A STOCHASTIC MODEL FOR IDENTIFYING AREAS OF INTEREST IN BLAST MOVEMENT MONITORING

assist. prof. eng. Dimitar Kaykov, UMG "St. Ivan Rilski"
prof. Ivaylo Koprev, PhD, UMG "St. Ivan Rilski"

ABSTRACT

The utilization of blast movement monitors (BMMs) is a successful method of observing ore movement after blasting. It is proven that using more BMMs in a single blast improves the levels of ore extraction due to the amount of information available. However, there is a physical limit of the amount of BMMs that can be used in a single blast. For this reason, a mathematical approach is used to identify the zones of higher priority for obtaining information about their movement. The ore zones where the risk of distorting the information is the highest, while the percentage of the potential loses and dilution are also the highest, are considered to be zones of top priority, where at least one BMM should be placed.

INTRODUCTION

The number of BMM installed depends on many factors but the primary question is where exactly should a BMM be placed and how can we guaranteed that it can provide a maximum practical effect. So far, practical experience for the past decades has been of tremendous help in order to pinpoint the zones where ore has moved after blasting. Therefore, certain principles for placing the BMM sensors have been established. However, all these principles of planning the BMM locations are based on the expert's level of understanding the blasting process and the movement of ore and its location inside the muckpile. Therefore, they are subjective. Up to this point very few attempts have been made to quantify some of the parameters, on which these principles are formed. This article regards the difficulties which derive from this approach and attempts to pinpoint a direction of further studies on assessing the uncertainty of the information and the magnitude of ore losses, deriving from BMM placement.

KEY FACTORS DETERMINING THE BMM LOCATIONS

The overall principles for planning BMM places are as follows (Thornton, D M, 2009; https://blastmovement.com/):

- Ore loss and dilution will have a greater economic impact on higher grade zones, therefore definition of the correct boundary of high grade polygons will have a higher priority than lower grade polygons.
- Movement of isolated ore polygons is hard to track due to the lack of a sharp cut-off between the ore and waste material. Usually a separate BMM is required for the whole ore polygon in order to acquire as much accurate data as possible.
- Placing a BMM in proximity to other BMMs of the same colour increases the chance of compromising the data, which can be acquired from both of them. Therefore, two BMMs of the same colour should not be placed at a close distance from each other.
- In benches with a bigger height, more than one BMM can be placed in a single drill hole, depending on the D-shaped curve of the blast movement.
- It is advisory that BMMs are placed close to ore polygon vertices so that the ore boundary transformation algorithm can work properly.
- Complex ore polygon boundaries are considered to be more important in case of monitoring than parallel boundaries.
- BMM locations should be near the body of the blasted area and as furthest as possible from the boundaries of the blast. This is crucial for generating representative vectors for the whole orebody of the blast instead of corrupting the data with unrepresentative movement vectors.
- Avoiding damaging the BMM sensors from the blast is achieved by installing them halfway between blast holes (fig. 1).

- It is also recommended that some BMMs should be placed in order to gain a better understanding of the movement in all regions of the blast in order to "fill in the gaps" in terms of information. This is crucial due to the limited amount of blast movement information acquired from each blast.

Therefore, to summarize, the key factors which determine the number of BMMs placed and their locations are: Bench height; Overall blast movement direction; Movement magnitude and direction variability; Size and shape of ore polygons; Neighbouring or isolated ore polygon boundaries; Location of ore polygons inside blasting area; Ore grade of ore polygons; Current price of metal; Current operational and auxiliary costs for utilizing the BMM technology; Variability in rock properties in blasting area, etc.

STOCHASTIC APPROACH IN BLAST MOVEMENT MONITORING

Following the assumption used by D. L. Taylor and I. R. Firth, 2003, for quantifying the ore loss, ore misclassification and ore dilution, based on a 2D model of the ore zones, this article also utilizes this approach. The 2D model is also used in other case studies around mining sites around the world for two main reasons:

1) Vertical dilution is difficult to quantify, as vertical movement vectors inside the blasting area are highly variable. The reason being is that it is difficult to properly assume the vertical and horizontal vectors for certain segments of the bench, due to the variability of the rock type, swelling factor inside the muckpile. However, a 3D approach to the problem is currently in development by Blast Movement Technologies and its reliability is yet to be tested (https://blastmovement.com/);

