divided into equal sub-divisions of quarrying. The sub-areas/sub-divisions are identified in the algorithm by (m_x=i,m_y=j), where i is the number of the sub-areas in the X direction and j is the number of the sub-areas in the Y direction. For example, when an area is computed in the algorithm using (m_x=2,m_y=2), this means that this area contains four sub-divisions of quarrying zones defined by (i=1,j=1), (i=2,j=1), (i=1,j=2), and (i=2,j=2). If (m_x=1,m_y=1), the algorithm will work on a single tested area without sub-areas.

The input/output files of BlockCutOpt have the same features of the input/output files of SlabCutOpt, considering some differences in the file containing the input parameters, named BlockCutOpt.par. In addition, in case of using the sub-division of the tested area option, the Results.log file of BlockCutOpt lists the results separately for each sub-division zone.

3. Case studies and results

3.1. Limestone quarry of Italy

3.1.1. Input data

BlockCutOpt was applied to a bench of limestone quarry where fractures were modeled deterministically in 3D based on Ground Penetrating Radar (GPR) survey. The site description and the fracture model are presented in detail in (Elkarmoty et al., 2018b) .The final goal of applying BlockCutOpt software on this case study was to investigate the effect of fractures modeling as 3D surfaces on the production optimization results. In this case study, one commercial size block has been tested in BlockCutOpt. By personal communication with the quarry technical manager, the preferred block dimensions reported are 3.0 m length, 2.0 m width and the thickness of the block is limited to the thickness of the strata. In this case study, the surveyed bench had four strata (a, b, c, and d), as shown in (Elkarmoty et al., 2018b). BlockCutOpt was used to test the referred block size with its relevant thickness for each stratum in order to find the solutions for the maximum number of non-intersected blocks and the related optimum recovery.

In this case study, the cutting direction has been tested with an angle step of 3.0° and using a horizontal displacements of 0.5 m in the X and in the Y directions for the 3D cutting grid of blocks. The thickness of the material-lost-by-quarrying was assumed 5.0 cm. See Appendix A as an example for an input file for this case study considering a no sub-divisions of the tested area.

3.1.2. Optimization results

The results of applying BlockCutOpt to the different blocks sizes provided that the maximum number of non-intersected blocks were found variable with the cutting direction, and also with the displacements for each cutting direction tested. Mainly this is due to modeling fractures as 3D surfaces allowing results change between strata. A graphical representation for the results of Strata a and d are shown in Fig. 2 and visualized in Fig. 3. The material lost by quarrying can be also observed in the zooming part of Fig. 3. For better visualization of Stratum d in Fig. 3, the fractured/intersected blocks of Stratum a were hidden.

The time consumed to solve the problem by BlockCutOpt, for the four strata, was 11.0 minutes. This considers selecting write_vtu=2 in the PAR file (parameter for writing only the maximum number of non-intersected blocks), and using a computer of the following specifications: 64-bit operating system Windows 7, processor Intel(R) Core (TM) i5-4460 CPU @ 3.20 GHz, and installed memory (RAM) 8.00 GB.

