Quadruple Helix Model for Industrial Mathematics Infrastructures in Malaysia

Zainal Abdul Aziz[1] **and Arifah Bahar**[2]

UTM Centre for Industrial and Applied Mathematics (UTM-CIAM) and MYHIMS Solutions LLP, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

e-mail: [1] zainalaz@utm.my, [2] arifah@utm.my

Abstract

In Malaysia, most of the collaborations with industry and external parties in the realm of industrial mathematics (IM) bring benefits to applications of R&D&I/knowledge & innovations in industry and community at large, creating opportunities for talent and capacity development in academic circle & government agency and providing accessibility to funding from government & industry. Applying a Quadruple Helix (QH) innovation model/framework characterises this cooperation between the four main clusters involved (government, industry, academia & community user/civil society), which embraces close interaction in the forms of relation, mobility, transfer and formality to produce innovations. Our current proposed QH framework facilitates and sustains the mechanisms of our national innovative IM infrastructures/services via a synergistic & entrepreneurial partnership between the research centre, UTM Centre for Industrial & Applied Mathematics (UTM-CIAM) and its spin-off company, MYHIMS Solutions LLP.

1 Introduction

The initiative world-wide in making industrial mathematics to be seen as significantly applicable to diverse industrial problems has taken place with much effort [1, 2]. This is done through a wide variety of activities such as universitys programmes, study groups, consulting platforms and the like are now in existence. Obviously in terms of the scale of activity, Europeans, North Americans and Australians/New Zealanders are leading the Industrial Mathematics (IM) action league. Nonetheless, there are thriving and increasing activities in Malaysia and as well as in our Northern Asian and North Eastern neighbours, particularly in India, China, Hong Kong and Japan. Our own Malaysian Mathematics-in-Industry Study Group (MMISG) [3, 4, 5, 6] continues to grow and has been up and running till now, alas in various forms and strengths (e.g. Malaysian Mathematics in Industry Workshop (MMIW), Malaysian Mathematical Modelling Camp (MMMC), Malaysian Mathematics in Industry Challenge (MMIC)), which had much to do with the current financial constraints and economic slowdown.

The OECD reports [7, 8] are exceptional records outlining on these matters. These reports undertake that industrial innovation is becoming more and more dependent on the results and

techniques of scientific research, which intrinsically being supported and driven by industrial mathematics (refer Figure 1). In implication, these reports stated that while many industrial problems have substantial mathematical components and industrial challenges, these problems either fall within topical areas of current research in the mathematical sciences or embrace well beyond the envelope of classical topics in mathematics.

