A nanotechnology strategic key research areas foresight model for improved innovation and technology transfer

by

BRIAN MASARA

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SUPERVISOR: Professor Malik Maaza

CO-SUPERVISOR: Professor John Andrew van der Poll

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DECLARATION

Name: ___________Brian Masara_________

Student number: ___________79218547____________

Degree: ___________Doctor of Business Leadership (DBL) _____________

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I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution.

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SIGNATURE **DATE**

PUBLICATIONS

The following publications emanated from this research:

1. Masara, B., van der Poll, J.A., and Maaza, M. (2021). **The “Nanotechnology Innovation Diamond”, a Model for Successful Nanoscience Research and Development**”, *Journal of Nanoparticle Research*, **23,** 60 (2021). https://doi.org/10.1007/s11051-021-05150-3 Springer (WoS & Scopus indexed)

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ABSTRACT

Nanotechnology revolutionised industrialisation and economic development and is predicted to drive the next Schumpeterian wave of economic growth. Most countries are strategically positioning themselves to benefit from nanotechnology, being a general-purpose technology. Hence, to ensure prudent use of limited resources, countries must select and focus on key strategic nanotechnology research areas that have the potential to generate competitiveness and return on investment. However, no model currently exists on critical success factors for nanotechnology innovation management. Also, there is a lack of effective nanotechnology-specific foresight models. Furthermore, although nanotechnology foresight relates to the Multi-criteria Decision Making (MCDM) analysis, the use of MCDM methods in a foresight context has not been thoroughly explored yet.

This research developed the Nanotechnology Innovation Diamond, a model for successful nanoscience research and development. The model was validated using confirmatory factor analysis (CFA) from a survey of 167 nanotechnology experts from South Africa. The results indicated that, at a 95% confidence level, the model satisfied the minimum CFA model fit requirements. The research further developed a nanotechnology-specific foresight model that integrates the Nanotechnology Innovation Diamond, technology mining, scientometrics, and the Analytical Hierarchical Process Multi-criteria Decision Making (AHP-MCDM) model.

The AHP-MCDM foresight model was empirically tested in South Africa. The results showed that South Africa’s nanotechnology publications grew exponentially from 68 papers in 2000 to 1 672 in 2019, representing an increase of 2 459%. Compared to the other BRICS countries, namely, Brazil, Russia, India, and China, South Africa has the lowest nanotechnology productivity, scoring an activity index of 0.68. Universities are the most prominent publishers on nanotechnology, while the private sector has produced few publications. Only 48 patents were identified compared to 11 265 publications, and a meagre 3.5% of papers were found to report on nano-enabled products. This lack of reporting on nano-enabled products can negatively impact the commercialisation of nanotechnology. The top collaborating countries, top researchers, top institutions, and nanotechnology economic hubs are reported in this study. The key strategic research areas identified for South Africa include nanomaterials, nano-photoluminescence and optics, nanomedicine, nanocatalysis, nanoelectronics, nanobiotechnology, and energy. The results were benchmarked using an expert-survey foresight method, which gave 70% similar priority fields of research. The research contributes to the discourse on nanotechnology innovation management, technology-specific foresight methods, nanotechnology-specific foresight methods, and the utilisation of quantitative tools in foresight.

KEY TERMS

Nanotechnology, Innovation Management, Technology Foresight, Multi-criteria Decision Making (MCDM), Analytical Hierarchical Process (AHP), Scientometric Analysis, Technology Mining, Nanotechnology Foresight, Nanotechnology Innovation Critical Success Factors, Nanotechnology Innovation Diamond, Nanotechnology Research Portfolio Selection, Key Technologies

OPSOMMING

Nanotegnologie het ’n omwenteling in industrialisering en ekonomiese ontwikkeling teweeggebring en daar word voorspel dat dit die volgende Schumpeterse golf van ekonomiese groei sal aandryf. Die meeste lande is besig om hulself strategies te posisioneer om uit nanotegnologie voordeel te trek, aangesien dit ’n meerdoelige tegnologie is. Om dus verstandige gebruik van beperkte hulpbronne te verseker, moet lande strategiese sleutelnavorsingsareas in nanotegnologie wat die potensiaal het om mededingendheid en opbrengs op belegging te genereer, kies en daarop fokus. Daar bestaan egter nie op die oomblik ’n model ten opsigte van kritiese suksesfaktore vir nanotegnologie-innovering-bestuur nie. Boonop is daar ’n tekort aan doeltreffende nanotegnologie-spesifieke toekomsbeplanningsmodelle. Hoewel toekomsbeplanning vir nanotegnologie verband hou met die Multi-criteria Decision Making (MCDM)-ontleding, is die gebruik van MCDM-metodes in ’n toekomsbeplanning-konteks nog nie behoorlik ondersoek nie.

In hierdie navorsing is die Nanotechnology Innovation Diamond ontwikkel – ’n model vir suksesvolle nanowetenskap-navorsing en -ontwikkeling. Om die geldigheid van die model te bepaal, is bevestigende faktorontleding (CFA) van ’n opname onder 167 nanotegnologiekundiges van Suid-Afrika gebruik. Die resultate het aangetoon dat die model aan die minimum CFA-modelgeskiktheidvereistes voldoen het, met ’n 95%-vertroubaarheidsvlak. Verder het die navorsing ’n nanotegnologie-spesifieke toekomsbeplanningsmodel ontwikkel wat die Nanotechnology Innovation Diamond, tegnologie-ontginning, scientometrie, en die Analytical Hierarchical Process Multi-criteria Decision Making (AHP-MCDM) -model integreer.

Die AHP-MCDM-toekomsbeplanningsmodel is empiries getoets in Suid-Afrika. Die resultate het getoon dat Suid-Afrika se nanotegnologie-publikasies eksponensieel gegroei het van 68 artikels in 2000 tot 1 672 in 2019 – dit verteenwoordig ’n toename van 2 459%. In vergelyking met die ander BRICS-lande, naamlik Brasilië, Rusland, Indië, en China, het Suid-Afrika die laagste syfer ten opsigte van nanotegnologie-produktiwiteit, met ’n bedrywigheidsindekssyfer van 0.68. Universiteite is die mees prominente uitgewers wanneer dit by nanotegnologie kom, terwyl die private sektor ’n paar publikasies opgelewer het. Slegs 48 patente is geïdentifiseer in vergelyking met 11 265 publikasies, en daar is bevind dat ’n skamele 3.5% van die artikels oor nano-geaktiveerde produkte verslag doen. Hierdie gebrek aan verslagdoening oor nano-geaktiveerde produkte kan ’n negatiewe uitwerking op die kommersialisering van nanotegnologie hê. In hierdie studie word verslag gedoen oor die lande, navorsers, instansies, en nanotegnologie- ekonomiese middelpunte wat die voortou neem. Die strategiese sleutelnavorsingsareas wat vir Suid-Afrika geïdentifiseer is, sluit nanomateriale, nano-fotoluminessensie en optika, nanomedisyne, nanokatalise, nano-elektronika, nanobiotegnologie, en energie in. Die resultate is genormeer met behulp van ’n kundige-opname-toekomsbeplanningsmetode, wat 70% soortgelyke-prioriteit-navorsingsvelde gelewer het. Die navorsing dra by tot die gesprekvoering oor nanotegnologie-innoveringsbestuur, tegnologie-spesifieke toekoms beplannings metodes, nanotegnologiespesifieke toekomsbeplanningsmetodes, en die benutting van kwantitatiewe middele in toekomsbeplanning.

SLEUTELTERME

Nanotegnologie, Innoveringsbestuur, Tegnologie-toekomsbeplanning, Multi-criteria Decision Making (MCDM), Analytical Hierarchical Process (AHP), Scientometriese Ontleding, Tegnologie-ontginning, Nanotegnologie-toekomsbeplanning, Kritiese Suksesfaktore in Nanotegnologie-innovering, Nanotechnology Innovation Diamond, Nanotegnologie-navorsingsportefeulje-selektering, Sleuteltegnologieë

ISIFINQO

Igatsha lobuchwepheshe elibhekene nobukhulu nokubekezelelana liguqule ukuthuthukiswa kwezimboni nokuthuthukiswa komnotho futhi kubikezelwa ukuthi liza ngomkhulu umfutho olandelayo le-Schumpeterian lokukhula komnotho. Amazwe amaningi azibeka esimweni esifanele ukuze ahlomule egatsheni lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana kuhlobene nokuhlaziywa kocwaningo Lokwenziwa Kwezinqumo Ngemibandela eminingi (LKNE), ukusetshenziswa kwezindlela ze-LKNE esimweni elibhekene nobukhulu kanye nokubekezelelana, okuwubuchwepheshe benjongo evamile. Ngakho-ke, ukuze kuqinisekiswe ukusetshenziswa okuhlakaniphile kwezinsizakusebenza ezilinganiselwe, amazwe kufanele akhethe futhi agxile ezindaweni ezibalulekile zocwaningo lwegatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana ezinamandla okukhiqiza ukuncintisana kanye nembuyiselo ekutshalweni kwezimali. Kodwa-ke, ayikho imodeli ekhona njengamanje ezicini zempumelelo ezibalulekile zokuphathwa kokusungulwa kwegatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana. Futhi, kukhona ukuntuleka kwamamodeli okubona into engakenzeki aqondene negatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana. Ngaphezu kwalokho, nakuba ukubona into ingakenzeki kwegatsha lobuchwepheshe sokubona izinto zingakenzeki akukahlolisiswa ngokugcwele okwamanje.

Lolu cwaningo lwenze igatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana kuhlobene Nokwenziwa Kwezinqumo Ngemibandela Eminingi, imodeli yocwaningo nokuthuthukiswa kwesifundo sezinto, izenzakalo esikalini senanomitha. Imodeli yaqinisekiswa kusetshenziswa ukuhlaziya isici sokuqinisekisa (UIS) ocwaningweni lochwepheshe abayi-167 beGatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana baseNingizimu Afrika. Imiphumela ibonise ukuthi, ngezinga lokuzethemba elingama-95%, imodeli yanelisa ubuncane bezidingo zemodeli ye-UIS. Ucwaningo luqhubekile nokuthuthukisa imodeli yokubona okungakenzeki okuqondene neGatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana ehlanganisa iGatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana Kokuqamba kabusha kweDayimane , izimayini zobuchwepheshe, isayensi yamametrikhi, kanye nemodeli ye-Analytical Hierarchical Process Multi-criteria Decision Making (AHP-MCDM).

Imodeli ye-AHP-MCDM yokubona okungakenzeki kwahlolwa ngokunamandla eNingizimu Afrika. Imiphumela ikhombise ukuthi izincwadi zaseNingizimu Afrika zeGatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana - likhule kakhulu lisuka kumaphepha angama-68 ngonyaka wezi-2000 zaya kuyi-1 672 ngowezi-2019, nokumele ukukhula nge-2 459%. Uma kuqhathaniswa namanye amazwe e-BRICS, okuyiBrazil, Russia, India, neChina, iNingizimu Afrika inokukhiqiza okuphansi kweGatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana , ithole inkomba yemisebenzi engu-0.68. Amanyuvesi abashicileli abagqama kakhulu ku-egatsheni lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana, kuyilapho imboni ezimele ikhiqize izincwadi ezimbalwa. Amalungelo obunikazi angama-48 kuphela ahlonziwe uma kuqhathaniswa nokushicilelwe okuyi-11 265, futhi kwatholakala ama-3.5% omncane wamaphepha ukubika ngemikhiqizo enikwe amandla yinano. Lokhu kuntuleka kokubika ngemikhiqizo enikwe amandla enano kungaba nomthelela omubi ekuhwebeni kwegatsha lobuchwpheshe elibhekene nobukhulu kanye nokubekezelelana. Amazwe aphezulu asebenzisanayo, abacwaningi abaphezulu, izikhungo eziphezulu, nezizinda zezomnotho zegatsha lobuchwepheshe elibhekene nobukhulu kanye nokubekezelelana kuyabikwa kulolu cwaningo. Izindawo zocwaningo zamasu ezibalulekile ezihlonzwe eNingizimu Afrika zihlanganisa izinto zenano, inano yephotholuminensi kanye ne-opthikhi, igatsha lemithi yenano, ikhathalysisi yenano, i-elektronikhi yenano, ubuchwepheshe bebhayiloji, namandla. Imiphumela yalinganiswa kusetshenziswa indlela yokuhlola kungakenzeki into yochwepheshe, enikeze ama-70% izinkambu zocwaningo ezibalulekile ezifanayo. Ucwaningo lunikela enkulumweni emayelana nokuphathwa kokusungulwa kwegatsha lobochwepheshe benano, izindlela zokubona izinto kusengaphambili eziqondene nobuchwepheshe obuthile, izindlela zokubikezela kusengaphambili eziqondene netheknoloji yenano, kanye nokusetshenziswa kwamathuluzi obuningi ekuboneni kusengaphambili.

AMAGAMA ABALULEKILE

Ubuchwepheshe benano, Ukuphathwa Kwezinto Ezintsha, Ubuchwepheshe Bokubona izinto kusengaphambili , Ukwenziwa Kwezinqumo Ngemibandela eminingi (UKNE), Inqubo Yokucwaninga Yokulandelana (IYY), ukucwaningi isayinomektrikhi, Imayini yezobuchwepheshe, Ubucwepheshe benano kwakhaphambili, Ubuchwepheshe benano Bezinto Ezintsha Ezibalulekile Zempumelelo,

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The delay in doing my doctoral studies until my early 40s after several years of experience in science management was worth it. The work experience enabled me to research in an area I am passionate about, and one that can positively impact society. I worked on a research topic that is practical and whose results can be used to improve innovation in nanotechnology and impact society by addressing socio-economic challenges and enhancing society's quality of life through better scientific innovations management and technology foresight.

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LIST OF ABBREVIATIONS/ACRONYMS

Abbreviation/Acronym	Meaning
AHP	Analytical Hierarchical Process
ANP	Analytic Network Process
APEC	Asia Pacific Economic Cooperation
BRICS	Brazil, Russia, India, China and South Africa
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CI	Consistency Index
CNSE	College of Nanoscience and Engineering
COWS	Criteria Options Weight and Scoring
CR	Consistency Ratio
CSF	Critical Success Factor
CSIR	Council for Scientific and Industrial Research
DEA	Data Envelopment Analysis
DF	Degrees of Freedom
DHET	Department of Higher Education and Training
DSI	Department of Science and Innovation
DST	Department of Science and Technology
ELECTRE 1	ELimination Et Choice Translating REality
EPO	European Patents Office
GFI	Goodness of Fit Index
GPT	General Purpose Technology
H5-Index	5-year Hirsch-index
H-index	Hirsch-index
IBM	International Business Machines
ICT	Information and Communications Technology
IT	Information Technology
MCDM	Multi-Criteria Decision Making
NBIC	Nanotechnology Biotechnology Informatics and Cognitive Sciences

Abbreviation/Acronym	Meaning
NFI	Normed Fit Index
NSI	National System of Innovation
PCA	Patent Co-citation Analysis
PPP	Public Private Partnership
R&D	Research and Development
RAHP	Revised Analytical Hierarchical Process
RI	Random Index
RMSEA	Root Mean Square Error of Approximation
RNI	Relative Noncentrality Index
SAIP	South African Institute of Physics
SEM	Structural Equation Modelling
SPSS	Statistical Package for Social Science
SRMR	Standardised Root Mean Square Residual
SWARA	Stepwise Weight Assessment Ratio Analysis
SWOT	Strength Weaknesses Opportunities and Threats
TCA	Technology Cluster Analysis
TF	Technology Foresight
TLI	Tucker-Lewis Index
TSI	Technology Strength Indicators
UK	United Kingdom
USA	United States of America
WIPO	World Intellectual Property Organisation
WoS	Web of Science
WPM	Weighted Product Method
WSM	Weighted Sum Method

GLOSSARY OF KEY CONCEPTS

Term	Definition
Invention	An invention is the creation of a new, novel or improved idea for a product, process or service using either new knowledge, pre-existing knowledge or a combination of these (Roberts, 2016). In science and technology, inventions result from knowledge gained through R&D and often extend the boundaries of human knowledge (Toner and Tompkins, 2008; Tang, 2009).
Innovation	The process through which an invention is first put into use is known as innovation. It entails developing or refining a novel concept, designing, testing, manufacturing prototypes, and finally, commercialising the invention for wider market utilisation (Jensen *et al.*, 2011; Tang, 2009). Hence, innovation can be summarised as "innovation = invention + practical /commercial exploitation" (Roberts, 2016).
Scientific innovation / technological innovations	Scientific innovation or technological innovation is an innovation that is driven by scientific-based research, development, knowledge and capabilities. It focuses on successfully exploiting and incorporating science and technology inventions in products, services, and processes (Tang, 2009). The terms scientific

Term	Definition
	innovations and technological innovation are used interchangeably in this research.
Nanotechnology innovation	Nanotechnology innovations are innovations that are driven by inventions/discoveries in nanoscience and nanotechnology.
Successful innovation	According to (Palmberg, 2002), “A successful innovation is defined as one that attains a significant market penetration and/or made a profit, while an unsuccessful one is associated with the bankruptcy of the commercialising firm, withdrawal of the innovation from the market, or failure of the innovation to reach commercialisation”. Thus, successful innovations result in exploiting new ideas through a product, service or process that contributes to wealth creation, solving socio-economic problems and profitability via large-scale diffusion of these innovations (Scuola et al., 2005).
Successful nanotechnology research	Successful nanotechnology research is nanotechnology research that results in the production of intended outputs, mainly innovations on new and improved products, licences, spin-off companies, new start-up businesses (Schultz, 2011; Maine, 2014; and Aithal and Aithal, 2016) patents, scholarly publications (Tanaka,

Term	Definition
	2013; Karpagam et al., 2011; Islam and Miyazaki, 2010; Pouris, 2007; Hullman and Meyer, 2003; Marinova and McAleer, 2002) among others.
Innovation management	The process of managing an organisation's innovation processes, from the first step of ideation to prototyping, pilot testing and the ultimate stage of practical implementation, is referred to as innovation management. It includes all of the decisions, actions, and procedures involved in developing and implementing an innovation strategy (Wong *et al.*, 2011; Mekhala, 2016).
Technology Foresight	Technology foresight is the practice of methodically evaluating the long-term prospects of ongoing scientific R&D, the economy, and socio-economic imperatives to determine the most critical R&D areas that will have the most significant socio-economic impact on society (Martin, 1995). According to Ronde (2003), the ultimate goal of technological foresight is to guarantee those research domains with the most significant probability to result in socio-economic benefits are identified, developed, and supported.

Term	Definition
An effective nanotechnology-specific foresight method	Technology foresight is the practice of methodically evaluating the long-term prospects of ongoing scientific R&D, the economy, and socio-economic imperatives to determine the most critical R&D areas that will have the most significant socio-economic impact on society (Martin, 1995) hence one can define "an effective nanotechnology-specific foresight method" as a methodical process that guarantees that nanotechnology research domains with the most significant probability to result in socio-economic benefits are identified, developed, and supported.
Scientometrics	Scientometrics is the study of scientific research, development and innovation performance using publications such as academic articles, patents, and government policy documents (Jacobs, 2010; Leydesdorff and Milojevic, 2012). Scientometrics is closely related to bibliometrics.
Technology mining (Tech-mining)	Technology-mining utilises big data techniques in analysing science and technology bibliometric datasets to answer essential foresight and innovation management questions such as what research and development is being conducted in a specific

Term	Definition
	technological sector, and the parties involved, towards what market objectives and what are the prospects for successful commercialisation, among other pertinent questions (Porter and Cunningham, 2005b).

Chapter 1: Introduction

The goal of this thesis is to develop a nanotechnology-specific foresight model. The model is critical for strategic management and R&D portfolio management to promote successful innovations and technology transfer. The model helps countries select and rank key strategic research areas in nanotechnology during technology foresight exercises. As a result, governments can cost-effectively utilise limited resources by focusing and concentrating resources on those nanotechnology research areas having the most significant potential for boosting socio-economic development, competitiveness, and return on investment.

This introductory chapter aims to present an overview of why the study is necessary. It starts by showing the importance of scientific innovations in socio-economic development. The chapter gives an overview of how nanotechnology can contribute to socio-economic development as an emerging research area. Discussions are done on key technology management relevant factors such as the global nanotechnology race, the challenges with identifying areas in which countries can effectively compete, and why nanotechnology specific foresight methods are needed. This first chapter also presents the problem statement, research questions, research objectives, limitations, and delimitations.

1.1 Overview

Scientific innovations create value by creating new and improved products and services, resulting in new businesses, jobs, and markets. One of the scientific fields currently leading disruptive innovations in various economic sectors is nanotechnology. Nanotechnology is a rapidly evolving field of research devoted to studying and manipulating atomic-scale properties of matter to create new and innovative applications. (Robinson, Rip and Mangematin, 2007; Salerno, Landoni and Verganti, 2008; Karpagam *et al.,* 2011). The market for nanotech-enabled products is expanding exponentially, mainly because nanoscience discoveries have multiple practical applications (Islam and Miyazaki, 2009). By the year 2013, the market for nanotechnology-enabled commercial products had surpassed US$1 trillion (NSF, 2014), and it was expected to be worth more than US$3 trillion by 2020, creating six million jobs (Roco, 2017).

Nanotechnology advancements have such a broad impact across businesses such that peer-reviewed management journals have started to publish articles on nanotechnology innovation management (Shea *et al.,* 2011). According to various academics, it is anticipated that the next wave of global economic expansion will be primarily driven by developments in nanotechnology (Mangematin *et al.,* 2012; Linton and Walsh, 2008). Hence, several countries, such as the United States of America (USA), Great Britain, Germany, Japan, India, South Korea, and South Africa, have implemented national nanotechnology programmes to benefit from nanotechnology (Kane *et al.,* 2016; Miyazaki and Islam, 2007; Roco, Mirkin and Hersam, 2011; Ali and Sinha, 2014).

It is also argued that scientific innovations, including nanotechnology, provide solutions to social-developmental problems, for example, the United Nations Sustainable Development Goals, which include food provision, improved health, clean water, and environmental protection (United Nations, 2015). The paper "Nanotechnology for a Sustainable Future: Addressing Global Challenges with the International Network for Sustainable Nanotechnology" (Pokrajac et al., 2021) discusses how nanotechnology has a vital role to play in international efforts to address sustainability and how current and future capabilities in nanotechnology align with and support the United Nations' Sustainable Development Goals. The DSI White Paper on Science and Technology (DST, 2019) clearly states this link as follows: "STI plays three main roles in achieving the SDGs. First, STI is a goal in itself as a driver of economic growth and job creation. Second, STI is central to the implementation of other goals, e.g., new technological solutions can help address challenges around energy and food security. Third, scientific knowledge can help to both translate the targets associated with the SDGs into national policies and evaluate their impact.” The African Union Agenda 2063 also state how scientific innovations must be used to address socio-economic development goals for Africa (African Union Commission, 2020). Finally, it is essential to note that the United Nations declared the year 2022 the International Year on Basic Science for Sustainable Development (IYBSSD2022), recognising the critical role that scientific innovations such as those derived from nanotechnology contribute to SDGs. The background message for the IYSSD2022 state that “contributions of basic innovations, curiosity-based, sciences are not well appreciated, basic science innovations provide the essential means to meet crucial challenges such as universal access to food, energy, health coverage and communication technologies. They enable us to understand the impact of the currently nearly 8 billion people on the planet and to act to limit, and sometimes even to reduce it: depletion of the ozone layer, climate change, depletion of natural resources, extinction of living species” (IYBSSD, 2022).

Other examples of how nanotechnology discoveries address the SDGs include innovations for water purification at a reasonable price (Mamba *et al*., 2007; Mwabi *et al*., 2011), solar photovoltaics with high efficiency for energy provision (Banin *et al*., 2020), and medicinal products, such as nano-based face masks to reduce COVID-19 transmission (De Sio *et al*., 2021). Therefore, ultimately scientific innovations improve the quality of life.

At the national level, scientific innovations enhance the competitiveness of nations through a transformation towards knowledge-based economies (Porter, 1990; Reinhilde and Kul, 2014; Sasikumar and Mohan, 2014). As a result, it is argued that most countries' economic development strategies aim to improve competitiveness through technological innovations and the creation of knowledge-based economies. The African continent's policy and strategic plans from the Africa Union also suggest that the continent is moving towards a knowledge-based economy, for example, the African Union Agenda 2063 (African Union Commission, 2015). In particular, one of the policy documents state, "In June 2014, the 23rd Ordinary Session of African Union Heads of State and Government Summit adopted a 10-year Science, Technology and Innovation Strategy for Africa (STISA-2024). The strategy is part of the long-term people centered AU Agenda 2063, which is underpinned by science, technology and innovation as multi-function tools and enablers for achieving continental development goals. ……… With the advent of STISA-2024, the African Union possesses a wonderful tool to accelerate Africa's transition to an innovation led, knowledge based economy" (African Union Commission, 2020).

To support these African policy imperatives, recent research (Mutanga et al., 2021; Younis et al., 2021) also suggest that African countries will be forced into technology-driven knowledge economies, even if they are agro-based or mineral/natural resourced based those industries and the economic system will need to be technologically driven for competitiveness. In South Africa, the strategy to move towards a knowledge-based economy is highlighted in the strategic government documents such as the National Development Plan (NDP) Vision for 2030, Industrial

Policy Action Plan (IPAP), Strategic Integrated Projects (SIPs), the South African Nanotechnology Strategy (DST, 2005) and White Paper on Science Technology and Innovation (DST, 2019).

1.2 Research background

Nanotechnology is a multi-purpose technology such that it has applications in almost every industry. Naturally, countries and enterprises cannot engage in nanotechnology R&D in all possible and available research domains. To ensure judicious use of limited resources; instead, they must choose only critical nanotechnology research areas with the greatest potential to deliver socio-economic development and return on investment (Lee & Song, 2007; Connel *et al.,* 2001; Shen *et al.,* 2010). As a result, nanotechnology-specific foresight methods are necessary to identify critical research areas on which to focus (Salerno *et al*., 2008). Proper foresight method design for nanotechnology is vital because the quality of technology foresight greatly depends on applying appropriate techniques (Mishra *et al*., 2002; Firat, Woon and Madnick, 2008; Salerno *et al*., 2008).

According to Firat, Woon and Madnick (2008), currently, there is limited academic literature on matching technology foresight methods to a specific technology, that is, current foresight methods and approaches focus on macro-level methodology, but little research has been conducted to develop micro-level technology-specific foresight methods. This knowledge gap was also observed by Salerno *et al*. (2008). They report that there is a wide range of foresight methods to determine research focus areas at a macro level, but foresight techniques to determine where to focus within these priority research fields are still in their infancy. Also, key technology foresight exercises discussed in the literature (Wagner and Popper, 2003; Grebenyuk and Shashnov, 2012; Durand, 2005; Keenan, 2003) are macro-key-technologies. None of them is focused on a particular discipline. Hence this research developed a nanotechnology-specific foresight model, that is, the study focuses on micro-key-technologies foresight as opposed to macro-key-technologies foresight.

Salerno *et al*. (2008) add that technology-specific foresight methods are critical when considering nanotechnology because most countries are investing substantially in this technological area. However, given the diversity of possible nanotechnology applications, governments need to identify key strategic research areas in nanotechnology on which to focus and concentrate.

The few papers identified that discuss nanotechnology foresight do not give models for key-nanotechnology-foresight models (Ciontu, 2005; Tegart, 2006; Santo *et al.*, 2006; Salerno, Landoni and Verganti, 2008; Streletskiy *et al.*, 2015)**.** However, these papers propose factors to consider in nanotechnology foresight design which include the use of text mining, bibliometrics, patent landscaping, and specific characteristics of nanotechnology**.** Only one publication (Lee and Song, 2007) reports a method on key nanotechnology foresight. In their work to identify and select key nanotechnology research areas for South Korea, Lee and Song (2007) used technological cluster analysis combined with an expert's survey.

To determine and select the key strategic research areas in nanotechnology, foresight planners must consider a complex set of multiple criteria affecting successful nanotech innovations. These factors include nanotech being a general-purpose technology, multidisciplinarity, hybridisation, agglomeration, public perceptions of nanotech, and government developmental priorities, among other factors (Meyer 2007; Miyazaki &

Islam, 2007; Linton and Walsh 2008; Battard 2012). Therefore, selecting a critical strategic research area in nanotechnology must follow a Multi-Criteria Decision Making (MCDM) process.

Lee and Song's (2007) method can be improved by using the MCDM foresight protocol, which combines criteria affecting successful nanotech innovation, a country's specific needs and Technological Strength Indicators (TSI) from scientometric statistics. However, as already mentioned, Salo *et al*. (2003) highlighted that the potential application of Multi-Criteria Decision Making approaches in foresight methods has yet to be fully explored. Also, even though key technologies identification is a MCDM decision making problem (Keenan, 2003) where several difficult choices have to be made based on several criteria, none of the key technologies foresight methodologies reviewed in the literature (Wagner and Popper, 2003; Grebenyuk and Shashnov, 2012; Durand, 2005; Keenan, 2003) used MCDM. The absence of application of MCDM in foresight is also reinforced by empirical evidence from Popper (2008), who reported that MCDM use constituted only 1.2% of methods used in foresight exercises. As a result, there is a pressing need to improve and expand the body of knowledge on nanotechnology-specific technology foresight methods and the use of MCDM in technology foresight.

1.3 Research problem and questions

1.3.1 Research problem

To the best of the researcher’s knowledge, no effective technology foresight method exists for determining and ranking a country’s key strategic research areas in nanotechnology.

Identifying, selecting and ranking key strategic research areas in nanotechnology help a country to cost-effectively utilise limited resources by focusing and concentrating resources towards those nanotechnology research areas with the highest potential for bringing socio-economic development, global competitiveness, and a positive return on investment.