2) Computational time required for calculating the estimates of the ore loss, ore misclassification and ore dilution volumes in a 2D model is generally less than in a 3D environment;

3) Results from applying a model for the random outcomes of a process such as blasting are never perfect, but a 2D approach is far simpler for getting a general idea of what to expect of the approximate location of the ore inside the muckpile. Furthermore, in many cases horizontal movement exhibits a good linear correlation with the 3D movement. This can derive from the high values of the coefficient of determination between the magnitude of the horizontal movement vector and the magnitude of the 3D movement vector (R^2>0,90), Zhi Yu, et al, 2021. In contrast, the vertical movement component has a relatively weak correlation with the 3D movement vector and therefore their relation is not obvious.

This reinforces the 2D approach for considering horizontal movement instead of the 3D movement to identify the locations of the post-blast ore volumes. However, one should know that this approach is not near-perfect but it allows mining engineers to establish a guideline for shovelling operations.

Technological constraints

There are four types of BMMs available, each identified by a different colour. Each one emits a different signal, which is dected after blasting. Therefore, it is possible to install more than one BMM per drill hole and/or place BMMs close together – assuming they are of a different colour. If there is inadequate separation between adjacent BMMs of the same colour, they may be impossible to locate due to signal interference. Furthermore, post-blast movement should also be taken into account into calculating the radius of placing BMMs of the same colour in the same blast (https://blastmovement.com/). Technological constraints can also apply to the possible locations where each BMM drill hole can be placed in order for the BMM sensor to remain undamaged after the blast (fig. 1)

Fig. 1. Possible locations for placing a BMM sensor (X-marks)

Key parameters for modelling

Each blast movement vector has two parameters – its magnitude and its direction. In the case of rock blasting the magnitude (M) and the direction (α) of the movement vector of blast movement are the two random variables. The magnitude of the horizontal movement vector in many cases obeys a certain distribution law, which is often proven to be close to the Normal distribution (Engmann, E, 2013; Harris, G.W., et. al. 2001; Isaaks, E, et. al., 2014; Hunt, T.W, Thornton, D.M., 2014). However, the direction of the horizontal movement vector does not always fit well into the Normal distribution law. Nevertheless, the randomness of angle deviation (α_d) is proven to have its limits and is described either by the deviation from the isochrones of the initiation scheme or by the deviation from the average movement direction. For this particular case study, the following key parameters have been considered in order to establish an overall idea of the variability of the horizontal movement vectors for each installed BMM:

Parameters concerning the horizontal movement vector's magnitude (M):

- **maximum magnitude**, M_{max} (m);
- **minimum magnitude**, M_{min} (m);
- **average magnitude**, $\bar{M}$ (m);
- **standard deviation of the magnitude**, σ_M (m);

Parameter concerning the horizontal movement vector's direction (α): **maximum angle deviation from the perpendicular of the isochrones in BMM location**, ± $\alpha_{d\,max}$ (°).

Due to the uncertainty of the outcome of the horizontal movement vector due to rock blasting, a stochastic approach gives the possibility of generating a number of different outcomes for the same horizontal vector, which can further be used for establishing the post-blast ore polygons as well as calculating the magnitude of the ore loss, misclassification and dilution (fig. 2).

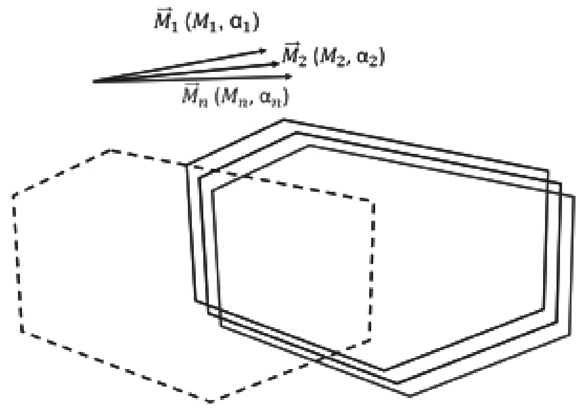

Fig. 2. Stochastic approach applied to vector outcome and post-blast ore polygon boundary