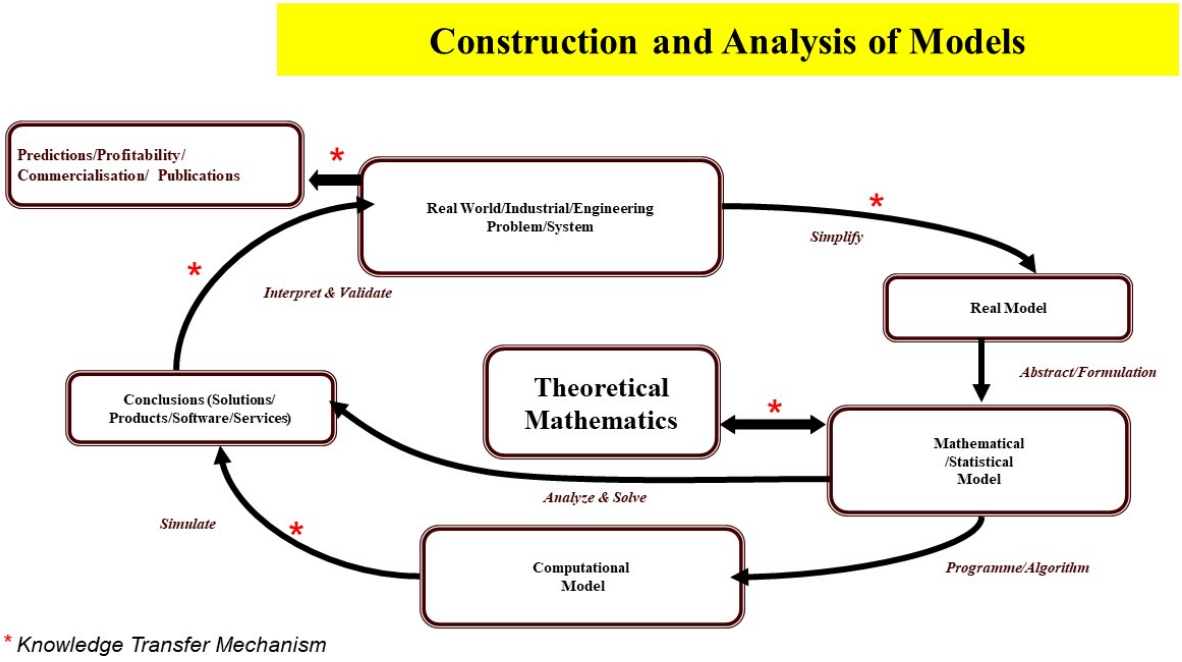

Figure 1: IM workflow on construction and analysis of models [3]

Generally these industrial problems could extend into diverse fields such as biological, medical, agricultural, social, and financial areas, as well as the conventional areas of engineering and the physical sciences. In addition, it is also noticed the importance that by having increasingly stronger links between mathematical sciences and industry will be "both beneficial to the partners and to national economies". We think that these links are much related to the idea of Quadruple Helix (QH) model of interactions, and will inspire new ideas in the mathematical sciences academia and enhance the competitive advantage of companies, public authorities and civil society.

In Malaysia, we have realized that collaborations with industry and other external parties in the jurisdiction of IM bring benefits to Science, Technology, Engineering & Mathematics (STEM) teaching and skills development; access to external funding and empirical data from industry; reputation enhancement; application of knowledge; opportunities for talent/capacity development by both students and staff; and promotion of entrepreneurship. Concurrently with the Malaysian Ministry of Educations initiatives in promoting linkages and knowledge transfer, our efforts in creating partnerships and collaborative efforts with industry need to be streamlined and enhanced. The QH model is used to facilitate the investigation on the role of IM infrastructures or services in economic development of the region. We deem that the results would strengthen; sustaining and identifying further interactive partners with Malaysian industries. The realisation of this framework is being carried out

through an ambitious model of collaborative & entrepreneurial partnership between UTM-CIAM and MYHIMS Solutions LLP (refer Figure 2).