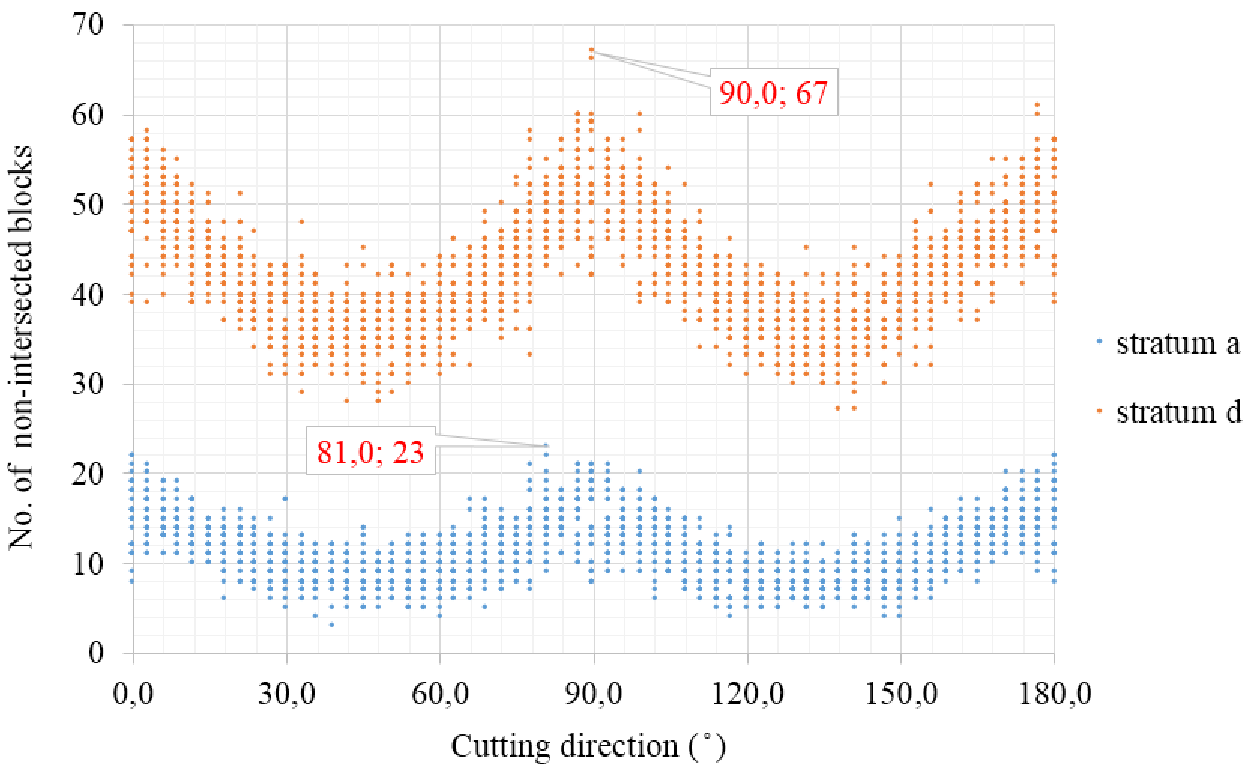

Fig. 2. The optimization results of Strata a and d.

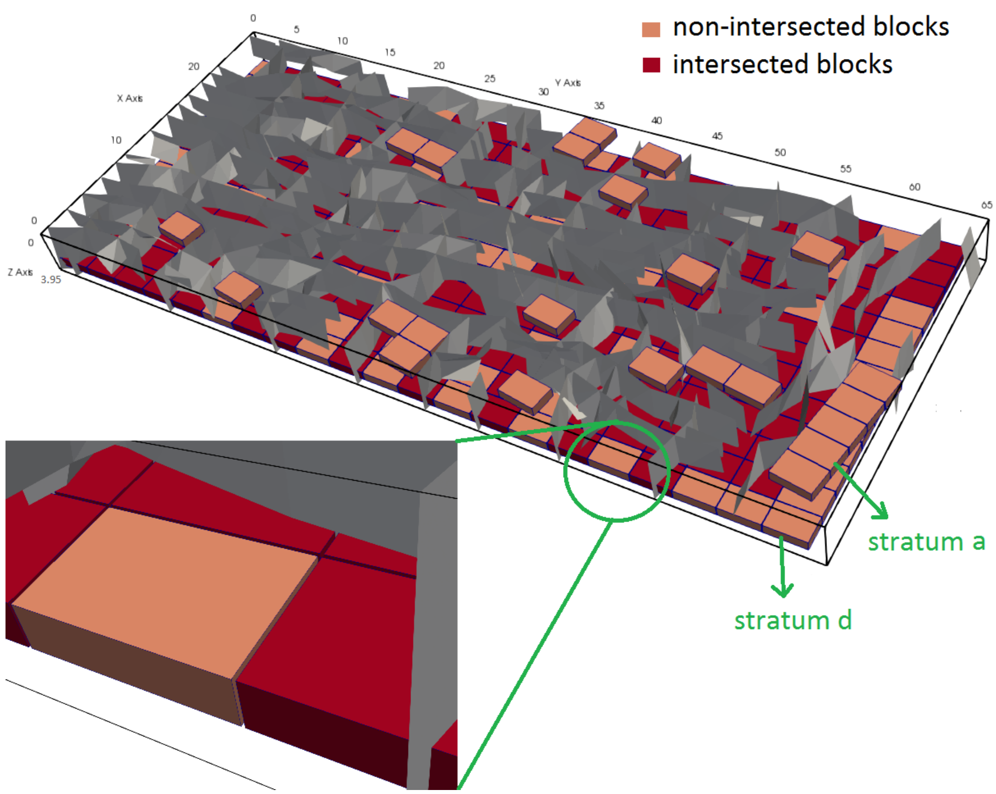

Fig. 3. 3D visualization of the optimum solutions, for Strata a and d.