1.3.2 Research questions

A summary of this study's five research questions is given below;

1. What are the Critical Success Factors (CSF) that promote nanotechnology research that results in successful innovations?
2. What are the relative weights of the identified CSF when used as criteria in Multi-Criteria Decision-Making models?
3. How does one categorise and characterise nanotechnology publications into nanotechnology research alternatives for a particular country?
4. What scientometric indicators can measure CSF that promotes nanotechnology research that results in successful innovations?

5. How can one develop a Multi-Criteria Decision-Making based foresight model to rank a country's strategic key-research areas in nanotechnology effectively?

1.4 Research aim and objectives

1.4.1 Research aim

This research's overarching goal was to determine an effective nanotechnology-specific MDCM based foresight model for selecting and ranking the key nanotechnology strategic research areas in which a country must focus and concentrate resources in order to increase its rate of successful innovations, technology transfer, and hence improve its competitiveness.

1.4.2 Research objectives

The following specific objectives are addressed in this research:

1. Establish the Critical Success Factors for successful innovation and technology transfer in nanotechnology and how they interact.
2. Estimate the numerical weights for identified criteria for successful nanotech innovations.
3. Determine how to categorise the nanotechnology research areas and access their respective properties.
4. Determine the set of scientometric indicators to measure CSF for nanotech research areas.
5. Develop a MCDM based foresight model to effectively rank strategic key research areas in nanotechnology.

1.5 Significance of the study

This research achieves the following;

1. Despite substantial research on technological innovation strategies, little research on nanoscale innovation management has been done. (Meyer, 2007; Linton and Walsh, 2008). This research presents the Nanotechnology Innovation Diamond, a management framework with critical success factors (CSF) for ensuring successful nanotechnology research. As a result, the study contributes to the body of knowledge on managing innovation and technology transfer in nanotechnology R&D through the Nanotechnology Innovation Diamond,
2. It presents a nanotechnology-specific foresight model and hence contributes to closing that knowledge gap.
3. Various complex decisions are required in R&D and technology management. Instead of managers relying on bounded rationality based on limited knowledge of experts, the MCDM model presents a rational decision-making protocol that is computer-based, quantitative, objective, systematic and credible. The model is relevant to the following facets of innovation management;
    a. Strategic management in the following areas, Technology foresight, Technology Road-mapping, Technology intelligence to scan and study the technology environment and R&D portfolio management.
    b. Due diligence in the following critical decisions: mergers and acquisitions for technology companies and multilateral and bilateral cooperation analysis.
    c. Competitor analysis.

    d. Improve R&D Portfolio Management Decision Making, for example;

        - The dilemma of allocating finite resources among various competing projects is one that R&D managers face regularly; the model guides managers to invest limited resources in areas that promise the most significant return on investment.

        - When expert surveys are done to decide on strategic portfolios, the decision-maker is negatively affected by bounded rationality or influenced by lobbying experts, but this model guides the manager through quantitative, credible scientific data.

        - It removes the problem of information overload in decision-making, e.g., processing tens of thousands of patents and research papers by humans is not easy.

4. Incorporate MCMD in the designed foresight method hence contribute to closing the gap in the lack of MCDM methods used in the foresight context.

5. Contribute to operations research tools for strategic planning and decision-making in innovation management.

6. Improve on the models that R&D policymakers can use in selecting strategic research areas in nanotechnology; therefore, provide tools for government R&D strategy and policy formulation to ensure that scarce R&D resources are used wisely and efficiently.

7. Support economic competitiveness by providing a tool for identifying and selecting key strategic research areas in nanotechnology.

8. Contribute to improving society's quality of life in general as more nanotechnology-based innovations find their way to the market, hence providing socio-economic benefits to the world.
9. Finally, the model reported in this research and the methodology followed can be adapted to develop other technology-specific foresight models that are specific to other fields of science and technology.

1.6 Limitations and delimitations

1.6.1 Limitations

- The Nanotechnology Innovation Diamond was validated through Confirmatory Factor Analysis (CFA) with responses from only 167 experts, all based in South Africa, most of whom work in nano-materials. Thus, the model needs to be tested with a bigger pool of experts as CFA requires large samples.
- The foresight model was only tested for South Africa.
- Publication scientometric indicators are lagging indicators of scientific research and development evaluation because journal articles take on average a year or more to publish, unlike expert opinion, which is always current.
- Analysis of publications was utilised as the primary data source, but a limitation exists in that some researchers may not patent or publish their research, choosing trade secrets, especially in the private sector.
- Publications suffer from the lack of standardisation; for example, individual data for writers, particularly addresses and the way names are written, are not standardised, making analysis difficult (Zitt, 2006).

- Technology mining may help determine who, what, and when, but questions about how and why must typically be answered by subject experts (Porter and Cunningham, 2005b),
- At best, scientometric indicators are proxies for more “intangible” research dimensions like “research quality” or “research cooperation.” For example, “Research quality” is often equated with “citation impact,” and “research cooperation” is equated with “co-authorship” in scientometrics. As a result, present bibliometric approaches are simply insufficient to appropriately quantify such research metrics; hence, additional evaluation methods are required to support scientometric indicators.
- This research assumes publication indicators used as proxies to measure different performance aspects of nanotechnology innovation reflect those aspects as closely as possible.

1.6.2 Delimitations

- The study's goal is to develop a model for micro-level identification of critical research areas in nanotechnology. The analysis assumes that the democratic processes at the macro-level are completed through exercises such as Delphi, Expert Panels and Scenarios and nanotechnology was identified as one of the critical focus areas for the country at the macro-level.
- This research uses a quantitative, deterministic, and evidence-based approach to technology foresight.
- This research focuses on the development of a deterministic MCDM foresight method. Fuzzy and stochastic decision models are not part of this study.

- This research focuses on selecting key focus areas in those nanotech areas in which a country already has some level of competency. It does not focus on greenfield nanotech areas where a country needs to build capacity from scratch.

1.7 Ethical considerations

The research has two units of analysis, documents, and nanotechnology experts. An online database with publicly available information, the Web of Science (WoS) Core Collection was utilised for technology mining and scientometrics. The second unit of analysis are experts who took part in an online survey.

The study was conducted in a manner that fulfils legal and ethical requirements. Before beginning the research, ethical approval was sought from the University of South Africa Graduate School of Business Leadership (SBL). The ethical clearance letter is appended to Appendix 6.

1.8 Thesis layout

This thesis is presented as follows.

Chapter 1: Introduction – The first chapter gives an overview of the research area, the research gap and problem statement, and outlines the research questions and research objectives. It also summarises the significance of the study, the research limitations and delimitations.

Chapter 2: Literature Review - This chapter summarises the relevant literature for understanding the development of a key technologies nanotechnology-specific foresight model. It covers current knowledge gaps, critical success factors for nanotechnology research, technologies foresight approaches and their limitations, the use of scientometrics and MCDM in foresight. The chapter concludes by summarising how a nanotechnology-specific key research areas foresight model can be developed.

Chapter 3: Research Methodology - This chapter outlines the quantitative approach followed for this research to enable the researcher to answer the research questions, test hypotheses and validate proposed models. The chapter outlines the four steps followed, which were nanotechnology experts' survey, technology-mining, scientometric analysis, and foresight model development using the analytical hierarchical process (AHP) multi-criteria decision making (MCDM). The positivism / empirical realist epistemology of foresight was followed.

Chapter 4: Results and Discussion – This chapter summarises and discusses the research results. The results reported cover the expert survey, CFA analysis of the proposed Nanotechnology Innovation Diamond model, the scientometric study of nanotechnology publications for South Africa, and the AHP-MCDM foresight model. The chapter goes on to present a nanotechnology foresight perspective of South Africa using the AHP-MCDM model. The chapter ends by benchmarking the AHP-MCDM model foresight results with those from the experts' key-technology survey method.

Chapter 5: Conclusions and Recommendations – This chapter presents the conclusions and recommendations of the research. It summarises the research's contributions to knowledge and recommends some directions for future research in improving nanotechnology innovation management and foresight. The chapter concludes by recapping the contributions made by this study to innovation management and how the results will impact and enhance socio-economic development.

1.9 Summary

This chapter laid the foundation and gave an overview of nanotechnology innovation management and technology foresight research. The chapter presented the research problem and the need for a nanotechnology-specific foresight model.

Outputs of this research can assist countries or institutions to cost-effectively utilise limited resources by focusing and concentrating support on key strategic nanotechnology research areas, resulting in more innovations and increasing national competitiveness. The developed foresight model can assist developing countries in entering the nanotechnology race. Countries investing in nanotechnology R&D do not need to invest in all areas of nanotech. Instead, they can use the model presented in this research to select strategic research areas of focus. Hence, they are more likely to save resources and benefit from nanotechnology opportunities.

The next chapter, chapter 2, presents the literature review relevant to developing a nanotechnology-specific MCDM foresight model. The literature review starts with an introduction to nanotechnology and summarises current research gaps in nanotechnology specific foresight method development. The following items are presented in chapter 2;

- Critical success factors for nanotechnology research that leads to successful innovations,
- A review of current key technologies foresight approaches,
- The utilisation of Multi-Criteria Decision Methods in technology foresight,
- Scientometric methods in foresight and their relevance to nanotechnology foresight, and
- A discussion of how technology foresight exercises and models are designed.

Chapter 2: Literature Review

The previous chapter provided an outline of the research and its significance in the context of innovation management and technological foresight studies. Chapter 1 covered the problem statement, research questions, the research, objectives, study contributions, limitations, and delimitations.

This chapter gives a synopsis of the relevant literature necessary for understanding the development of a key technologies nanotechnology-specific foresight model. The chapter starts with section 2.1, covering an introduction to nanotechnology and summarising current research gaps in nanotechnology specific foresight method development. Section 2.2 reviews critical success factors for nanotechnology research that leads to successful innovations, and this is crystallised into the proposed Nanotechnology Innovation Diamond. Section 2.3 reviews and critiques the current key technologies foresight approaches, including their limitations. Next, the present state of the use of Multi-Criteria Decision Methods in technology foresight is given, followed by scientometrics in foresight and how it can be used in nanotechnology foresight. Section 2.6 concludes the chapter by looking at how technology foresight exercises and models are designed and how a nanotechnology key research areas foresight model can be developed.

2.1 Introduction

Robert Feynman, a Nobel Laureate in physics, was the first to foresee nanotechnology development when he presented his famous paper, “There is plenty of room at the bottom” in 1959 (Feynman, 1960). Nanoscience deals with manipulating molecules and atoms at scales between 1 nm to 100 nm. Nanoscience includes all science disciplines from basic sciences such as biology, chemistry and physics to applied sciences such as electronics, medicine and engineering (Baig *et al.*, 2021). Nanoscience then leads to nanotechnology, where nanotechnology becomes the capability for observing, manipulating, and manufacturing matter at the nanometre scale to exploit unique applications in various contexts (Bayda *et al.*, 2020).

Nanotechnology is described as having a “disruptive” and “revolutionary” impact on industrialisation (Cologne, 2004). It is a general-purpose technology (GPT) that covers many fields of application, for example, energy, electronics, textiles, construction, automotive, medical and biological sciences, among other areas, and discoveries on other nanotechnology applications are increasing at an exponential rate. Therefore nanotechnology has brought enormous opportunities for wealth creation (Linton and Walsh, 2008). As a result, it is argued that most countries are making considerable investments in nanotechnology research programmes (Miyazaki and Islam, 2007; Kane *et al.*, 2016; Roco, Mirkin and Hersam, 2011; Ali and Sinha, 2014).

In addition, according to StatNano, an institution that tracks nanotechnology research worldwide, 106 countries (54%) out of the 195 countries worldwide are now active in nanotechnology research (StatNano, 2022). The StatNano database is updated regularly. In addition, literature also supports the position that most countries are investing in nanotechnology, for example, the following;

- “Nanotechnology is widely considered as one of the most promising areas of scientific and technological development for future decades. As a consequence, almost every country in the world has chosen to invest significantly in this area." (Salerno *et al.*, 2008b)

- Ezema et al. (2014) report that their research indicates that "although nanotechnology is new globally, most countries of the world have had growing public and private investments aimed at pooling enough resource capital required for activities in nanotechnology." (Ezema et al., 2014)

Although nanotechnology focuses on small things, it offers a significant business opportunity. The nanotechnology market had already surpassed $1 trillion in value by 2013 (NSF, 2014), and there is an exponential increment in nanotechnology R&D activities and outputs globally (Islam and Miyazaki, 2009). In a nutshell, nanotech is predicted to drive the next Schumpeterian wave of economic growth (Mangematin *et al*., 2012; Linton and Walsh, 2008; Tuncel, 2015).

However, nanotechnology is a vast and diverse discipline, so countries should not invest in all possible nanotech research areas but rather focus their efforts on critical nanotechnology research areas relevant to their country's needs and most likely to result in socio-economic development. (Meyer, 2007). Thus, these countries must carry out technology foresight to identify and select critical strategic R&D focus areas in which to focus and concentrate. Technology foresight exercises are routinely carried out, generally at five-year intervals, by high-tech countries such as the United Kingdom, United States of America, France, Britain, South Korea, Taiwan, and Japan, among others to successfully increase their technological innovations and national economic competitiveness (Pouris and Raphasha, 2015; Martin and Johnston, 1999).

The primary task for countries that need to have a competitive edge in nanotechnology innovation is to carry out foresight exercises that identify critical strategic research areas in nanotechnology. However, the problem is that there is no effective nanotechnology-specific foresight method that they can use (Salerno, Landoni and Verganti, 2008; Lee and Song, 2007). This chapter reviews relevant literature that enables the development of an effective nanotechnology-specific foresight method. The model developed in this research was empirically tested in South Africa using nanotechnology research and development experts working at various stages of the nanotechnology value chain. The South African Nanotechnology Initiative (SANi) was established in 2002, and after that the nanotechnology research in South Africa grew rapidly (Cele *et al.*, 2009). Subsequently, South African developed the 10-year plan for nanotechnology, the Nanotechnology Strategy, in 2006 and the inclusion of nanotechnology into the NDP Vision for 2030 in the subsequent years.

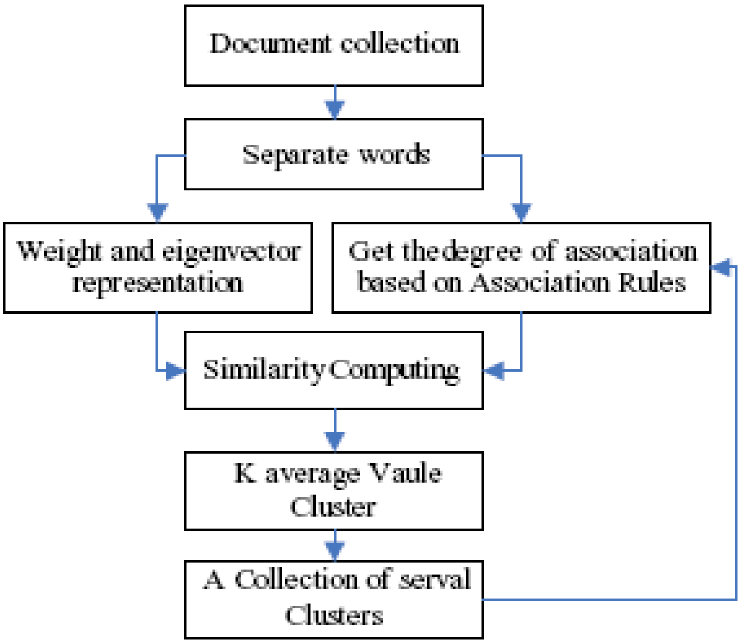
2.2 Knowledge gaps in nanotechnology innovation and foresight

The quest to develop an effective MCDM-based nanotechnology-specific foresight method is fraught with many challenges and gaps in the literature; these deficiencies are summarised in this section.

To begin with, despite extensive research into innovation management strategies, there has been minimal research into frameworks for managing nanotechnology R&D and innovation (Linton and Walsh, 2008 and Meyer, 2007;). The first step in any foresight method design is mapping the technology and foresight method characteristics on a common scale (Mishra, Deshmukh, and Vrat, 2002). The correct selection and application of appropriate technology-specific foresight methods is critical to the quality of any technological foresight exercise (Mishra, Deshmukh and

Vrat, 2002; Sasikumar and Mohan, 2014; Firat, Woon and Madnick, 2008; Salerno *et al*., 2008; Firat, Woon and Madnick, 2008; Levary and Han, 1995;). No framework exists on successful nanotechnology innovation management. Hence, before designing the nanotechnology-specific foresight method, a framework with the main characteristics of successful nanotechnology innovations was determined.

Secondly, to identify alternative research areas in nanotechnology, one must group related research. Because nanotechnology is a relatively new field of study, the system for categorising nanotechnology research articles into research fields is still in its infancy (Tanaka, 2013). There is currently no automated system for organising nanoscience research publications. Although it is not complete, Tanaka (2013) provided a framework; it solely classifies papers into core science topics. e.g., nanophysics, nanochemistry, and nanoengineering. In their research to identify nanotechnology research areas in South Korea, Lee and Song (2007) first grouped related papers using technological clustering, then asked experts to name the identified research domains. This approach is time-consuming. Therefore a standardised automatic categorisation system must be developed. An example of a general automatic academic papers and patents categorisation process is shown in Figure 2.1 below.



Source:(Vishal Gupta, 2009)

Figure 2.1: Document categorisation algorithm

Thirdly, technology-specific foresight models for selecting key strategic research areas are still in their infancy of development (Lee and Song, 2007). In order to carry out technology foresight in nanotechnology, one has to select and combine the most appropriate technology foresight methods from a large number of methods available because choosing and applying the most suitable techniques is critical to the quality of technology foresight (Firat, Woon and Madnick, 2008; Salerno *et al*., 2008; Mishra *et al*., 2002;).

According to Firat *et al*. (2008), there has been minimal research towards matching technology foresight methodologies to specific technologies. This knowledge gap is shared by Salerno *et al*. (2008). They report that much effort has gone into developing foresight methodologies at a macro level; however, studies on foresight techniques for deciding where to focus inside selected priority micro technological areas are scarce.

In addition, Salerno *et al.* (2008) emphasise the importance of micro-foresight methods in relation to nanotechnology owing to its recent global expansion where most countries have decided to invest in this field. Given that nearly any scientific area and business can profit from nanotechnology, a country's decision to invest in it is merely the first step. The next step is for governments to identify key strategic research areas in nanotechnology on which to focus and concentrate. Besides, nanotechnology possesses specific characteristics that should be considered when designing the right technology foresight methods.

As shown in Table 2.1 below, evidence from the literature supports the scarcity of nanotechnology-specific foresight methodologies. The few papers identified that discuss nanotechnology foresight do not provide explicit and specific models for key-nanotechnology-foresight (Ciontu, 2005; Tegart, 2006; Santo *et al.*, 2006; Salerno, Landoni and Verganti, 2008; Streletskiy *et al.*, 2015). Only one publication (Lee and Song, 2007) reports a method on key-nanotechnology foresight. However, all the papers propose factors to consider in nanotechnology foresight which include the use of text mining, bibliometrics, patent landscaping, and specific characteristics of nanotechnology.

Table 2.1: Publications discussing nanotechnology foresight

Publication	Key Highlights
(Ciontu, 2005) "NANOSPRINT : An Infrastructure for Nanotechnology Foresight."	• Proposes the NANOSPRINT, a decision support system to aid managers, policymakers and researchers to make decisions on nanotechnology-related planning, • The proposed design is based on a server that stores facts and meta-knowledge on nanotechnology and (semi)-automatically derives answers to new questions based on stored facts, and • No prototype was built and tested in the paper.
(Tegart, 2006) "Nanotechnology : the technology for the twenty-first century."	• Reports on a nanotechnology foresight study carried out 2002 - 2003 by APEC Centre for Technology Foresight, • A scenario-based foresight approach was used, and three scenarios for 2015 were created; these are summarised as; 1) Nano-paradox assuming that even though there is a negative perception on nanotech nano continues to grow, 2) Green energy causes energy markets to collapse as nano-based energy technologies take the lead, e.g. hydrogen-powered vehicles, and 3) Nanodevices to detect and neutralise lethal microorganisms developed in response to bioterror war threats. • The scenarios approach is a challenge to use in key research areas selection where one needs to consider several research areas. Scenario planning typically works well with only four or fewer scenarios; dealing with more than four scenarios is a big challenge.

Publication	**Key Highlights**
(Santo *et al.*, 2006) "Text mining as a valuable tool in foresight exercises: A study on nanotechnology."	• Discusses the prospective use of text mining for environmental scanning then followed by qualitative techniques, • Reports on a scientometric study of nanotechnology in Brazil and compares the position of Brazil to other countries, • Concluded that text mining can be used to predict trends as well as analyse strengths, weaknesses, opportunities, and threats (SWOT analysis) and • No foresight example was discussed in the paper.
(Lee and Song, 2007) "Selecting the key research areas in nanotechnology field using technology cluster analysis: A case study based on National R&D Programs in South Korea."	• This is the only nanotechnology specific foresight paper identified identifying critical areas in nanotechnology, • They used technology cluster analysis and expert survey to identify key research areas in nanotechnology for South Korea, • Recommend that patent mapping, scientometric analysis, and technology cluster analysis should all be carried out concurrently to improve foresight results, • Their method could be enhanced by using MCDM methods, and • Their approach did not take into consideration nanotechnology specific characteristics.
(Salerno *et al.*, 2008a) "Designing foresight studies for Nanoscience and Nanotechnology future developments."	• Argue that a nanotechnology specific foresight method must be designed that takes into consideration specific characteristics and peculiarities of the field, • Mention that interdisciplinarity and pervasiveness must be taken seriously in nanotech foresight design,

Publication	Key Highlights
	• Recommend that quantitative methods such as bibliometrics must play a more significant role as compared to traditional scenario planning methods, and • No foresight model is given in the study, just recommendations for developing the method.
(Streletskiy *et al.*, 2015) “Patent Landscape for Nanotechnology.”	• Proposed a systematic approach to patent landscaping for foresight in figuring out thematic educational initiatives in nanotechnology, and • The method proposed is just searching and analysing clusters and landscapes; it does not consider characteristics of nano.

In their work to forecast key nanotechnology research areas for South Korea, Lee and Song (2007) used Technological Cluster Analysis combined with experts’ survey. This method can be improved by using a MCDM protocol that combines criteria affecting successful nanotech innovation, a country’s specific needs and Technological Strength Indicators (TSIs) from scientometric statistics. However, Salo *et al*. (2003) contend that the potential application of MCDM approaches in foresight methods is yet to be fully explored. The limited use of MCDM approaches in foresight exercises is also backed by empirical evidence from Popper (2008) ’s research, which found that MCDM approaches accounted for only 1.2% of foresight methods. As a result, there is a need to develop and expand the literature on nanotechnology technology foresight approaches and the usage of MCDM in the context of technology foresight.

2.3 Characteristics of successful nanotechnology research

On the one hand, successful nanotechnology research is considered as the ability to commercialise nanoscience R&D outputs resulting in the provision of new products and services or improving existing ones. The establishment of start-ups, technology licencing, and spin-off companies are some of the commercialisation strategies used (Schultz, 2011; Maine, 2014; and Aithal and Aithal, 2016). Patents and scholarly publications, on the other hand, are frequently utilised as markers of successful nanotechnology R&D and innovation (Tanaka, 2013; Karpagam et al., 2011; Islam and Miyazaki, 2010; Pouris, 2007; Hullman and Meyer, 2003; Marinova and McAleer, 2002;). As a result, successful nanotechnology research is expected to yield a wide range of research outputs, including new and improved products, licences, patents, scholarly publications, spin-off companies, new start-up businesses, among others.

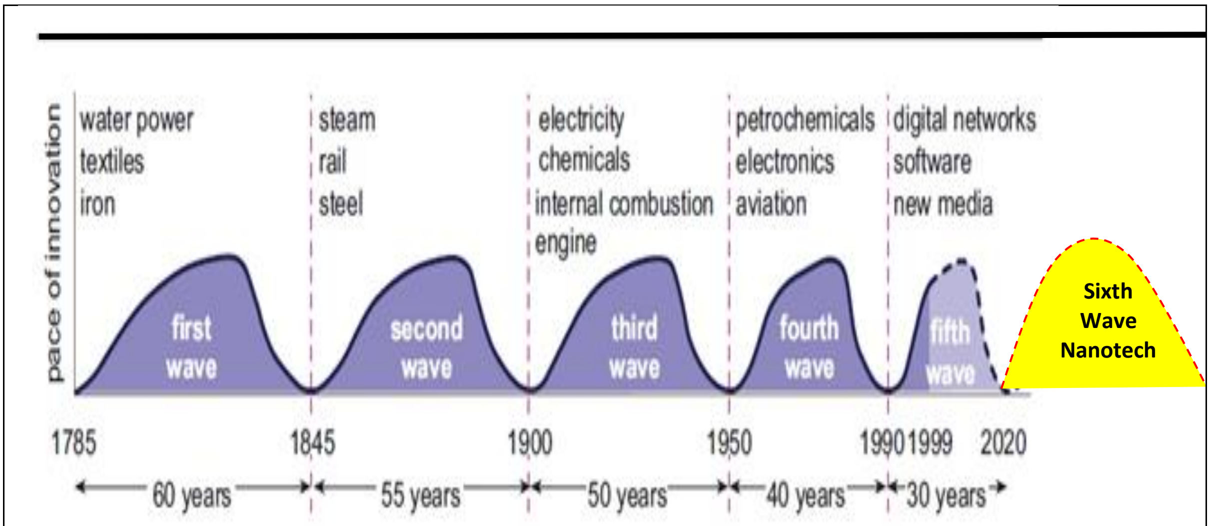
This section reviews the characteristics of nanotechnology research that support successful nanotechnology innovations. The identified factors are summarised in the proposed Nanotechnology Innovation Diamond presented at the end of this section. The Nanotechnology Innovation Diamond presents criteria (factors) for identifying and managing nanotechnology research areas with the most significant potential to produce successful applications and innovations. These criteria can also be used to determine and rank key research areas in nanotechnology.

2.3.1 Nanotechnology as a General-Purpose Technology (GPT)

A General Purpose Technology (GPT) is defined as a fundamental invention that is "shared within and across industries and enables valuable inventions and innovations" in a broad spectrum of industries and technological areas (Bresnahan and Trajtenberg, 1995). According to several authors, nanotechnology is a General-

Purpose Technology that can be applied in every economic sector (Bresnahan and Trajtenberg 1995; Shapira & Youtie 2008; Youtie *et al*. 2008; Roco *et al*. 2011; Cunningham and Werker, 2012; Battard, 2012; Kreuchauff and Teichert, 2014; Shea *et al*., 2016). For example, Schultz (2011) contends that nanotechnology is found in almost every industry such that it is nearly impossible to define what is a "nano job". Kane *et al*. (2016) also add that nanotechnology has resulted in several inventions and breakthroughs having a diverse set of uses, including energy, medical diagnostics, information technology, materials, catalysis, and agriculture. According to Salerno et al. (2008), considering the vast range of applications covered by nanotechnology, it is justifiable to infer that the "nanotechnology revolution will impact nearly all aspects of human life". Hence, nanotechnology is considered a significant contributor to advanced innovations and the transition to a knowledge-driven economy. Consequently, nanotech's importance has led governments and the private sector to invest huge amounts of money into the technology.

Due to its GPT nature, nanotechnology has also brought about a "disruptive" and "revolutionary" impact on industrialisation and wealth creation (Schulenburg, 2004; Shea *et al*., 2016). As a GTP, nanotechnology is widely predicted to drive the next Schumpeterian wave of economic growth (Mangematin *et al*., 2012; Linton and Walsh, 2008; Tuncel, 2015). Figure 2.2 below depicts Schumpeter's wave of economic development driven by technological innovations.



Adapted from The Economist

Figure 2.2: Schumpeter's Wave of Economic Growth

GPTs have three distinctive characteristics that make them engines of economic growth (Shea *et al*., 2016; Kreuchauff and Teichert, 2014; Cummins and Violante, 2002; Bresnahan and Trajtenberg, 1995). Firstly, they generate significant innovations that impact a wide range of manufacturing processes; secondly, they are pervasive in all technological sectors; thirdly, GPTs improve with time, as evidenced by a decline in prices and/or quality improvement. According to Kreuchauff and Teichert (2014), nanotechnology characteristics perfectly fit a GPT. The pervasiveness of use is ensured by the ability to organise nanoscale structures containing novel material characteristics for virtually endless applications in diverse industries such as electronics, nanomedicine, precision manufacturing, fuel cells, and catalysis. Nanotech advances are continuously improving. For example, in the last few years, nanotechnology improvements have enabled significant reductions in the size and cost of electronics. Nano-applications in semiconductors have, for example, contributed to an extensive decrease in the size and cost of electronics. Youtie *et al*. (2008) concluded that the GPT characteristic of "innovation spawning is seen in the nanotechnology value chain" that includes the initial stage of nanomaterials development, then the intermediate stage of nano-intermediates such as sensors and electronic components, and, lastly, downstream innovations that produce nano-enabled devices for the market.

2.3.1.1 Implications of GPT on nano-hybridisation

In conclusion, the understanding that nanotechnology exhibits the characteristics of a general-purpose technology helps in planning for nanotechnology foresight exercises. Decision-makers need to understand that, as a GPT, nanotechnology has a widespread penetration into the economy that is similar or comparable to prior GPTs such as electricity and ICT (Roco *et al.*, 2011). According to Hullman (2007), nanotechnology may have a more significant economic impact than ICT. Shea *et al.* (2016) go on to add that, as GPTs are pervasive and have spillover effects across all economic sectors, looking at nanotechnology from the perspective of GPTs should encourage investment in nanoscience.