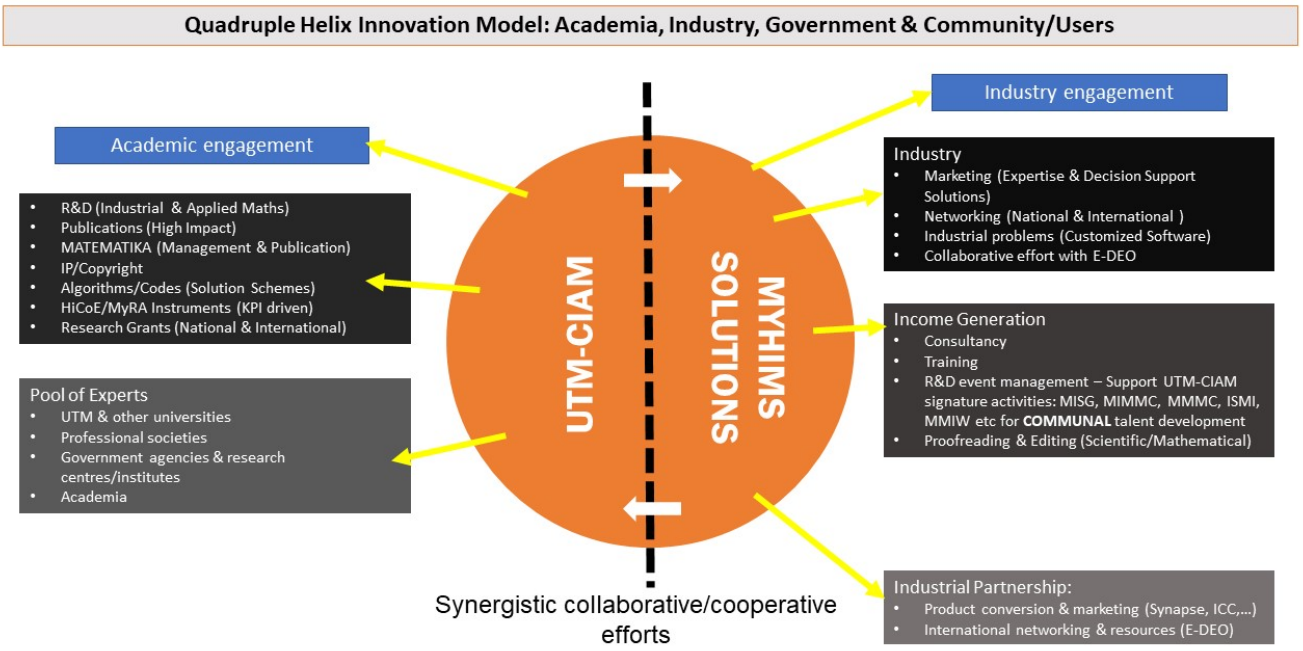

Figure 2: A synergistic collaborative model of UTM-CIAM and MYHIMS Solutions LLP based on the QH model

2 Quadruple Helix (QH) Model

A general definition of the Quadruple Helix (QH) innovation model refers to an innovation cooperation model or innovation environment in which community users, industry/private firms, universities/academia and government/public authorities cooperate in order to produce innovations. These innovations can be anything that is considered useful for the partners in innovation cooperation, for example, technological, social, product, services, commercial, non-commercial, private and public-sector innovations [9, 10]. This QH innovation model also refers to an outline describing the interaction between four main clusters of interest and is usually applied to assist in characterizing our connection between these clusters in industrial mathematics (IM) infrastructures or services, involving interaction in the forms of relation (involving contract research, consultancy, etc.), mobility (encompassing research training, modelling workshop, study group, etc.), transfer (comprising copyright, commercialization, etc.) and formality (relating MOU, MOA, LOC, LOI, etc.). This description suits well with our IM action plan and roadmap in strengthening, sustaining and identifying further interactive partnerships with the Malaysian industries, public authorities, universities and citizenry/community. We plan to use this framework to illustrate the inner workings of our regional innovation system whiles minimizing insufficient capability from various possible ”innovation gap” within the system.

The use of QH model possibly can aid understanding and help ensure that the actions to be taken have a sound theoretical basis. This model of open innovation has the potential to assist with our IM process/infrastructure/service when linked to knowledge management, particularly with regards to:

- *Evidence-based knowledge management*, where there is significant support between the four helices of the quadruple helix model (academia, industry, government, community) and the four sources of evidence (scientific literature, practitioners, organisation, and stakeholders).
- *Knowledge management for development*, where there is a noticeable attempt towards knowledge co-creation involving multiple stakeholders and a crossing of the boundaries between STEM scientists and society.

QH model has been applied in the private and public sectors as well as in several operational areas, including telecommunications, health, well-being, housing, tourism, energy, and governance, and these cases suggest that QH model has wide application possibilities. In addition to innovation, this concept plays also other roles, for example, in entrepreneurship and venturing, and essentially in knowledge and technology transfer as well. QH model development platforms and environments could be seen as an enhancement to other traditional cluster and regional innovation policies (linear innovation model, regional and territorial innovation models, to Triple Helix model and user-centric model) and as a new kind of intermediary configuration that supports the involvement of users in the R&D&I activities.

We believe that QH model should take a more multi-faceted look at innovation via system-oriented theory and research of innovation. This outlook of the innovation process plainly knows the potentially complex interdependencies and possibilities for multiple kinds of interactions between the various elements of the innovation process. It also accords great importance to the demand side rather than concentrates primarily on the supply side [11]. The innovation system concept can be understood in both a narrow and a broad sense [12]. A narrow definition of the innovation system mainly incorporates the R&D functions of universities, public and private research institutes and corporations, reflecting a top-down model of innovation. A broader conception of the innovation systems is more interactive and bottom up, including 'all parts and aspects of the economic structure and the institutional set-up affecting learning as well as searching and exploring' [13]. We propose to implement a QH innovation business model/system based on the latter concept which embeds and supports the involvement of community users.