The algorithm results give the optimum solution in terms of non-fractured blocks, further consideration must be taken in account, such as the comparison between several block sizes and the market values (selling prices) that usually depend on sizes, as presented in (Elkarmoty et al., 2020). Table 1 summarizes the optimization results of this case study. The total number of non-intersected blocks in the bulk volume of the bench was 150 blocks leading to a bulk recovery ratio of 11.4 %. It is worth mentioning that the cutting direction actually used in this bench was 0.0 ° (traditionally fixed for all the strata) which is found not consistent with the optimization results.

Table 1
A summary of optimization results for each stratum.

stratum	max. No. of non-intersected blocks	max. recovery (%)	dx (m)	dy (m)	cutting direction (°)
a	23	7.86	-0.51	-1.01	81.0
b	23	7.68	-1.01	0.99	90.0
c	37	12.65	-1.01	0.99	90.0
d	67	22.91	0.99	0.99	90.0

3.2. Granite extraction area, Portugal - photogrammetry data

3.2.1. Input data

The objective of this case study was to verify and validate the use of BlockCutOpt in a very large scale quarrying area, for the target of a long-term optimization plan. In particular, when a large area of exploitation can be divided into sub-areas where the optimum cutting direction varies. Published data was used as input in this case study. A map of regional fracturing (figure 7 of (Sousa et al., 2016)), obtained by aerial photogrammetry, in a large quarrying zone of granite, was reproduced. The fracture map in (figure 7 of (Sousa et al., 2016)) has been converted in a format readable by BlockCutOpt through manual picking and automatic exporting of fracture coordinates to an excel worksheet using the AutoCad add-on utility “click2xls”, which facilitated the transformation of the fracture data into a PLY file. The reproduced fractures map is visualized in Fig. 4. It was assumed that the whole fractures were vertical, persistent and continuous planes. It is worth mentioning that no horizontal fractures data were detected or considered for the map of the tested quarrying area.

The total area under study is 5650.6 X (m) *x* 5675.8 Y (m). The border of the studied zone in BlockCutOpt was assumed to be the same border of the original map. Since this case study is a very large scale area, the optimization results could be provided within the two possible options, the first considers the sub-division option and the second considers the whole area.

