THE USE OF TECHNOLOGY DEVELOPMENT ENVELOPE AND TECHNOLOGY ROADMAPPING PRINCIPLES FOR DEVELOPING COUNTRIES AS A BASIS FOR LONG-TERM TECHNOLOGY PLANNING IN SOUTH AFRICA

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ABSTRACT

The aim of this study is to improve the Technology Development Envelope (TDE) framework with the principles derived from a technology roadmapping framework for developing countries. The TDE framework focuses on emerging technology trends, organisation objectives and assessment of technology value based on the ability of individual technologies to achieve the desired objectives. The technology roadmapping framework for developing countries introduces principles such as technological capability development, adoption of third generation technology roadmaps, window of opportunity, technology leapfrogging, etc. This exploratory study focuses on the application of robotic technology for improvement of competitiveness within the South African industry. The robotics technology trends from across the world are used to represent the consensus around technology futures. In addition to the robotics technology trends, national objectives are incorporated into the analysis. The hierarchical model includes criteria and factors such as the desired complementarity to the existing and new technological capabilities as well as the extent of resonance with the innovation landscape.

The preliminary findings show that there are several candidate robotics technologies that can be key in improving the competitiveness of the South African manufacturing sector. These root technologies include reconfigurable assembly, cooperative robots, computer vision, machine learning, simulation, system architecture and adaptation. These technologies have a potential impact in adding capabilities such as adaptable and reconfigurable assembly, rapid deployment of assembly lines, integrated manufacturing through cooperative robots and novel product development through machine learning. The innovation landscape factors such as the government's objectives to eliminate unemployment, poverty and inequality have potential influence on the acceptability of these candidate robotic technologies. The proposed technology planning framework for developing countries is useful in driving the technology prioritisation agenda that resonates well with the innovation landscape conditions for the organisation, industry or the country.

Key words: Technology Roadmap, Technology Development Envelope, Prioritisation, Robotics; Manufacturing

INTRODUCTION

Technology planning is important for any country in terms of prioritisation of focus on selected research and development (R&D) and other innovation related activities. An achievement of this prioritisation is important in consideration of multiple programmes and initiatives that are typically competing for the limited resources. Technology planning also helps to explicitly communicate the country's rational view of the technological future, an important manoeuvre in attracting the investment by the private sector and other stakeholders. Various frameworks exist for technology planning and these include a strategic technology planning framework by Chen, Ho and Kocaoglu (2009) which incorporates the hierarchical decision model and sensitivity analysis. This hierarchical model links an organisation's competitive goals and strategies in evaluating the technology alternatives' overall contributions to an organisation's success; and the sensitivity analysis helps to forecast and implement possible future changes in the economic environment, industry policies, and organisation strategies.

The technology planning tools that are typically used include technology foresights, forecasting, roadmapping, hindsight and backcasting. Both technology hindsight and backcasting involve a retrospective analysis of the past and current technology investment decisions in terms of successes and failures (Ivanov et al. 2015). This is useful in avoiding replication of similar mistakes in the future. Although technology forecasting, foresights and roadmapping are all the future oriented technology analysis and planning tools, they differ mainly in terms of a planning time horizon. Technology forecasting makes use of the predictable generic technology evolution trends that determines the evolution of technical systems (Mann 2003). These generic technology evolution trends include increased system controllability, increased complexity followed by reduced complexity, increased space segmentation, etc. Although both the technology roadmaps and foresight seek to collect and document future technology expectations in terms of what is likely to happen, technology roadmaps combine this with future desires of the key stakeholders and commitments from these stakeholders (McDowall, 2012).

The purpose of this paper is to incorporate the technology roadmapping principles into the technology development envelope (TDE) framework in order to showcase a framework for the long-term technology planning in South Africa as well as other developing countries. To achieve this purpose, the next section will review the relevant literature and this is proceeded by analysis of robotics megatrends, as a proxy for foresighting of robotics technologies. The country's objectives and priorities, which are key to the selection of technologies, are derived from the government's key strategic documents such as the Robotics Strategy of South Africa and the Industrial Policy Action Plan. The roadmapping principles that are incorporated to the TDE framework largely influences the organisation's objectives and priorities as well as the technology factors.

LITERATURE REVIEW

The technology roadmapping field is still evolving (Letaba, Pretorius and Pretorius 2015) through the three concurrent roadmapping generations. This section reviews the scholarly work on the third generation technology roadmaps, the TDE as well as technology roadmapping in developing countries. Further literature in robotics and automation would be incorporated in the next section.