3 UTM Centre for Industrial and Applied Mathematics (UTM-CIAM)

UTM Centre for Industrial and Applied Mathematics (UTM-CIAM) is a research centre of excellence in Universiti Teknologi Malaysia [3]. UTM-CIAM is established with the strategic cooperation of Oxford Centre for Industrial and Applied Mathematics (OCIAM). It was launched via a collaborative agreement which was signed on 12 December 2012 in the presence of the Malaysian Minister for Higher Education at St. Anne College, University of Oxford. The establishment of UTM-CIAM is to facilitate the research cooperation with the

industry and other disciplines including engineering and technology. This research would notably embed modelling and prepare to generate an innovative and optimal solution to be shared with the industry as portrayed in Figure 1. In parallel with UTM-CIAMs vision to become a global renowned centre and to pioneer mathematics in the nations industry, the main agendas of UTM-CIAM are to advance multidisciplinary research, to promote collaborative mathematical research with various disciplines, and to encourage practical applications of industrial and applied mathematics in order to produce high quality research outcomes and innovations.

In the efforts to increase research alliances with the industry, UTM-CIAMs researchers consistently visit and link up with potential industries to discuss the related research projects and in the long run to strengthen the respective industrial partnership. Some of the industries that have been identified to retain active working relationship are Institut Penyelidikan Hidraulik Kebangsaan Malaysia (NAHRIM), KPJ Healthcare, Petronas Melaka, J-Biotech Environment Sdn. Bhd, PROTON Berhad, Jabatan Penerbangan Awam (DCA), Hospital Universiti Sains Malaysia (HUSM), MARDI, PROSPECT, I-Factors, CREST and many more to come. In order to formalise this relationship, we normally propose MOU, MOA, LOC, LOI such as the Memorandum of Understanding (MOU) which has been agreed between UTM-CIAM and HUSM, and UTM-CIAM and J-Biotech.

One of the main flagship activities being organized by UTM-CIAM is Mathematics in Industry Study Group (MISG). The first MISG was organised in 2011 under the auspices of the Mathematical Sciences Department. In 2014, UTM-CIAM collaborated with OCIAM, a world renowned centre for mathematics research in industry, in holding the 2nd MISG Malaysia (MMISG). The study group refers to intensive workshop for problem solving where mathematician's expertise is being employed to overcome real life problems proposed by the industry. In relation to that, many academicians with relevant backgrounds from OCIAM international network and local institutions were invited. They quickly helped to determine the important scientific-industrial concerns and challenges of the study group upon facing with various solutions of the industrial problems. The problems provided by the industries were prepared and identified, and thus proposed during the problem solving discussion session. Subsequently it was then determined that there were six industrial problems which would involve mathematical modelling. These included oxidation pond problem, riverbank filtration problem, electromagnetic shock absorber problem, paddy field pest population problem, blood flow at bifurcated artery, and water complex and heat integration in industrial process. These problems came from J-Biotech Environment Sdn. Bhd, NAHRIM, MARDI, KPJ Healthcare, PROTON Berhad and PROSPECT respectively.

As a result, MMISG has given us the opportunity to close the previous rift between academics, and industrial practitioners and scientists from the industries. It is proven that MMISG has become a vital platform to disseminate policy and emphases on the field of industrial and applied mathematics in numerous difficult industrial problems. We would like to emulate our European counterparts [14, 15, 16] with excellent examples of European industry and mathematical sciences coming together to overcome various complex challenges of European industries face. We had a successful 3rd MMISG in 2015 with further seven different industries providing the industrial problems. We then had to postpone future MMISG due to financial constraint and current economic slowdown. Nevertheless, we were then able to conduct other signature activities which entailed less financial burden, but instead were generating income into our coffer. These activities include International Seminar on Math-

ematics in Industry (ISMI) in 2013, 2017, 2018 where ISMI2017 and ISMI2018 had a special tailor-made event embedded within i.e. Malaysian Mathematics in Industry Workshop (MMIW), which is simply a mini version of MMISG. Furthermore we were able to organise capacity building events specifically for the postgraduates and postdoctoral fellows in the Malaysian Mathematical Modelling Camp (MMMC) in 2015 and for the undergraduates in Malaysian Mathematics in Industry Challenge in 2016 and 2018. We too had a unique workshop to train researchers to become industry technology translator in Young Talent Camp 2016, with an exclusive cooperation from the Smith Institute, United Kingdom [17].