Furthermore, because nanotechnology is pervasive, decision-makers must identify all potential stakeholders during foresight studies because a single discovery or idea could have multiple uses across multiple technological sectors. (Salerno *et al.*, 2008a). Nanotechnology can readily solve problems in existing markets, and one may consider areas such as building radiative cooling, affordable clean water, stain-resistant clothing, greenhouse emissions management, and energy provision as examples of existing challenges that nanotechnology might improve. In other words, as nanotechnology is integrated into existing products and markets, nanotechnology advances will result in hybrid industries such as nano-photovoltaics, nanomedicine, nanomaterials, nano-agriculture, nano-polymers, -, and nanocatalysis (Avenel *et al.*, 2007; Aithal and Aithal, 2016). A single nanoscience discovery or development could have various applications in various industries (Salerno *et al.*, 2008; Shea, Grinde and Elmslie, 2011). As a result, integrating nanotechnology with current industries and socioeconomic demands (nanotechnology hybridization) is crucial to nanotech research and development success.

2.3.2 Nanotechnology value chain

The nanotechnology value chain is a three-step process that takes nanotechnology inventions from conception to commercialisation (Shapira, Youtie and Kay, 2011; Wang and Guan, 2012; Gkanas *et al.*, 2013; Foladori *et al.*, 2017). Nano-materials, which are the raw materials for nanotechnology, are produced at the initial point of the nanotech value chain; examples of nano-materials include nanowires, quantum dots, carbon nanotubes and nanofilms. Nano-intermediate items are made at the second phase of the value chain. These are goods that make innovative use of nanoscale features, and examples include nano-coatings, nano-composites, electronic components and various types of sensors. The intermediate stage is where most of the innovation in nanotechnology is taking place and the stage with the greatest profit potential (LuxResearch, 2009). Most of the companies in the nano-intermediates are new start-ups. The third segment of the nanotech value chain produces nano-enabled consumer products. Large firms mostly manufacture nano-enabled products based on intermediate items. Nano-enabled consumer products include medical equipment, sun screens lotions, paints, automotive components, cosmetics, and apparel, among others. Nano-tools, which are used to manipulate and assemble nanomaterials are an important aspect of the nanotechnology value chain. Figure 2.3 below illustrates the nanotechnology value chain concept.

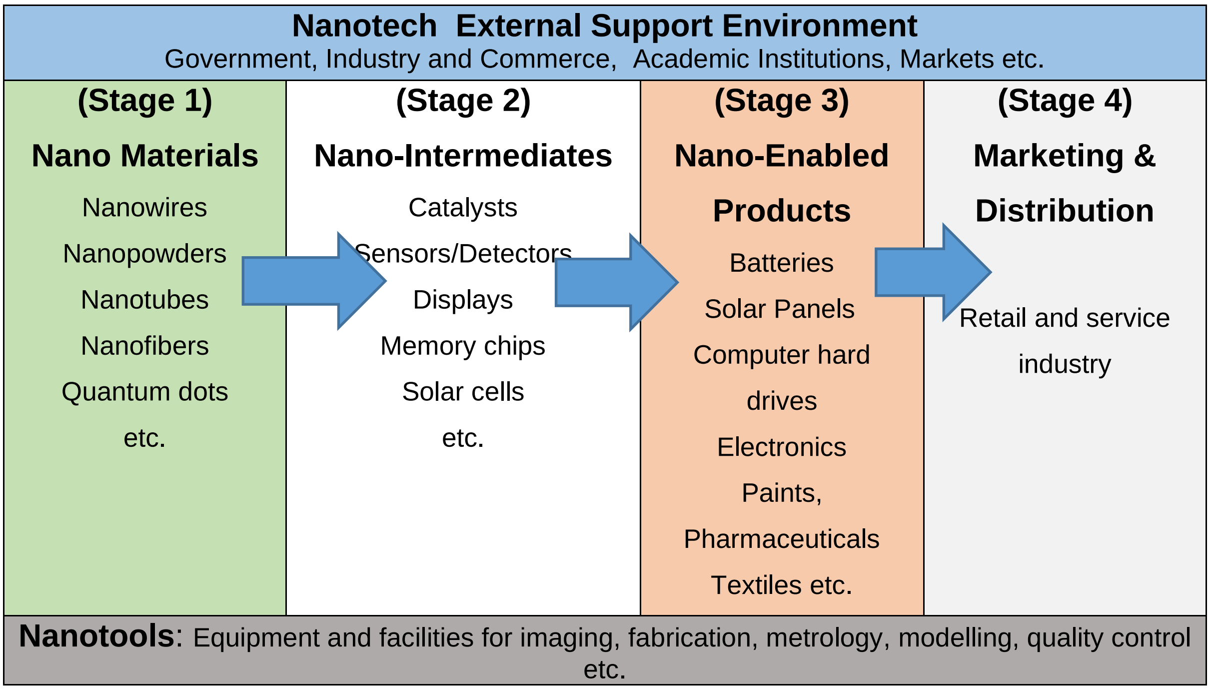


Figure 2.3: The nanotechnology value chain

2.3.2.1 Conclusion on nanotech value chain

The value chain allows decision-makers to categorise nanotechnology research areas based on where they contribute to the nanotech value chain: nanomaterials are more linked to basic research, while nano-intermediates are more connected to applied research, and big commercial companies contribute more to nano-enabled products and services. Analysis of nanotechnology patents using the nanotechnology value chain categorisation system can significantly support policy decision making and foresight exercises. For example, if most patents are on nanomaterials, that indicates that academia in basic research are the prominent participants in the nanotechnology value chain; hence there will be a need to put in place necessary support structures to produce and patent more valuable nano-intermediate and nano-enabled products.

2.3.3 Multidisciplinarity, interdisciplinarity and convergence in nanotechnology

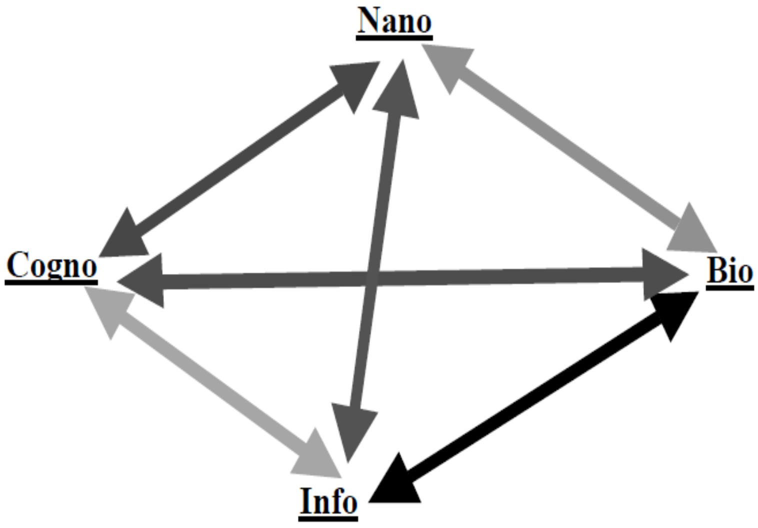
Cross-functional or interdisciplinary teams are among the most crucial success factors in technology innovation (Torkkeli and Tuominen, 2002; Connel *et al.*, 2001). Science lawmakers have often highlighted interdisciplinarity in nanotechnology research as a top goal (Schummer, 2004); for example, both nanotechnology policy in the United States (Battard, 2012) as well as in South Africa (DST, 2005) call for increased multidisciplinary cooperation with regards to research in nanotechnology.

A research area is considered to be multidisciplinary when several diverse disciplines are actively working in that particular research field. (Schummer, 2004); for example, nanotechnology is multidisciplinary because there are physicists, chemists, engineers, and biologists, among other disciplines, working in nanotechnology research. In a multidisciplinarity field, interaction is not necessary; the involved disciplines can be working in silos; for example, physicists may work alone, chemists work alone and material scientists on their own. On the other hand, interdisciplinary research involves collaboration between researchers from different fields to advance a common research area (Schummer, 2004), for example, a biologist working with a physicist in nanotechnology. Thus, a research area might be multidisciplinary but not interdisciplinary. Interdisciplinary only occurs when researchers from different disciplines start to work together and collaborate (Schummer, 2004).

It is undisputed that nanotechnology is multidisciplinary; various scholars agree on this (Battard, 2012; Karpagam *et al*., 2011; Porter and Youtie, 2009; Schummer 2004; Roco *et al*., 2011; Miyazaki and Islam, 2007; Gkanas *et al*., 2013). However, the degree of interdisciplinarity in nanotechnology is a point of contention among authors. In one sense, academics view nanotechnology as an interdisciplinary endeavour that has joined researchers from various science fields (Karpagam *et al*., 2011; Tuncel, 2015). Meyer and Persson (1998) and Hullman and Meyer (2003) report that nanotechnology is more interdisciplinary in comparison to other R&D disciplines. Some scholars fall somewhere in the middle, claiming that nanotechnology has a moderate level of interdisciplinarity, for example, Schummer (2004). At the other end of the spectrum, researchers argue that nanotechnology is multidisciplinary more than interdisciplinary (Battard, 2012; Porter and Youtie, 2009).

2.3.3.1 Technological convergence in nanotechnology

Nanotechnology is emerging as a focal point for the confluence of numerous fields due to its transdisciplinary and interdisciplinary character (Meyer, 2007; Battard, 2012; Porter and Youtie, 2009; Islam and Miyazaki, 2009; Roco, 2020). However, Mangematin *et al.* (2012) argue that incorporating nanotechnologies into current industries and markets appears to be moving at a slower pace than scientific convergence. Nanotechnology is at the crossroads of several scientific disciplines, bringing together multiple technological research domains based on the scientific ability to manipulate matter at the nanoscale. This convergence has resulted in a field of study known as NBIC that combines nanotechnology, biotechnology, information technologies, and cognitive sciences (Salerno, Landoni and Verganti, 2008; Battard, 2012). Islam and Miyazaki (2009) assert that nanotechnology is crucial to sustaining the rapid growth of IT and biotechnology, without which they cannot continue to grow. Figure 2.4 below shows the interconnectedness of nanotechnology with the disciplines within NBIC.



Source: (Roco and Bainbridge, 2003)

Figure 2.4: Nano-Bio Info and Cognitive sciences (NBIC) tetrahedron

According to Roco and Bainbridge (2003), NBIC technologies can enhance human performance and productivity, for example, through improving human sensory and cognitive capabilities for better human-machine interactions, automation and artificial intelligent systems essential for the 4th industrial revolution (4IR). Hence, Salerno *et al*. (2008) proposed that the emerging discipline of NBIC is the research field with the most potential for ground-breaking innovations.

2.3.3.2 Conclusion on Multi and Interdisciplinarity

In conclusion, the literature reports that multidisciplinarity and interdisciplinarity are central features of nanotechnology. However, it is necessary to ascertain whether they are also a crucial success factor in nanotechnology research and development. If interdisciplinary capabilities are vital for nanotechnology innovation success, research and development leaders must cultivate these capabilities in their research teams. Additionally, foresight planners may consider an interdisciplinary team in a research project as one criterion for identifying nanotechnology research with a high chance of delivering innovative breakthroughs.

2.3.4 Agglomeration in nanotechnology

A distinguishing aspect of R&D activity, according to Palmberg, Denis and Miguet (2009), is their concentration (agglomeration) in certain areas rather than being evenly distributed throughout a country. Porter and Stern (2001) support this point of view, claiming that the actual location of R&D institutions is an essential element for successful innovations and that particular places offer a competitive edge in terms of R&D, innovation, and commercialisation. These locational advantages result in the development of technology clusters or technology agglomeration. Literature reports agglomeration is also taking place in nanotechnology research. For example, nanoclusters have been established in Greece, France, the United States, Germany and Netherlands (Robinson et al., 2007; Shapira and Youtie, 2008; Fiedler and Welpe, 2011; Gkanas et al., 2013).

Geographic agglomeration of economic activity improves the technological and financial performance of the firms situated in the cluster (Peneder, 1997). According to Marshal (1920), several factors contribute to the economic benefits of technological agglomeration. These factors include knowledge spillovers between firms, local supply of specialised raw materials, shared services and a geographically concentrated pool of specialised human capital with necessary skills. Furthermore, according to Fiedler and Welpe (2011), geographical proximity/clustering minimises operational expenses for companies.

Not all authors agree on the economic benefits of geographic agglomeration. Lublinski (2003) suggests that companies do not need to be physically close in the technology age but can network and share information virtually. According to the literature, there is an ideal degree of spatial concentration of high-tech enterprises, and that ‘over-agglomeration' can have detrimental impacts on businesses, resulting in the collapse of certain high-tech parks (Fiedler and Welpe, 2011; Audretsch, 2001).

The issue that comes to mind is what impact does functioning in a cluster have on the success of nanotechnology R&D? One may ask, do research projects located in clusters possess a better probability of success than those isolated? Is technological clustering or technological agglomeration a CSF for nanotechnology innovation?

Evidence from literature (Carlino and Kerr, 2015; Palmberg, Denis and Miguet, 2009; Shapira and Youtie, 2008; Robinson *et al*., 2007) supports the idea that technical agglomeration is an essential aspect in nanotechnology's development. For example, Robinson et al. (2007) suggest that high-tech parks are vital for nanotechnology's success because they allow entrepreneurs to pool resources, share skills and tap into professional networks**.** The effectiveness of nanotechnology districts is demonstrated by the following examples.

- Nanotechnology clusters produce the bulk of nanotechnology patents (Carlino and Kerr, 2015; Shapira and Youtie, 2008), and
- companies inside a cluster have a significantly bigger market share than those outside clusters (Fiedler and Welpe, 2011).

Another observation about nanotechnology clusters is that they tend to occur where there are already other R&D activities. According to Shapira and Youtie (2008), renowned innovation centres such as Silicon Valley and Boston attract a significant amount of nanotechnology research and development. This observation is shared by Mangematin *et al*. (2012), who notes that cluster growth in nanotechnology is primarily driven by the hybridisation of nanotechnology with existing industry and consumer needs such as in electronics, energy and medicine.

2.3.4.1 Conclusion on nanotechnology agglomeration

In conclusion, the proliferation of nanotechnology clusters and empirical evidence of them outperforming units outside nanoclusters regarding sales, the number of patents and the ability to license innovations indicate the importance of technological agglomeration to nanotechnology. Organisational clustering enhances establishing industry networks, sharing research facilities and tacit industry knowledge, which act as catalysts and accelerators for nanotech inventions and commercialisation. As a result, it can be concluded that technological agglomeration is a critical success factor in nanotechnology R&D.

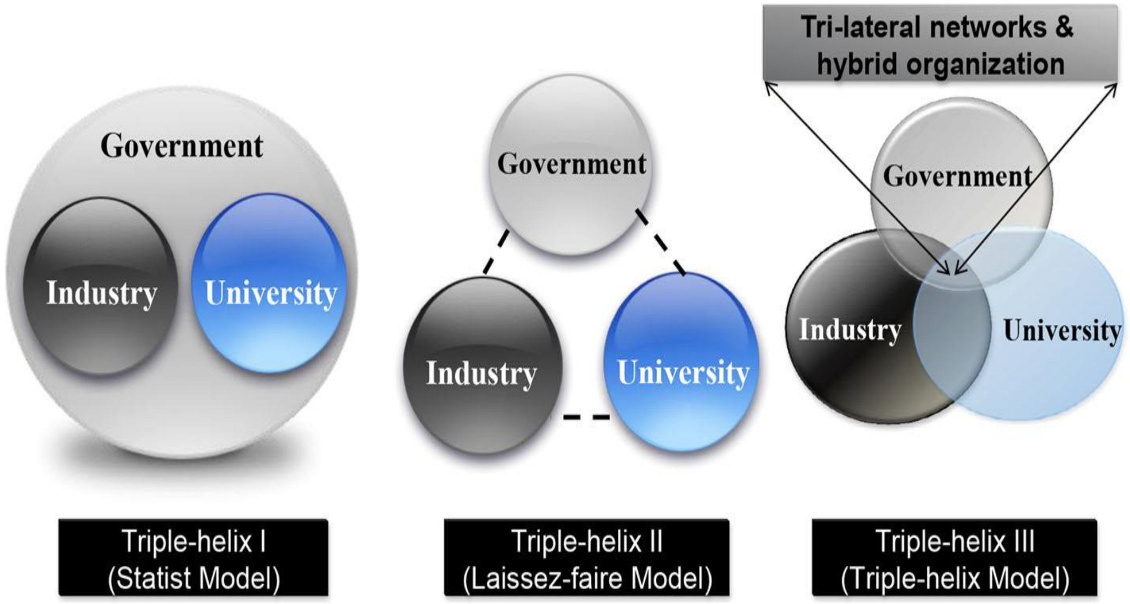
2.3.5 R&D skills and nanotechnology innovation environment

The critical success factors for technological innovation traditionally focus on the organisation's internal capabilities, such as R&D competencies, product development, and commercialisation management processes. As a result, successful nanotechnology R&D is expected to produce a variety of outputs. These outputs include new products, product improvements, patents, scholarly papers, start-ups, and spin-off companies. To accomplish the outcomes outlined above an R&D entity requires employees with expertise in science and technology research, academic publishing, intellectual property management, and commercialisation of research. Maine (2014) coined the phrase "scientist-entrepreneur" to describe researchers with such abilities. However, Porter and Stern (2001) suggest that the environment within which innovation takes place has an equal impact on technology-based firms' success. At the national level, the environment in which technological innovation occurs is termed the National System of Innovation (NSI). According to Freeman (1987, p1), the NSI is defined as a network of public and private sector entities whose activities and connections generate, acquire, improve, and disseminate innovative technologies. Academia, industry, and government are the three major institutions interacting in the NSI. The academia composed of universities and national research institutions generates ideas from conducting basic and applied research. Industry commercialises research innovations, making innovative solutions available to the public, and the government creates the policy framework within which the parties interact (Yoon, 2015; Mok, 2016).

2.3.5.1 The Triple Helix

Etzkowitz and Leydesdorff (1997) coined the term The Triple Helix (TH) to describe the conducive innovation environment created through government, universities, and industry connections. The relevance of Triple Helix partnerships for innovation has been widely recognised by both innovation management academics and policymakers (Schultz, 2011; Yoon, 2015; Choi et al., 2015). The three principal partners of the Triple Helix are involved in interrelated roles. Each party takes on roles beyond its traditional responsibilities (Yoon, 2015**;** Schultz, 2011), such that the Triple Helix has given rise to terms such as “tri-lateral networks’’, ‘‘entrepreneurial universities’’, ‘‘enhancing existing roles’’ and ‘‘institutions taking the role of another’’ (Meyer *et al.*, 2014).

As illustrated in Figure 2.5, the Triple Helix may be implemented in three different ways. The first model shows the statist paradigm where the government directs and coordinates the interactions between academia and industry. The second model shows the laissez-faire model with very limited interaction among the three partners. In the third model, which is the trilateral hybrid, there is an active interaction and overlapping of responsibilities among the institutional partners, and thus it is the most desirable model.



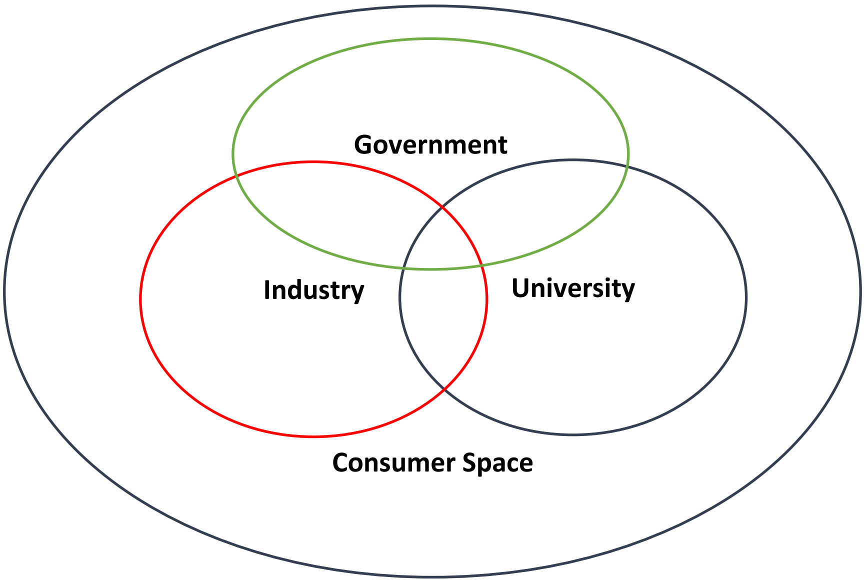
Source (Yoon, 2015)

Figure 2.5: Three models of the Triple Helix

Several Triple Helix expansions have been proposed to include other stakeholders, and these suggestions include the "Quadruple", "Quintuple", and "N-tuple helices" (Ivanova, 2014; Meyer *et al*., 2014; Miller *et al*., 2016). The quadruple proponents argue that 'society' or 'consumers' are a fourth core principle for a conducive innovation environment. This argument recognises consumers' role in innovation systems through using and applying the innovations and creating the market for innovative products. However, Leydesdorff and Etzkowitz (2003) disagree with this addition; they argued the general public could not be a fourth component of the Triple

Helix because society is not a formal institution able to interact with the other three formally. Therefore, the public, users or consumers do not constitute a legal institution; hence, they cannot be regarded as a new component of the Triple Helix.

Ivanova (2014), on the other hand, advocated for an adjustment to the Triple Helix to include consumers in the innovation system. According to Ivanova (2014), the advancement of nanotechnology led to the Triple Helix system being reconfigured. It is submerged in an area established by customers or the general public, as indicated in Figure 2.6 below.



Adapted from Ivanova (2014)

Figure 2.6: The Triple Helix model inside the consumer space

In nanotechnology and biotechnology, where customer preferences typically dictate the success and acceptance of technologies, this framework in Figure 2.6 is the best fit. Environmental pressure groups, consumer organisations, and the government determine legislation and labelling choices for nanotechnology goods. Therefore, they impact customer perceptions of nano-enabled products (Berube *et al.*, 2011; Giles *et al.*, 2015; Yue *et al.*, 2015). The rejection of Genetically Modified (GM) foods by some governments is an excellent illustration of the consumers and public affect the success of commercial nanotechnology products (Paarlberg, 2014). However, some authors contend that the general public does not realise they buy nanotechnology-based goods and do not read the labelling (Casolani *et al*., 2015; Berube *et al.*, 2011).

2.3.5.2 Public-private partnership in nanotechnology innovation

"Public-private partnership' (PPP) describes "working arrangements based on a mutual commitment (over and above that implied in any contract) between a public sector organisation with any organisation outside of the public sector" (Bovaird, 2004). PPPs provide the following benefits; pooling of resources to address issues that a single entity cannot address, sharing risk, attracting external partners, attracting funding, focusing R&D priorities in consultation with stakeholders and concentrating resources on issues of national interest (Woodson, 2016; Witters, Marom and Steinert, 2012). Various countries have PPPs in nanotechnology (Woodson, 2016).

According to Woodson (2016), PPPs are especially critical for research in social development issues such as innovations in diseases of poverty, like medical applications of nanotechnology (nanomedicine). If companies cannot recoup their R&D expenditures, they do not have any incentive to develop new technology. As a result, public-private partnerships are currently the prominent organisations researching nanomedicines for poverty-related diseases (Woodson, 2016).

Nanotechnology innovation experts cite several successful PPP cases. For example, the success of Israeli enterprises' inventions is attributed to a favourable climate for innovation produced by strong industry-academia collaborations and the availability of skilled scientist-entrepreneurs (Porter and Stern, 2001). Another example of a successful PPP is the College of Nanoscale Science and Engineering (CNSE) created through a partnership of International Business Machines (IBM), the University of Albany and New York State. According to Schultz (2011), the number of publications and patents generated by CNSE has been significantly higher than what is produced in other nanotechnology research facilities. In addition, there is an overall growth in the size of nanotechnology-related companies operating within the CNSE cluster.

2.3.5.3 Conclusion on R&D skills and innovation environment

This section has identified three critical success factors for nanotechnology innovation which are the right R&D skills, a conducive environment and consumer needs. Based on this section's discussion and the interdisciplinary character of nanotechnology, multi-sector collaborative research environments such as the Triple Helix and PPP appear to be necessary for nanotechnology success. Therefore, nanotechnology research and development must be aligned to government strategy, address industrial needs through symbiotic and synergetic relations between academia, industry, and the government.

In addition, for nanotechnology innovations to succeed, consumers must accept and understand these nanotechnology innovations. This applies particularly to nanotech innovations for agriculture, food, cosmetics, and medicine. Ivanova (2014) proposed an innovation environment created by the Triple Helix immersed within consumer space to integrate consumers' engagement in the innovation system. This framework presents a compelling nanotechnology innovation environment model, in which consumer choices often decide the success and acceptance of new products. As a result, consumer needs and government requirements are the key drivers of the nanotechnology products industry, and both must be factored into product design (Khosravi and Sadeghi, 2014).

2.3.6 Nanotechnology Innovation Diamond

Based on the discussion on the characteristics of successful nanotechnology discussed in the literature, it is observed that nanotechnology research and development has six interrelated critical success factors, which are consumer needs and preferences, nanotechnology-hybridisation with existing industries and market needs, multi- and inter-disciplinarity, technological agglomeration, availability of the proper R&D (scientist-entrepreneur) skills and a conducive innovation environment. The six factors identified have been summarised into the Nanotechnology Innovation Diamond shown in Figure 2.7 below.

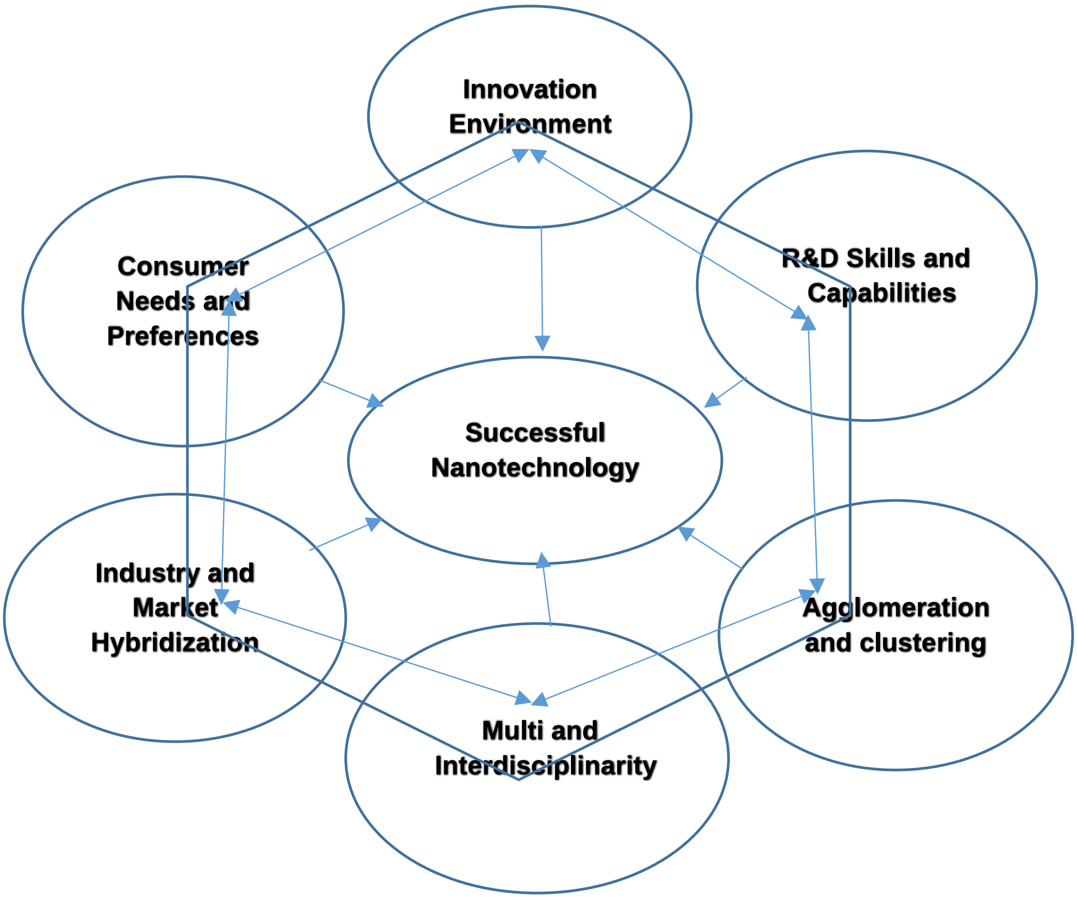


Figure 2. 7: Nanotechnology Innovation Diamond

These six factors are summarised in sections 2.3.6.1 to 2.3.6.6 below.

2.3.6.1 Consumer needs and preferences

Consumer demands, preferences, and acceptance of nanotechnology goods, particularly those with medical, environmental, cosmetic, agricultural and food, are at the heart of nanotechnology R&D success (Cologne, 2004). The market for nano-enabled items is constantly shaped and determined by consumer needs and preferences. Therefore, for nano innovations to be successful, they must be accepted by the final consumer, the public and industry.

2.3.6.2 Nanotechnology-hybridisation

The needs of the market and industry must be satisfied by integrating nanotechnologies into current industries and socioeconomic needs (nanotechnology-hybridisation). Nanomedicine, nanoelectronics, nanocosmetics, and nanoengineering are all examples of nanotechnology hybridization. Furthermore, because nanotechnology is a GPT, a single nanoscience invention might have numerous applications in various technical disciplines (Salerno *et al.*, 2008; Shea, Grinde and Elmslie, 2011). As a result, nanotechnology researchers must continually search for ways to integrate their innovations with current industry and socioeconomic needs.

