Institution: Queen Mary University of London (QMUL)

Unit of Assessment: B15 (General Engineering)

Title of case study:

Fracture modelling saves money, increases productivity and makes mining safer

1. Summary of the impact (indicative maximum 100 words)

From 1995 Professor Munjiza's research at QMUL has led to the development of a series of algorithms which can predict the movement and relationship between objects. These algorithms have been commercialised by a range of international engineering and software companies including Orica, the world's leading blasting systems provider (via their MBM software package), and the software modelling company, Dassault Systems (via their Abaqus software). Through these commercialisation routes Munjiza's work has generated significant economic impact which is global in nature. For example, his predictive algorithms have enabled safer, more productive blast mining for Orica's clients – in one mine alone, software based on Munjiza's modelling approach has meant a 10% increase in productivity, a 7% reduction in costs and an annual saving of $2.8 million. It has also been used in Dassault Systems' Abaqus modelling software, which is the world's leading generic simulation software used to solve a wide variety of industrial problems across the defence, automobile, construction, aerospace and chemicals sectors with associated economic impact.

2. Underpinning research (indicative maximum 500 words)

Between 1995 and 2004 Professor Antonio Munjiza (QMUL 1995-present), a computational engineer, conducted research that led to the development of the combined finite discrete element method [he has written three monographs on the subject, see s.3]. As part of a project with ICI (now Orica), this method was used to produce a software package for rock blasting (MBM). Following further research he developed the next generation of related algorithms, which included No Binary Search (NBS) and a number of open-source software packages called 'Y'. In 2010, NBS became a part of Dassault Systems' Abaqus Explicit modelling software package, incorporated within their Smoothed Particle Hydrodynamics (SPH) method suited for solving fluid and large strain Lagrangian simulations.

Although finite element methods were well established in many branches of engineering and routinely used in the solution of large-scale industrial problems, the finite element description is not the most appropriate model. Munjiza's contribution was to marry discrete and finite elements into predictive models for progressive fractures. The combined finite/discrete element (FDEM) approach, in which the problem is analysed by a combination of the two methods, is particularly suited to problems in which progressive fracturing takes place as is the case in rock blasting situations and missile impact situations [1, 2]. Munjiza's research has focused on the numerical modelling of particulate processes in environmental science. While most discontinuum modelling uses spheres to represent particles, his work has led to developments that tackle the complexity of realistically shaped bodies such as those exhibited by rock fragments [3].

Munjiza's work has also led to efficient computational simulation of these fracture mechanics [4], which has resulted in advances in modelling software, both in industry and in the research sector. He has invented a number of original algorithmic solvers such as NBS linear search, MR linear search (widely employed in molecular dynamics), a combined single-smeared approach to fracture, and several others. These methods require less computational resource (in terms of time and memory) than their predecessors, while still resulting in faithful models of the interaction between molecules, for example, or the propagation of fractures from an explosion.

A number of research institutions around the world have developed research software using FDEM in the form of Y-code, which is open source enabling technology developed by Munjiza. For instance Munjiza, in collaboration with the University of Toronto has developed Y-geo, Y-gui and Y-blast based on Y [5]. Imperial College London, in collaboration with Munjiza, have developed VGEST based on Y. Through these software developments the technology is now being used

across a variety of industrial sectors, such as mining, petroleum, mineral processing and aerospace. Further, several government labs in the USA are pursuing research based on Munjiza's FDEM.

3. References to the research (indicative maximum of six references)

1. Munjiza, A., Andrews, K.R.F. (1998). NBS contact detection algorithm for bodies of similar size. *Int. J. Num. Methods Eng.*, 43, 131-149.
2. Munjiza, A., Andrews, K.R.F (2000). Penalty Function Method for Combined Finite-Discrete Element Systems Comprising Large Number of Separate Bodies. *International Journal for Numerical Methods in Engineering*, 49 (11), pp. 1377-1396
3. Latham, J.-P., Munjiza, A. (2004). The Modelling of Particle Systems with Real Shapes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 362 (1822), pp. 1953-1972.
4. Rougier, E., Munjiza, A., John, N.W.M. (2004). Numerical Comparison of Some Explicit Time Integration Schemes Used in DEM, FEM/DEM and Molecular Dynamics. *International Journal for Numerical Methods in Engineering*, 61 (6), pp. 856-879.
5. Mahabadi, O. K.; Grasselli, G.; Munjiza, A. (2010). Y-GUI: A graphical user interface and pre-processor for the combined finite-discrete element code, Y2D, incorporating material heterogeneity. *Computers & Geosciences*, 36, pp. 241-252.

4. Details of the impact (indicative maximum 750 words)

Munjiza's fracture modelling algorithms are used to develop predictive simulation software for a wide range of industries including the defence, automobile, construction, aerospace and chemicals industries. But they have generated greatest impact in the global mining industry, where his research into finite and discrete element modelling (FDEM) results in more accurate and detailed predictions of blast mechanics, which are computationally tractable. Predictive software based on Munjiza's algorithms has generated commercial and economic impact for major mining companies through increased productivity, a reduction in extraction costs resulting in enhanced profitability for the companies and reduced commodity price for customers. Further, the safety of the process is improved, delivering benefit to employees working within the mine.