4 MYHIMS Solutions LLP

UTM-CIAM engages industries and has a lot of activities involving capacity building and problem solving with industries and communities as mentioned in the above section and depicted suitably in Figure 1, and these certainly require substantial financial support and with the current scenario of economic slowdown, this situation and ecosystem is thus unsustainable. Moving forward, to maintain UTM-CIAM and its important and impactful signature activities, we require ways to generate finance and aggressive marketing of UTM-CIAM's expertise & "products".

Further consultation with OCIAM & Smith Institute, UK, in search for a sustainable business model, we have decided to set up UTM-CIAM's dedicated business arm or a spin-off company - MYHIMS Solutions LLP and proposed a synergy based on the Quadruple Helix Innovation Model. MYHIMS Solutions LLP is simply a dedicated business arm of UTM-CIAM. MYHIMS Solutions LLP is a Limited Liability Partnership (LLP) company that offers industrial mathematics and statistics consultancy services via a national network of STEM experts in solving industrial problems. This company is set up with the main aim to manage the industry and community engagements whiles bridging these with the academia and government as illustrated suitably in Figure 2. This is done mainly by strictly managing the signature activities related to UTM-CIAM, and as a result generating income and satisfying the return on investments strategies. The next step in MYHIMS's workflow is to gather all the solution procedures or algorithms based on the signature activities (together with the respective signed non-disclosure agreements) and transform all these into customised or generic software as our pre-commercialised products. After procuring the respective copyrights and patents, the products are then market-ready to be commercialised. We deem that commercialisation is the way to monetise the value of R&D&I based on our flagship events (refer to Figures 1 and 2). The other main objective of MYHIMS's existence is to support financially UTM-CIAM in order for UTM-CIAM to excel in its forefront R&D activities, particularly by securing outstanding researchers and excellent facilities (e.g. refer [18, 19]). Thus the model adjoining the two entities together primarily seems ambitious but currently we think this is the most financially sustainable model for us to move forward beyond the Malaysian Industrial Mathematics for Industry.

5 Beyond Malaysian Industrial Mathematics for Industry

In order to progress beyond the Malaysian landscape and to strengthen and sustain the partnership between UTM-CIAM and the industries locally and globally, UTM-CIAM has cre-

ated the spin-off company MYHIMS Solutions LLP. This business model which in nature and operation is based on a QH framework is set up as a synergistic and collaborative effort between the two entities as shown in Figure 2. This endeavour basically prepared UTM-CIAM and MYHIMS Solutions LLP for the next level of engagement with the four clusters in this framework, whereby it is strongly hope that this effort would bring us to another level of commitment which goes beyond the Malaysian industrial mathematics for industry.

To ensure that industrial mathematics becomes important and more relevant to the Malaysian scenario, and with the background of our business model in Figure 2, the following specific recommendations are proposed:

- Industrial Mathematics for Industrial Innovation possibilities include the creation of a national IM network hub based on the model as shown in Figure 2, where special positions in industrial mathematics are made available, the scheduling of workshops and seminars (much like our MMISG, ISMI, MMIW, MMMC) [4, 5], and specialist workshops to highlight novel mathematical techniques relevant for industry can be well supported by the business model.

- Education and Training based on the experience of this business model, a revision of the traditional curriculum in Industrial Mathematics, both in content and approach, should transpire to include provision of opportunities for secondary school teachers to engage in academicindustrial interactions [20, 21]. This revision must include in the training: mathematics curriculums at all levels need to be redesigned to reflect the ever-growing interest in mathematical and statistical modelling and provide our students with the basic skills necessary to become real modellers. The concept of modelling is central to the practical applications of industrial mathematics.