Third Generation Technology Roadmaps

Technology roadmaps are important long-term technology and market planning tool. A generic technology roadmap has four vertical layers of market, products portfolio, technologies and research portfolio (Figure 1). This is a simplified outcome of an extensive consultative process of matching future market needs to product portfolio, product portfolio to technological capability and desired technological capacity to portfolio of the R&D projects. Technology roadmaps are also useful in translating strategies into implementable actions, with clear targets and timelines. According to Gindy, Cerit and Hodgson (2006), the aims of technology roadmaps are widely seen as to include the following:

i. Identification of gaps;

ii. Prioritisation of issues;

iii. Target setting/creating action plans; and

iv. Communication across the organisation.

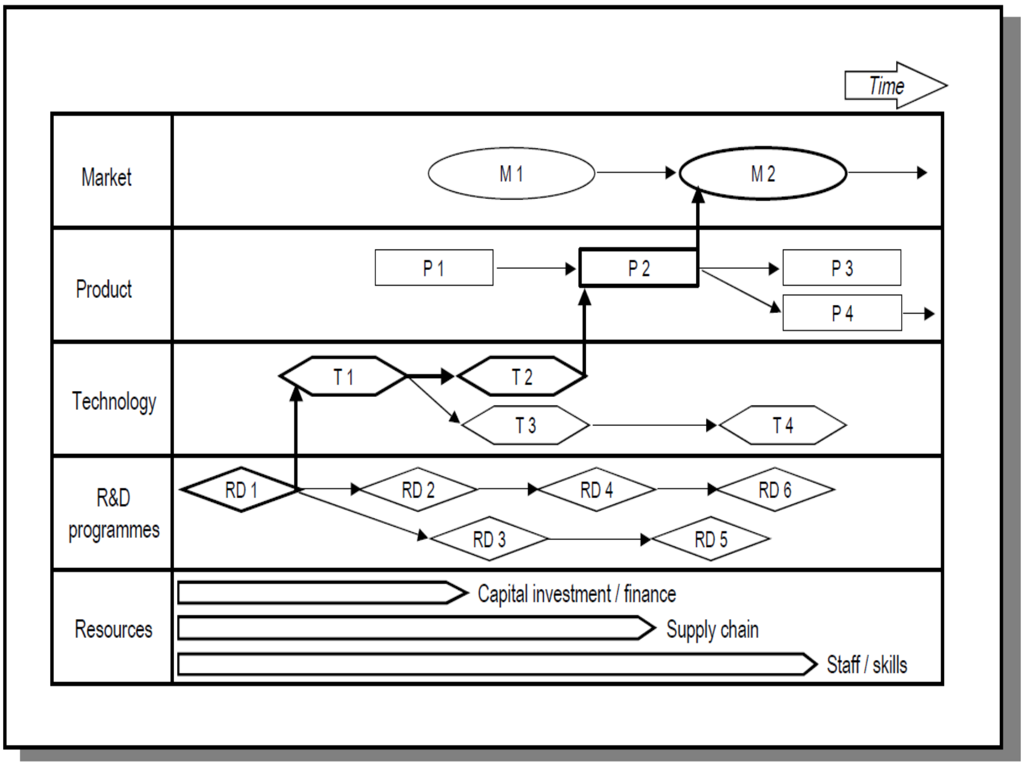

Figure 1: generic technology roadmapping model, Source: EIRMA 1997

There is a recent emergence of a new form of technology roadmaps that involves convergence of multiple root technologies. A third generation technology roadmapping approach proposed by several authors (Tierney, Hermina and Walsh 2013; Gindy, Arman and Cavin 2009; Kamtsiou et al. 2014) recognises the changing nature of technological innovation in a sense that most of the current innovations depend on converging or competing multiple root technologies (Kamtsiou et al., 2014). Complex interactions and technology developments are done without an obvious direct benefit of the predetermined architecturally stable product-process platforms (Tierney, Hermina and Walsh, 2013). The multiplicity of these technologies and the complex interactions that involves the innovation landscape, dominant innovation regime and the niche innovators call for improved methodologies and frameworks for technologies assessment and selection as part of third generation technology roadmaps development.

Some of the tools that are used to accommodate complex technology planning process that are part of the third generation technology roadmaps are the Technology Readiness Levels (TRLs). Giasolli et al. (2014) embraced the TRL concept as a means to provide a pathway to solve both the issue of multiple technologies integration as well as a pathway to investigate the progression of each individual technology for a given product paradigm over time. The use of TRLs with third generation technology roadmaps prompted a need to incorporate Technology Readiness Assessment technique in order to decide on appropriate technology pathways to follow. Similar to TRLs, Technology Readiness Assessment technique has been in existence for a fairly longer period as it was used by Karandikar, Wood, and Byrd Jr. (1992) as part of the strategies to implement the Concurrent Engineering (CE), which involves transformation of organisational culture, practices and technology.

Technology Development Envelope

The Technology Development Envelope (TDE) framework which was introduced by Gerdsri (2007), uses the combined Delphi method and Analytical Hierarchy Process (AHP), and it is useful for technology forecasting, assessment and selection in relation to the organisation's objectives. This technique is also useful for reprioritisation of technologies as the organisation's environment or technology landscape changes. This addresses many weaknesses in keeping the roadmap alive and also takes into account the changing innovation landscape as the technology roadmap is implemented.