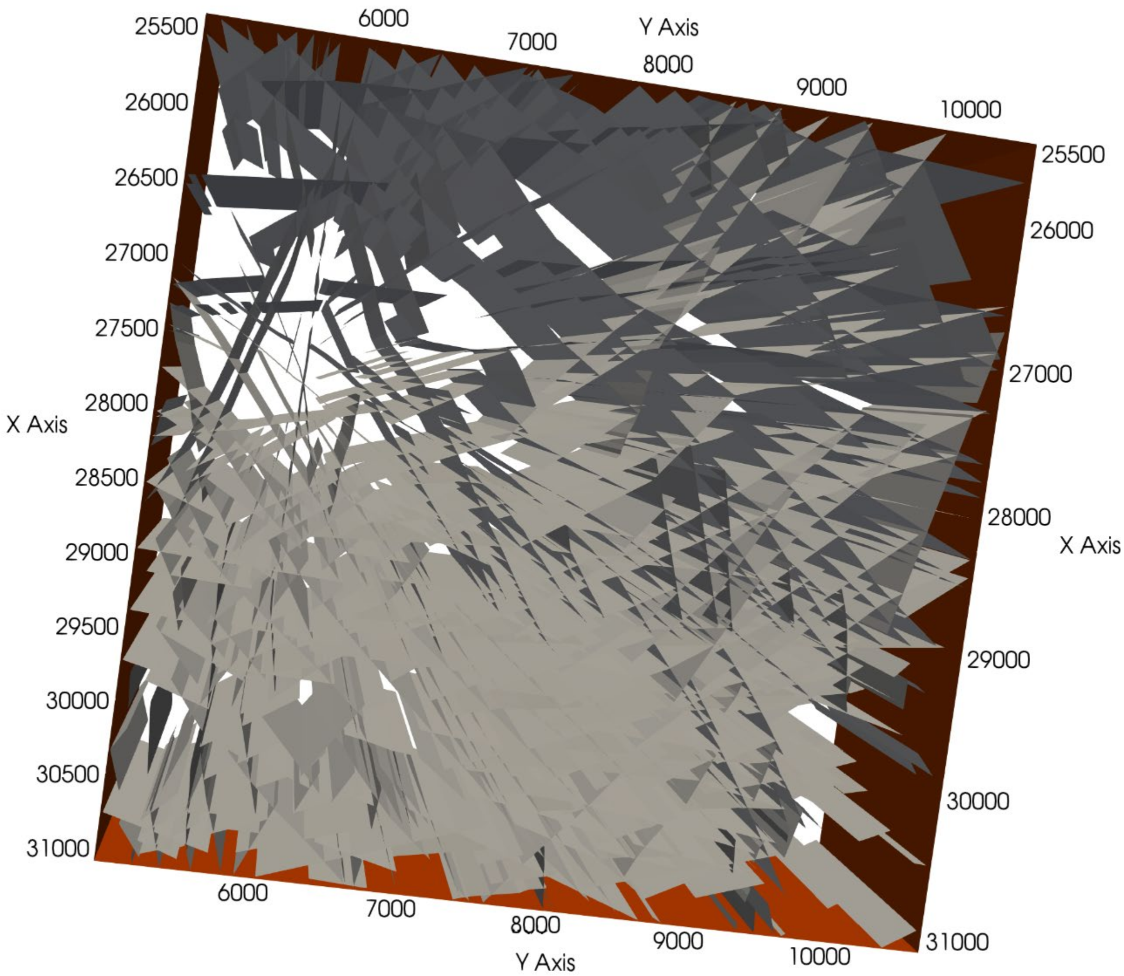

Fig. 4: Oriented 3D visualization of the fracture data, reproduced from (figure 7 of (Sousa et al., 2016)).

For the application of BlockCutOpt in this case study, the tested size of the block was the LVB. This is the most common size cut in marble and granite quarries. The LVB volume is usually in the 1000s of m^3 range: length of 20.0-30.0 m, width of 9.0-12.0 m, and height of 6.0-7.0 m (Ashmole and Motloung, 2008). The dimensions of a large block are generally determined considering the machinery limitations. However, in this case study, and since there are no more available data, the author simulated a size of LVB (Table 2) that has similar dimensions and volumes given by (Ashmole and Motloung, 2008).

Table 2
The dimensions of tested LVB in BlockCutOpt.

length, X(m)	width, Y(m)	height, Z(m)	volume (m^3)
21.0	9.0	6.0	1080.0

In this case study, the cutting direction will be tested within angles interval of 3.0° and using maximum horizontal displacements of 7.0 m in the X direction and 5.0 m in the Y direction. The thickness of the material lost by the cutting systems was set as 5.0 cm. See Appendix B as an example for an input file for this case study considering the sub-division of the tested area.

3.2.2. Optimization results

Firstly, the results will be presented considering the non-division of the tested area. The results of applying BlockCutOpt to the tested size of LVB is graphically presented in Fig. 5. It is found that the recovery ratio changes with the cutting direction. For the tested angles of the cutting direction, BlockCutOpt finds solutions for several displacements of the cutting grid. The variability range of the recovery ratio was limited (80.40-83.29 %). The high recovery ratio was expected, in this case study due to the small surface area of the LVB tested, compared to the quarrying area studied and the fracture data set, just about the main fractures at the regional scale. The maximum number of non-intersected LVBs was found at the cutting direction of 93.0˚, at a displacement of dx = -10.01 m and dy = 0.49 m, providing the maximum recovery of 83.29 %. The maximum number of non-intersected LVBs solution is visualized in Fig. 6 where the cutting direction of the optimum solution is 93.0˚. The time consumed by BlockCutOpt to solve the problem was 26.0 hours, considering write_vtu=2 in the PAR file, and using a computer of the following specifications: 64-bit operating system Windows 10, a processor Intel i7-3770K CPU @ 3.7 GHz , and an installed memory (RAM) of 8.00 GB.