- Interface between Industrial Mathematics and Industry the formation of "joint teams" [22, 23], positions for industry "technology translators", web access for information about problems, methods, solutions, centres of excellence and available expertise, with networks of experts across institutional boundaries and the sharing of things like model agreements on intellectual property rights would be made easily accessible via the business model.

- Academic Infrastructure to be transformed accordingly to support interdisciplinary activities, recognitions to be given for faculty members' involvement in outreach activities, the creation of faculty positions for researchers from industry (which would provide much-needed role models for students), and the maintenance of quality control of industrial mathematics projects.

- Industry Infrastructure the need for the availability of positions in industry for qualified researchers (notwithstanding the different perspectives industry and researchers have in regard to the timescales involved in solving various industrial problems), the willingness of industries to participate in workshop activities and the like, and the provision of industry support for the enhancement of industrial mathematics in industry.

- National and International Coordination this is materialising, but a more concerted (and less competitive) approach is needed to maintain critical mass, the sharing of expertise, and minimising of the uneconomical duplication of our present effort. It is

acknowledged that Malaysia (through UTM's Department of Mathematical Sciences, UTM-CIAM, MYHIMS Solutions LLP) has made some steps in this direction but much more should and could be done.

Following the publication of the OECD reports [7, 8], UTM-CIAM and MYHIMS Solutions LLP have plans to form an "Experts' Working Group" to review and report on the various mechanisms used to further activities in Industrial Mathematics for Malaysian industries. The objective of this is to provide an outline that other interested research groups and centres of excellence could follow suit.

6 Conclusion

Mathematical modellers in STEM field hold a unique position in the scientific world and industrial region with their ability to interact with industry practitioners in so many different areas in industry, the sciences and engineering. In our opinion, to date this advantage has not been exploited to its fullest extent, partly because of the lack of recognition of industrial mathematics by the mathematical and various types of communities at large [24, 25]. It is our recommendation that the way forward in this direction involves transforming mathematics curriculums such as to place more emphasis on aspects of mathematical and statistical modelling in solving realistic problems from industry [26, 27, 28]. Mathematics in Industry study groups (e.g. MMISG and MMIW) with industry are clearly one of the most significant ways of strengthening the industry and industrial mathematics interface but such interactions can only become fully matured if the STEM researchers could develop a set of skills more suited for real industrial problems (e.g. MMMC and a revised IM curriculum).

From the Malaysian perspective, the forward look at industrial mathematics and industry arose from the firm belief that our centre of excellence such as UTM-CIAM and its business arm MYHIMS Solutions LLP have the potential to become an important economic and STEM skilled human capital resources for the Malaysian industry, helping its innovation and hence its capacity and capability of competing on the global market. The creation of UTM-CIAM and MYHIMS Solutions LLP (much like the UK's Smith Institute [17]) are indeed to steadily close the gap between the industrial mathematicians and the industry practitioners, government, and civil society. Thus based on the above discussions, the streamlined programmes and initiatives set out by this model, the future plan is to generate more positive impact and response via the quadruple helix innovation model mechanism. Besides mathematics, we are increasingly reliant on science, technology and engineering to help boost innovation and economic growth and to improve our quality of life. With this dependence comes a growing need for improved education and training in STEM subjects including mathematical modelling, operational research and statistics, both for the scientific and technical workforce and for the general public in a gradually more technological and digital world.

Fostering a successful interface between the four clusters via the QH model i.e. industrial mathematicians/STEM researchers, industry, government and users, requires much effort but the returns are definite. Public authorities and industry provide new and interesting scientific/industrial problems; while industrial mathematicians and STEM researchers provide understandings and advices which allow the practitioners to improve their products based on

the users demand. This collaborative set up between UTM-CIAM and MYHIMS would enable this workflow cycle of IM infrastructure to take effect and finally achieve a sustainable ecosystem of knowledge transfer (refer Figures 1 and 2).