A generic TDE framework entails the following key steps:

i. Technology forecasting;
ii. Technology characterisation;
iii. Technology assessment;
iv. Hierarchical modelling (objective, criteria, factors and measures of effectiveness);
v. Technology evaluation; and
vi. Formation of technology development envelope.

Chan (2013) successfully demonstrated the use of TDE roadmapping framework in developing a strategic policy choice framework for technological innovation within the Chinese pharmaceutical industry. Similarly, this technology evaluation framework has been used by Gerdsri and Kocaoglu (2007) to build a decision model to assess the contributions of emerging technologies and to evaluate their impacts on a country's objective. In this work, the strategic information regarding potential emerging technologies, including their estimated introduction date and their characteristics, is obtained through the Delphi technique, a method for obtaining experts' opinions. Once these emerging technologies have been identified, they were then evaluated using a hierarchal decision model, namely: 1) country's strategic objectives, 2) country's priorities, 3) technological factors and 4) technology alternatives.

The TDE framework synchronises well with technology roadmapping framework as both entail identification of the innovation landscape drivers (at firm, sector or country level) that influence the choice of technologies. As TDE involves multiple technology pathways that are ranked according to their Technology Value scores (Gerdsri 2007), third generation technology roadmaps fit well into this framework. The main advantage of TDE over the technology roadmapping framework is the ability to take into account the technology factors as part of technology assessment and evaluation. However, technology roadmaps have their own strengths such as an ability to visiualise a complex set of information that integrates various stakeholders within the innovation value-chain. The combined TDE and technology roadmapping frameworks provide a valuable tool for the third generation technology roadmapping.

Technology Roadmapping in Developing Countries

A recent study conducted among technology roadmapping practitioners in South Africa revealed a dominance of the third generation technology roadmaps in developing countries (Letaba 2017). This comes as no surprise as the developing countries are typically the innovation laggards (Lederman 2010) who lack leadership in product technology platforms. These countries are faced with competing multiple technologies from other lead countries (Ekekwe 2010) as well as the presence of local niche innovators. The developing countries also have a complex innovation landscape that is characterised among other others by the poor culture of innovation.

Since technology roadmaps are the strategic lens for the innovation dynamics that is taking place, a framework that guides the development of technology roadmaps in developing countries was developed by firstly identifying the innovation dynamics from the perspective of technology roadmapping stakeholders in South Africa. These include issues such as the need for technological capability development, technology development and market integration, timing of the innovation landscape's window of opportunity and adoption of novel innovation pathways. The innovation dynamics is also influenced by the global megatrends such as the fourth industrial revolution. According to Wu, Ma and Shi (2010:52), "the phenomena of technological paradigm shifts open a window of opportunity for latecomer firms to realise technological leapfrogging by importing emerging technologies from developed countries".

The principles developed by Letaba (2017) for technology roadmapping in developing countries include among others 1) the technology leapfrogging for the private sector technology roadmaps, 2) adoption of transition-based technology roadmaps, 3) a balance between involvement of the stakeholders from the dominant product-technology platform and those who seek new modes of innovation, 4) the use of scenario planning in selecting the technologies and products that are part of technology roadmaps and 5) frequent monitoring and update of technology roadmaps.

These technology roadmapping principles for the third generation technology roadmaps in developing countries are much related with the TDE framework as they both recognise the complexity involved for the development of technology roadmaps in developing countries. The TDE framework places greater emphasis on keeping the roadmap alive (Gerdsri and Kocaoglu 2007) as the organisation objectives and priorities as well as technology factors and value are changing. Hence the principles of frequent update of technology roadmaps as well as the use of scenario planning gel well with the TDE framework. The interests of various stakeholders can be accommodated through the organisation's objectives and priorities and this can be a critical step in driving the transition-based technology roadmaps.

TOWARDS THE IMPROVED TECHNOLOGY DEVELOPMENT ENVELOP FRAMEWORK

In this section, the principles for technology roadmapping in developing countries, and by implication for the third generation technology roadmaps, are incorporated into the TDE framework. A specific case study in this case is prioritisation of industrial robots in South Africa.

Industrial Robots Technology Trends

The use of industrial robots is gaining momentum due to recent advancements in robotics technology and a reduction in price of robots. The move towards smart factories is motivated by the potential to meaningfully meet the individual customer needs; ability to accommodate last minute changes to production schedule through the dynamic business and engineering processes; ability to facilitate end-to-end transparency through optimised manufacturing decision-making; and an opportunity to unleash new ways of creating value and novel business models (Kagermann et al. 2013).