2.3.6.3 Multi-and inter-disciplinary teams

Nanotechnology is not a stand-alone discipline; it is both multidisciplinary and interdisciplinary. Nanotech is already leading to the convergence of several disciplines in the form of NBIC. NBIC is postulated as the science research field with the most potential for ground-breaking innovations (Salerno *et al*., 2008). Successful nanotech innovations usually have researchers from various disciplines working together as a team (Battard, 2012; Miyazaki and Islam, 2007; OECD, 2013). In addition, due to its multidisciplinary nature and applicability to all technological fields, successful nanotechnology requires interdisciplinary research teams and operating in high technology industry clusters.

2.3.6.4 Research and development skills

The successful implementation of nanotechnology R&D programmes relies on "scientist-entrepreneurs" (Maine, 2014); these are people with expertise in basic and applied research, scholarly publishing, intellectual property management, and taking R&D innovations from the lab to the market. Hence appropriate education systems are needed to develop these “scientist-entrepreneurs”. The Triple-Helix model is also necessary for providing a proper education and training system (Schultz, 2011; Choi *et al.*, 2015; Yoon, 2015). When universities work closely with business and government, they can better understand and provide the education and skills training to satisfy private sector and government needs. In turn, industry and government will support education through student industrial attachments and work-based learning opportunities, bursaries, and funding joint research programmes, thereby creating strong industry-academia collaborations and building the science engineering and technology human capital pool.

2.3.6.5 Agglomeration and clustering

As a GPT, nanotechnology innovations can benefit all industrial sectors (Avenel *et al.,* 2007; Battard, 2012; Mangematin *et al.,* 2012). Thus, nanotechnology researchers need to constantly search for opportunities in all industries to identify potential applications of their innovations. Nanotechnology enterprises can enhance their innovation capacity and commercialisation opportunities by locating in a science park or close to other industries. Entities in high tech clusters gain from information spillovers, industry associations, tacit knowledge spillovers, specialised infrastructure such as nanofabrication centres, and locally available skilled labour. These factors, in turn, result in opportunities in which to integrate their innovations with other industries. The emergence of nanoclusters in nanotechnology coupled with their better comparative performance is proof that technological agglomeration is important for the success of nanotechnology research and innovation (Robinson *et al.*, 2007).

2.3.6.6 Conducive innovation environment

A conducive innovation environment provided by the cordial collaboration of the universities, research facilities, government and industry via the Triple Helix system and Public-Private Partnerships (PPP) is another crucial component driving successful nanotechnology R&D.

2.3.7 Hypothesis on the Nanotechnology Innovation Diamond

There are six CSFs in the Nanotechnology Innovation Diamond. There are two hypotheses put forward as shown below:

Hypothesis 1: There is no statistical difference between the means of Nanotechnology Innovation Diamond's critical success factors.

H_o: $\mu_1 = \mu_2$ (the paired population means are equal for all six CSFs)

Alternate Hypothesis 1: There is a statistical difference between the means of Nanotechnology Innovation Diamond's critical success factors.

H_a: $\mu_1 \neq \mu_2$ (the paired population means are not equal for all six CSFs)

Null Hypothesis 2: The Nanotechnology Innovation Diamond's six crucial success factors are not statistically significant for successful nanotechnology research and development.

Alternate Hypothesis 2: The Nanotechnology Innovation Diamond's six crucial success factors are statistically significant for successful nanotechnology research and development.

2.4 Technology foresight

This section gives an overview of technology foresight. It defines technology foresight, reviews the epistemological approaches to foresight, and discusses the most commonly used technology foresight methods. This research's primary goal is developing a nanotechnology-specific key technologies foresight model to determine and identify critical nanotechnology research areas on which a country must focus and concentrate. Hence the emphasis in this section is given to reviewing key technologies foresight techniques.

2.4.1 Introduction

Technology foresight is the practice of methodically evaluating the long-term prospects of ongoing scientific R&D, the economy, and socioeconomic imperatives to determine the most critical R&D areas that will have the most significant socio-economic impact on society (Martin, 1995). According to Ronde (2003), the ultimate goal of technological foresight is to guarantee that those research domains with the most significant probability to result in socioeconomic benefits are identified, developed, and supported. That is, technology foresight aims to identify 'critical' or 'key' areas of research and establish research priorities. As a result, technology foresight exercises are a fundamental prerequisite for long term strategic planning for any county's science and innovation strategy (Firat *et al.*, 2008).

2.4.1.1 Technology foresight drivers

The primary driver for technology foresight activities is the strong link between competitiveness, economic growth and technological innovation as proven by theories such as the Schumpeterian growth model (Tuncel, 2015) and the competitiveness of nations (Porter, 1990). This link is also supported by empirical evidence that shows tremendous economic success for countries that carry out routine foresight exercises

(Zaidman, 1997). As a result, some scholars claim that there is a proliferation of technology foresight activities as countries strive to improve national competitiveness through technological innovation planning (Cedefop, 2021; Parandian, 2012; Salo et al., 2003).

Martin (2001) adds two more drivers of technology foresight exercises. Firstly, he notes that, even though countries need new innovations and technologies to stay competitive, governments do not have adequate resources to finance all research domains in which their country's scientists work. Choices for key research areas are then identified using technology foresight. Secondly, governments experience significant public expenditure constraints and pressure for accountability and value for money in the use of public funds. Therefore they must develop policies and priorities for research and development, funding only those areas with the greatest potential for socio-economic benefits; again, foresight offers a valuable tool for policy formulation by governments.

Lastly, (Martin, 2001) concludes that the foresight process can also be used as an awareness instrument and glue to wire up the National System of Innovation (NSI). He argues that activities carried out during foresight such as interviews, seminars, panel discussions and consensus-seeking through processes such as Delphi naturally lead to the development of a social contract among the participants and an understanding of the future science priorities, including where and how each stakeholder can contribute.

2.4.1.2 A comparison of technology foresight and forecasting

Scholars use the phrases "technology foresight" and "technology forecasting" interchangeably in the literature to refer to the same concept and process. This becomes clear when researchers describe these concepts and describe their drivers, aims, and techniques for achieving them. However, Martin (2001) maintains that scholars must distinguish between technological foresight versus forecasting. Martin (2002) clarifies that “technology forecasting” is based on the assumption that there is just one possible future. As a result, the planner should be as precise as possible in predicting future research areas when it comes to forecasting.

On the other hand, in “technology foresight”, it is assumed that there are many potential futures and that future technological research areas would be determined by the decisions made through the foresight planning process. Hence foresight process supports countries in moulding the future by identifying several future R&D research areas and ranking them in order of criticality. Therefore, the phrase "technology foresight" is used in this study.

2.4.1.3 Technology foresight versus technology selection

Another area that is closely related to technology foresight is technology selection. Gregory (1995) defines technology selection as choosing which technologies to select, support and implement in a company. Shehabuddeen, Probert and Phaal (2006) add that technology selection can involve prioritising physical equipment, materials, IT systems or production systems that do not need additional research and development once purchased. Technology selection involves identifying a need, obtaining information about potential alternative solutions, and evaluating the most appropriate technology options. Payback period (PB), internal rate of return (IRR), and return on investment (ROI) have traditionally been used to evaluate the financial and economic attractiveness and suitability in technology selection (Chan *et al.*, 2000). In addition, various MCDM methods are also widely used in technology selection (Kazemi, Homayouni and Jahangiri, 2015; Georgakellos, 2011; Simunovic *et al.*, 2009; Khouja, 1995; Aruldoss, Lakshmi and Venkatesan, 2013).

Therefore, it can be summarised that while technology foresight concentrates on the broader picture, usually at the national level and tries to identify key research areas for extensive R&D, technology selection, on the other hand, is typically done at the organisational or project level to identify technologies ready for exploitation that do not require extensive R&D efforts.

2.4.2 Epistemology of foresight

The two broad approaches to foresight exercises are the quantitative/empirical/realist epistemology of foresight and the qualitative interpretive/critical epistemology. The quantitative approach to foresight was used in this research to develop a nanotechnology-specific key technologies foresight model that is a MCDM-based, rational decision-making protocol and uses quantitative and evidence-based data from nanotechnology publications.

2.4.2.1 Quantitative / empirical / realist epistemology of foresight

One school of thinking in foresight holds that future knowledge is gained through projecting into the future after analysing the historical and current state of the world. Quantitative foresight approaches are founded on this school of thought, such as environmental scanning, statistical tools, patent analysis, and extrapolation to anticipate the future. According to this perspective, Von Wright (2009) postulated the Laplace's Demon, an observer who could foresee the actual future state of the world based on its perfect knowledge. However, Kalle and Rafael (2015) concluded that it is probabilistic and uncertain to forecast the future using information from the past. They go on to add that one can seldom be sure that the world's structure will not change over the time of interest; hence, one can only forecast the future subject to the extrapolation method limitations.

2.4.2.2 Qualitative/ interpretive / critical epistemology of foresight

Another perspective in foresight studies is described by Hideg (2007), as referenced by Kalle and Rafael (2015), suggesting that "… the future is interpreted as something that already exists in the present in the thoughts and emotions of people. … Future thoughts are forming and reforming in the process of discourses, so the futures existing in the present are open and humanly constructed." As a result, Kalle and Rafael (2015) claim that the future is already present in people's thoughts and emotions. The qualitative approaches to foresight are founded on this school of thought. As a result, several approaches such as expert surveys, Delphi, and creative workshops, can be used to obtain knowledge about the future by attempting to grasp thoughts and visions of the future that already exist in people's minds. However, other researchers see shortcomings with qualitative approaches to foresight, arguing that there could be a severe problem if one anticipates finding 'the future'' based on the thought processes of a few ''experts'' (Heraud and Cuhls, 1999; Turpin, 2004).

2.4.3 Technology foresight approaches

Foresight exercises come in many shapes and sizes and are often aimed at different objectives. Achieving these objectives requires various foresight methods and approaches (Porter, 2010; Popper, 2008). Therefore, several methodologies can be used in technology foresight. The most widely used methods are reviewed and summarised in this section. The section concludes by emphasising key technology foresight techniques in line with the goal of this research which is to develop a nanotechnology-specific key technologies foresight model.

2.4.3.1 Normative and exploratory approaches to foresight

Technology foresight exercises can take two broad approaches, namely, exploratory and normative (Martino, 1993; Porter *et al.*, 2004; Salerno, Landoni and Verganti, 2008). Exploratory exercises start with past and present conditions and attempt to project these to estimate future needs; they explore the possible futures implicit in past and present conditions. On the other hand, normative methods start with future anticipated requirements and identify required technologies to satisfy the anticipated needs. Martino (1993) goes on to say that normative and exploratory techniques are frequently employed in tandem to complement one another. For example, an exploratory foresight has implicit within it the idea that the capability will be desired when it becomes available and, vice-versa, a normative foresight has implicit within it the idea that the required performance can be achieved by a reasonable extension of past technological progress.

2.4.3.2 Foresight methods classification systems

Foresight methods also differ in approach and skills required. As already mentioned, some are quantitative (empirical, numerical, statistical) while others qualitative (judgmentally based, reflecting tacit knowledge, opinions) (Porter *et al.*, 2004; Salerno, Landoni and Verganti, 2008). An extensive study and categorisation of technology foresight methods was done by Porter *et al*. (2004), where over fifty TF methods were grouped into nine categories. A summary of the nine broad TF method families is shown in Table 2.2 below.

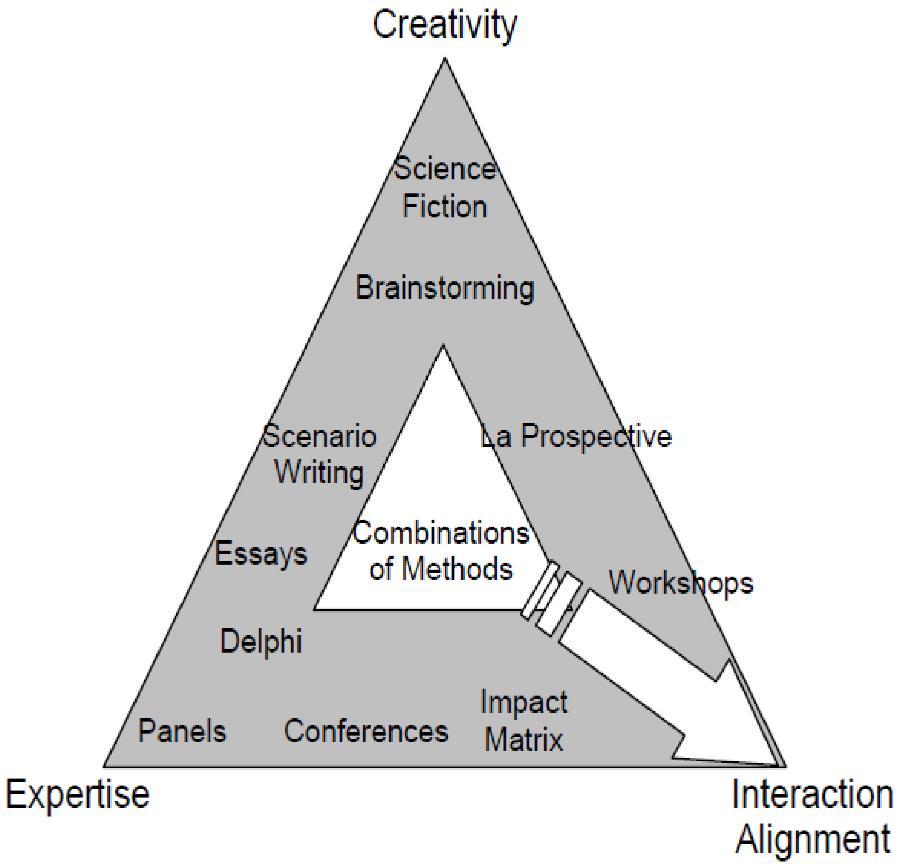
Table 2.2: Technology foresight methods

TF Method Family	Methods
1. Expert Opinion	Focus groups, Delphi, interviews
2. Trend Analysis	Trend Extrapolation, Trend Impact Analysis, Precursor Analysis, Long Wave Analysis
3. Monitoring and Intelligence	Monitoring, environmental scanning, technology watch
4. Statistical	Correlation Analysis, Demographics, Cross Impact Analysis, Risk Analysis, Scientometrics, Bibliometrics (research profiling; patent analysis, text mining)
5. Modelling and Simulation	Agent Modelling, Cross Impact Analysis, Sustainability Analysis (life cycle analysis), Causal Models, Diffusion Modelling, Complex Adaptive System Modelling (CAS) (Chaos)
6. Scenarios	Scenarios (scenarios with consistency checks; scenario management), Scenario-simulation (gaming; interactive scenarios), Field Anomaly Relaxation Method (FAR)
7. Valuing/Decision/Economics	Relevance Trees (futures wheel), Action (options) Analysis, Cost-benefit analysis, Decision analysis (utility analyses), Economic base modelling (input-output analysis)
8. Descriptive and Matrices	Analogies, Backcasting, Checklist for Impact Identification, Innovation System Modelling, Institutional Analysis, Mitigation Analysis, Morphological Analysis, Roadmapping (product-technology road mapping),
9. Creativity	Brainstorming (brainwriting; nominal group process (NGP)), Creativity Workshops (future workshops), TRIZ, Vision Generation

Adapted from Firat *et al.*, (2008) and Porter *et al*., (2004)

a) Foresight Triangle

Another prominent foresight model, the Foresight Triangle, proposed by Cameron *et al*. (1996), is shown in Figure 2.7 below.



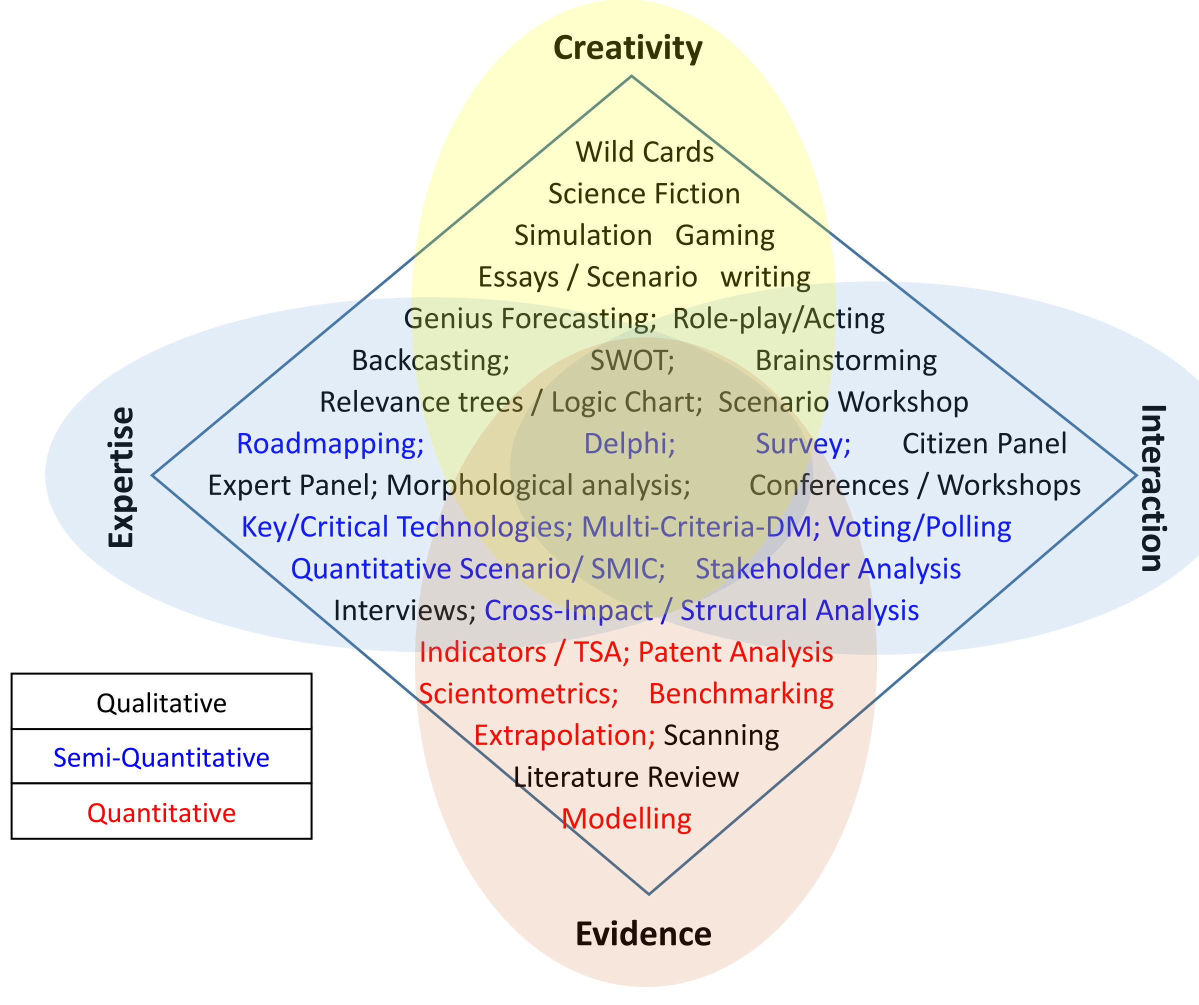
Source: Cameron *et al*. (1996)

Figure 2.7: Foresight Triangle

This model in Figure 2.7 suggests that there are three central tenets in foresight which are “expertise”, “creativity”, and “interaction”. However, the foresight triangle was criticised for not showing how evidence-based and quantitative methods are used in foresight exercises. Popper (2008) argued that it lacked techniques such as trend extrapolation, literature review, benchmarking, and patent analysis, and he improved this through the Foresight Diamond framework.

b) Foresight Diamond

The most recent foresight classification system, the Foresight Diamond, is a comprehensive foresight method mapping model developed by Popper (2008). Figure 2.8 below shows the Foresight Diamond mapping.



Adapted from Popper (2008)

Figure 2.8: Technology foresight methods diamond

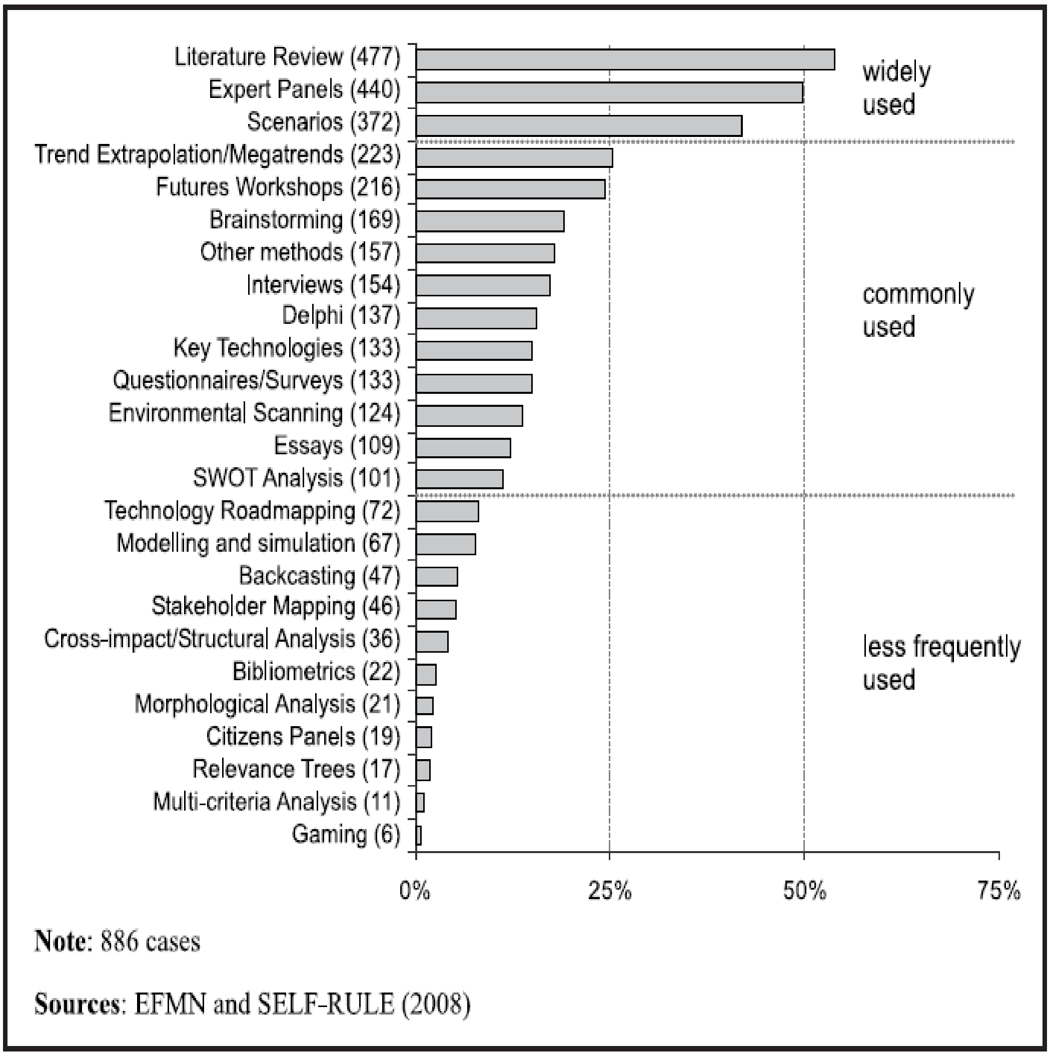
Popper (2008) proposed two dimensions of foresight method categorisation, which are the **nature** of the method and **capability**. The nature dimensions are qualitative, semi-quantitative and quantitative, whereby:

a. **Qualitative methods** meaningfully interpret thought processes, attitudes, beliefs, personal views, and events. They are based on subjectivity and creativity.
b. **Quantitative methods**, on the other hand, measure variables and apply statistical analysis, using reliable and valid data, and
c. **Semi-quantitative methods** quantify subjectivity using mathematical concepts, e.g., viewpoints of experts and commentators and then weighing them on a scale.

Under the methods capabilities dimension, Popper (2008) classified methods based on their capacity to acquire and analyse data based on “evidence”, “expertise”, “interaction”, and “creativity”. This research focuses on developing a nanotechnology-specific foresight model that is evidence-based using semi-quantitative and quantitative methods. Qualitative foresight techniques such as scenario planning that require creativity and interaction of experts are not part of this research model.

2.4.3.3 The popular technology foresight methods

According to literature, qualitative methods comprising literature review, expert opinion, Delphi, and scenario planning are the most common and widely used methods in technology foresight (Firat, Woon and Madnick, 2008; Popper, 2008; Sasikumar and Mohan, 2014; Porter *et al.*, 2004; Shen *et al.*, 2010). Figure 2.9 shows the prevalence of the use of various foresight approaches and methods.



Source: (Popper, 2008)

Figure 2.9: Frequency of use of foresight methods

Considering results in Figure 2.9 above, it is clear that there is a lack of quantitative and semi-quantitative methods use in foresight. These results imply a need to contribute to foresight models that use evidence-based, quantitative, and semi-quantitative methods. Hence this research worked on closing this knowledge gap through the development of a nanotechnology-specific key technologies foresight model that uses MCDM techniques, a rational decision-making protocol based on quantitative and evidence-based data from nanotechnology publications.

2.4.3.4 Literature review

The most widely implemented technology foresight approach is a literature review (Popper 2008). It assists in surveying the environment and the generation of conceptions that guide the foresight exercise. It produces descriptive reports structured around themes for foresight. It is often carried out by experts in the field who analyse pertinent books, journal articles, news, and websites to identify trends and their possible implications.

2.4.3.5 Expert opinion

Expert opinion methods are achieved through intensive consultation with subject matter experts from all key stakeholders. Expert opinion solicitation can be done through face-to-face meetings such as focus groups, technology road mapping sessions, strategic planning sessions, or anonymous surveys. In these expert opinion methods, a group consensus must be reached.

According to Shen *et al.* (2010), expert group-decision-making suffers from specious persuasion, indifference to authority, reluctance to modify publicised opinions and bandwagon effects. Another potential drawback of face-to-face meetings is that the most vocal and persuasive participants may have an undue influence on the results. A fundamental shortcoming of relying on expert opinion is the fact that humans suffer from bounded rationality (Ronde, 2003). Experts are bound in their rationality due to varying degrees of expertise, limits to the amount of information, the cognitive limitations of the mind, among other issues. As a result, experts like any other human may use heuristics and rules of thumb, particularly in complex decision problems like technology foresight, resulting in biased judgments and sub-optimal decisions (Turpin, 2004). This view is shared by Heraud and Cuhls (1999), who added that there could be a serious problem if one anticipates finding ‘‘the future’’ in the thought processes and perceptions of a few selected experts.

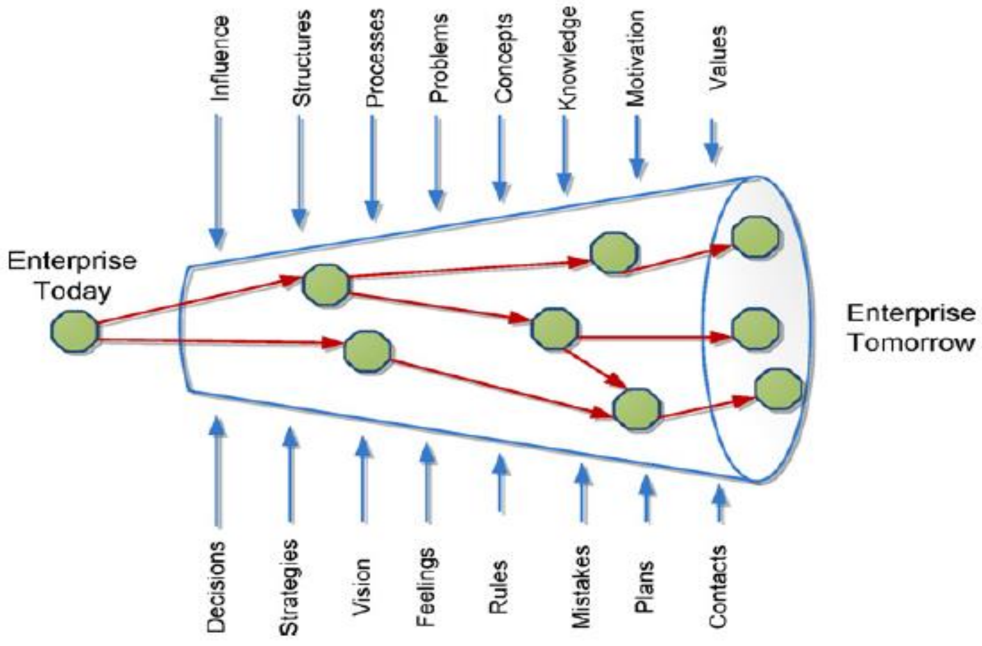
Those who support expert option methods argue that foresight exercises have much broader benefits that include networking, awareness building, and idea-sharing, which they claim are more important than the foresight exercise itself (Salo, Gustafsson and Ramakrishnan, 2003; Porter *et al.*, 2004). In addition, Martin (2001) adds that interactive foresight exercises create a glue and wiring system that holds the National System of Innovation together by facilitating a platform that facilitates the creation of a social contract among the participants and an understanding of the future science priorities, including where and how each stakeholder can contribute.

2.4.3.6 Delphi

To try and address the problems mentioned above with the expert option methods, foresight planners use group decision support systems such as the Delphi method (Porter, 2010; Martino, 1993; Porter *et al.*, 2004). Literature shows that the Delphi, with various adjustments, such as fuzzy-Delphi, is now among the most popular and commonly used technology foresight methods (Ronde, 2003**;** Salerno, Landoni and Verganti, 2008**;** Martin, 2001**;** Sasikumar and Mohan, 2014)**.** The Delphi method brings in the anonymity of responses. However, Shen et al. (2010) contend that, while the Delphi approach allows for comprehensive integration of various experts' viewpoints, it requires a lot of time, is expensive, and has low survey return rate since it attempts to get convergent findings using repeated surveys. Popper (2008) adds that Delphi suffers from senior experts’ bias as they rate their own research higher and do not change direction in view of mainstream answers. Over and above this, expert opinions are still affected by bounded rationality, are at times subjective and ambiguous.