The different outcomes for the magnitude of the horizontal movement vector can be generated by using a random number generator, which follows a Normal distribution law with an input of the average magnitude ($\bar{M}$), the standard deviation of the magnitude (σ_M) and/or the minimum and maximum magnitude, (M_{min} and M_{max}). In contrast, the different outcomes for the horizontal movement vector angle deviation can be generated in the interval [- $\alpha_{d\,max}$; + $\alpha_{d\,max}$] as random numbers or by values from the whole interval can be assumed with a certain step size in between. Assuming there are a total of n generated values of the vector magnitude and a total of m outcomes for the vector direction (α_d), the total number of outcomes for the horizontal vector is n.m. In most cases each blast requires more than one BMM that should be installed inside the blasting area, which leads to an extremely large number of cases which should be considered in order to estimate the blast movement ore losses and dilution for every combination of movement vectors. This can lead to complications (model-wise) which are unnecessary in such an early planning stage of determining the areas of interest in a blasting area

After generating all the possible outcomes for the movement vectors for each BMM, their installation locations, the economic values of the ore loss, ore misclassification and ore dilution are calculated. For this case study a simple translation of the ore polygon was applied. However, the method of modelling the polygon displacement can be carried out using any of the standard estimating techniques, such as Triangulation, Polynomial Surface Fit, Inverse Distance, Kriging, as D. L. Taylor and I.R. Firth, 2003, remark. Furthermore, J. Loebb, 2014, points out that the three dimensional movement vectors are then used in a software program to translate ore blocks using proprietary logarithms derived from over ten years of blast movement research. It is important to clarify that the considered method in this study is used only to "bootstrap" the risk assessment model and illustrate the importance of the BMM location placement, which can sometimes be neglected.

CASE STUDY

This purpose of this case study is to assesses the risk of establishing higher levels of ore losses and their respective magnitude due to placing BMMs far from ore polygons or in areas of interest, which are not representative for the blast movement in the respective area of the BMM drill hole. The main objective of this case study is to order the ore polygons or blast zones for each blast area depending on the magnitude and the variance of the expected ore loss. The ore polygons which have the highest variances and magnitudes for ore loss and dilution are the ones which should be thoroughly monitored by installing at least one BMM inside or near them.

In a blast, where there are of about 300 blast holes, there are a total of over 700 locations where a BMM sensor can be placed. When taking into account the technological constraints of the BMM, deriving from its signal capabilities and the minimal radius between two BMMs, the number of possible cases drops significantly. Nevertheless, they still remain a number so large that it is impractical to consider all of them. Furthermore, when applying a stochastic approach for each BMM location, the number of cases increase exponentially, which makes the consideration of the whole set of possibilities impossible to consider. Therefore, a simpler approach is proposed in this article, where the assumption of using only 1 BMM per ore polygon is made. We assume that if 1 BMM is used for the whole ore polygon area, the information it gathers is representative only for a certain area of the blasting zone. If a second BMM is placed near or inside the same ore zone, the number of cases required for calculation increase exponentially, as argued. Using the approach of a single BMM neglects the alteration effect of the of the post-blast ore polygon shape. However, generating a big number of possible outcomes can prove to partially elude this problem. The purpose of the 1-BMM-approach is to simplify the modification the post blast ore boundaries and give a general idea where one should place one or more BMMs and rank the ore zones according to their priority. In addition, the purpose of this article is illustrate the risk assessment methodology. The search for the most suitable locations is a topic for another study.

The blasting area is consisted of 3 ore strings with different ore contents:

- Ore polygon 1 (green) – MEDIUM GRADE;
- Ore polygon 2 (red) – HIGH GRADE;
- Ore polygon 1 (blue) – LOW GRADE;

The grades of the ore polygons are not mentioned intentionally.

For each ore polygon different outcomes of the movement vectors were generated in order to estimate the avoided levels of ore losses. From the field studies an average estimate of the horizontal movement vector is:

- Ore polygon 1 (green) and Ore polygon 2 (red) $\bar{M}$ = 1,8 m and the standard deviation for the movement vector is σ_M = 0,6 m. The maximum angle of deviation is $\alpha_{d\,max}$ = ± 15°;
- Ore polygon 3 (blue) $\bar{M}$ = 1,6 m and the standard deviation for the movement vector is σ_M = 0,3 m. The maximum angle of deviation is $\alpha_{d\,max}$ = ±10°;

Notice that the parameters $\bar{M}$ and $\alpha_{d\,max}$ can be established more precisely by the approach proposed by Zhi Yu, et al, 2020, Zhi Yu, et al, 2021 by utilizing machine learning for predicting blast movement in different zones of the blasting area.