According to Robotics (2013), the following are the promising robotics R&D areas: 1) learning and adaptation, 2) modelling, analysis, simulation and control, 3) formal methods, 4) control and planning, 5) perception, 6) novel mechanisms and high-performance actuators, 7) human-robot interaction and 8) architecture and representations. Learning and adaptation has potential to reduce the costs of programming and reconfiguring robots in factories. Other researchers are taking this further towards machine reasoning, an algebraic manipulation of previously acquired knowledge in order to answer a new question (Bottou 2014). As demonstrated by Carnegie Mellon University's developed Rainbow autonomics framework (Figure 2), learning and adaptation can be grouped together with formal methods, human-robot interaction as well as architecture and representation to a field of autonomic computing (Coronado et al. 2016).

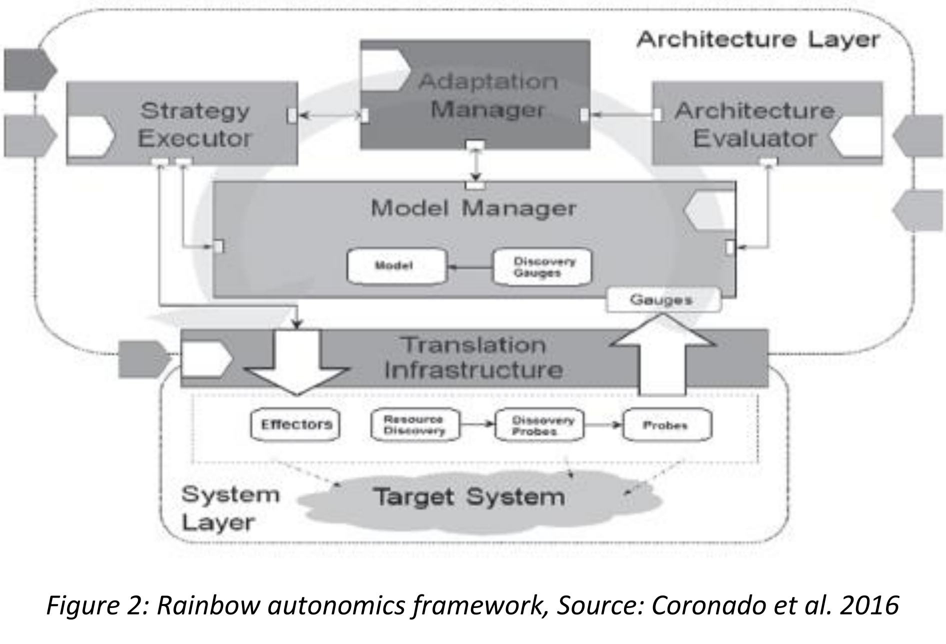

Figure 2: Rainbow autonomics framework, Source: Coronado et al. 2016

This newly evolving research field aims at making modern distributed IT systems self-manageable, i.e. capable of continuously self-monitoring and selecting appropriate operations (Lalanda, McCann and

Diaconescu 2013). Formal methods are the mathematical models and the tools of logic that are used to guide specification, development, and verification of software and hardware systems (Robotics 2013) and are useful in mission critical systems such as a spacecraft. Standardisation and reference architecture have been identified by the Industry 4.0 Working Group of the National Academy of Science and Engineering (Germany) as one of the eight main priority areas for successful implementation of the fourth industrial revolution (Kagermann et al. 2013).

Robotics (2013) identified the following critical capabilities for industrial robotics: 1) perception to enable operation in unstructured environment, 2) human-like dextrous manipulation, 3) adaptable and reconfigurable assembly, 4) robots working with humans, 5) autonomous navigation, 6) rapid deployment of assembly lines, 7) green manufacturing, 8) model-based integration and design of supply chain, 9) interoperability of component technologies and 10) nano manufacturing. Table 1 shows benchmarking of South African knowledge generation on artificial intelligence/ robotics technologies and critical capabilities. All the missing technologies/ capabilities indicate that there were no publications in those areas such as formal methods, perception, machine reasoning, integration and nano robots.

Table 2: benchmarking of South African artificial intelligence/ robotics publications, 2012-2016, Source: Clarivate Analytics "Incites"

	No. of publications	**% of SA AI/ robotics publications (Total = 230)**	**SA as % of relevant BRIC publications**	**% of BRIC AI/ robotics publications (Total = 11,582)**	**Strength relative to BRIC**
Architecture	2	0.87	2.56	0.67	High
Control	26	11.30	1.51	14.83	Low
Planning	6	2.61	1.77	2.93	Normal
Machine learning	11	4.78	2.96	3.20	High
Adaptation	9	3.91	2.04	3.82	High
Modelling	20	8.70	1.79	9.63	Normal
Simulation	10	4.35	2.86	3.02	High
Actuators	1	0.43	0.80	1.08	Weak
Human-robot interaction	5	2.17	1.23	3.51	Low
Sensors	5	2.17	1.40	3.07	Low
Robotic arm	6	2.61	0.65	7.98	Weak
Reconfigurable assembly	5	2.17	8.93	0.48	Superior
Navigation	2	0.87	1.26	1.37	Low
Computer vision	8	3.48	3.65	1.89	High
Robot swarms	9	3.48	4.52	1.72	High