2.4.3.7 Scenario planning

A scenario in strategic planning is defined as a potential event or combination of events that could be relevant to the organisation’s future due to risks or opportunities it may present (Amer *et al.*, 2013). Scenarios are alternate imaginary future possibilities that may act as a guideline for planning for the future. In developing a possible scenario, one considers diverse viewpoints on the historical, current, and emerging trends (van Notten, 2005). Figure 2.10 below depicts the scenario generation process of interconnected events.



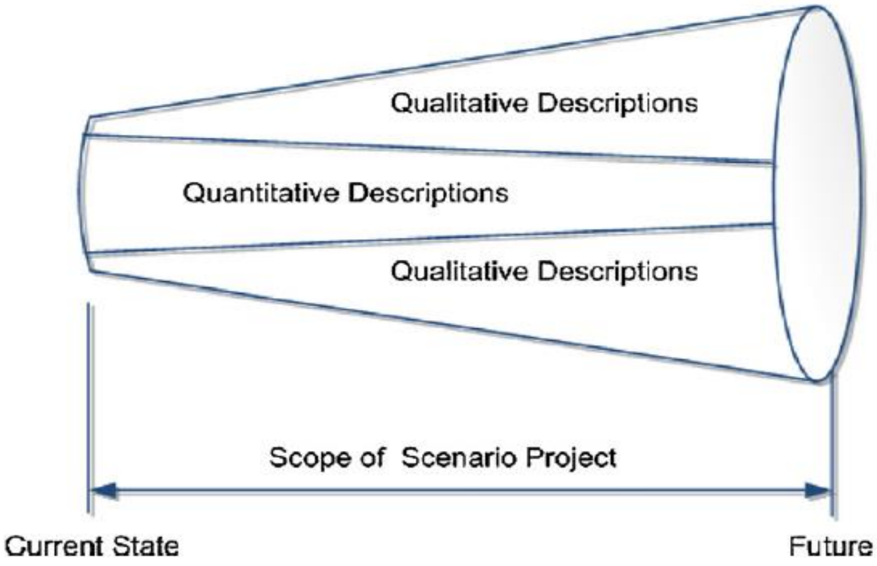
Source: (Amer *et al.*, 2013)

Figure 2.10: Scenario planning process

In technology foresight, scenario planning can generate possible futures and evaluate how emerging technologies may evolve under certain possible future circumstances.

(Drew, 2006). Scenario generation is a qualitative, expert-driven, and often interactive method of planning the future (Popper, 2008). Scenarios depend on creativity, artistic and storytelling expertise. Hence, researchers argue that this is one of the reasons scenarios are widely used because foresight and strategic planning are by nature about imagining and creating what the future holds (Popper, 2008; Drew, 2006).

In some cases, some tools are utilised to change scenario planning from a purely qualitative to a semi-quantitative process. Despite using various tools to make scenario planning semi-quantitative, scenario analysis remains a qualitative and entirely subjective discipline. Quantitative scenario approaches are suited to limited scope foresight across a shorter time horizon, whereas qualitative methods are suited to a longer time horizon. As illustrated in Figure 2.11, the utility of quantitative-scenario planning approaches decreases as one projects more and more into the future (Amer et al., 2013).



Source: (Amer *et al.*, 2013)

Figure 2.11: Scenario planning primarily a qualitative process

Although scenario planning is prevalent and has become a de-facto approach to foresight and strategic planning, it still suffers from several constraints (Mietzner and Reger, 2005; Amer, Daim and Jetter, 2013; Popper, 2008). The main disadvantages of scenario planning arise from its qualitative nature and the need for an expert opinion to have a firm understanding of the subject of research. Therefore, scenarios planning depend on getting groups of experts in the field under study; hence it also suffers similar limitations to expert opinion. The second problem is the restriction on the number of alternatives that can be adequately analysed. Due to limited human rationality and intellectual limits, as well as financial and time restrictions, scenario planning specialists advise limiting the number of scenarios to a minimum of two and a maximum of four. The cost of drafting five and above scenarios is very high and not justifiable (Drew, 2006; Amer, Daim and Jetter, 2013;). Lastly, scenarios generation is expensive and time-consuming as one has to develop detailed accounts and descriptions on how various scenarios may arise and be responded to (Mietzner and Reger, 2005).

2.4.3.8 Monitoring and intelligence foresight methods

Another widely used foresight method is monitoring and intelligence (Sasikumar and Mohan, 2014; Porter *et al.*, 2004; Firat, Woon and Madnick, 2008; Intepe, Bozdag and Koc, 2013). The set of methods in this group is based on the assumption that technology progress frequently follows a predictable series of milestones. A typical innovation process might start with basic research resulting in scientific findings and inventions, then laboratory feasibility, prototype and finally commercialisation. Using techniques such as scanning to identify and monitor any trends, it may be possible to predict when inventions and scientific discoveries are ready for commercialisation.

2.4.3.9 Key technologies / critical-technologies foresight methods

Foresight exercises have several aims like building consensus, wiring up the NSI, awareness building, determining a list of key/critical technologies or a combination of these. This research's primary goal is developing a nanotechnology-specific foresight method to identify and determine a list of key nanotechnology research areas in which a country must focus and concentrate. Hence more emphasis is given to reviewing key technologies techniques.

Due to the limited resources for R&D, countries or industries cannot invest in every possible area of research (Klusacek, 2004). Key-technologies foresight, which is sometimes referred to as the critical-technologies foresight method, is utilised by policymakers in government and industry managers as a planning tool for identifying priority research areas. Several countries, for example, the USA (Wagner and Popper, 2003), Russia (Grebenyuk and Shashnov, 2012), France (Durand, 2005) and the UK (Keenan, 2003), among others, have regularly undertaken key technologies foresight exercises. These countries carry out critical technology foresight exercises to identify and determine R&D areas that maximize the public benefit of limited public funds. As a result, it is envisaged that chosen critical technologies would bring economic benefits and address societal requirements (Klusacek, 2004).

According to literature (Klusacek, 2004; Durand, 2005; Grebenyuk and Shashnov, 2012), at the national level, key technologies must satisfy the five characteristics listed below:

1. **Policy-relevant** – that is aligned with the country's socio-economic goals,
2. **Distinct** - one must be able to distinguish between critical and non-critical technologies,

3. **Reproducible** - the used method should be transparent such that those not participating can reproduce the list,
4. **Generic in nature** - their exploitation should benefit the broader economy and society, and
5. **Emerging technologies** - their research should have been well advanced such that it will be ready within 5 – 20 years.

The critical technologies foresight process typically follows six stages, as shown in Figure 2.12 below. The initial stage is to define the goals of the foresight exercise. The second step is determining the criteria and approach for assessing the criticality of technologies, then assembling the team. The initial list of technologies can be identified from past foresight exercises, literature review, brainstorming sessions, discussions in expert panels, bibliographic and scientometric studies etc.

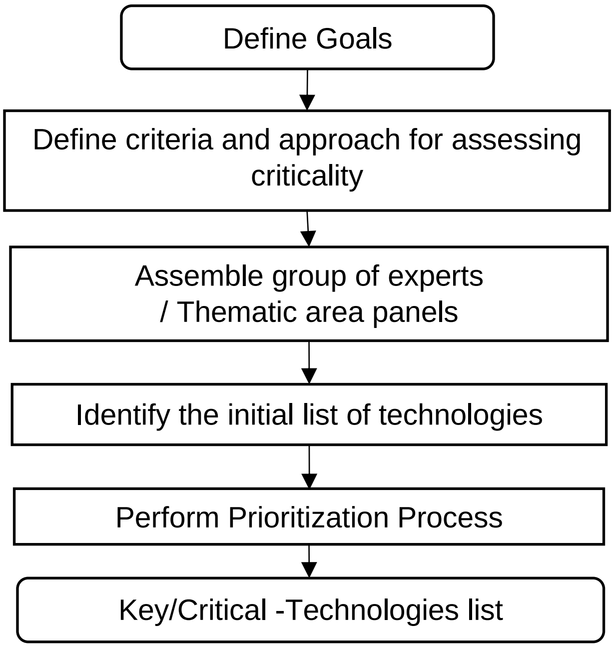
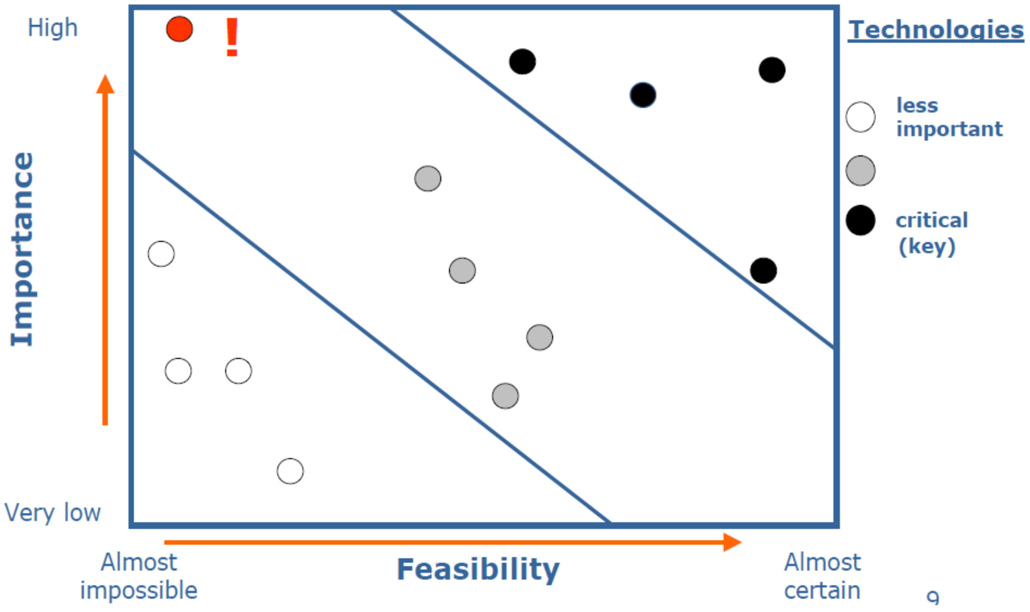


Figure 2.12: Typical key technologies foresight steps

Once the foresight goals are defined, the next step is to define the criteria that are used in assessing the criticality of identified research alternatives. The most frequently used approach is to categorise all identified criteria into two categories of (1) attractiveness or importance on one side and (2) feasibility or likelihood on the other hand (Klusacek, 2004; Durand, 2005; Grebenyuk and Shashnov, 2012). Usually, market-related factors are ranked under attractiveness, and R&D advances are evaluated under feasibility.

Prioritisation is perceived as the most challenging and risky step of the critical technologies foresight exercise (Keenan, 2003) since prioritisation removes most technologies on the initial list. At this stage, in participants' eyes, their research areas are now either “winners” or the “losers”. When expert panels are used, this is the stage where intense lobbying takes place, and results may be compromised. The most widely used approach (Keenan, 2003) to critical technologies prioritisation is to determine attractiveness/importance and feasibility/likelihood parameters for each research area/technology on the initial list. Then the scores are plotted on a scatter plot as shown below in Figure 2.13. Research fields that score well on both metrics are chosen for the key technologies final list. The disadvantage with this scatter plot method is that there is no clear-cut ranking of the alternatives. In addition, the cut-off limits for critical and non-critical are subjective and have to be decided by the planners.

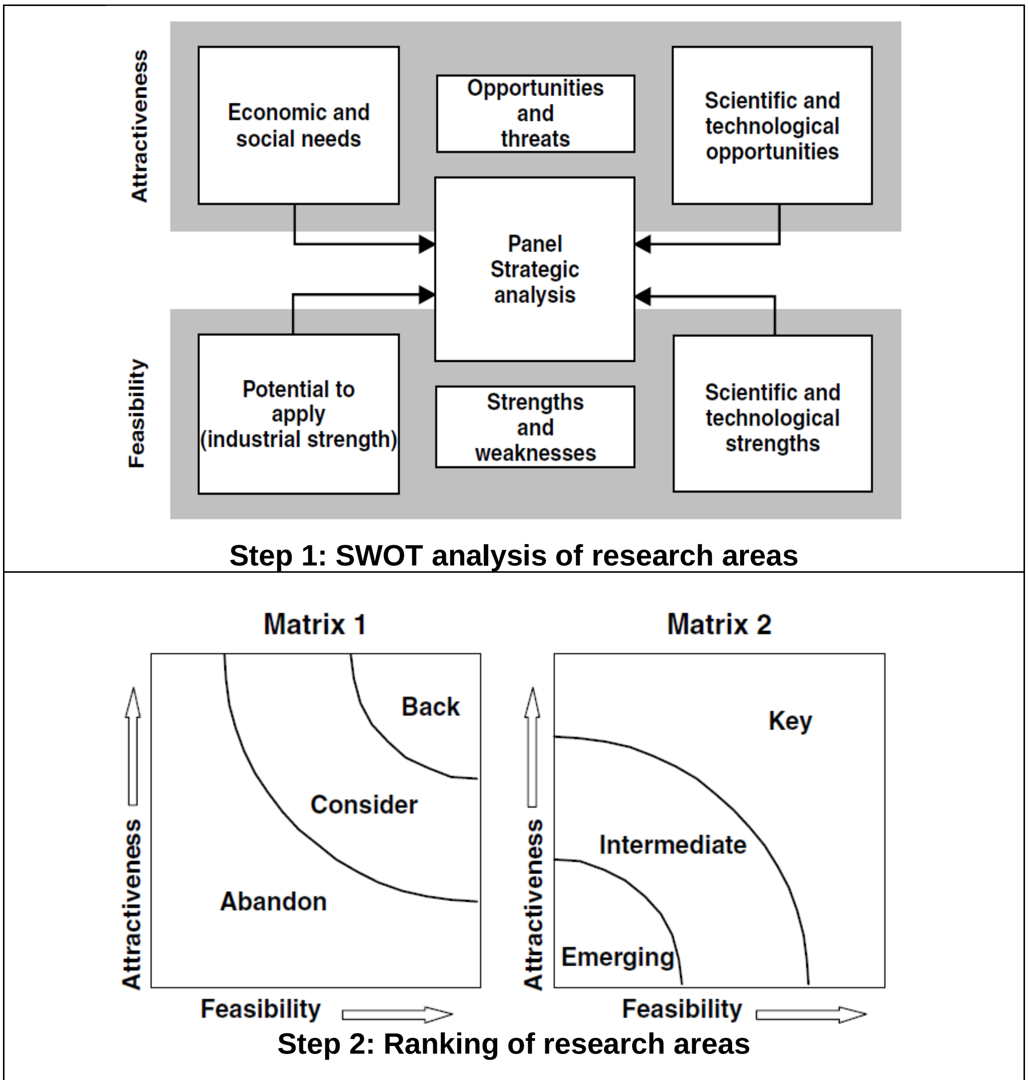


Source: (Keenan, 2003)

Figure 2.13: Typical prioritisation model for key technologies

Various adaptations of the two-dimensional assessment approach of attractiveness and feasibility are reported in the literature, for example UK, Australia, and the Czech Republic. In Australia's foresight exercise, the dimension of Technology Attractiveness was defined by the product of ‘scores’ for two ‘criteria’, namely ‘potential benefits of the technology to the country’ and ‘ the country’s ability to exploit the benefits presented by that particular technology’. Research and innovation aptitude and capacity were used to assess feasibility. (Keenan, 2003).

A different approach was used in the United Kingdom, and Figure 2.14 shows the UK key technologies methodology.

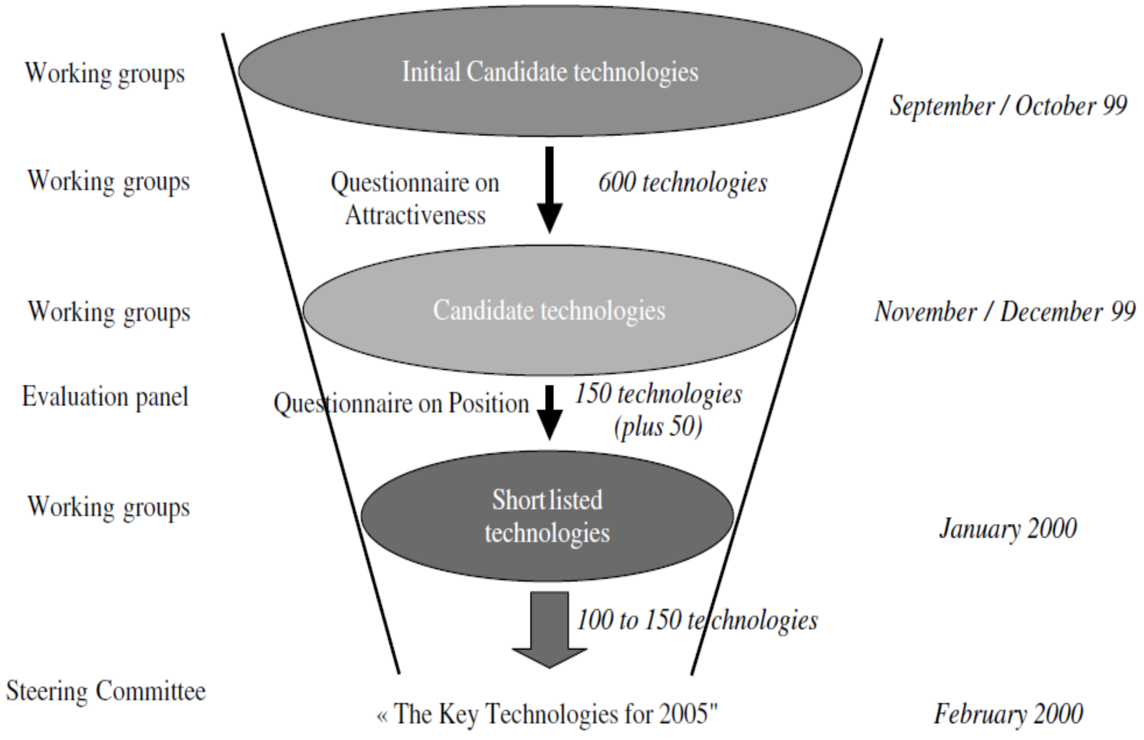


Source: (Keenan, 2003)

Figure 2.14: UK key technologies methodology

As shown in figure 2.14 above, a two-step process was followed in the UK. First, the Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis approach was carried out to classify attractiveness under opportunities and threats and then feasibility under strengths and weaknesses. The second step was to rank the research areas according to feasibility and attractiveness. Furthermore, the team expected that some criterion would be more significant than others and, as a result, must be given more weight. (Keenan, 2003).

On the other hand, the French key technologies process (Durand, 2005) followed a funnelling approach. It was decided to stay away from weighting factors as this was felt to be too mechanistic. Figure 2.15 below shows the French key technologies foresight method.



Source: (Durand, 2005)

Figure 2.15: French key technologies foresight funnelling model methodology

As shown in Figure 2.15 above, the first step was to select technology items for their intrinsic attractiveness. The second selection round was carried out by checking the fit between the pre-selected items and economic needs (Durand, 2005).

In Russia, the key technologies process (Grebenyuk and Shashnov, 2012) had priority areas and critical technologies within the critical area, which increased the level of focus of the process, e.g. in nanotechnology, the following key-areas were found; materials modelling, manufacturing and construction nanomaterials.

Economic push factors forced the USA to start looking at critical technologies foresight because, during the 1970s and 1980s, the US was losing trade competitiveness to Japan and Germany (Wagner and Popper, 2003). The government then passed legislation that required that a panel be convened consisting of experts from the government and the private sector who would deliberate and determine the top thirty “national critical technologies” for the next five to ten-year period. No additional criteria were offered in the original legislation: determining what is ‘critical’ was left to the panel members. This was a costly exercise. The four reports cost the federal USA government between $250,000 and $300,000 to produce (Wagner and Popper, 2003).

2.4.3.10 Conclusions on current key technologies foresight methodologies

The following three major conclusions can be drawn from the review of key technologies methodologies discussed in the literature. Firstly, critical technology foresight exercises discussed in the literature USA (Wagner and Popper, 2003), Russia (Grebenyuk and Shashnov, 2012), France (Durand, 2005) and the UK (Keenan, 2003) are macro key technologies; none of them focused on a particular discipline. Hence, this research proposes a nanotechnology-specific critical-technology identification methodology, i.e., micro key technologies versus macro key technologies. Secondly, during the process of identifying key technologies, there is a need to establish some criteria that will determine the criticality of technologies. Traditionally these criteria and sub-criteria are grouped under aspects of attractiveness/importance on one hand and feasibility/likelihood on the other. Hence one can review the criteria identified for successful nanotech R&D in the

Nanotechnology Innovation Diamond and map it against the dimensions of attractiveness and feasibility, as shown in Table 2.3.

Table 2.3: Mapping nanotechnology CFS to attractiveness and feasibility

Nanotechnology Innovation Diamond success factor	**Attractiveness / Feasibility**
1. Availability of **R&D Skills** (scientist-entrepreneurs)	Feasibility
2. Availability of **multi and interdisciplinary** teams	Feasibility
3. Suitable and **conducive innovation environment**	Feasibility
4. Availability of innovation **clusters and agglomeration**	Attractiveness
5. Existing **Industry/Market hybridisation**	Attractiveness
6. Existing **Industry/Consumer needs and preference**	Attractiveness

Lastly, although key technologies identification is clearly a MCDM decision-making problem, as Keenan (2003) pointed out, several tough decisions must be taken, which frequently necessitates weighing competing and complementary factors. None of the critical technologies' foresight methodologies reviewed used MCDM to assign weights to criteria and score the system. Salo *et al*. (2003) also observed that in the foresight context the potential use of MCDM methods has not yet been thoroughly explored, and this is further corroborated by actual evidence from a study by Popper (2008) in which it was discovered that MCDM use in foresight exercises constituted only 1.2% of methods. As a result, there is a need to research the application of MCDM methods in critical technology foresight. The following section will review MCDM methods and their potential use in foresight exercises.

2.5 MCDM in technology foresight

Decision making is the process of finding alternative solutions to a problem, evaluating and making a choice between the alternative options based on a goal or some criteria (Fülöp, 2005). The complexity of decision making varies from simple decisions with one criterion and finite alternatives on the one hand to complex multidimensional problems with infinite criteria and infinite alternatives on the other hand. One has the classic optimisation problem for single criteria and finite alternatives problems. Complexity arises when there are multiple criteria and multiple alternatives. Such types of problems are termed "Multi-Attribute Decision-Making" (MADM) problems or "Multi-Criteria Decision Making" (MCDM) problems (Fülöp, 2001; Triantaphyllou *et al.*, 1998).

In R&D management, most decisions made by government policymakers fall under MCDM. For example, when identifying research priorities in nanotechnology, several aspects such as strengthening the national industry, improving global competitiveness, resolving national social developmental issues and addressing national future strategic critical skills are some of the goals taken into consideration (Martin, 2001; Science and Technology Japan, 2006). In addition, while trying to resolve these issues, governments also face a budgetary and humanitarian duty to ensure that scarce public funds are spent judiciously (OECD, 2013). Hence, government policymakers and foresight planners can potentially benefit from utilising MCDM in selecting areas in which to concentrate.

However, although MCDM presents an excellent technique for setting priorities in foresight, there are a few publications on the employment of MCDM in technology foresight (Popper 2008, Lee *et al*., 2006; Salo *et al*., 2003). The empirical evidence supports the underutilisation of MCDM in the foresight context. The few papers identified that discussed MCDM and technology foresight are summarised in Table 2.4.

Table 2.4: Research papers reporting on using MCDM in foresight

Authors and Paper Title	Considered problem
(Salo *et al.* 2003) "Multicriteria Methods for Technology"	• Presented the lack of use of MCDM in foresight, • Highlights benefits that MCDM as rational methods of decision making can bring to foresight concerning making the process transparent, rigorous, and evidence-based, • Notes the limitation that MCDM is strong in determining research priorities, which is only one of the foresight goals. Other goals such as networking and awareness-raising cannot be carried out using MCDM, and • Recommended the need for practical deployment of MCDM foresight exercises.
(Lee *et al.*, 2006) "On the R & D Priority Setting in Technology Foresight : a DEA and ANP Approach"	• Proposed a two-stage MCDM foresight model that uses data envelopment analysis (DEA) and analytic network process (ANP), • DEA is the proposed tool to identify efficient alternatives using the cost-benefit analysis model, • ANP was a proposed tool for ranking alternatives according to technology attractiveness and technology feasibility criteria, and • There is no mention of an empirical test of the model.
(Ondrus *et al.*, 2014) "A Foresight Support System Using MCDM Methods"	• Designed a computerised foresight support system combining two MCDM methods, ELECTRE 1 (ELimination Et Choice Translating REality) and Weighted Sum Method (WSM), • ELECTRE 1 was utilised in alternative selection while SWM in ranking alternatives, and • The model was technology-specific for mobile payment systems foresight and tested in Switzerland.
(Zolfani *et al.*, 2015)	• Present a model that uses Step-wise Weight Assessment Ratio Analysis (SWARA) to assess the weights of criteria used in technology foresight,

Authors and Paper Title	Considered problem
"Technology Foresight About R & D Projects Selection ; Application of SWARA Method at the Policy-Making Level"	- The paper reports on weight assignment results for technological merit, market attractiveness, risk, and regulatory issues in Iran, and - No further work is reported on testing the model on a foresight exercise beyond the weight assignment.

2.5.1 MCDM methods overview

MCDM methods can be traced back to rational models of decision making as characterised by axioms on how a 'rational' decision-maker would choose among competing alternatives in the face of multiple objectives (Salo *et al.*, 2003). There are numerous MCDM approaches that utilise mathematical models to aid decision-makers in choosing the best option from a set of alternatives. There are several ways to classify MCDM methods (Triantaphyllou and Shu, 1998; Salo *et al*., 2003; Fülöp, 2001). For example, MCDM methods can be categorised on whether they are meant for a single decision-maker or several decision-makers in a group, whether they use the deterministic, stochastics or fuzzy approach, and, finally, on whether they are utility-based models, outranking methods, or goal methods.

Table 2.5 below summarises the MCDM methods and their respective advantages and disadvantages.

Table 2.5: MCDM methods, their advantages and disadvantages

MCDM Methods	Advantages	Disadvantages
Weighted Sum Model (WSM)	• Strong in single-dimensional problems.	• The difficulty emerges on multidimensional problems.
Weighted Product Model(WPM)	• It is dimensionless hence can work on multidimensional problems • Relative values are used rather than actual ones.	• No solution with equal weight of decision matrices.
Analytic hierarchy process (AHP)	• Flexible, intuitive and checks inconsistencies • The problem is constructed into a hierarchical structure; hence the importance of each element becomes clear. • Can use both subjective and objective evaluation measures	• A large number of pairwise comparisons are needed • Very difficult to distinguish scale. Sometimes, the decision-maker might find it tough to differentiate points on the 9−point pair-wise comparison scale.
TOPOSIS (Technique for Order of Preference by Similarity to Ideal Solution)	• It can be used for any number of attributes and criteria. • Easy to implement.	• Sometimes gives unreliable results. • Does not consider uncertainty in weightings.
PROMETHEE (Preference Ranking Organisation Method for Enrichment of Evaluations)	• PROMETHEE can simultaneously deal with quantitative criteria, and scores can be shown in their own units. • It requires a smaller number of inputs. • It is pretty easy to use.	• Suffers when a new alternative is introduced • It does not provide a chance to structure a decision problem. It is complicated when many criteria and options are available.

MCDM Methods	Advantages	Disadvantages
ELECTRE (ELimination Et Choice Translating REality)	• Its primary strength is that it considers uncertainty. • ELECTRE take qualitative and quantitative criteria.	• Time-consuming • It is tough to understand because of the idea used in finding the concordance and discordance matrices. • It is tough to translate subjective opinion into thresholds value. • ELECTRE process and the result can be hard to explain in layman's terms
Data envelopment analysis (DAE)	• Multiple inputs and outputs can be handled. • The relation between inputs and outputs are not necessary. • Comparisons are directly against peers 4. Inputs and outputs can have very different units	• Measurement error can cause significant problems • Absolute efficiency cannot be measured. • Statistical tests are not applicable. • Large problems can be demanding.

Adapted from Aruldos *et al*. (2013) and Samat *et al*.(2015).

The most widely used MCDM methods are the weighted sum method (WSM), the weighted product method (WPM), and the analytical-hierarchical process (AHP) (Triantaphyllou and Shu, 1998). The following section summarises these three methods in terms of the decision matrix **A** shown in Figure 2.16.

A multi-criteria decision making problem can be expressed as a ($M \times N$) decision matrix **A** in which element a_{ij} indicates the performance of alternative A_i when it is evaluated in terms of decision criterion C_j, (for i = 1,2, 3, M, and j = 1,2,3,..., N) (Triantaphyllou and Shu 1998). It is also assumed that the decision-maker has determined the weights of the relative performance of the decision criteria (denoted as W_j, for j = 1, 2, 3, ..., N). Figure 2.16 below illustrates the typical MCDM decision matrix.

	Criteria				
	C_1	C_2	C_3	...	C_N
Alternative	W_1	W_2	W_3	...	W_N
A_1	a_{11}	a_{12}	a_{13}	...	a_{1N}
A_2	a_{21}	a_{22}	a_{23}	...	a_{2N}
A_3	a_{31}	a_{32}	a_{33}	...	a_{3N}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_M	a_{M1}	a_{M2}	a_{M3}	...	a_{MN}

Figure 2.16: MCDM decision matrix A

Considering the decision matrix **A** the decision problem can be defined as follows:

a) Let ***A*** = {***A***i, for i = 1, 2, 3, ... M} be a finite set of decision alternatives

b) Let ***C*** = {***C***i, for j = 1, 2, 3, ..., N} a finite set of criteria/goals according to which the desirability of an action is judged.

c) Determine the optimal alternative A^* with the highest degree of desirability with respect to all relevant criteria/goals C_i.