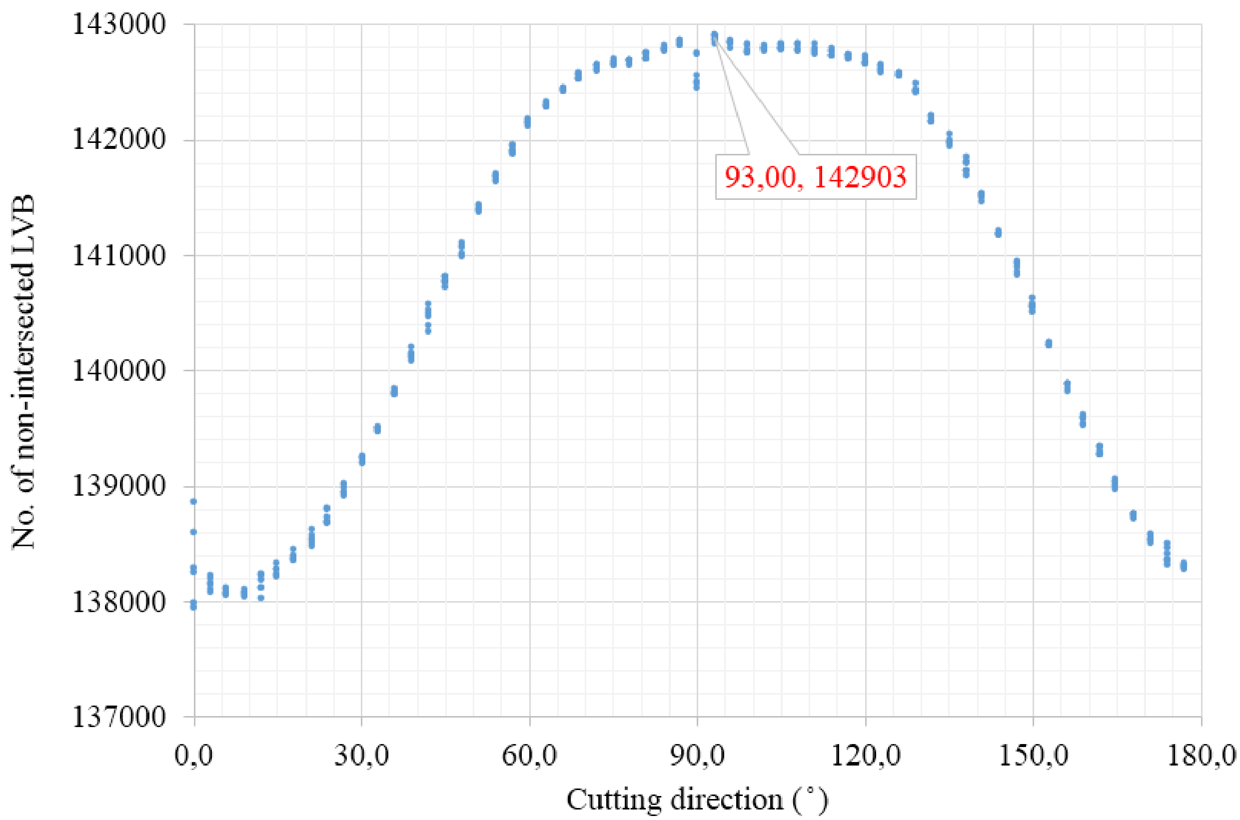

Fig. 5. The optimization results of the tested size of LVB, without sub-division, highlighting the optimum solution.