On a final note, we hope that from these programmes and initiatives, the Malaysian SMEs (small and medium-sized enterprises), multinational GLCs (government-linked companies) and the private ones will become progressively more aware of the consequence of the applications of industrial mathematics for their commercial resilience. These local industries should now come to terms and appreciate that industrial mathematics is one of the keys to expand and sustain their economies and profitability. Moreover, the professional and academic associations, including the Malaysian Mathematical Science Society (PERSAMA), Malaysian Institute of Statistics, Management Science and Operations Research Society of Malaysia, Malaysian Academy of Mathematical Scientists and Malaysian Academy of Science, should come out hand in hand in support of our vision and ought to be proactive in order to play a major role as catalysts in inspiring the culture and development of industrial mathematics and related mathematics-industry interface. These can be done by actively supporting high-profiled activities such as conferences, MMISG workshops, and weekly industrial problem solving gatherings in the field of industrial mathematics.

Acknowledgement

This research is partially been funded by the UTM RMC Flagship Grants Vot. Nos. 03G96 and 16H11.

References

[1] H. Ockendon and J.R. Ockendon, Alan Breach Taylor (obituary), Bull. London Math. Soc. (1998) Vol. 30, 429–431 . https://doi.org/10.1112/S0024609397003251

[2] A.B. Tayler, Mathematics: an industrial resource, Phys. World (1990) Vol. 3 (8), 23–24. https://doi.org/10.1088/2058-7058/3/8/23

[3] Z.A. Aziz and A. Bahar, UTM-CIAM: Transformation and Beyond Malaysian Mathematics in Industry, In: R.S. Anderssen, P. Broadbridge, Y. Fukumoto, K. Kajiwara, T. Takagi, E. Verbitskiy, M. Wakayama (Eds) *Applications + Practical Conceptualization + Mathematics = fruitful Innovation (Proceedings of the Forum of Mathematics for Industry 2014)*, Mathematics for Industry **11** (Springer, Tokyo, 2016) 1–14. https://doi.org/10.1007/978-4-431-55342-7

[4] Z.A. Aziz et al (Eds), The First Mathematics in Industry Study Group (MISG): Malaysia 2011 Short Reports, Universiti Teknologi Malaysia, Johor Bahru, Johor, Malaysia (14–18 March 2011).

[5] Z.A. Aziz et al (Eds), The Second Mathematics in Industry Study Group (MISG): Malaysia 2014 Short Reports, Universiti Teknologi Malaysia, Johor Bahru, Johor, Malaysia (17–21 March 2014).

[6] Z.A. Aziz and A. Bahar, The current scenario of industrial mathematics in Malaysia, AIP Conference Proceedings (2016) Vol. 1175 (1), 020001(1–13). https://doi.org/10.1063/1.4965120

[7] Global Science Forum, Report on Mathematics in Industry, Organisation for Economic Co-operation and Development (OECD) (July 2008). Retrieved from http://www.mcs-uab.com/docs/OECD.Rep_on_Mathematics_in_Industry.2008.pdf

[8] Global Science Forum, Report on Mechanisms for Promoting Mathematics-in-Industry, Organisation for Economic Co-operation and Development (OECD) (April 2009). Retrieved from https://www.eu-maths-in.eu/EUMATHSIN/wp-content/uploads/2016/02/2009_EU_OECD_MathsinIndustry_corollary.pdf

[9] R. Arnkil, A. Jarvensivu, P. Koski and T. Piirainen, Exploring quadruple helix: outlining user-oriented innovation models, Work Research Centre, Institute for Social Research, University of Tampere, Tampere, Finland (2010) 1–113. http://urn.fi/urn:isbn:978-951-44-8209-0

[10] E.L. Carayannis, T.D. Barth and D.F.J. Campbell, The quintuple helix innovation model: global warming as a challenge and driver for innovation, J. Innov. Entrep. (2012) Vol. 1 (2), 1–12. https://doi.org/10.1186/2192-5372-1-2

[11] C. Edquist and L. Hommen, Systems of innovation: theory and policy for the demand side, Technology in Society (1999) Vol. 21 (1), 63–79. https://doi.org/10.1016/S0160-791X(98)00037-2

[12] T. Piirainen and P. Koski, Integrating workplace development policy and innovation policy: a challenging task (Experiences from and reflections on the Finnish Workplace Development Programme), In: W. Fricke and P. Totterdill (Eds) *Action Research in Workplace Innovation and Regional Development*, Dialogues on Work and Innovation **15** (John Benjamins Publishing Company, Amsterdam, 2004) 313–331. https://doi.org/10.1075/dowi.15.18pii

[13] B-A. Lundvall (Ed), *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*, Pinter Publishers, London (2010).