Software used in the mining industry to accurately predict blasting

Munjiza's fracture modelling methods are widely used in the multi-billion dollar global mining and extraction industries. Many engineering and extraction activities are "one-shot" opportunities that, if they go wrong, cannot be repeated. Take, for example, the blasting of a rock face in open cut mining. The resulting fragments of ore must be within a certain range of sizes if they are to be suitable for onward processing. Until the introduction of the FDEM modelling approach, the development of a blast design (placing and timing charges of explosives so that the resulting explosion creates the desired pattern of fractures) was impossible to predict accurately. Munjiza's algorithms, based on his FDEM methods, have enabled the development of modelling software, which can predict the result of explosions in both time and space with sufficient accuracy that it can be used to design highly productive and safer blasts, for example via Orica's MBM package and Abaqus Explicit modelling software used by Coffey Mining.

Orica and the MBM package

Orica is a leading multinational corporation that has more than 15,000 employees and an annual revenue in 2010 of $6.5 billion. The company provides commercial blasting systems, mining and tunneling support systems in more than 50 countries worldwide. Orica's Mining Services Division is the world's largest single supplier of commercial explosives and blasting systems to the mining, quarrying and infrastructure sectors.

Orica is able to provide accurate blast designs for their customers worldwide using their Mechanistic Blasting Model (MBM) package, which is based on Munjiza's algorithm [Section 5, source 1]. This is provided as standard for all of their open-cut metal, coal and quarrying customers in Australia, Asia, Europe, the Middle East, Africa, North America and Latin America. As an example of how Orica uses the MBM package, the Eastern Creek site in Woolombi, Australia has a complex geology that had led to less output and greater costs than the mine's owners were happy

with. When Munjiza's approach was introduced by Orica at this site, it led to an increase in dragline productivity by 10%, a reduction in drill and blast costs at Eastern Creek of 7% and an annual saving of $2.8 million [Section 5, source 2]. Elsewhere in Australia, in Hunter Valley, Orica were faced with the challenge of blasting in an area that contained high-voltage power lines. The blast designers needed to accurately predict the impact of the blast in order to ensure that the power lines weren't damaged because this risked causing a blackout in a major city less than 40 miles away. They used the MBM software to predict the effect of the blast and to ensure that the power lines would not be brought down by the explosions [Section 5, source 3].

Use of the NBS algorithm in Abaqus software

Munjiza's NBS algorithm solver is used in Dassault Systèmes' Abaqus Explicit modelling software package, the world's leading generic simulation software [Section 5, sources 4,5]. The incorporation of the NBS algorithm into Abaqus has delivered economic/commercial impact both to Dassault Systèmes and to their customers, who use the software to solve engineering problems and improve their business competitiveness. The incorporation of the NBS solver within the Smoothed Particle Hydrodynamics (SPH) method in Abaqus Explicit 6.11 improves the functionality of the software and helps ensure competitive advantage of Dassault Systèmes as market leader with associated direct economic impact.

Dassault Systèmes S.A. provide several case studies relating to the economic impact their customers have obtained through the use of the NBS solver within the Abaqus Explicit package (see section 5). For example, this Abaqus Explicit software is used by Coffey Mining, a specialist consultancy to the international mining sector. The principal engineer for Coffey Mining, says that the modelling approach based on Munjiza's work allows them to "answer a number of questions simultaneously, [allowing Coffey] to work on the complete 3D mine geometry." This cuts down on the time spent creating models and leads to more accurate predictions [Section 5, source 6].

Eni S.p.A. is a multinational oil and gas consultancy that advises its clients on ways to better manage the lifespans of oil and gas fields. They use the modelling techniques developed by Munjiza within the Abaqus Explicit software to ensure that reservoirs of fossil fuels are managed as sustainably as possible [Section 5, source 7]. "It used to take almost two months to complete a single model suitable for running," says Silvia Monaco, geomechanical engineer in the petroleum engineering department of Eni E&P headquarters. "Now we can build a model in only four weeks… Moreover, the new iterative solver implementation provides a strong reduction in computational times and memory usage that further speeds up the execution of the study."

Abaqus Explicit predictive simulation software has a wide range of other applications including predicting ballistic impact in the defence industry, crashworthiness in car manufacturing, and other uses in the construction, aerospace and chemicals industries. It is expected that the latest combined finite discrete element method as described in three monographs will become an integral part of a number of generic and application-specific software packages, thus further improving productivity, reducing cost, increasing safety and leading to a better environment.

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. Blasting Technician, Orica Mining Services. Aspect corroborated: Software used in the mining industry to accurately predict blasting & Orica and the MBM package
2. Also see – improved mining efficiency using MBM package: www.oricaminingservices.com/uploads/Fragmentation/Open cut/100064_Case Study_ABT Smashing PerformanceNewlands Eastern Creek_English.pdf
3. Also see – MBM package used to avoid power lines during blasting: www.oricaminingservices.com/au/en/page/independent_pages/open_cut_vibration_management
4. Engineering Specialist, Automotive Industry at Dassault Systemes. Aspect corroborated: Use of the NBS algorithm in Abaqus software
5. Munjiza algorithm incorporated into Abaqus Explicit modelling software package: http://iwcmm22.jhu.edu/MS2-1.html
6. Coffey Mining uses Abaqus for geomechanical modelling: www.3ds.com/company/customer-

stories/details/customers/coffeymining/single/1105/?cHash=d136b8a20956be0c363f97cbb7d67e04

7. Eni uses Abaqus to model oil and gas reservoir structure: www.3ds.com/fileadmin/COMPANY/About-3DS/3DS-Magazines/SIMULIA-Community-News/PDF/simulia-scn-0612.pdf (pp 12-14 and Cover)