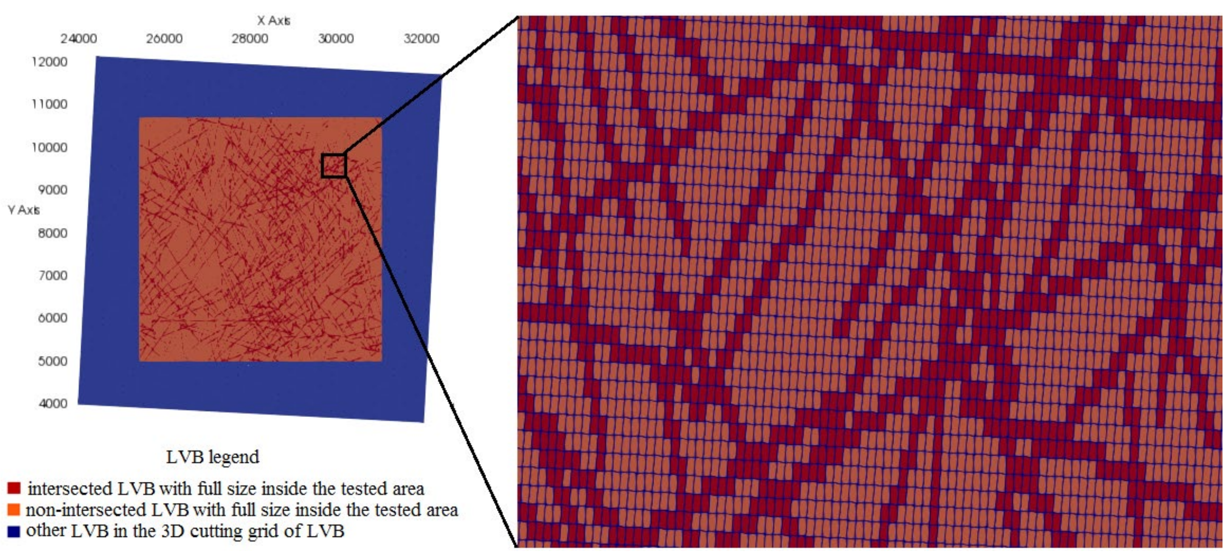

Fig. 6. Two-dimensional visualization of the optimum solution (non-intersected LVBs solution), without sub-division.

Considering the sub-division of the tested area, the whole tested area was firstly divided into 3 sub-areas of quarrying zones in the X direction and 2 sub-divisions of quarrying zones in the Y direction (m_x=3,m_y=2), leading to a total of 6 sub-divisions of quarrying zones. The computation results are shown in Table 3 for the 6 sub-divisions of quarrying zones. From the results in Table 3, it is shown that the maximum number of non-intersected blocks for the sub-division zones are found at different displacements, even if the optimum cutting direction of 90.0 is almost the predominant one. The maximum number of non-intersected LVBs, in all the sub-division zones, was 142701: less than in the without sub-division test, giving an overall optimum recovery of 83.17 %.

Table 3
The optimization results for each sub-division quarrying zone (mx=3,my=2).

i	j	max. No. of non-intersected LVBs	dx (m)	dy (m)	cutting direction (°)
1	1	25104	-3.01	-4.51	129.0
1	2	24718	-3.01	-4.51	90.0
2	1	21840	3.99	-4.51	90.0
2	2	22713	3.99	0.49	90.0
3	1	23744	-3.01	-4.51	90.0
3	2	24582	-3.01	0.49	90.0

For this case study, the use of sub-division zones shows a decrease of the maximum number of non-intersected blocks since the borders of the sub-division zones were acting as fractures. However, a noticeable variation of the optimum cutting direction for each sub-division quarrying zone is expected. This is logically obvious; nonetheless, BlockCutOpt can quantify and graphically visualize the results (using ParaView). A further test of increasing the sub-division zones was performed for (m_x=6,m_y=3). The results are visualized in Fig. 7 and summarized for each sub-division quarrying zone in Table 4. It is worth mentioning that the optimum cutting direction (93.0°) for the without sub-division test was not found in any optimum solution of the sub-division zones presented in both of Table 3 and Table 4.