During 2012-2016, South African researchers published 230 artificial intelligence/ robotics publications, which equates to 1.99% of BRIC group of countries. This is acceptable when taking into consideration that in 2016 South African population as a percentage of BRIC countries was 1.83%. If one uses this population ratio as an acceptable benchmark, South African robotics researchers are superior in terms of reconfigurable assembly. The publication outputs in this capability area include reconfigurable navigation of an automatic guided vehicle utilising omnivision (Kotze, Jordaan and Vermaak 2013), integration of an electrical discharge machining module onto a reconfigurable machine tool (Roberts, Gorlach and van Niekerk 2015) and synthesis of evolving cells for reconfigurable manufacturing systems (Padayachee and Bright 2014).

The other areas in which South Africa is benchmarking high are robot swarms/ cooperative robots, computer vision, machine learning, simulation, robotic system architecture and adaptation. Whereas planning and modelling publications are at the benchmark level of BRIC countries, the research/ capability areas in which South Africa is underperforming are on actuators, human-robot interaction, navigation, sensors and control sub-systems.

South African Objectives and Priorities

The conversation about the introduction of robotics into various modes of industrial production often brings complex viewpoints in support and against the robotics. Most critics of robotics are centred on issues such as job security, high unemployment rate in South Africa, inequality in terms of profit sharing, lack of high-end skills, etc. The proponents of robotics and automation expect the benefits such as cost efficiency, improved productivity, improved safety, increased sales and exports, enablement of innovation, global competitiveness and many other benefits. As alluded by the panel discussion of industrial robotics experts in South Africa, such benefits are self-evident within the automotive industry in which almost all of the vehicle parts are manufactured and assembled by the robots in order to ensure repeatability of the required safety standards (van der Groendaal 2012). The required levels of repeatability and precision are difficult to achieve if important tasks such as sorting, welding, assembly and packaging are carried out by the humans. In the South African mining sector, robotics and automation are thought to be useful in terms of reduction in mining fatalities that are mainly caused by a fall of ground followed by the transportation (Green et al. 2010).

Table 2 shows the summary of the objectives and the associated priorities of South Africa as outlined by the National Development Plan (NDP). The main objectives are to decrease the unemployment, poverty and equality. Several priorities have been articulated within the NDP to tackle these triple challenges. All the weights are set to be equal as they would typically be defined by the experts (Gerdsri 2007). The three challenges can be addressed efficiently through the priority of fast growth of economy in ways that benefit all South Africans. This would be achieved through an ambitious target of 5.4% economic growth per annum, a very high value compared to the current slow growth economic climate. In order to fundamentally transition the economy, investment in flexible manufacturing and robotics technology is required to achieve increase in exports and productivity growth (Naude 2017). Hence adoption of robotics technology in manufacturing is a necessity, and not a luxury.

According to Arntz, Gregory and Zierahn (2016), policy makers should focus on the qualifications of the workers to ensure that workers' skills match future skill requirements. As an example, Ślusarczyk and Kot (2011) suggested the investment in logistics training as a means to reduce high Polish unemployment.

Table 2: South African objectives and priorities as set by the National Development Plan

National Objectives	Weight	Priorities	Weight	Implications for Adoption of Robotics
Employment Creation	33.3%	Reduction of unemployment rate from 24.9% to 14% by 2020 and to 6% by 2030	25%	Skills upgrading (Arntz, Gregory and Zierahn 2016); Investment on logistics training (Ślusarczyk and Kot 2011)
		The proportion of adults working should increase from 41% to 61%	25%	Skills upgrading (Arntz, Gregory and Zierahn 2016); Investment on logistics training (Ślusarczyk and Kot 2011)
		Labour force participation rate should rise from 54% to 65%	25%	Skills upgrading (Arntz, Gregory and Zierahn 2016); Investment on logistics training (Ślusarczyk and Kot 2011)
		Fast growth of economy in ways that benefit all South Africans	25%	Technical change (e.g. robotics and flexible manufacturing) should be catalyst for economic growth (Naude 2017)
Reduction in Poverty	33.3%	No one should suffer from poverty induced hunger, thus no one should live below poverty line of R419 per day (2009 constant value)	33.3%	Adoption of the sharing economy concept to ensure social protection and distribution of digital economy gains (Degryse 2016)
		The unemployed working age population should have income support through various active labour market initiatives such as public works programmes, training and skills development, and other labour market related incentives	33.3%	Adoption of the sharing economy concept to ensure social protection and distribution of digital economy gains (Degryse 2016)
		Fast growth of economy in ways that benefit all South Africans	33.3%	Technical change (e.g. robotics and flexible manufacturing) as catalyst for economic growth (Naude 2017)
Promotion of Equity	33.3%	Uniting all South Africans around a common programme to achieve prosperity and equity	33.3%	Adoption of the sharing economy concept to ensure social protection and distribution of digital economy gains (Degryse 2016)
		Redress measures in the workplace should focus on enterprise development, access to training, career mobility and mentoring	33.3%	Skills upgrading (Arntz, Gregory and Zierahn 2016); Investment on logistics training (Ślusarczyk and Kot 2011)
		Fast growth of economy in ways that benefit all South Africans	33.3%	Technical change (e.g. robotics and flexible manufacturing) as catalyst for economic growth (Naude 2017)