Solving the MCDM problem basically involves four (4) steps. These four steps are termed the COWS (Criteria, Options, Weights and Scoring) approach summarised below.

- Step 1: Determine the relevant criteria (**C**riteria = C_j),
- Step 2: Determine the possible alternatives (**O**ptions = A_i),

- Step 3: Attaching numerical measures to the relative importance of the criteria and to the impacts of the options on these criteria (**W**eighting = W_j),
- Step 4: Process the numerical values to determine a ranking of each alternative (**S**coring).

2.5.1.1 Weighted sum method (WSM)

The WSM is probably the most well-known and commonly used approach, especially in single-dimensional problems. However, difficulty emerges when WSM is applied to multi-dimensional decision-making problems (Triantaphyllou and Shu, 1998). If there are *M* alternatives and *N* criteria, then the best alternative is the one that satisfies the following expression:

$$A_{WSM}^{*} = max_i \sum_{j=1}^{N} a_{ij} w_{j,} \ , for \ \ i = 1, 2, 3 \ldots., M \qquad (2.1)$$

where: A_{WSM}* is the WSM score of the best alternative for maximisation case, N is the number of decision criteria, a_{ij} is the actual value of the *i-th* alternative in terms of the *j-th* criterion, and W_j is the weight of importance of the *j*-th criterion.

2.5.1.2 Weighted product method (WPM)

When using the WPM, the best alternative is obtained by comparing the alternatives A_K and A_L, as given in the equation below:

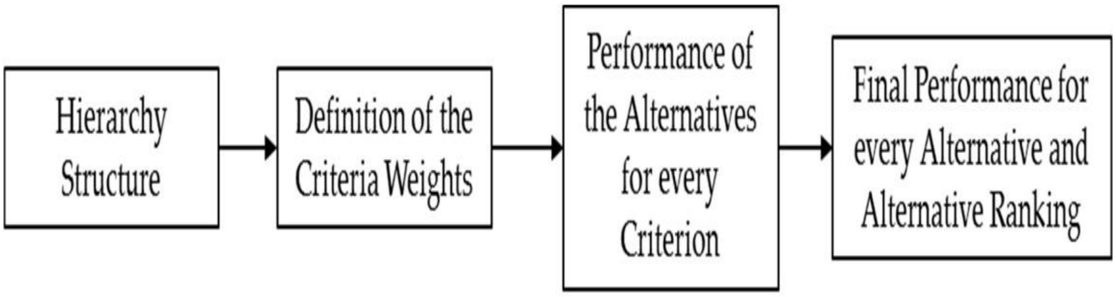
$$R\left(\frac{A_K}{A_L}\right) = \prod_{j=1}^{N} \left(\frac{a_{Kj}}{a_{Lj}}\right)^{W_j} \qquad (2.2)$$

where: N is the number of criteria, a_{ij} is the actual value of the *i-th* alternative in terms of the *j-th* criterion, and W_j is the weight of importance of the *j-th* criterion.

If the term $R\ (A_K / A_L)$ is greater than one, then alternative A_K is more desirable than alternative A_L in the maximisation case. The best alternative is the one that is better than or at least equal to all the other alternatives. The WPM is termed the dimensionless MCDM because it eliminates any units of measure. Hence WPM can be utilised for solving both one-dimensional and multi-dimensional problems.

2.5.1.3 Analytical-hierarchical process (AHP)

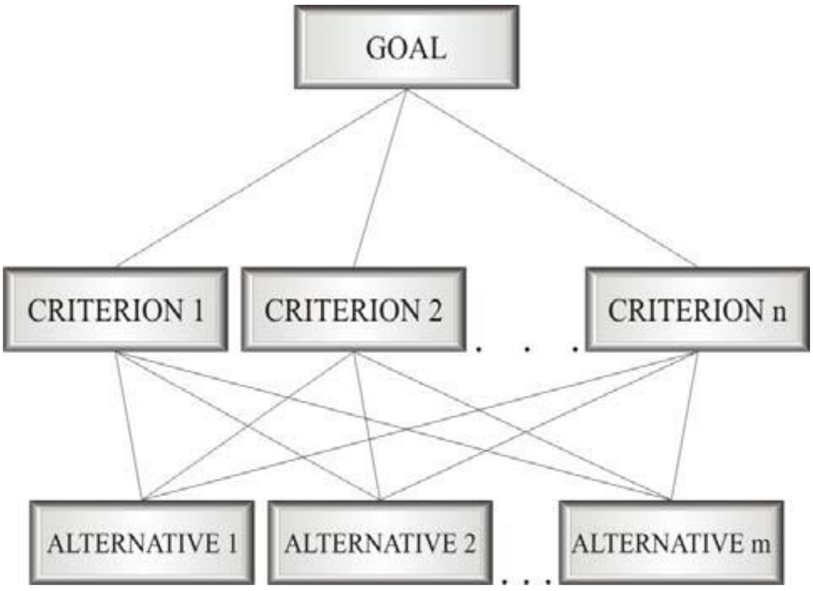
The analytic hierarchy process (AHP) was developed by Saaty (1980). It is based on decomposing a complex MCDM problem into a system of hierarchies. The AHP method has four steps, as shown in Figure 2.17.



Source: (Kolios *et al*., 2016)

Figure 2.17: Steps in AHP methodology

The first step is to structure the decision problem into a hierarchical structure. In the AHP hierarchy, the goal is at the top, followed on the next level by the criteria affecting the decision, then sub-criteria or sub-sub-criteria, etc. Finally, the alternatives are placed at the bottom of the hierarchy. The process of decomposing a problem using AHP is depicted in Figure 2.18.



Source: (Simunovic *et al*., 2009)

Figure 2.18: AHP hierarchical model with "n" criteria and "m" alternatives

AHP factor weights for each criterion are typically determined using the pairwise comparison method. A pairwise comparison matrix (*A*) or judgmental matrix is then constructed whereby entry in row *i* and column *j* of *A* (a_{ij}) represents how much more important criterion *i* is than *j* with respect to the alternative. Saaty (1980) proposed a pairwise comparison system for the quantification of qualitative data using a scale of relative importance. The available values for the pairwise comparisons are members of the set: {9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9} as shown in Table 2.6 below:

Table 2.6: Definition of pairwise comparisons

Equally important 1	Equally important 1/1
Equally or slightly more important 2	Equally or slightly less important 1/2
Slightly more important 3	Slightly less important 1/3
Slightly too much more important 4	Slightly to way less important 1/4
Much more important 5	Way less important 1/5
Much too far more important 6	Way too far less important 1/6
Far more important 7	Far less important 1/7
Far more important to extremely more important 8	Far less important to extremely less important 1/8
Extremely more important 9	Extremely less important 1/9

Source: (Saaty, 1980)

The weights of the individual criteria are calculated using the following two steps:

1. Create a normalised comparison matrix where each value in the matrix is divided by the sum of its column and then
2. Determine the weights *Wi* of the individual criteria by calculating the mean of each row of this second matrix.

Before the weights *Wi* can be used, a quality control check must be done through assessment of the consistency of the weights matrix using the equations below:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{i^{th} entry\ in\ the\ AW^{T}}{i^{th} in\ theW^{T}} \qquad (2.3)$$

where λ_{max} is the maximum Eigenvalue, A is the pairwise comparison matrix, and W is the weight vector.

The Consistency Index (CI) is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (2.4)$$

Where λ_{max} is the maximum Eigenvalue from the previous equation. The *CI* is then compared to the Random Index (RI) for the corresponding n-value. If $CI/RI > 0.10$, serious inconsistencies may exist, while if $CI/RI < 0.10$, the degree of consistency is considered satisfactory.

For AHP the best alternative (in the maximisation case) is the one that has the greatest value in the following expression:

$$AHP_{i-max}^{*} = max_i \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \times w_j \tag{2.5}$$

where AHP_{i-max}^{*} is the score of the i-th alternative, m is the number of alternatives, n is the number of the criteria, a_{ij} represents the actual value of the i-th alternative in terms of the *j-th criterion,* and w_j is the weight of importance of the j-th criterion.

2.5.2 Limitations of MCDM methods

In addition to method-specific disadvantages summarised in Table 2.5, the three generic limitations of MCDM methods which include data uncertainty, sensitivity to input data and the decision paradox are summarised in the following section.

2.5.2.1 Data estimation uncertainty

The fundamental difficulty with MCDM methods arises from the fact that decision-makers attempt to transform qualitative data into quantitative values, and this process is subjective, as it is difficult to accurately transform qualitative data into absolute quantitative values (Triantaphyllou *et al.*, 1998). Hence the weights of the criteria and the scoring of alternatives against these criteria always contain some level of uncertainty. This limitation is addressed by comparing the relative importance of alternatives in terms of each criterion using pairwise comparisons, but even in pairwise comparisons quantifying the linguistic choices remains a problem. Hence checking the consistency index of pairwise comparison tables is critical for the accuracy of MCDM methods (Shehabuddeen, Probert and Phaal, 2006; Triantaphyllou *et al.,* 1998; Saaty, 1980).

2.5.2.2 Sensitivity to input data

Closely related to data estimation uncertainty is the fact that when input data (i.e., the a_{ij} and w_j) are slightly changed into new values, the ranking of the alternatives might change significantly or not change at all. Therefore, sensitivity analysis must be performed on MCDM methods to determine how the ranking of the options might change when input data (i.e., the a_{ij} and w_j) are changed in various intervals. One needs to determine the intervals of the weights and scores within which the final ranking of the alternatives changes and does not change, therefore determining the intervals in which the weights and scores are allowed to vary (Fülöp, 2005; Shehabuddeen, Probert and Phaal, 2006).

Triantaphyllou *et al*. (1998) argue that sensitivity analysis in MCDM problems is too fundamental to be ignored. Several scholars demonstrated various methodologies for carrying out a sensitivity analysis of MCDM models on the input parameters. For example, Mészáros and Rapcsák (1996) proposed a general sensitivity analysis methodology for a broad class of MCDM models, while Triantaphyllou and Sanchez (1997) proposed a unified approach for sensitivity analysis for WSM, WPM, AHP, and RAHP.

2.5.2.3 MCDM decision paradox

The MCDM paradox arises from observing that MCDM methods recommend completely different the best alternatives for precisely the same set of alternatives and criteria. This should not be the case because whatever MCDM technique is selected, the best choice must remain the same. In their research, Triantaphyllou and Mann

(1989) observed that the AHP method was the most efficient MCDM method. They concluded that AHP is accurate in both single and multidimensional problems and does not suffer from the decision paradox problem. Further study (Kolios et al., 2016) backs this conclusion, indicating that the AHP is the most efficient approach when benchmarked to the WSM as a basic MCDM standard.

2.5.3 Conclusion on MCDM and foresight

This section covered the review of MCDM methods and the benefits that MCDM as rational methods of decision making can bring to foresight concerning making the process transparent, rigorous and evidence-based. The AHP presents several advantages that make it a favourable candidate for foresight exercises. These advantages include the aspects that the problem can be decomposed into a decision hierarchy, it has quality control through the consistency index, it can work with multidimensional problems, and research shows that AHP is the most efficient MCDM method. The nanotechnology foresight problem under discussion can be decomposed into an AHP where the goal to identify critical technologies is at the top, and the Nanotechnology Innovation Diamond CSFs are the criterion in the AHP model.

2.6 Scientometrics in technology foresight

This section gives an overview of scientometrics and its uses in evaluating research, development and innovation.

2.6.1 Scientometrics studies and the assessment of research and innovation

Scientometrics is the study of scientific research, development and innovation performance using publications such as academic articles, patents, and government policy documents (Jacobs, 2010; Leydesdorff and Milojevic, 2012). Scientometrics is closely related to bibliometrics. The field of scientometrics is currently experiencing a strong surge in use and demand mainly due to the availability of publications and patent data banks such as Web of Science and the European Patents Office, among others (Zitt, 2006).

Traditionally, scientometrics has been utilised for assessing the R&D efficiency, productivity and performance of individual researchers, institutions, or countries. The use of publications and patents as matrices to evaluate R&D and innovation is justified by the fact that all scientific innovations originate in basic science research, which feeds applied sciences and technological disciplines. As demonstrated in Figure 2.19, scientometrics uses research journals to estimate R&D activities closer to basic science research. At the same time, patents' statistics reveal efforts related to applied research and commercialisation.

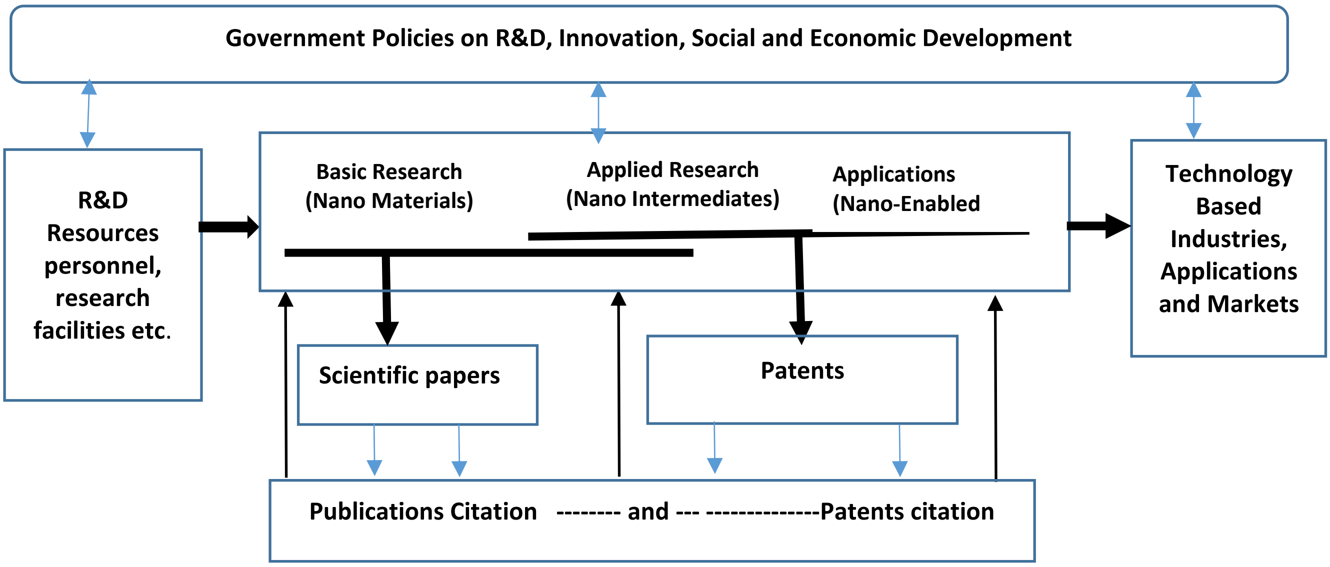


Figure 2.19: Scientometric indicators as intermediate measures of innovation

2.6.2 Scientometrics in nanotechnology evaluation

Several researchers have employed scientometric evaluations to examine nanoscience and nanotechnology in different countries (Marinova and McAleer, 2002; Hullman and Meyer, 2003; Islam and Miyazaki, 2010; Karpagam *et al*., 2011; Tanaka, 2013). Pouris (2007) examined nanotech research in South Africa using scientometrics. In addition, scientometric indicators data is combined with other statistics by the Organisation for Economic Co-operation and Development (OECD) to publish annual key nanotech indicators (OECD, 2015). However, few studies have utilised scientometrics to address nanotechnology foresight.

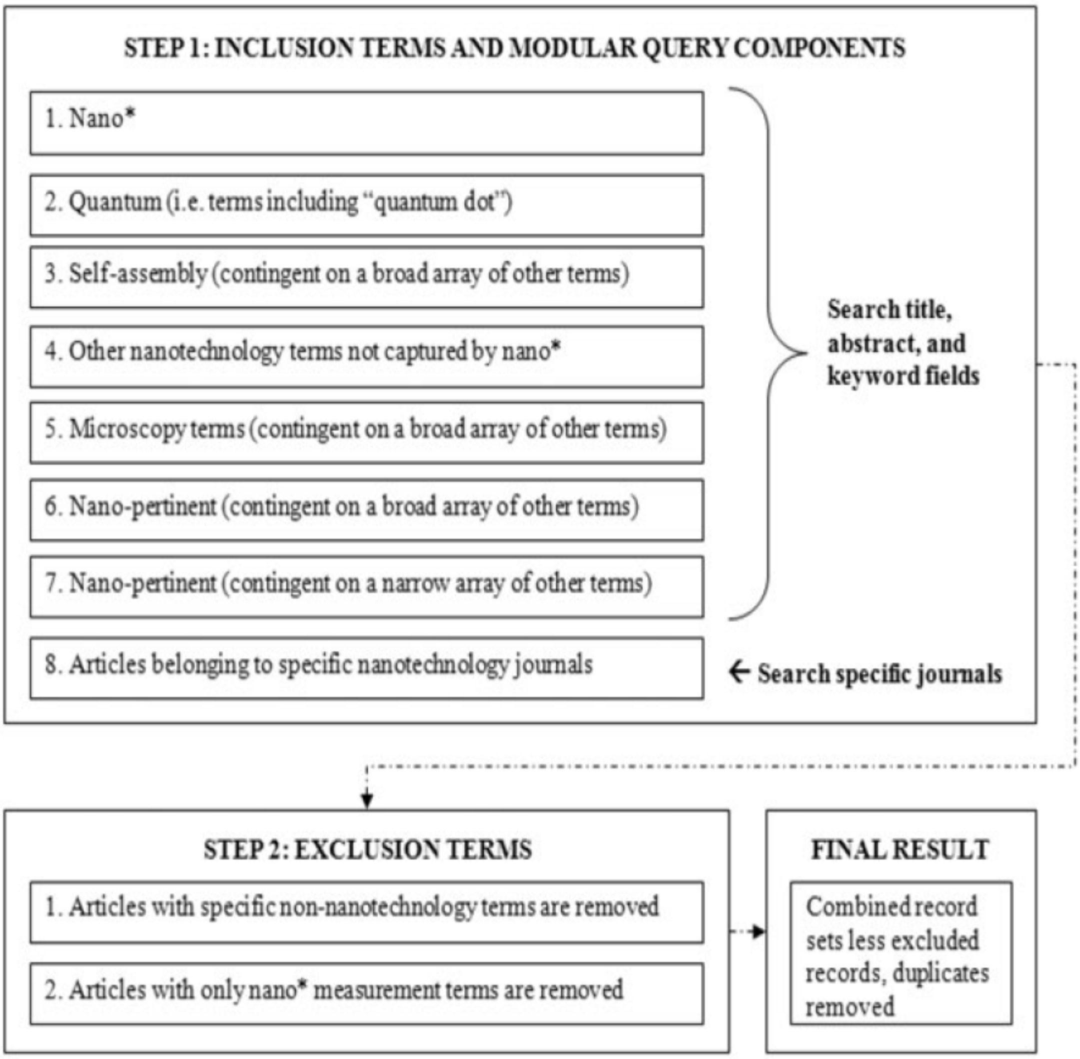
Scientometrics is a valuable foresight tool for technology foresight exercises (Popper, 2011). Several researchers recommend using scientometrics in nanotechnology foresight exercises (Streletskiy *et al.*, 2015; Salerno, Landoni and Verganti, 2008; Lee and Song, 2007; Santo *et al.*, 2006). One of the most important advantages of employing scientometrics in foresight is that it goes beyond the limitations and prejudices of experts, allowing the detection of facts and trends that would otherwise go unnoticed due to knowledge gaps or biased expert viewpoints.

2.6.3 Technology mining and scientometrics

Scientometrics has evolved to utilise tools such as technology-mining (tech-mining), a form of big data mining and analysis (Porter and Cunningham, 2005b). Technology-mining utilises big data techniques in analysing science and technology datasets to answer essential foresight and innovation management questions such as what research and development is being conducted in a specific technological sector, and the parties involved, towards what market objectives and what are the prospects for successful commercialisation, among other pertinent questions.

The foresight-oriented tech-mining process begins with developing a search query or strategy to extract relevant documents for analysis. An accurate search strategy is crucial in the scientometric analysis because it determines the quality and quantity of records that one can retrieve from bibliometric databases (Mikova and Sokolova, 2014). For example, when searching for nanotechnology-related documents, one can use the search term nano*, where the wild card* represents any word. However, such a strategy may result in recalling many documents, but some may not be related to nanotechnology, for example, nanosecond, nanosatellite, $NaNO_3$ – sodium nitrate compound, among others. A search query enables one to delineate the boundaries of the field of interest, balancing precision and recall. A high recall demonstrates that a search strategy retrieves most of the relevant documents if not all. In contrast, precision indicates the number of genuinely relevant records retrieved by the search query. (Arora *et al.*, 2013; Zitt, 2006; Vishal Gupta, 2009).

For nanotechnology, Porter et al. (2008) devised a modularized Boolean search protocol widely used in searching publications and patent data banks to retrieve nanotechnology research documents (Porter *et al.*, 2008). An outline of the strategy, which was improved by Arora *et al*. (2013), is shown in Figure 2.20.



Source: (Arora *et al.*, 2013)

Figure 2.20: Overview of the nanotechnology documents search query

2.6.4 Identifying technology alternatives from documents

Several sources of information can be utilised to identify research areas for consideration in technology foresight. Possible sources of information include patents, publications, government policy documents and experts' opinions. When documents are used as data sources, they often have information that overlaps. For example, publications in nanotechnology may have an article on the synthesis of carbon nanotubes whose technological application can belong to nanophotonics, nanomaterials, or nanosensors. To uncover alternate study areas, one must first classify and categorise relevant research together. Unfortunately, because nanotech research is still a new field, there is no widely accessible database or system for categorising nanoscience study fields (Tanaka, 2013).

Two approaches have been broadly utilised to achieve research area categorisation. These are Technology Clustering Analysis (TCA) (Lee and Song, 2007) and the patent co-citation approach (PCA) (Shen *et al.*, 2010). Lists generated from TCA and PCA require nanotechnology experts to name the possible research areas implicit in these generated lists. This can be improved by designing a standard categorisation/classification system for nanotechnology patents and publications, where information retrieved from publication databases can be automatically populated into research areas. Web of Science analytics provides a research area categorisation system; however, this is too broad for use in identifying nanotechnology research areas.

2.6.5 Scientometric indicators

The fundamental scientometric analysis involves tabulating the size-dependent indicators and/or calculating normalised size-independent indicators. These indicators are evaluated per field, author, institution, or country. The most widely used indicators include the following:

1) Total number of publications/patents,
2) Total number of citations,

3) Total number of co-authored papers,
4) Total number of single-authored articles,
5) Total number of assigned patents,
6) Trend analysis of publications/patents per field for over-time,
7) Breakouts from the above lists, for example, top 10 areas in terms of number of papers or number of patents, the number of citations, etc.,
8) Co-occurrence and autocorrelation from above tables, for example, matrix of authors by authors to see who collaborates with whom to help uncover knowledge networks and clusters.

A crucial step in scientometric analysis is calculating size-independent metrics, such as field activity and citation ratios. The size-independent indicators from analysis of papers/publications in a country can be represented by a matrix shown in Figure 2.21 below with elements p_{ij}, where p_{ij} denotes the paper/patent scientometric indicator i, and relative papers/patents research area j. Examples of paper/patent scientometric indicators include the number of papers/patents, the number of patents assigned, the number of citations, etc. Examples of research areas represented by j in a field such as nanotechnology are nanoelectronics nanophotonics, nanomaterials, nanomedicine etc.

$$\begin{array}{cc|ccccc}
 & & \multicolumn{5}{l}{\textbf{Paper/Patent Indicator Criteria } i} \\
 & & i_1 & i_2 & i_3 & \dots & i_n \\
\hline
\textbf{Nano Research Area } j & j_1 & p_{11} & p_{21} & p_{31} & \dots & p_{n1} \\
 & j_2 & p_{12} & P_{22} & p_{32} & \dots & p_{n2} \\
 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
 & j_m & p_{1m} & p_{2m} & p_{3m} & \dots & p_{nm}
\end{array}$$

Figure 2.21: Scientometric indicators matrix

The activity ratio/index, which is a measure of the ratio of how much a subsector j, holds patents or produces papers versus other sectors within a country, can be calculated using the equation below:

$$SS_{ij} = \left(p_{ij} \Big/ \sum_{j=1}^{m} p_{ij} \right) \tag{2.6}$$

Where,

- i is the number of patents/papers,
- p_{ij} denotes the total count of patents (e.g., nanomaterials) that belong to the nanotech subsector j,
- the higher the value of, SS_{ij} the more significant the relative country specialisation in nanotech sub-sector j

The citation ratio, which represents the quality of papers/patents produced, can be estimated by the following equation:

$$\mathrm{CR_j} = \mathrm{C_j} \Big/ \sum_{\mathrm{j=1}}^{\mathrm{m}} \mathrm{p_{ij}} \tag{2.7}$$

Where,

- i is the number of citations per paper/patent,
- C_j denotes the number of citations for all patents in sector j,
- $\sum_j p_{ij}$ is the total number of patents in nanotechnology for the country under analysis.

2.6.5.1 Publication analysis

Scientific publications reflect research activity, and they are traditionally used to evaluate productivity. The advantages and limitations of scientometric indicators derived from publications are shown in Table 2.7. Publications can be used to deduce such measures as a country's areas of competency relative to another by comparing the total number of publications (TNP) in a given area. Analysis of publications by institution, country or research area can also reveal clusters of activity showing areas of high productivity. Furthermore, Subramanayam's formula (Subramanyam, 1983) can be used to determine the extent or degree of collaboration, which indicates that the degree of collaboration C is a ratio of the number of multi-authored publications (NM) to the number of multi-authored articles (NM) + single-authored articles (NS).

$$C = \frac{NM}{NM + NS} \qquad (2.8)$$

where,

- NM = number of multi-authored papers
- NS = number of single-authored papers

Another metric used in publication analysis is the H-index. The H-index is a metric that measures the effectiveness of a researcher's research papers. It is a crucial scientometric indicator produced via publication analysis (Hirsch, 2005). Researchers, national R&D facilities and universities are now routinely evaluated using the H-index or its modified form, the five-year H-index, abbreviated as H5-index (Karpagam *et al.*, 2011).

Table 2.7: Advantages and disadvantages of scientometric indicators based on publications

Advantages	Disadvantages
1. Publications are closely linked to research activity. 2. They have been subject to peer review for quality control. 3. They span a wide variety of scientific fields. 4. Publication data are available as long time series. 5. They are publicly accessible at a low cost.	1. English-language dominates the primary data sources, i.e., publication databases as the mainstream outlets. 2. Targeted searches from different databases are cumbersome. 3. Data from scientific publications only cover the codified parts of scientific research. 4. Science research fields have different publication rate characteristics

Adapted from Palmberg, Denis and Miguet(2009)

2.6.5.2 Patent analysis

One of the critical cornerstones of any country's National System of Innovation (NSI) is intellectual property protection through patenting systems. Patents are an indicator of knowledge generation and can be utilised to predict the probability of an innovation being commercially exploited (Marinova and McAleer, 2002). Patent analysis supplies information for measuring and evaluating technological innovation performance of countries, industries or research disciplines. Patent analysis does not only help in assessing past performance. Ernst (1997) contends that patent analysis can also predict early trends in technological shifts. Hence, patent scientometrics can be utilised to select future technologies that are most likely to achieve market success and competitive advantage. The advantages and limitations of patent derived scientometric indicators are shown in Table 2.8.

Table 2.8: Advantages and disadvantages of patent data indicators

Advantages	**Disadvantages**
1. Inventions and patents are inextricably connected. 2. They cover a broad spectrum of technologies 3. The information of patent filings is a wealth of knowledge. 4. Patent data is accessible for time series analysis 5. Patent databases make them easily accessible.	1. Most patents never get used in practice; hence they are worthless 2. Many innovations are not patented either because they are not patentable, or innovators may utilise alternative methods to protect their inventions. 3. The tendency to patent varies by country, industry, and company. 4. Patent laws differ per country, making it difficult to compare. 5. Patent law changes over time make it difficult to track trends over time.

Adapted from Palmberg, Denis and Miguet (2009)

2.6.6 Conclusion on scientometrics and technology foresight

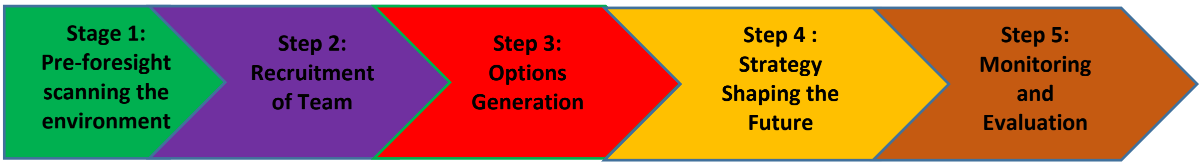
This section gave an overview of technology mining and scientometric analysis and their use in measuring science and technology. The section also summarised the merits and limitations of using patents and publications for science R&D evaluation.

2.7 Designing technology foresight exercises

This section first reviews the steps required in developing and carrying out foresight exercises, followed by a discussion on the factors to consider in designing foresight exercises. Finally, these factors are combined with nanotechnology characteristics to recommend a nanotechnology-specific key technologies foresight process.