A random number generator is used to generate 400, 200 and 100 iterations for each vector outcome of the ore polygon zones. Using the standard BMM approach for calculating the avoided levels of ore dilution and losses, the ore losses are calculated for each iteration. It is generally known that ore loss is costlier than dilution, therefore it is crucial that the recovery of the mineral is maximal. Thus, in this articles we consider ore losses instead of dilution.

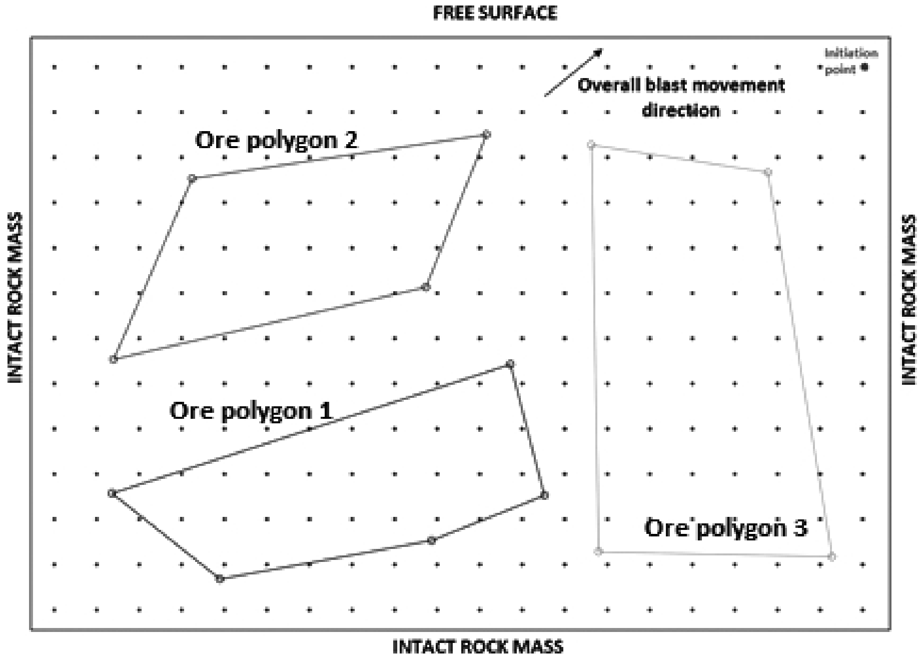

Fig. 3. Isolated ore polygons in blasting area

The bench height for this case study is 5 m and it is assumed that only 1 BMM is placed per drill hole.
Tables 1, 2 and 3 represent the results from the different cases of iterations and the Average metal lost and its Standard deviation are pointed out for the three Ore polygons.

Table 1. Avoided ore losses for each ore polygon and for each case of iterations

	400 iterations		200 iterations		100 iterations	
	Average metal lost, t	**Std. dev. of metal lost**	**Average metal lost, t**	**Std. dev. of metal lost**	**Average metal lost, t**	**Std. dev. of metal lost**
Ore polygon 1 (green)	1353.67	509.76	1343.97	526.78	1393.47	519.26
Ore polygon 2 (red)	1311.21	281.01	1347.63	244.31	1294.73	267.49
Ore polygon 3 (blue)	719.01	142.10	734.22	133.05	735.96	144.70

The results on fig. 4 show that the given that the movement vector has a distribution law close to the Normal one, the avoided ore losses also resemble a distribution close to the Normal one as expected. These shown results are only for Ore polygon 3, but the results for polygons 1 and 2 resemble a Normal distribution in a similar manner.