A share of profit by labour, capital owners, government and society from improved productivity through robotics and automation technologies is another issue of contestation with regard to poverty and inequality (Degryse 2016). Within a digital economy, the sharing economy concept needs further exploration as a means to ensure the social security and an equitable wealth sharing. This concept is based on the practise in which individuals offer and purchase goods and services from each other through an online platform (Berke 2016). This takes place without necessarily giving away these personal services or goods. According to Hamari, Sjöklint and Ukkonen (2016), sharing economy, also known as collaborative consumption, is expected to alleviate societal problems such as hyper-consumption, pollution and poverty by lowering the cost of economic coordination within communities. Cryptocurrency is intertwined with this concept of a sharing economy and they are believed to be driven by the significant and rising consumer debt, inequality, low savings rates, internet penetration and the perceived inefficiencies of regulation (Nwogugu 2017).

Robotics Technology Development Pathways

Once technology trends are identified and the organisational objectives and criterion (priorities) are identified, the next steps in TDE framework (Figure 3) are to determine the technology factors and evaluation of candidate technologies. The latter doesn't part of this exploratory study.

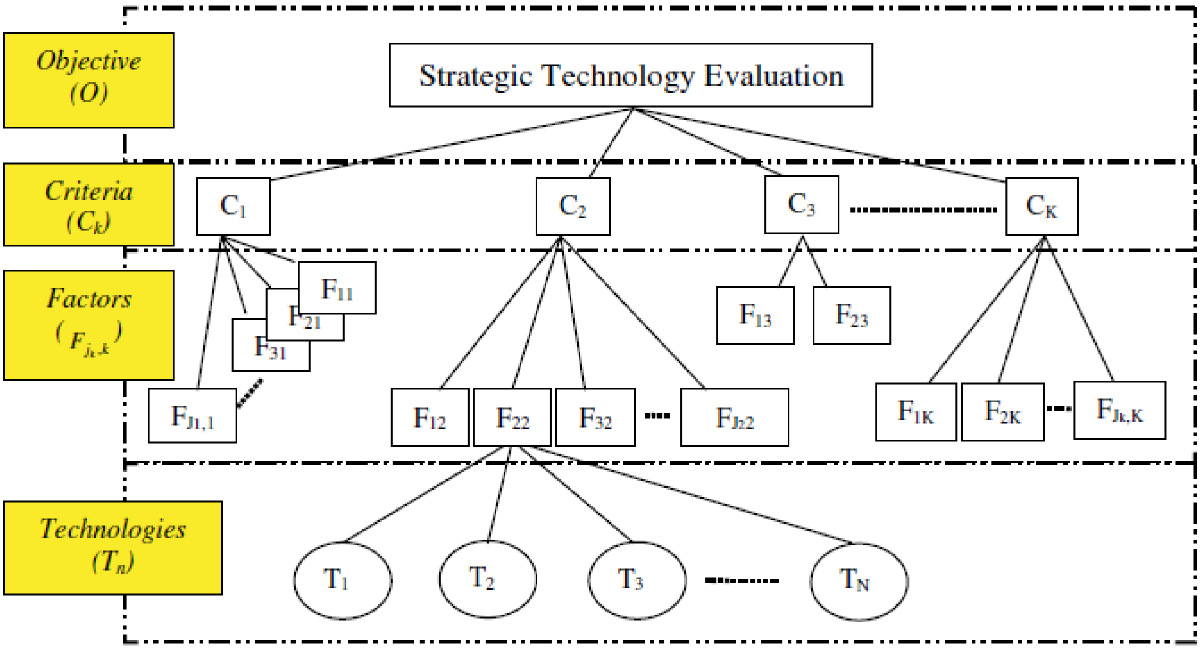

Figure 3: hierarchical model for evaluation of emerging technologies, source: Gerdsri (2007)

The following technology roadmapping principles for developing countries/ third generation technology roadmaps (Letaba 2017) can be applied to influence the choice of technology factors:

i. Clear intention for transition from slow economic growth environment to the state of high economic growth. This can be achieved by fully embracing the industrial robotics technology in order to stimulate performance of the manufacturing sector.

ii. Technological capability development. Improvement of technological areas that support the government to tackle the triple challenges of poverty, unemployment and inequality.

iii. The use of external networks as sources of competitive advantage. Strengthening of local capability through capabilities of international partners (e.g. BRIC countries).

iv. Timing of the innovation landscape window of opportunity might means that the prioritisation of industrial robots technologies should take into account the existing R&D capabilities, enabling environment and response of the incumbents on areas such as automation.

v. The need to balance advancement in technology and the interests of social protection and skills development (change versus status quo).

vi. Development of novel innovation pathways on promising niche areas.

vii. Predevelopment of most of these promising industrial robotic technologies to accommodate various possible future scenarios.