2.7.1 The foresight process

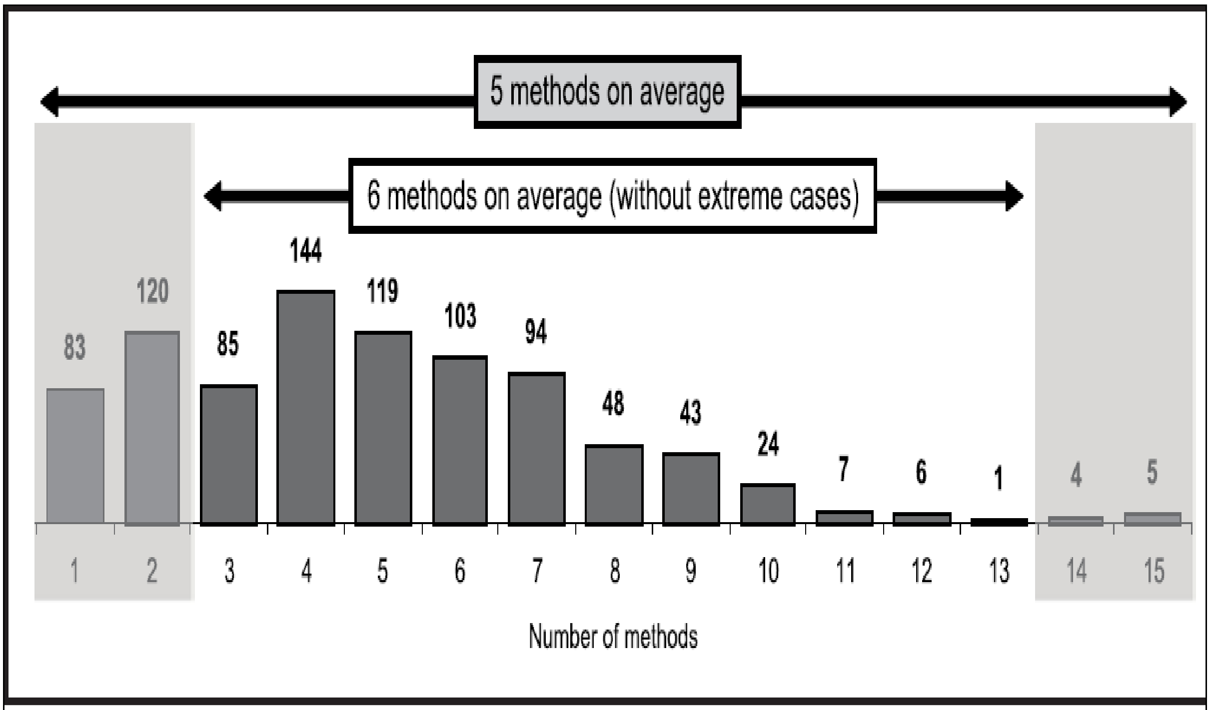
Any foresight exercise typically follows the steps shown in Figure 2.22 (Popper, 2008). The first step involves understanding the goals of the particular foresight exercise, given that foresight exercises can have several purposes. The second stage consists of identifying the expert skills required, the list of stakeholders, and then mobilising and engaging potential participants. The third and most crucial step of any foresight exercise is generating new knowledge, checking trends, and anticipating possible futures through the choice and combination of various foresight methods. The fourth step involves strategic planning, for example recommending a priority list of technologies and shaping the future using outputs from the generation phase.



Adopted from Popper (2008)

Figure 2.22: The foresight process

The generation phase is at the core of every foresight exercise. It is where documented information is evaluated and assimilated, tacit knowledge is acquired and contrasted to the knowledge base, and new insights and alternatives are developed (Popper, 2008). On the other hand, technology foresight exercises have several goals, and to achieve these several goals, a single foresight exercise can combine several methods. According to research done by Popper (2008), on average, a single foresight exercise combines five techniques, as shown in Figure 2.23.



Source: (Popper, 2008)

Figure 2.23: Distribution of methods combination per foresight exercise

This research focuses on how evidence-based, quantitative, and semi-quantitative methods can be combined to develop a robust nanotechnology-specific foresight model.

2.7.2 Factors to consider in foresight design and methods choice

When designing a foresight exercise, one cannot randomly pick methods from a basket. First and foremost, it must be noted that the choice and use of suitable foresight methods has a considerable impact on the quality of foresight (Mishra, Deshmukh and Vrat, 2002; Sasikumar and Mohan, 2014; Firat, Woon and Madnick, 2008; Salerno *et al*., 2008; Levary and Han, 1995; Firat, Woon and Madnick, 2008). Therefore, one needs to consider the characteristics of the particular technology under consideration. Hence the first step in any foresight method design is mapping the technology characteristics and possible foresight characteristics on a common scale (Mishra, Deshmukh and Vrat, 2002).

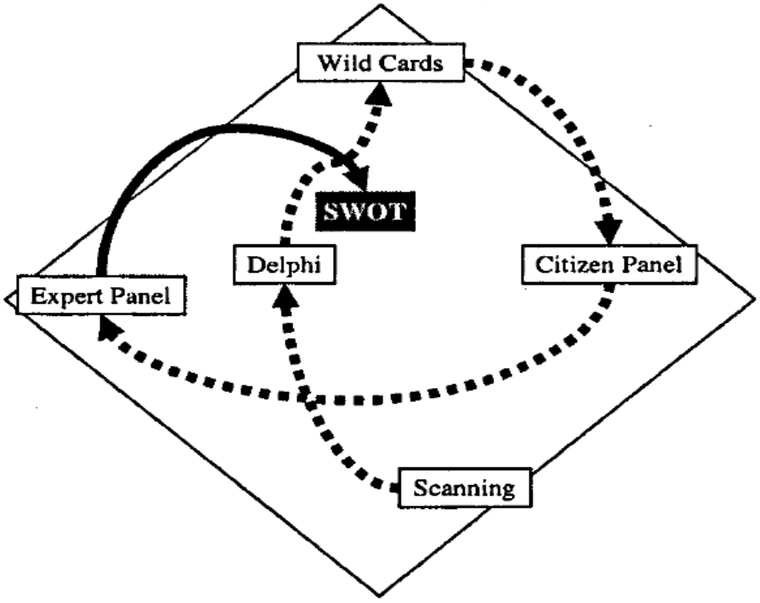
The second item to consider is the goal of the technology foresight exercise, whether it is product-oriented or process-oriented (Porter *et al.*, 2004; Firat, Woon and Madnick, 2008). Product-oriented goals of foresight aim to produce outputs such as priority lists, research area lists, or reports arguing the case for a particular innovation strategy. On the other hand, process-oriented is aimed at network building, awareness building, forming new alliances, and wiring up the national system of innovation. Porter (2010) notes that product and innovation-focused foresight exercises require deeper consideration of how socio-economic factors interact with new technology to produce socio-economic growth. Hence, methods such as modelling, environment scanning, key technologies, and MCDM are good candidates for product-oriented foresight. On the other hand, when conducting process-orientated foresight exercises, there is a need for methods that favour group interactions and networking, such as expert opinion, Delphi, scenarios-planning, and brainstorming sessions.

A third aspect to consider in technology foresight method design is the availability of quality data (Levary and Han, 1995; Firat, Woon and Madnick, 2008; Cheng, Chen and Chen, 2008). When there is little documented data available, a foresight strategy that relies on a team of experts is the best option. Trend analysis and statistical techniques are appropriate when dealing with medium to large volumes of high-quality documented data.

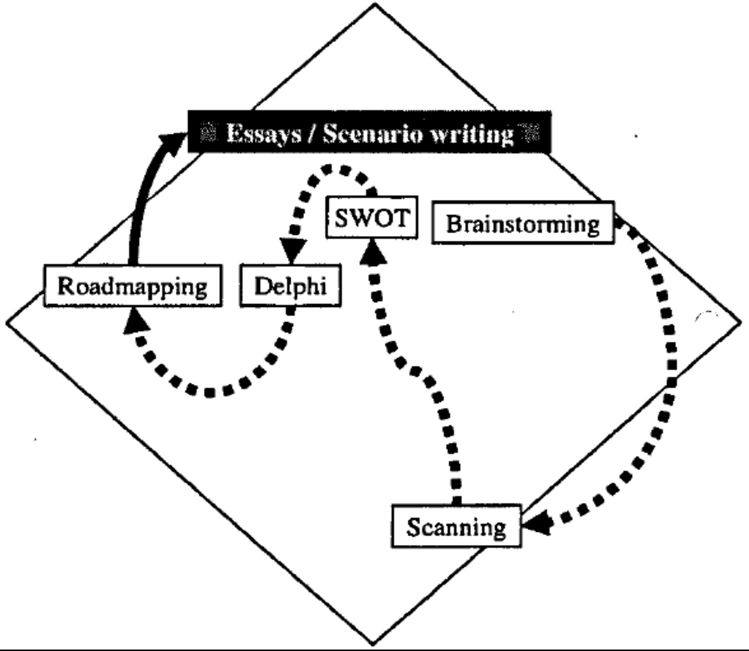
The fourth aspect to consider is technology development path predictability (Cheng *et al.*, 2008). A predictable development path means that monitoring and intelligence methods such as environmental scanning, scientometric analysis, and tracking experts in the field are suitable foresight methods. Lastly, the methods must consider ease of operation, adaptability and overall cost of developing and implementing the foresight (Intepe, Bozdag and Koc, 2013; Levary and Han, 1995; Cheng, Chen and Chen, 2008).

After considering the above guidelines, one finds that they may need to combine several methods in parallel or sequence to satisfy one foresight exercise's goals. In addition, when planning a foresight exercise, it is essential to evaluate the capabilities of the foresight team. Popper (2011) argues that one can produce several million combinations of methods to achieve a specific foresight exercise. For example, Figure 2.24 below shows a possible combination of techniques for a foresight exercise that is exploratory in nature. In this case, foresight planners want to start with past and present situations to develop a foresight for the future.

Explorative Foresight Possible Approach 1



Explorative Foresight Possible Approach 2



Source: (Popper, 2011)

Figure 2.24: Possible methods combinations for an explorative foresight exercise

Finally, Popper (2011) recommends three essential considerations to explore if one needs to produce novel technology foresight results that are beyond business as usual. Popper (2011) contends that, when designing foresight exercises, foresight practitioners need to move away from traditional popular foresight methods and must start to consider the following,

1. First, **consider less frequently** used methods, for example, undertake time-consuming and rigorous quantitative approaches such as multicriteria analysis, modelling and simulation,
2. **Improve prospective analysis** by using advanced data and text mining tools to analyse documents; statistical tools for network/cluster analysis and visualisation structures; co-word, co-authorship and co-citation methods to provide guidance as to new clusters of ideas in scientific areas, and
3. **Develop expert systems** to guide managers in evidence-based decision making during the foresight process.

2.7.3 Towards a nanotechnology-specific foresight model

Based on the characteristics of nanotechnology observed in the literature, the goals of this research (critical technologies foresight exercise) and factors to consider in foresight methods and design, a mapping is done in Table 2.9 below to determine a possible nanotechnology foresight process.

Table 2.9: Matching nanotechnology to factors in foresight design and methods selection

Foresight Design Factors	Nanotechnology Method Approach
A specific goal of the foresight exercise	1. This research aims to develop a foresight model to identify and select key research areas that will lead to successful innovations. Therefore, it is a product-oriented foresight exercise.
Technology specific characteristics	2. The Nanotechnology Innovation Diamond identified the crucial success factors for successful nanotechnology innovation. These factors present the basis for developing evaluation criteria for the nanotechnology research area alternatives.
Availability of quality data	3. There has been an exponential rise in nanotechnology publications and patents since the year 2000. Hence high-quality data is readily available. Therefore, patents and publications in nanotechnology present a suitable data source. 4. A quantitative statistical approach that uses advanced scientometrics is suitable since high-quality data is available in massive quantities.

Foresight Design Factors	Nanotechnology Method Approach
Technology development path predictability	5. Scientific innovation takes a systematic process from fundamental research inventions to applied research prototyping, patenting and commercialisation. Nanotechnology innovations development goes through the nanotechnology value chain that moves from nanomaterials to intermediary materials then nano-enabled products. Therefore, an environmental scanning of publications and patents will be suitable for identifying research stages and research areas with a high probability of success.
Stakeholders involvement	6. The realisation that nanotechnology is a GPT and it is multidisciplinary requires that the nanotech foresight method includes all science and technology disciplines, hence, a) the analysis of publications and patents must consist of all science, engineering, and technology disciplines, and b) identify all possible stakeholders and experts from across many possible disciplines involved in nanotechnology.
Consider less frequently used methods	7. The literature review showed that quantitative methods are less frequently used in technology foresight with MCDM accounting for only 1.2%. MCDM methods also hold potential regarding lending rigour, repeatability, and transparency to foresight processes. Hence MCDM is a suitable candidate for nanotechnology foresight.
Improve prospective analysis through advanced text mining tools	8. Given that there are vast amounts of publications on nanotechnology, technology-mining and scientometric analysis are good candidates for nanotechnology foresight. 9. The use of text mining software can also address cognitive limitations of the human mind, as a computer-based system can handle large amounts of data.

In conclusion to this section and drawing on the discussion in Table 2.10, four foresight methods can be combined in sequence as shown in Figure 2.25 to carry out a quantitative nanotechnology key technologies foresight. One can start with a literature review, followed by technology-mining and text analytics, then scientometric evaluations, and finally MCDM to rank the identified research areas.

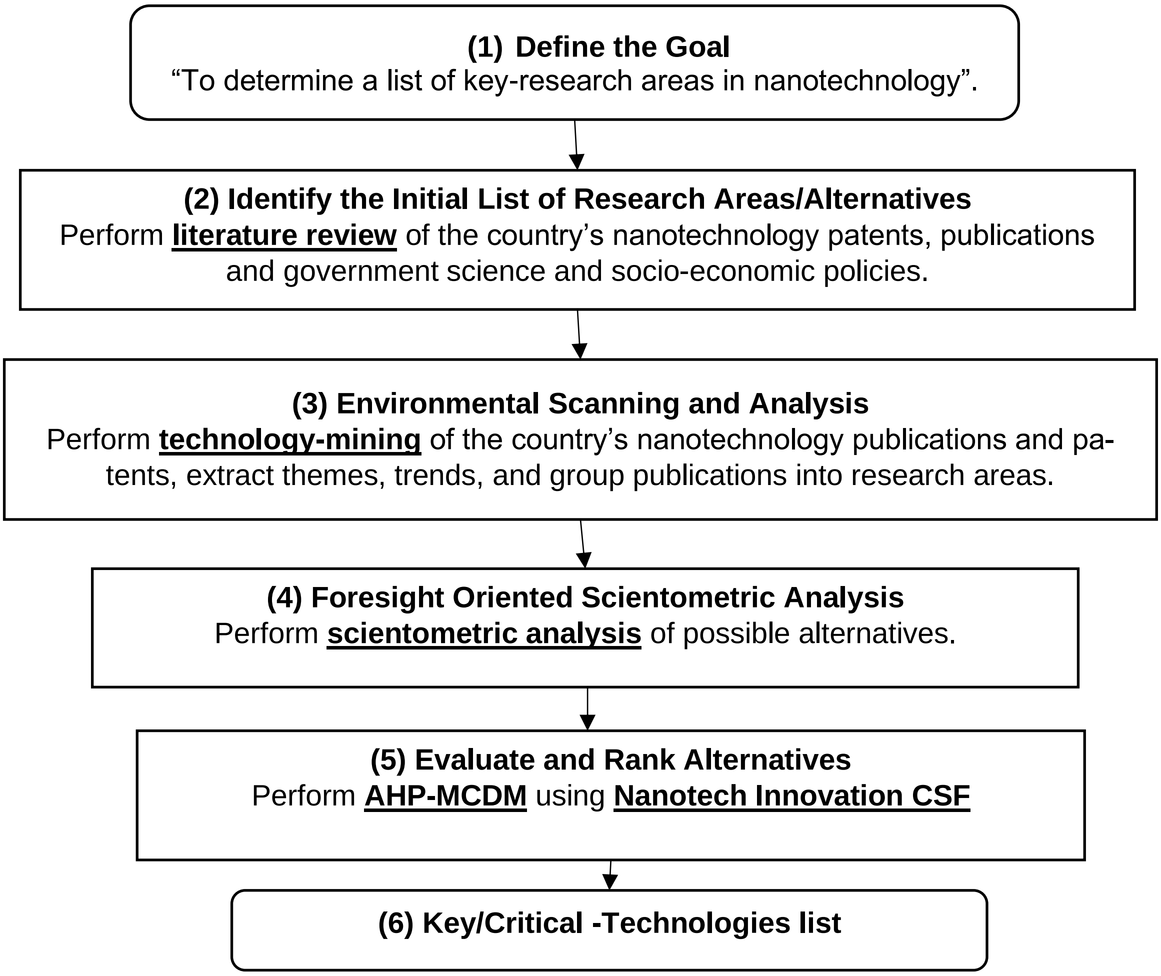


Figure 2.25: Nanotechnology specific foresight process

2.8 Conclusion to literature review

This chapter began by introducing the relevance of nanotechnology in socio-economic development and the exponential growth in nanotechnology research, followed by a summary of the need for a nanotech specific technology foresight method. Next, the knowledge gaps in the quest to develop a nanotechnology specific foresight method were discussed.

In order to develop a theoretical framework to identify nanotech winners early, the characteristics of nanotech R&D that leads to successful nanotechnology innovation were reviewed. Key highlights of this section include the need to view nanotechnology as a general-purpose technology, the nanotechnology value-chain that begins from nanomaterials to nano-enabled products, and then everything is concluded by the introduction of the proposed Nanotechnology Innovation Diamond. The Nanotechnology Innovation Diamond summarised the nanotechnology innovation critical success factors (CSF) deduced from literature. These CSF can be used to both manage successful nanotechnology R&D as well as criteria in identifying key research areas likely to be successful.

The following section reviewed technology foresight literature and the various approaches used in technology foresight. It was observed that quantitative methods and MCDM methods in particular are not frequently used in technology foresight. The main focus of this project is to develop a foresight model for determining key-strategic research areas in nanotechnology. Hence, the emphasis was placed on key technologies foresight approaches, whereby it was concluded that key technologies exercises must identify some criteria that will determine the criticality of technologies. According to reviewed literature, these criteria are traditionally grouped under aspects of attractiveness/importance on one hand and feasibility/likelihood on the other. Each technology's attractiveness/importance, and its feasibility/likelihood, are assessed during the prioritisation process. Technologies that score well in both dimensions are then selected for the final list of priority technologies. An attempt was made to map the critical success factors observed under the Nanotechnology Innovation Diamond into two categories of attractiveness and feasibility.

It was observed that even though critical technologies identification is clearly a MCDM decision making problem, whereby several difficult choices must be made, often requiring an assessment of opposing and synergistic criteria, none of the methodologies reviewed used MCDM in either assigning weights to criteria or technologies for ranking. Hence, there is a gap to investigate the use of MCDM in key technologies foresight exercises. Following the observation above, the next section was devoted to reviewing the use of MCDM methods, scientometrics and patent analysis as possible quantitative methods in nanotechnology foresight.

The last section reviews how foresight methods are designed, whereby one can combine several methods in sequence or parallel to achieve the foresight goal. The section is concluded by proposing specifications for a nanotechnology specific foresight method underpinned by the characteristics of nanotechnology observed in literature, goals of this research, literature on foresight methods and the recommendation by Popper (2011) that in order to produce novel ground-breaking foresight results, there is a need to consider using less frequently used methods such as MCDM, scientometrics, and advanced data and text mining techniques to enable one to gain new insights into new clusters of ideas in merging and disruptive scientific areas. The chapter is concluded by proposing a quantitative nanotechnology-specific key technologies foresight process that combines technology-mining, advanced scientometric and MCDM.

The next chapter, chapter 3, presents the research methodology and research design.

Chapter 3: Research Methodology

The previous chapter, chapter 2, reviewed the literature relevant to developing a nanotechnology specific foresight method. Chapter 2 identified the critical success factors for successful nanotechnology and proposed the Nanotechnology Innovation Diamond. Various approaches to technology foresight were also reviewed. The chapter was concluded by laying a foundation for a conceptual framework on how a nanotechnology foresight process can be developed using quantitative methods of foresight. This chapter outlines how the research process was carried out to validate the proposed Nanotechnology Innovation Diamond and develop the nanotechnology specific foresight model using a new conceptual framework developed by the researcher.

3.1 Introduction

The chapter starts by recapping the research problem and research questions. Next, the four steps and related activities followed in this research are presented. These are nanotechnology experts survey, technology-mining, scientometric analysis, and foresight model development using the analytical hierarchical process (AHP) multi-criteria decision making (MCDM) model.

The positivism / empirical realist epistemology of foresight was followed in developing the foresight model. Therefore, it is assumed that statistical data from the analysis of nanotechnology publications and government policies may be used to assess nanotechnology research performance against the nanotechnology innovation critical success factors (CSFs). Then, this data can be combined with AHP - MCDM to study the past and present state of nanoscience to determine the critical research areas in nanotechnology.

3.2 Purpose of the research

This section recaps the research problem, research aim, research questions, and objectives.

To the best of the researcher's knowledge, no effective technology foresight method exists for determining and ranking a country's key strategic research areas in nanotechnology.

Identifying and ranking strategic key-research areas in nanotechnology helps a country to cost-effectively utilise limited resources by focusing and concentrating resources on those nanotechnology research areas with the highest potential for bringing socioeconomic development, global competitiveness, and a positive return on investment.

This research aims to develop a nanotechnology-specific, Multi-Criteria Decision Making (MCDM) based foresight model that uses evidence-based and quantitative scientometric indicators from publications to identify and rank a country's key research areas in nanotechnology.

In order to develop the MCDM foresight model, the researcher had to answer five research questions and address their related objectives as listed in Table 3.1.

Table 3.1: Research questions and their respective objectives

Research Questions	Research Objectives
1. What are the Critical Success Factors (CSF) that promote nanotechnology research that results in successful innovations?	Establish the Critical Success Factors for successful innovation and technology transfer in nanotechnology and how they interact.
2. What are the relative weights of the identified CSF when used as criteria in Multi-Criteria Decision-Making models?	Estimate the numerical weights for identified criteria for successful nanotech innovations.
3. How does one categorise and characterise nanotechnology publications into nanotechnology research alternatives for a particular country?	Determine how to categorise the nanotechnology research areas and access their respective properties.
4. What scientometric indicators can measure CSF that promotes nanotechnology research that results in successful innovations?	Determine the set of scientometric indicators to measure CSF for nanotech research areas.
5. How can one develop a Multi-Criteria Decision-Making based foresight model for ranking a country’s strategic key-research areas in nanotechnology effectively?	Develop a MCDM based foresight model to effectively rank strategic key research areas in nanotechnology.

3.3 Research hypotheses

The first set of data to develop the foresight model was collected through the expert survey questionnaire. The data was used for the following:

1) Determining factor means of the critical success factors in SPSS and checking if there was any significant difference between the factor population means,
2) Validating the Nanotechnology Innovation Model using Confirmatory Factor Analysis (CFA), and
3) Determining the factor weights for use in the Multi-Criteria Decision Making (MCDM) foresight model from the optimised CFA model.

There were two hypotheses put forward in Chapter 2, as shown below:

Hypothesis 1: There is no statistical difference between the means of Nanotechnology Innovation Diamond's critical success factors.

H_o: $\mu_1 = \mu_2$ (the paired population means are equal for all six CSFs)

Alternate Hypothesis 1: There is a statistical difference between the means of Nanotechnology Innovation Diamond's critical success factors.

H_a: $\mu_1 \neq \mu_2$ (the paired population means are not equal for all six CSFs)

Hypothesis 1 was tested by using the SPSS Paired Samples t-Test at a 95% confidence level.

Null Hypothesis 2: The Nanotechnology Innovation Diamond's six crucial success factors are not statistically significant for successful nanotechnology research and development.

Alternate Hypothesis 2: The Nanotechnology Innovation Diamond's six crucial success factors are statistically significant for successful nanotechnology research and development.

Hypothesis 2 was tested by performing Confirmatory Factor Analysis (CFA) and then checking model fit indices, optimising the model and evaluating if all CSFs factors made a statistically significant contribution in the optimised model.

Once the CFA model was validated and optimised, the next activity was to determine the relative weights of the identified CSF when used as criteria in MCDM models.

3.4 Research design

Explanatory research's main objective is to describe why phenomena occur and to anticipate future events (Kothari, 2004; Jonker and Pennink, 2010). This study can be classified as explanatory because it aims to explain the key factors that promote nanotechnology research that leads to successful innovations. Secondly, the research seeks to develop a model to predict future occurrences of successful nanotechnology research that leads to innovation success.

Various strategies can be used to carry out explanatory research, and these include case studies, surveys, experiments, and archival records analysis (Creswell, 2014). According to Yin (2003), the most critical condition in deciding and selecting a suitable research strategy is by identifying the type of research questions being asked in the research. Table 3.2 below summarises the research strategy versus forms of research questions. Therefore, this research used the survey and archival records analysis strategies.

Table 3.2: Research situations and respective research strategies:

Strategy	Form of Research Question	Requires Control	Research Questions in this Study
1. Experiment	how, why?	Yes	
2. Survey	who, what, where, how-many, how-much?	No	1, 2 and 4
3. Archival Records Analysis	who, what, where, how-many, how-much?	Yes / No	3 and 5

Adapted from (Yin, 2003)

The plan of action for this research was achieved in four stages, which were:

- **Stage 1:** Experts' survey,
- **Stage 2**: Technology-mining of nanotechnology publications,
- **Stage 3**: Scientometric analysis of nanotechnology publications, and
- **Stage 4:** MCDM modelling combining AHP, nanotechnology CSF, and scientometrics.

Table 3.3 below links these four stages to their respective research objectives and research activities.

Table 3.3: Research process stages and related activities

Research Stage	Research Goal	Activities
Stage 1: Experts Survey	1. Determine the Critical Success Factors for successful innovation and technology transfer for nanotechnology.	1.1 Online experts' survey. 1.2 Confirmatory Factor Analysis of the Nanotechnology Innovation Diamond using survey results.
	2. Determine numerical weights for identified criteria for successful nanotech innovations.	2.1 CFA model analysis to calculate factor scores.
Stage 2: Technology-mining of nanotechnology publications	3. Determine the nanotechnology research categories and their respective properties.	3.1 Perform a literature review of publications and socio-economic policies to identify possible research areas. 3.2 Perform country technology mining publications and patents. 3.3 Develop a protocol for clustering related publications into research areas/alternatives. 3.4 Categorise papers according to the nanotechnology value chain. 3.5 Characterise the identified research areas regarding who is doing what research, where, and with who?

Research Stage	Research Goal	Activities
Stage 3: Scientometric analysis of nanotechnology publications	4. Determine the set of scientometric indicators to measure CSF for nanotech research areas.	4.1 Determine the scientometric indicator values for each paper. 4.2 Determine the overall scientometric score of each alternative per criteria (CSF)
Stage 4: MCDM modelling combining AHP, nanotechnology CSF, and scientometrics	5. Determine a MCDM based foresight model to rank strategic key-research areas in nanotechnology effectively.	5.1 Combine the CSF into the Analytical Hierarchical Process (AHP) foresight model 5.2 Use the scientometric scores to rank research alternatives in the AHP - MCDM foresight model 5.3 Benchmark the list of key research areas resulting from the AHP-MCDM model with the list resulting from experts' survey foresight results

3.5 Survey research

A survey is a method of obtaining information about a population's properties or views (Creswell, 2014; Kothari, 2004; Jonker and Pennink, 2010). Independent and dependent variables are used to define the scope of an investigation in survey research. Prior to conducting the survey, the researcher develops a plausible theoretical model in the form of a proposition or hypothesis that specifies the predicted relationships between these variables (Creswell, 2014). The survey is then conducted to check or validate the proposed model against actual observations.

This study proposed the Nanotechnology Innovation Diamond, and a survey was performed to establish the relative weights of the essential success criteria. Nanotechnology specialists in South Africa participated in the cross-sectional survey.

3.5.1 Population and sampling frame

Experts in nanotechnology-related fields from South Africa make up the survey population. The study population was built by combining databases of nanotechnology experts from the Council for Scientific and Industrial Research's (CSIR) Nanotechnology Centre, the South African Institute of Physics (SAIP), and information on diverse nanotechnology research initiatives around the country that is freely available on the internet.

To form the sampling frame, six hundred and thirty-two (632) specialists were identified from 245 organisations. The number of specialists coming from each respective institution ranged from 1 to 47. The economic sectors in which the organisations operate were divided into 37 categories. Universities, agricultural and veterinary medicine, pharmacology, cosmetics, materials science, energy, aviation and engineering were among the economic sectors represented.

3.5.2 Sample size

Krejcie and Morgan (1970) presented a technique for estimating sample size in survey research in their paper "Determining Sample Size for Research Activities." They proposed the following formula:

$$s = X^2NP(1-P) \,/\, [d^2(N-1) + X^2P(1-P)] \tag{3.1}$$

where

s = required sample size.

$X2$ = the table value of chi-square for 1 degree of freedom at the desired confidence level (3.841).

N = the population size.

P = the population proportion (assumed to be .50 since this would provide the maximum sample size).

d = the degree of accuracy expressed as a proportion (.05).

Using the Krejcie and Morgan (1970) equation at 95% confidence level, the required sample size was determined to be 239 units. The second consideration was what the literature says about the number of responses required for Confirmatory Factor Analysis. According to Hair et al. (2010), CFA needs a minimum of 150 responses for a model with seven latent components and a minimum of four variables, like the suggested Nanotechnology Innovation Diamond. The sample size was modified to 478 using the equation below since the researcher predicted a 50% response rate.

$$Final\ Sample\ Size = \frac{Calculated\ sample\ size}{[1 - (Nonrespose\ rate\ expected)]} \qquad (3.2)$$

3.5.3 Sampling strategy

The research used stratified random sampling to achieve a uniform representation of all economic sectors specified in the sampling frame. The survey population was divided according to the economic sector to ensure coverage of all identified economic sectors because nanotechnology is a pervasive GPT and has widespread penetration into all economic sectors (Roco *et al.*, 2011). Therefore nanotechnology pervasiveness implies that all the possible stakeholders' economic sectors must be identified during foresight studies because the same discovery, or invention, could lead to a variety of applications in various technological fields (Salerno *et al.*, 2008a).