[14] T. Lery, M. Primicerio, M.J. Esteban, M. Fontes, Y. Maday, V. Mehrmann, G. Quadros, W. Schilders, A. Schuppert and H. Tewkesbury (Eds), *European Success Stories in Industrial Mathematics*, Springer-Verlag Berlin Heidelberg (2012). https://link.springer.com/book/10.1007/978-3-642-23848-2.

[15] European Science Foundation, Forward Look on Mathematics & Industry - Final Report, European Science Foundation, Strasbourg (2010). Retrieved from https://www.eu-maths-in.eu/EUMATHSIN/wp-content/uploads/2016/02/2010-Forward-Look-MathIndustry.pdf

[16] W. Schilders, Industrial Mathematics in Europe, In: M. Wakayama, R.S. Anderssen, J. Cheng, Y. Fukumoto, R. McKibbin, K. Polthier, T. Takagi and K.C. Toh (Eds) *The Impact of Applications on Mathematics (Proceedings of the Forum of Mathematics for Industry 2013)*, Mathematics for Industry **1** (Springer, Tokyo, 2014) 35–49.

[17] Smith Institute for Industrial Mathematics and System Engineering, Mathematics: Giving Industry the Edge. Smith Institute, Oxford, United Kingdom (2004). www.smithinst.ac.uk/News/Roadmap/Roadmap

[18] S. Mustafa, M. Darwish, A. Bahar and Z.A. Aziz, Analytical modeling of well design in riverbank filtration systems, Groudwater (2019) Vol. 57 (5), 756–763. https://doi.org/10.1111/gwat.12868

[19] S. Mustafa, A. Bahar, Z.A. Aziz and S. Suratman, Modelling contaminant transport for pumping wells in riverbank filtration systems, Journal of Environmental Management (2016) Vol. 165 (1), 159–166. https://doi.org/10.1016/j.jenvman.2015.09.026

[20] The Mathematics Tuning Group, Towards a common framework for mathematics degrees in Europe, *Newsletter of the European Mathematical Society* (September 2009) No. 45, 26–28. Retrieved from http://www.emis.de/newsletter/newsletter45.pdf

[21] R. Mill, Effective Teacher Professional Learning - Sabbatical Report, Wainuiomata High School, New Zealand (2007). Retrieved from http://www.educationalleaders.govt.nz/content/download/773/6227/file/rob-mill-sabbatical-report.pdf

[22] M.A. Cameron, Developing Mathematicians for Industry Research Teams, In: M. Wakayama, R.S. Anderssen, J. Cheng, Y. Fukumoto, R. McKibbin, K. Polthier, T. Takagi and K.C. Toh (Eds) *The Impact of Applications on Mathematics (Proceedings of the Forum of Mathematics for Industry 2013)*, Mathematics for Industry **1** (Springer, Tokyo, 2014) 157–166.

[23] G. Chen, Interdisciplinary research—Mathematical interactions viewed from four portrayals, *Notices of the American Mathematical Society* (2012) No. 59 (9), 1246–1252.

[24] K. Devlin, *The Language of Mathematics: Making the Invisible Visible*, Holt Paperbacks and W.H. Freeman & Company, New York (2000).

[25] J.M. Stockie, Mathematics for Industry: A Personal Perspective, Cornell University Library, New York (2015). Retrieved from https://arxiv.org/pdf/1509.03272

[26] A.C. Fowler, *Mathematical Models in the Applied Sciences*, Cambridge University Press, Cambridge (1997).

[27] J. Ockendon, S. Howison, A. Lacey and A. Movchan, *Applied Partial Differential Equations*, Oxford University Press, Oxford (1999).

[28] R.M.M. Mattheij, S.W. Rienstra and J.H.M ten Thije Boonkkamp, *Partial Differential Equations: Modeling, Analysis, Computation*, SIAM, Philadelphia (2005).