Table 3 shows the suggested technology factors for evaluation of South African industrial robots per each selected government priority. The weights are not reflected as they will typically be decided by panel of the experts. Once all the weights are decided, the candidate industrial robotic technologies identifies will typically be evaluated against national objectives, priorities and technology factors.

Table 3: incorporation of developing countries' technology roadmapping principles on choice of technology factors

Priority	**Factor**
Reduction of unemployment rate from 24.9% to 14% by 2020 and to 6% by 2030	Human-robot cooperation capability (**accommodation of status quo**: mass employment)
	Mass production technology (high volumes)
	Safe industrial robotic systems
Fast growth of economy in ways that benefit all South Africans	**Development** and **adoption** of game changer technologies to grow economy (**window of opportunity**, **transition**)
	Development of **novel technologies**
	Cost effective systems
	High profit margin systems (**change of status quo: transition**)
Redress measures in the workplace should focus on enterprise development, access to training, career mobility and mentoring	Less complex robotic systems (**accommodation of status quo**: mass employment)
	Initial **predevelopment** of all promising technologies
	Compatible/ standard system architecture (**accommodation of status quo**: skills level)

CONCLUSION

This exploratory study has demonstrated the incorporation of technology roadmapping principles/ third generation technology roadmaps with the TDE framework for strategic evaluation and prioritisation of South African industrial robots. South Africa has is showing good performance in relation to BRIC group of countries for the knowledge generation on robotic technologies and capabilities. Although some R&D areas such as human-robot interaction are inferior on this international benchmarking, the national objectives such as the need to reduce unemployment, poverty and inequality might add more evaluation scores to these areas. This addresses the principle of local technological capability development and the need to address the needs of stakeholders who seek transition and those who are comfortable with the status quo. The unavoidable reality for the South African industry is the need to transition into the adoption of smart factories while preserving the jobs and maintaining social security.

There are several limitations in this work that can be addressed through future work. The robotics publications in different technology/ capability areas were classified using the title of papers. An improvement can be achieved if paper abstracts are also used. As this paper was an exploratory research, further research is needed in collating the experts' input regarding the future robotics technology trends, national objectives and technology factors. This will be accompanied by allocation of the appropriate weights. The future technology trends, national objectives and priorities will need to reflect different periods, e.g. year 5, 10 and 15, in order to develop the TDE.

REFERENCES

Arntz, M., Gregory, T. and Zierahn, U, (2016), ELS issues in robotics and steps to consider them. Part 1: Robotics and employment. Consequences of robotics and technological change for the structure and level of employment. ZEW-Gutachten und Forschungsberichte.

Berke, D., (2016), Products Liability in the Sharing Economy. Yale Journal on Regulation, 33(2), 603-653.

Chan, L., (2013), Developing a strategic policy choice framework for technological innovation: case of Chinese pharmaceuticals. Doctoral dissertation, Portland State University, Portland, United States.

Chen, H., Ho, J. C., and Kocaoglu, D. F., (2009), A strategic technology planning framework: a case of Taiwan's semiconductor foundry industry. IEEE Transactions on Engineering Management, 56(1), 4-15.

Coronado, B., Gustafson, E., Reeder, J. and Lange, D. S., (2016), Mixing formal methods, machine learning, and human interaction through an autonomics framework. In 2016 AAAI Fall Symposium Series.

Degryse, C., (2016), Digitalisation of the economy and its impact on labour markets. Working Paper No. 2016.02, European Trade Union Institute.

EIRMA, (1997), Technology roadmapping – delivering a business vision. European Industry Research Management Association, Working Group Report No. 52, Paris.

Ekekwe, N., (2010), Nanotechnology and microelectronics: the science, trends and global diffusion. In Nanotechnology and Microelectronics: Global Diffusion, Economics and Policy, 1-25.

Gerdsri, N., (2007), An analytical approach to building a technology development envelope (TDE) for roadmapping of emerging technologies. International Journal of Innovation and Technology Management, 4(2), 121-135.

Gerdsri, N. and Kocaoglu, D.F., (2007), Applying the analytic hierarchy process (AHP) to build a strategic framework for technology roadmapping. Mathematical and Computer Modelling, 46(7), 1071-1080.