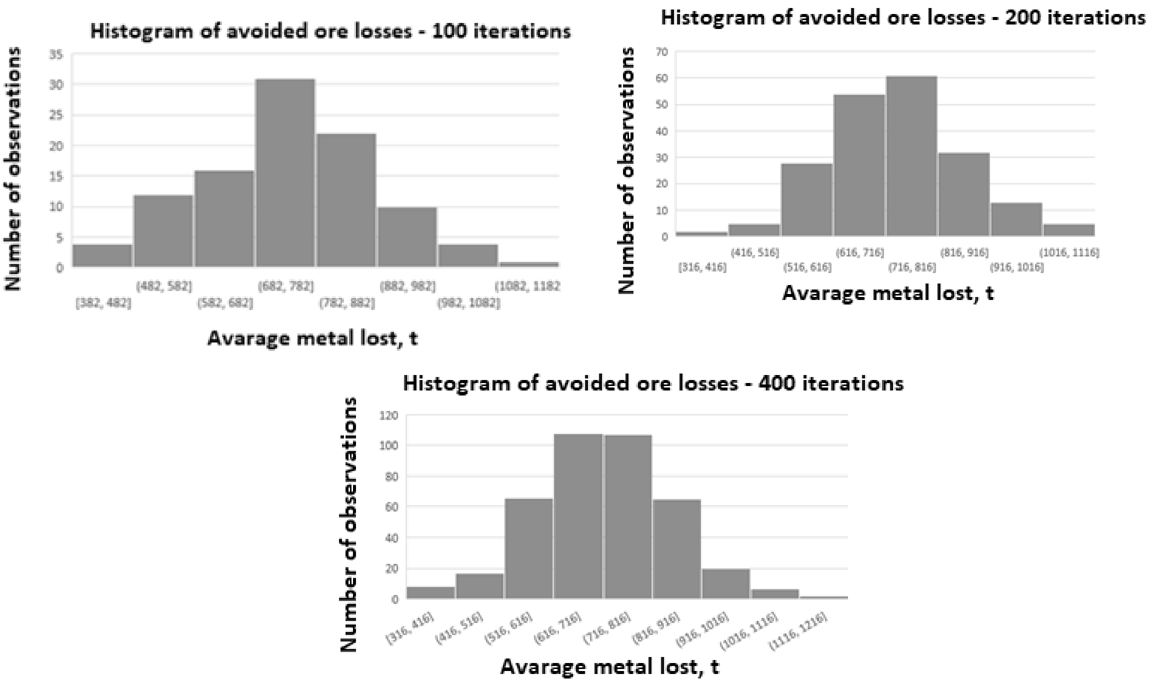

Fig. 4. Histograms of avoided ore losses (metal losses in tones) for each considered case

A Pareto frontier optimization is used to rank the priority level of the ore polygons. These polygons of higher level of importance for monitoring are the ones which have a higher level of standard deviation of avoided ore losses (result uncertainty) and at the same time a higher values of average avoided ore losses (bigger scale of potential losses). The results, represented on fig. 5, show that Ore polygons 1 and 2 dominate over Ore polygon 3, which is the one with least movement deviation and the lowest ore grade. The results are the most variable for Ore polygon 1, which can be explained due to its proximity to the initiation point. The higher priority for Ore polygon 2 derives from its higher ore content. However, there is a higher priority to monitor Ore polygon 1 due to the uncertainty of the end result of the volume of avoided ore losses and its larger overall area. In terms of feasibility Ore polygon 1 and Ore polygon 2 are almost equivalent.

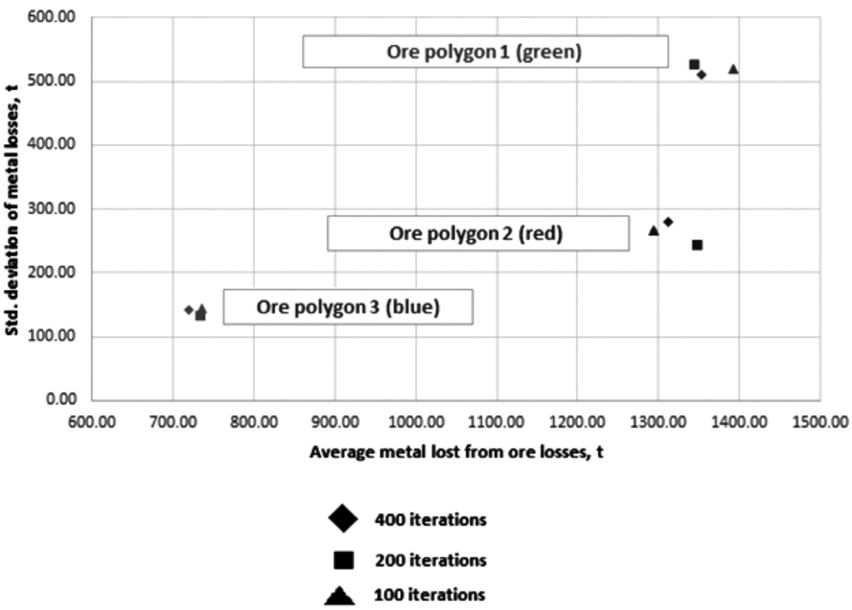

Fig. 5. Pareto optimization for BMM sensor placement priority

Therefore, for this example in the case study there are 2 options:

- A second BMM can be placed near Ore polygon 2 due to the close values for the avoided ore losses (Average metal lost).
- A second BMM cannot placed if the technological constraints, deriving from the signal interference, are unavoidable.