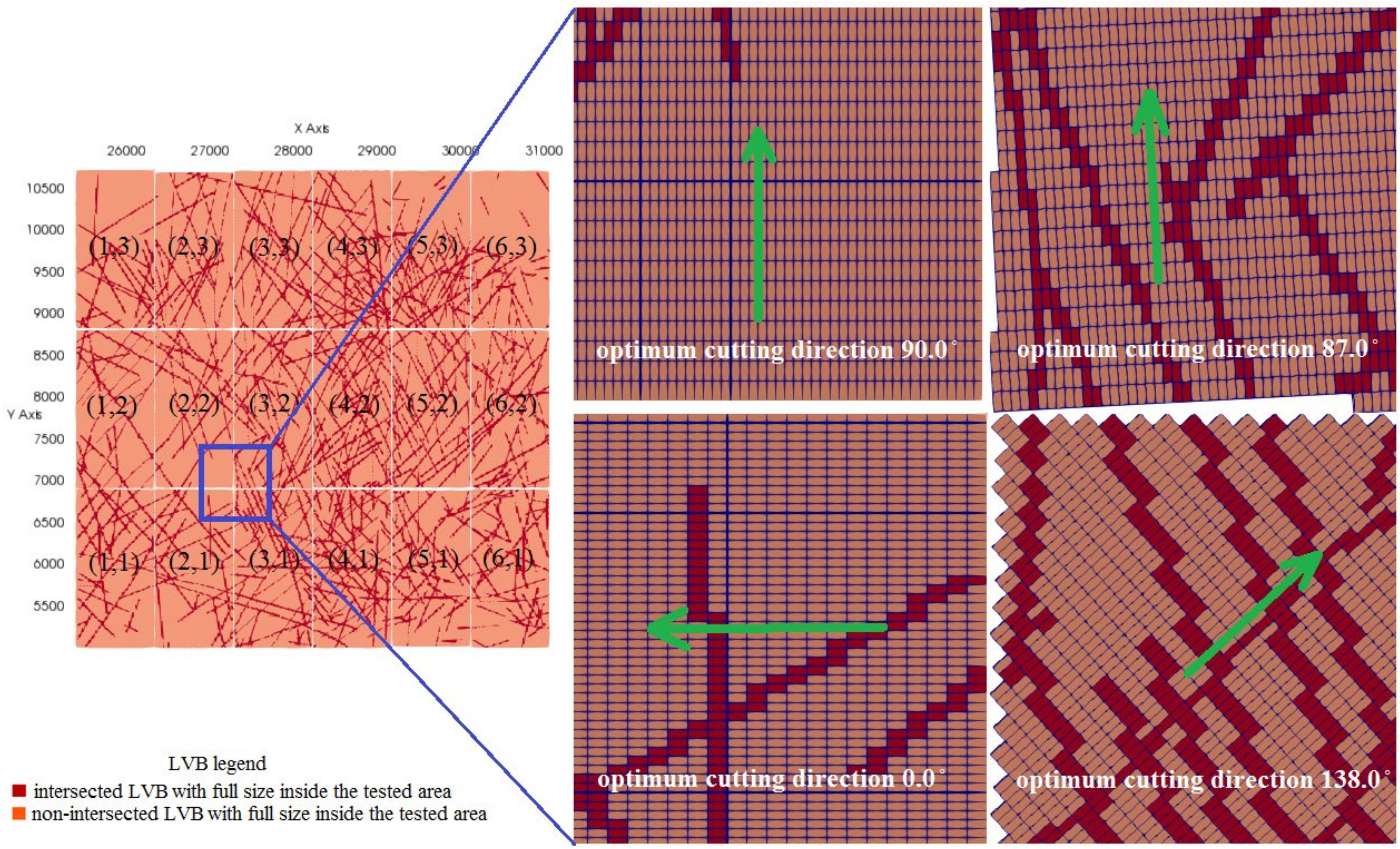

Fig. 7. 2D visualization of the optimum number of non-intersected LVBs solution, with sub-divisions of (mx=6,my=3).

Table 4
The optimization results for each sub-division quarrying zone (mx=6,my=3).

i	j	max. No. of non-intersected LVBs	dx (m)	dy (m)	cutting direction (˚)
1	1	8123	-10.01	-4.51	0.0
1	2	8219	-10.01	-4.51	132.0
1	3	8514	-10.01	-4.51	0.0
2	1	8294	-10.01	-4.51	0.0
2	2	8374	-3.01	0.49	90.0
2	3	8076	-3.01	-4.51	90.0
3	1	7403	-3.01	0.49	138.0
3	2	7672	-3.01	-4.51	87.0
3	3	7971	-3.01	0.49	90.0
4	1	6956	-10.01	0.49	138.0
4	2	6970	-3.01	0.49	90.0
4	3	7295	-3.01	0.49	132.0
5	1	7870	-10.01	-4.51	90.0
5	2	7515	-10.01	0.49	90.0
5	3	7761	-10.01	0.49	90.0
6	1	8008	-10.01	-4.51	0.0
6	2	7837	-3.01	0.49	90.0
6	3	8854	-10.01	0.49	90.0

It was noticed that the total number of non-intersected LVBs decreased (Table 5) with increasing the sub-division zones. This is due to the borders effect of the sub-division zones acted as additional "synthetic" fractures. The sub-division method can give better bulk recovery impact, in case a large area of quarrying shall be divided into sub-zones for planning, business, or geographic reasons. Given that, the optimum solution found for each sub-division zone is the one providing the best recovery for that area.