Giasolli, R., Marinakis, Y. D., Tierney, R. H., and Walsh, S., (2014), Using technology readiness levels in the pharmaceutical landscape: the next generation of technology roadmapping. Commercial Micro Manufacturing International, 7(6), 46-48.

Gindy, N., Arman, H. and Cavin, S., (2009), Linking R&D investment strategies to business needs: strategic technology alignment roadmapping (STAR). In Proceedings of the Portland International Conference on Management of Engineering and Technology (PICMET 2009), IEEE, 2455-2465.

Gindy, N. N., Cerit, B. and Hodgson, A., (2006), Technology roadmapping for the next generation manufacturing enterprise. Journal of Manufacturing Technology Management, 17(4), 404-416.

Green, J. J., Bosscha, P., Candy, L., Hlophe, K., Coetzee, S., and Brink, S., (2010), Can a robot improve mine safety?. In Proceedings of 25th International Conference of CAD/ CAM, Robotics & Factories of the Future Conference, 13-16 July 2010.

Hamari, J., Sjöklint, M. and Ukkonen, A., (2016), The sharing economy: why people participate in collaborative consumption. Journal of the Association for Information Science and Technology, 67(9), 2047-2059.

Ivanov, Y. B., Yashkina, O. I., Іванов, Ю. Б., Яшкіна, О. І., Иванов, Ю. Б., & Яшкина, О. И., (2015), The marketing information system of industrial enterprises in the context forecasting research. ЕКОНОМІКА: реалії часу, 6 (22), 66-70.

Kagermann, H., Helbig, J., Hellinger, A. and Wahlster, W., (2013), Recommendations for implementing the strategic initiative INDUSTRIE 4.0: securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group. Forschungsunion, National Academy of Science and Engineering.

Kamtsiou, V., Koskinen, T., Makropoulos, C., Manolessos, Y., Stergioulas, L.K. and Telonis, P., (2004), Roadmapping methodology for technology-enhanced professional training. WSEAS Transactions on Information Science and Applications, 1(5), 1383-1388.

Karandikar, H. M., Wood, R. T., and Byrd Jr, J., (1992), Process and technology readiness assessment for implementing concurrent engineering. In Proceedings of the Second Annual International Symposium of the National Council on Systems Engineering (NCOSE), 20-22.

Kotze, B., Jordaan, G. and Vermaak, H., (2013), Reconfigurable navigation of an automatic guided vehicle utilising omnivision. In Robotics and Mechatronics Conference (RobMech), 2013 6th, IEEE, 80-86.

Lederman, D., (2010), An international multilevel analysis of product innovation. Journal of International Business Studies, 41(4), 606-619.

Letaba, P., Pretorius, M. W. and Pretorius, L., (2015), Analysis of the intellectual structure and evolution of technology roadmapping literature. In Portland International Conference on Management of Engineering and Technology (PICMET), IEEE, 2248-2254.

Letaba, T.P., (2017), Complex technology roadmap development in the context of developing countries. Unpublished Doctoral Dissertation, University of Pretoria, South Africa.

Mann, D. L., (2003), Better technology forecasting using systematic innovation methods. Technological Forecasting and Social Change, 70(8), 779-795.

McDowall, W, (2012), Technology roadmaps for transition management: the case of hydrogen energy. Technological Forecasting and Social Change, 79(3), 530-542.

Naudé, W., (2017), Entrepreneurship, education and the fourth industrial revolution in Africa. IZA Discussion Paper No. 10855.

Nwogugu, M. C., (2017), International capital flows, complexity and the illegality of the 'sharing economy' and digital currencies. Electronic copy available at: https://ssrn.com/abstract=3015529.

Padayachee, J. and Bright, G., (2014), Synthesis of evolving cells for reconfigurable manufacturing systems. In IOP Conference Series: Materials Science and Engineering, 65.

Roberts, B. H., Gorlach, I. A. and van Niekerk, T. I., (2015), Integration of an electrical discharge machining module onto a reconfigurable machine tool. In Pattern Recognition Association of South Africa and Robotics and Mechatronics International Conference (PRASA-RobMech), IEEE, 160-165.

Robotics, V. O., (2013), A roadmap for US robotics: from internet to robotics. Robotics Virtual Organization.

Ślusarczyk, B. and Kot, S., (2011), Logistics education as a way for unemployment reduction. Proceedings of the IETEC, 11.

Tierney, R., Hermina, W. and Walsh, S., (2013), The pharmaceutical technology landscape: a new form of technology roadmapping. Technological Forecasting and Social Change, 80(2), 194-211.

van der Groendaal, H., 2012, Robotics in industry – an exploration. EngineerIT.

Wu, X., Ma, R. and Shi, Y., (2010), How do latecomer firms capture value from disruptive technologies? A secondary business-model innovation perspective. IEEE Transactions on Engineering Management, 57(1), 51-62.