A rational decision for this case study is to place 1 BMM sensor near or inside the boundaries of the 3 ore polygons and 1 BMM sensor between Ore polygons 1 and 2 as there is no interference between the BMMs of different colours. This case study also followed the conclusion drawn from J. Loeb, (2014) that the practical number of BMMs can be reached earlier than the feasibility limit of using BMMs in a single blast.

CONCLUSIONS

- The avoided ore losses (Average metal lost) appear to also follow a Normal distribution law as expected, which can be used for further analysis. However, this should be done so after acquiring more simulated vector data via more iterations (preferably sever thousands of iterations).
- The Pareto optimization can prove useful for quantifying the priority level for monitoring ore polygons when it comes to monitoring them with BMM sensors.
- The number of iterations can impact the Pareto optimization solution and therefore more iterations are required for conflicting polygons (polygons which are similarly susceptible to movement variation, polygons which are of similar grades, etc.).
- However, in cases where there are fewer or no conflicting polygons, a smaller number of iterations can also provide a good foundation for the engineer's decisions.

POSSIBILITY FOR FURTHER RESEARCH

In order to gain better understanding of the stochastic nature of the blast movement process and data analysis, further research could focus on these directions:

- Establishing the smallest reliable number of iterations required to draw truthful conclusions;
- Implementing more variables into the optimization problem such as ore dilution and misclassified ore volumes;
- Attempting to quantify the optimal places for installing BMM sensor, based on pre-established possibilities for BMM drill hole locations.
- This approach could also be used for tracking the movement of zones in a blasting area, which are different from the ore zones, e.g. zones of different rock types. However, this hypothesis has yet to be proven.

REFERENCES

1. Engmann, E. et al. "Measurement and modelling of blast movement to reduce ore losses and dilution at Ahafo Gold Mine in Ghana." Ghana Mining Journal 14 (2013): 27-36.
2. Harris, GW & Mousset-jones, Pierre & Daemen, J. (2001). Blast movement measurement to control dilution in surface mines. CIM Bulletin. 94. 52-55.
3. Hunt, T.W, Thornton, D.M. (2014). Modeling vs Monitoring Blast Movement: The cost of Variation. Proc. 40th Annual Conference on Explosives and Blasting Technique, Denver, Colorado, USA, 9-12 February 2014
4. Isaaks, E, Barr, R, and Handayani, O, 2014. Modeling blast movement for grade control, in Proceedings Ninth International Mining Geology Conference 2014, (The Australasian Institute of Mining and Metallurgy: Adelaide).
5. Loeb, Jeff. (2014). A Cost Benefit Analysis to Explore the Optimum Number of blast movement monitors.

6. Taylor, D. L. and Firth, I. R. (2003), "Utilization of Blast Movement Measurements in Grade Control", in Application of Computers and Operations Research in the Minerals Industry (Southern African Institute of Mining and Metallurgy: Marshalltown), pp. 243-247.
7. Thornton, D M, 2009. The implications of blast-induced movement to grade control, in Proceedings Seventh International Mining Geology Conference 2009, pp 147-154.
8. Yu, Z., Shi, X., Zhou, J. et al. Feasibility of the indirect determination of blast-induced rock movement based on three new hybrid intelligent models. Engineering with Computers 37, 991–1006 (2021). https://doi.org/10.1007/s00366-019-00868-0
9. Yu, Z., Shi, X., Zhou, J. et al. Prediction of Blast-Induced Rock Movement During Bench Blasting: Use of Gray Wolf Optimizer and Support Vector Regression. Nat Resour Res 29, 843–865 (2020). https://doi.org/10.1007/s11053-019-09593-3
10. https://blastmovement.com/ (Last opened 15th July 2021)