Table 5
Comparison between the with and without sub-division solutions.

	without sub-division	sub-division (mx=3,my=2)	sub-division (mx=6,my=3)	sub-division (mx=9,my=4)
optimum recovery (%)	83.29	83.17	82.60	82.04
optimum No. of non-intersected LVBs	142903	142701	141712	140767

4. Conclusions

The presented algorithm allowed to find the optimum cutting direction in quarries that maximizes the number of non-fractured blocks or Large Volume Blocks (LVBs) and consequently the recovery ratio. The algorithm was successfully coded in the C++ programming language (named BlockCutOpt), allowing fast calculation and visualization of the results.

BlockCutOpt was applied in two case studies. The first one was a limestone bench where fractures were modeled deterministically based on GPR survey. The modeling of fractures as 3D surfaces plays a significant rule in the optimization results. The results of BlockCutOpt showed that the optimum cutting grid design (cutting direction and displacement) may vary vertically between strata deposited in the same bench providing consequently different maximum recovery ratios for each stratum. For this case study, as selling prices of different commercial-sizes blocks are variable, the BlockCutOpt can be used to find the optimum block size providing the maximum revenue as well.

The second case study was a granite deposit with a large area where regional fractures were mapped (in literature) by photogrammetry. BlockCutOpt proved its ability to solve a very large scale problem contains a huge number of blocks in a reasonable time of computation. In this case study, the problem was solved for a size of LVB from which commercial-size blocks cut. Therefore, the results in this case study are limited to the optimization of LVBs considering the limitations of the aerial mapping of fractures. The optimum cutting direction was found variable within the sub-divided zones. Increasing the number of the sub-divided zones led to increasing the variability of the optimum cutting directions and the displacements of the optimum cutting grids. The total optimum recovery slightly decreased, as compared to the non-division solution, when the number of sub-divisions of quarrying zones increased (the borders acted as synthetic fractures). However, the maximum recovery ratio found for each sub-division zone is significant when a large area shall be divided into sub-zones for planning, business or geographic reasons. Interestingly, the optimum cutting direction in the non-division solution could not be found in the whole sub-division solutions of (mx=3,my=2) (mx=6,my=3).

To conclude, the implementation of BlockCutOpt in the two case studies showed that optimum cutting direction of blocks can vary and that BlockCutOpt is able to provide geometric information about the cutting grid of blocks that optimizes the resource exploitation, maximizing recovery and minimizing waste. For future work, it is suggested to perform a field comparison study between the results obtained from BlockCutOpt and the field results of cutting blocks from benches of quarries. Considering production costs and energy saving aspects in the algorithm is recommended.

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Appendix A

The input parameter file (BlockCutOpt.par) in BlockCutOpt program for stratum a in the case study of limestone quarry, considering the non-division of the tested area.

```
#BlockCutOpt parameters file
x_max=+27.00 #
x_min=+0.0 #
y_max=+65.00 #comment
y_min=+0.0 #comment
z_max=0.8 #
z_min=0.0 #comment
psi_max=3.1416 #
psi_step=0.0523598775598299 #
dx_step=0.5 #
dy_step=0.5 #
dim_block_x=3.025 #
dim_block_y=2.025 #
dim_block_z=0.825 #
mx=1
my=1
read_bound=0 #
BiDimensional=0 #
material-lost-by-quarrying =0.05 #
read_block_dimension=1 #
write_vtu=2 #
rotation_method=1 #
read_PLY_FileList=1 #
end=end
```

Appendix B

The input parameter file (BlockCutOpt.par) in BlockCutOpt program for the case study of the large scale granite quarrying area, considering the sub-division of the tested area (mx=6,my=3).

```
#BlockCutOpt parameters file
x_max=+31070.80449 #
x_min=+25397.77196 #
y_max=+10723.88741 #comment
y_min=+5007.604247 #comment
z_max=6.00 #
z_min=0.0 #comment
psi_max=3.1416 #
psi_step=0.0523598775598299 #
dx_step=7.0 #
dy_step=5.0 #
dim_block_x=21.025 #
dim_block_y=9.025 #
dim_block_z=6.025 #
mx=3
my=2
read_bound=0 #
BiDimensional=1 #
material-lost-by-quarrying=0.05 #
read_block_dimension=1 #
write_vtu=2 #
rotation_method=1 #
read_PLY_FileList=1 #
end=end
```