The 478 units of analysis were drawn using proportional stratified random sampling. The sample frame was divided into 37 economic sectors, and the proportional representation of each sector was then used to randomly sample units from each respective cluster.

3.5.4 Data collection

The data was collected using an online electronic survey. A pilot survey was done to test and improve the questionnaire.

3.5.4.1 Electronic online survey

Electronic methods of survey data collection are increasing in use and taking over from posted surveys or human administered surveys, and their advantages include speedy response, low cost, and easy distribution (Jansen, Corley and Jansen, 2005; Andrews *et al.*, 2017; Kiesler and Sproull, 2017). For this study, an electronic survey was used for the following reasons:

1. The sample size of 478 is large and geographically spread throughout South Africa. Hence an electronic survey is a cheaper and more practical method to contact 478 people than a postal survey or interviews.

2. Nanotechnology research development and innovation experts in the population all have email contact details. Hence, electronic surveys are most appropriate to this group.

3. The researcher had time constraints to either do interviews or wait for postal questionnaires since time-consuming technology-mining and scientometric analysis of nanotechnology publications also had to be done.

3.5.5 Survey instrument design

The questionnaire shown in Appendix 2 was developed for this study. The instrument has four sections described below:

Section A: Demographic information – The respondents' demographic data was collected in this section. This data is used for two goals, firstly, as a quality control measure that ensures that the right nanotechnology innovation experts respond. Secondly, it is used to identify the stage at which a respondent is involved in the nanotechnology innovation value chain. Nominal data is collected in this section using closed-ended questions.

Section B: Characteristics of successful nanotechnology R&D - This section is designed to evaluate the “successful nanotechnology” construct. It uses a set of five-point Likert scale questions to assess what experts perceive as successful nanotechnology R&D. Table 3.4 shows the research questions linked to this construct and related literature sources.

Table 3.4: Successful nanotechnology and its related measurable variables

Construct	Measurable variables affecting the construct (Questionnaire item)	References
Successful nanotechnology research and development	5(a) Successful nanotechnology R&D results in the development of new products and services 5(b) Successful nanotechnology R&D results in the improvement of existing products and services 5 (c) Successful nanotechnology R&D results in the production of patents and/or trade secrets 5 (d) Successful nanotechnology R&D leads to new technology licensing opportunities 5(e) Successful nanotechnology R&D leads to commercialisation of research results 5(f) Successful nanotechnology R&D leads to the formation of new companies and/or spin-off companies	(Aithal and Aithal, 2016) (Maine, 2014), (Schultz, 2011)

Section C: Nanotechnology Innovation Diamond - This section is designed to answer research question one, and therefore test the related hypothesis about the critical success factors for successful nanotechnology innovations. This section has six questions that use a five-point Likert scale to investigate these CSFs. Table 3.5 shows the research questions linked to the six CSFs identified and related literature sources.

Table 3.5: Nanotechnology CSFs and their related measurable variables

Critical Success Factor (CSF)	**Measurable variables affecting the construct (Questionnaire item)**	**References**
A conducive innovation environment is critical for nanotech success	6(a) The primary factor driving successful nanotechnology innovations is a conducive innovation environment created by government policies. 6(b) Most successful R&D innovations in nanotechnology are those aligned with government priorities. 6(c) Strategic partnerships between government, industry, academia, and research institutions are important for successful nanotechnology innovation. 6(d) Government-supported research infrastructure and skills development are critical for successful nanotechnology innovations.	(Porter and Stern, 2001), (Etzkowitz and Leydesdorff, 1997), (Choi *et al*., 2015), (Yoon, 2015), (Schultz, 2011), (Bovaird, 2004)
Consumer needs and preferences are critical for nanotechnology products success	7(a) In order for nanotech innovations to be successful, they must be accepted by the final consumer. 7(b) Market perceptions of nanotechnology products by the public is a key success factor for nanotech innovations, especially those with applications in medicine, environment, cosmetics, and food. 7(c) Successful nanotechnology research must incorporate consumer and market needs early in the research. 7(d) Most consumers of nanotechnology products are not aware that they are using nanotechnology-based products.	(Ivanova, 2014) (Yue *et al*., 2015), (Giles *et al*., 2015), (Paarlberg, 2014), (Berube *et al*., 2011) (Khosravi and Sadeghi, 2014), (Casolani *et al*., 2015)

Critical Success Factor (CSF)	**Measurable variables affecting the construct (Questionnaire item)**	**References**
Agglomeration and clustering of nano R&D facilities and companies are critical for nanotech success	8(a) The physical location of nanotechnology R&D facilities is a significant factor that contributes to innovation success; some locations present a competitive advantage in facilitating successful nanotech innovations. 8(b) There is a higher success rate for nanotechnology research conducted within nanotech research centres, science parks, and clusters. 8(c) Working within a nanocluster enables sharing tacit knowledge, specialised infrastructure, and resources. Hence it increases the success rate of nanotechnology innovations. 8(d) Nanotechnology clusters and nanotech centres of excellence provide a conducive environment for entrepreneurs and nanotech start-up companies.	(Porter and Stern, 2001), (Palmberg, Denis and Miguet 2009) (Carlino and Kerr 2015), (Shapira and Youtie 2008), (Robinson *et al*. 2007), (Fiedler and Welpe, 2011), (Gkanas *et al*., 2013)
R&D, innovation and commercialisation skills (Scientist-entrepreneurs) are critical nanotech success	9(a) Successful nanotechnology innovations emanate from R&D teams with high skills in scientific research, e.g., teams that have a high number of publications, a high number of citations, etc. 9(b) Successful nanotech innovations emanate from R&D teams with innovation management and commercialisation skills. 9(c) Successful nanotech innovations emanate from teams with intellectual	(Porter and Stern, 2001), (Maine, 2014)

Critical Success Factor (CSF)	**Measurable variables affecting the construct (Questionnaire item)**	**References**
	property management skills such as the ability to patent and license innovations. 9(d) Successful nanotech innovations emanate from R&D teams with technological entrepreneurship skills.	
Nano R&D hybridisation to existing industries and socio-economic needs is critical for nanotech success	10(a) Successful nanotechnology innovations must be aligned to existing industry sectors, for example, nano-energy, nanobiotechnology, nanoelectronics, nanoagriculture, and nanomedicine. 10(b) Industry and academia collaboration are essential for successful nanotechnology innovations. 10(d) Successful nanotechnology innovations must be aligned to socio-economic needs, e.g., energy security, clean water, medical needs, among others. 10(e) Strategic R&D partnerships between industry and national research facilities are important for successful nanotechnology research.	(Salerno, Landoni and Verganti, 2008), (Avenel *et al*., 2007), (Hullman, 2007), (Kane *et al*., 2016), (Kreuchauff and Teichert, 2014) (Aithal and Aithal, 2016)
Multi and Interdisciplinary teams are critical for nanotech success	11(a) Nanotechnology is a multidisciplinary field. 11(b) Successful nanotechnology innovations are produced by interdisciplinary teams. 11(c) Nanotechnology cannot be viewed as a stand-alone discipline but combines several cross-cutting scientific skills.	(Connel *et al*., 2001), (Battard, 2012), (Karpagam *et al*., 2011) (Porter and Youtie, 2009) (Schummer, 2004), (Roco *et al*., 2011)

Critical Success Factor (CSF)	Measurable variables affecting the construct (Questionnaire item)	References
	11(d) Due to its multidisciplinarity and interdisciplinarity nature, nanotechnology is emerging as the core for the convergence of several disciplines.	(Islam and Miyazaki, 2010), (Gkanas *et al*. 2013), (Meyer and Persson, 1998), (Hullman and Meyer, 2003), (Salerno, Landoni and Verganti, 2008)

Section D: Key technologies expert survey - In this section, nanotechnology research areas identified through a literature review of nanotechnology publications and government policies on science and socio-economic development are ranked using the expert survey method. The expert survey ranking enables benchmarking of the developed MCDM model with the traditional technologies survey method.

3.5.6 Pilot survey

To increase the validity and reliability of the survey, a pilot survey was conducted. The pilot survey targeted 10% of the 478-sample size, which is 48 experts who were requested to participate in the pilot. However, only six experts responded, giving a 12.5% pilot-phase response rate. Due to time limitations, the researcher could not wait longer for more responses or solicit additional pilot phase responses. Six nanotechnology specialists from the following institutions participated in the pilot survey and consultation the University of Pretoria, CSIR Nanotechnology Centre, the University of Venda, Nelson Mandela University and iThembaLABS. After the pilot survey, the study instrument was adjusted.

3.5.7 Statistical and confirmatory factor analysis

The survey data was analysed using the Statistical Package for the Social Science (SPSS) Software Student Edition Version 26. Microsoft Excel was used to complement data analysis. Both descriptive and inferential statistics were used to present results, interpret data and test the proposed hypotheses. Confirmatory Factor Analysis (CFA) of the Nanotechnology Innovation Diamond model was done using SPSS AMOS GRAPHIC Student Edition version 26.

3.5.8 Survey validity and reliability

According to Yin (2003), research validity has three dimensions, namely construct validity, internal validity and external validity.

3.5.8.1 Construct and survey internal reliability

A comprehensive literature review on nanotechnology innovation and technology foresight was conducted to establish the constructs used in nanotechnology innovation and technology foresight research. Concepts used in earlier innovation and foresight exercises were adapted for this research. Also, the survey instrument and protocol were evaluated by a statistician, following which the researcher did a pilot survey to ensure that the process developed measured what research aimed to assess.

Cronbach's alpha and Composite Reliability were also used to assess the reliability of the constructs studied in the study (CR). Cronbach's alpha of 0.7 and CR > 0.6 are the minimum acceptable reliability values for these two measurements (Connell, 1987). Cronbach's alpha was used to assess the measurement tool's reliability for both the individual latent constructs and the composite model. The individual latent constructs met both Cronbach's alpha and CR minimum requirements, as shown in Table 3.6.

Table 3.6: Individual latent constructs reliability measurement results

Latent Construct	Cronbach's Alpha	Composite Reliability
Successful nanotechnology	0.847	0.848
Conducive innovation environment	0.733	0.753
Consumer perceptions and needs	0.759	0.733
Agglomeration and clustering	0.746	0.720
R&D, innovation, and commercialisation skills	0.786	0.754
Nano-hybridisation	0.701	0.749
Multi and interdisciplinarity	0.762	0.676

Cronbach's alpha value for the entire 30 variable measurement scale is 0.95, indicating that the measurement instrument has a high internal consistency and reliability level.

3.5.8.2 External validity

The population studied was the nanotechnology research and innovation community in South Africa. A large sample of 478 was selected through proportional stratified random sampling on 37 economic sectors involved in nanotechnology in South Africa. A total of 171 replies were received, representing a response rate of 36%. Four survey responses were eliminated from the study because they did not complete all the CFAevaluation questions; hence, 167 responses were used in the analysis. The fact that the survey population was divided according to the economic sector ensured that all identified economic industries that are involved in nanotechnology were represented because nanotechnology is a General Purpose Technology that is pervasive with widespread penetration into all economic sectors (Roco *et al.*, 2011). Hence, the results of this research can be generalised.

3.5.9 Limitations of the survey research

The study was empirically tested only in South Africa. This research was carried out using responses of experts all based in South Africa, and most of them work in nanomaterials, so there is a need to test the model with a different pool of experts from other parts of the world.

3.6 Technology-mining and scientometric analysis

This section discusses the steps followed in carrying out foresight-oriented technology-mining and scientometric analysis of nanotechnology publications. Tech-mining tools are used to mine structured databases in research and technology to produce empirically grounded technology management indicators for decision making and foresight planning. Tech-mining was carried out in three steps: planning, data analysis, and reporting, and these three steps will now be outlined below.

3.6.1 Tech-mining planning

The technology-mining and scientometric analysis planning involved four steps. The first step was to find the right software to use. In this research, Vantage Point Student Edition was identified as suitable software. Vantage Point software's basic and advanced tech mining features help elicit correlations across data fields such as authors, institutions, research disciplines, research topics, citations and co-authorship. Vantage Point can also extract key terms from records, cluster related documents, map research networks (co-authoring, co-citation), and develop co-occurrence and autocorrelation matrices for different fields. Clarivate Analytics from Web of Science was used to complement Vantage Point.

The second planning step involved finding and adapting a suitable search strategy/query to retrieve relevant records while balancing precision and recall of records. The third step involved identifying the initial list of possible nanotechnology research areas for South Africa, and the last planning step involved specifying the technology mining questions and proposing how to answer them using tech-mining and scientometrics.

3.6.1.1 Search strategy

Porter *et al.* (2008) developed a modularized Boolean technique for querying and retrieving nanotechnology papers from structured databases. Arora *et al.* (2013) enhanced the method even more. This search approach was adopted, modified, and used in this study to retrieve nanotechnology academic articles for analysis.

3.6.1.2 The initial list of possible nanotechnology research areas

A review of South Africa's National Development Plan (NDP) Vision for 2030, the 10-Year National Innovation Plan, and the Nanotechnology Strategy 2006 yielded the initial list of potential nanotechnology research fields for the country. Food, agriculture, automotive, cosmetics, mining, material science, energy, medicine, textiles, communicable diseases, electronics, photoluminance and optics, water, nanotools, sensors, catalysis, magnetism, biotechnology, nanofibers, and nanofibers were identified as possible socio-economic relevant research areas

3.6.1.3 Clustering strategy

Once nanotechnology publications were retrieved for analysis, the next step was to group them into the research themes/research areas identified above. Unfortunately, being a new field of study, the classification system for nanotechnology research is still in its infancy. There is no software tool for categorising nanotech papers into the identified research fields. A software protocol for automatically classifying nanotechnology publications into research areas was created using the Vantage Point thesaurus feature combined with appropriate search terms and keywords for each research field mentioned above. The protocol was utilised to categorise South African nanotech papers into foresight research areas automatically. The developed protocol used one-to-many mapping; for example, an article on nanofibres can sometimes fit into material science or textiles research, yet another paper in nanotubes may fit into sensors, electronics or energy research. Detailed search term classification developed for this research is provided in Appendix 3.

3.6.1.4 Foresight-oriented questions for tech-mining

Foresight-oriented questions were crafted to determine and characterise nanotechnology research in South Africa. These questions were answered from technology mining are shown in Table 3.7 below:

Table 3.7: Foresight-oriented questions and answers from tech-mining

Foresight intelligence questions	Answer from tech-mining
1. How has South Africa's nanotechnology output evolved over the last 20 years?	• Total number of publications and time series plot between 2000 - 2019
2. What are the nanotechnology research fields in which South Africa is involved?	• Publications are clustered into research fields using keyword co-occurrence thesaurus
3. Which countries are collaborating with South Africa, and in which fields?	• Papers co-authored with South Africans

Foresight intelligence questions	Answer from tech-mining
4. How is nanotechnology productivity in South Africa compared to the BRICS countries (Brazil, Russia, India, China) and the USA?	• Total number of publications between 2000 – 2019 per country • Activity index per country
5. Who is involved in what research, where, and when?	• Frequency tables with the research area, author name, institutions, country, and publication years,
6. What are the R&D competencies for the various research fields in terms of quality and quantity?	• Total number of publications per author, institution, and country • Total number of citations per research area
7. What is the level of research collaboration in the different research fields?	• Total number of single-authored papers per research and per institution • Total number of co-authored articles per research and per institution
8. How are research areas clustered/agglomerated in South Africa?	• Total number of publications per research area per cluster/province
9. What is the overall stage of each research field within the nanotechnology value chain?	• Total number of papers in the different stages of the nanotechnology value chain per research area

3.6.1.5 Data sources

The basis for scientometric analysis is that any indicator or metric can only be as good as the source of data it is based on. This research was empirically tested in South Africa to determine key nanotechnology research areas for the country. Therefore, the research databases used must provide comprehensive coverage of the South African science and technology system to reflect the scientific activities of the country accurately. Therefore, the Web of Science Core Collection was selected as the most suitable database. Patent information was accessed from the European Patent Office (EPO) database which provides an advanced Boolean logic search engine and has a record of worldwide patents.

A search of South Africa's publications and patents between 2000 and 2019 was done on the two databases. The year 2000 was chosen as the starting point since it was at that time when nanopublications began to grow at a rapid rate (Islam and Miyazaki, 2009). According to the findings in this study, South Africa published 11265 articles on Web of Science compared to only 43 patents in the EPO database. Hence, due to their small number patents were not analysed in this research. Hence only South African scientific publications published between 2000 – 2019 were analysed in this study.

3.6.2 Tech-mining data analysis

The data analysis phase involved extracting knowledge to help answer the foresight question posed in Table 3.7 above. The data was cleaned before the analysis began.

3.6.2.1 Data cleaning

Data cleaning involved the following activities:

a) confirming the search boundaries in terms of the period of publication and author country as South Africa,

b) consolidating "author name" variations, "institutional name" variations, and developing a thesaurus that aggregates institutional and author name variations,

c) removing duplicate records, and

d) checking precision by scanning key terms and removing records that are not nanotechnology-related publications.

3.6.2.2 Scientometric analysis

Data analysis involved the following steps:

Step 1: Grouping research articles into nanotechnology research fields, therefore identifying possible critical research areas or foresight alternatives for South Africa.

Step 2: The second step involved extracting frequency tables that show activity counts that tell how much of something is taking place. These include:

1) The total number of publications per field, author, institution, province, and country.
2) The total number of citations per field, author, institution, province, and country.
3) The total number of co-authored papers per field, author, and institution.
4) The total number of single-authored papers per field and institution.
5) The total number of publications in each stage of the nanotechnology value chain per field, institution, province, and country.
6) Trend analysis of publications per field, for example, cumulative publications over time.
7) Breakouts from the above lists, for example, top institution, top authors, and most productive clusters per field in terms of the number of papers published.
8) Co-occurrence and autocorrelation from the above tables, for example, the matrix of country-by-country knowledge on international collaboration networks and clusters.

Step 3: Calculate normalised scientometric indicators for each alternative/field. These include field citation ratios, specialisation ratios, and co-authorship ratios.

Step 4: Reporting the tech-mining results in the form of frequency tables and graphs.

3.6.3 Tech-mining and scientometrics validity and reliability

To assure the validity and reliability of this study's tech-mining results, a well-established Boolean nanotechnology search approach (Porter et al., 2008) was adapted to extract target records from the Web of Science core collection. Additionally, data cleaning was performed to ensure that the search technique was accurate in extracting nanotechnology-specific documents for study. Secondly, a large sample of publications was analysed (11 265), thereby minimising sampling error. Sampling error increases when the number of objects being measured is small; in this situation, the number of objects being measured is enormous.

3.6.4 Limitations of scientometrics

Although scientometric metrics give quantifiable and evidence-based metrics for foresight research, they are not without limitations. These limitations are summarised:

1. Publications suffer from the lack of standardisation; for example, individual data for writers, particularly addresses and the way names are written, are not standardised, making analysis difficult (Zitt, 2006).

2. Publication scientometric indicators are lagging indicators of scientific research and development evaluation because journal articles take on average a year or more to publish, unlike expert opinion, which is always current.

3. Technology mining may help determine who, what, and when, but questions about how and why must typically be answered by subject experts (Porter and Cunningham, 2005b),

4. Some researchers may not patent or publish their research, choosing trade secrets, especially in the private sector; for example, an academic scientist or engineer is 45 times more likely to publish their research than an industrial scientist/engineer (Porter and Cunningham, 2005b).

5. Not every research component can be quantified or measured to the same extent; hence, scientometric metrics are partial indications. "Research" or "knowledge generation" is a complicated concept that cannot be encapsulated in a single or small set of measurements.

6. At best, scientometric indicators are proxies for more “intangible” research dimensions like “research quality” or “research cooperation.” For example, “Research quality” is often equated with “citation impact,” and “research cooperation” is equated with “co-authorship” in scientometrics. As a result, present bibliometric approaches are simply insufficient to appropriately quantify such research metrics; hence, additional evaluation methods are required to support scientometric indicators

7. Tech-mining is still new to technology managers; as such, it faces credibility issues. Hence many decision-makers may feel more comfortable using an expert opinion (Porter and Cunningham, 2005b).

8. The distributions of scientific publications are substantially asymmetrical, according to Lotka's Law (Phillips, 2013). Leaders tend to produce large

amounts of articles, whilst the remainder appear in "ones and twos," which means that essential contributions made by less prolific authors who publish and patent less frequently may be overlooked.

3.7 A foresight model combining MCDM, nanotech CSF, tech-mining and scientometrics

This section presents the development of a new, novel conceptual model for identifying and ranking a country’s key strategic research areas in nanotechnology. The new model blends quantitative, evidence-based methods comprising environmental scanning, MCDM, scientometric analysis, and the Nanotechnology Innovation Diamond critical success factors. The model is a micro-level key technologies foresight method that is nanotechnology specific.

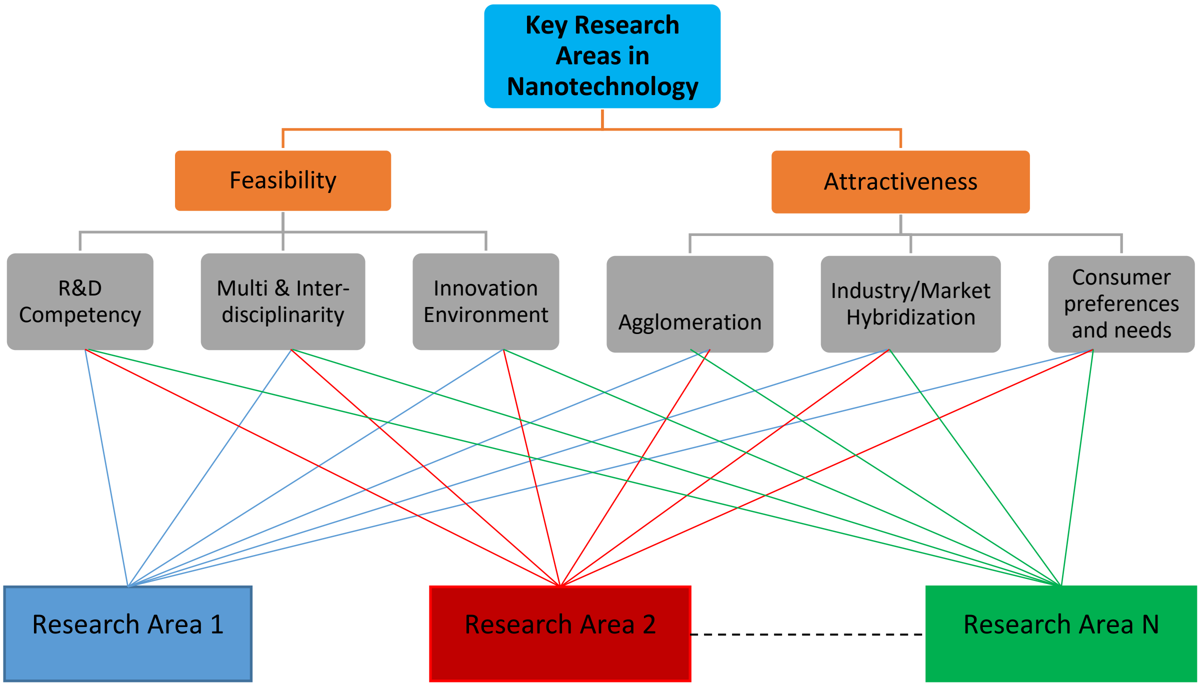
This methodology was developed to close gaps found in the literature that include the lack of use of quantitative methods in foresight, lack of use of MCDM in foresight, and lack of nanotechnology specific foresight methods. The approach followed was recommended by Popper (2011), who argues that to produce novel technology foresight results that are beyond business as usual, foresight practitioners and strategic managers need to move away from traditional popular foresight methods and must start to consider quantitative and evidence approaches; therefore, they need to:

1. First, consider less frequently used methods, for example, undertake time-consuming and rigorous quantitative approaches such as multi-criteria analysis, modelling and simulation, and
2. Second, improve prospective analysis by using advanced data and text mining tools to analyse documents; statistical tools for network/cluster analysis and

visualisation structures; co-word, co-authorship and co-citation methods as a guide to new clusters of ideas in scientific areas.

Figure 3.1 below depicts the model and steps that were followed. A MCDM approach, the AHP was used to decompose the problem. Criteria for the MCDM model were derived from the Nanotechnology Innovation Diamond. The sub-criteria were evaluated using scientometric indicators.

Source: Synthesised by researcher.



<table>
<tr><td colspan="5">Step 4: Map of the scientometric indicators to the CSF of R&D Competency, Multi and Interdisciplinarity, Innovation Environment, Agglomeration, Hybridisation and Consumer preferences and the use of the AHP model to score and rank the research alternatives</td></tr>
<tr><td>Research Area 1 Scientometric indicators</td><td></td><td>Research Area 2 Scientometric indicators</td><td>---------------------</td><td>Research Area N Scientometric indicators</td></tr>
<tr><td colspan="5">Step 3: Determine the scientometric indicators for each research area</td></tr>
<tr><td>Research Area 1</td><td></td><td>Research Area 2</td><td>---------------------</td><td>Research Area N</td></tr>
<tr><td colspan="5">Step 2: Cluster papers and patents into research areas</td></tr>
<tr><td colspan="5">Step 1: Identify a bibliometric database and perform technology mining on the country’s nanotechnology publications and patents</td></tr>
</table>

Figure 3.1: Nanotechnology key-research area selection model steps from bottom up

The following steps are followed when determining a country’s key research areas in nanotechnology:

Step 1: Perform environmental scanning of the country's nanotechnology research capabilities by performing a tech-mining of relevant nanotechnology patents and publications published by the country's researchers.

Step 2: Perform cluster analysis to group patents and publications into thematic research areas in nanotechnology. Allow one-to-many mapping; some papers may fit into more than one nanotechnology research area. These research areas are then used as the nanotechnology research alternatives in the MCDM model.

Step 3: Determine the scientometric indicators for each identified research alternative or research cluster.

Step 4: Evaluate the research alternatives using the AHP MCDM making model.

For AHP the best alternative (in the maximisation case) is the one that has the greatest value in the following expression:

$$AHP_{i-max}^{*} = max_i \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \times w_j \qquad (3.3)$$

where AHP_{i-max}^{*} is the score of the *i-th* alternative, m is the number of alternatives, n is the number of the criteria, a_{ij} represents the actual value of the *i-th* alternative in terms of the *j-th criterion* and w_j, is the weight of importance of the *j-th* criterion.

3.7.1 Reliability of AHP-MCDM key technologies foresight model

The AHP-MCDM foresight model was constructed by combining the Nanotechnology Innovation Diamond, data from the scientometric analysis, and the analytical hierarchical process (AHP). Validity was ensured at each stage according to the precautions described below.

Composite Reliability (CR) and Cronbach's alpha were used to estimate the Nanotechnology Innovation Diamond model's reliability. The minimum values of reliability for these two measures are 0.7 for Cronbach's alpha and CR > 0.6, respectively (Connell, 1987), which were achieved in this research. The Cronbach's alpha value for the entire 30 variable measurement scale of the survey instrument for CFA is 0.95, demonstrating a high level of internal consistency and reliability. The model satisfied the minimum fit requirement for a Confirmatory Factor Analysis.

To make sure the results of this study are valid and reliable, the following precautions were taken: In the first step, a well-known and accepted Boolean logic nanotech search query (Porter *et al*., 2008; Arora *et al*., 2013) was adapted to retrieve nanotechnology publications from the WoS bibliometric database. Moreover, manual inspection was done to ensure that the search method was retrieving nanotechnology-specific records with precision. Furthermore, 11 262 papers were examined, lowering the sampling error. Sampling error is more likely to occur when the sample size is small, but the selection used was very large in this case.

For the AHP-MCDM model, a quality control check was done by assessing the consistency of the pairwise comparison of weights. The consistency ratio was calculated to be 0.0013, which is less than the threshold of 0.10 (Saaty, 1980); hence the weights determined in the CFA can be reliably used.

Finally, the results from the developed AHP-MCDM foresight model were benchmarked with results from an expert survey key technologies method which gave closely similar priority fields of research.

3.7.2 Limitations of MCDM models in technology foresight

The most significant limitation of using MCDM in foresight is that MCDM is strong in determining research priorities, which is only one of the foresight goals. Other goals such as networking and awareness-raising cannot be done through MCDM. The other generic limitations of MCDM methods are sensitivity to input data and the decision paradox. A benchmark of the MCDM foresight model results with an expert survey-based foresight model was carried out to address these limitations.

3.8 Ethical considerations

Before beginning the study, the University of South Africa Graduate School of Business Leadership gave ethical clearance. An ethical clearance letter is shown in Appendix 6. Participation in the survey was voluntary, and participants were provided with a relevant research background. The documents used in the scientometric analysis are publicly available on the Web of Science.

3.9 Conclusion

The research method used in the current study is described and explained in this chapter. The positivist/empirical realist epistemology of foresight was used in this study. Therefore, it is assumed that statistical data from nanotechnology publications can be used to evaluate the performance of nanotechnology research against the nanotechnology innovation critical success factors and innovation models. Then, this data can be combined with MCDM techniques to study the past and present state of nanotech research in order to determine the critical research areas in nanotechnology.

In summary, the following steps were followed in this research:

1. **Determine the nanotechnology innovation critical success factors.**
    a. Determine a model for Critical Success Factors promoting successful nanotechnology research.
    b. Validate the critical success factors model using Confirmatory Factor Analysis (CFA).
    c. Calculate the weights of each factor from the optimised CFA model.
2. **Perform tech-mining and scientometric analysis of nanotechnology publications.**
    a. Identify a data source and extract nanotechnology publications for the country and period by adapting a proven Boolean algorithm for nanotechnology database searches (Porter *et al.*, 2008; Arora *et al.*, 2013).
    b. Perform tech-mining and cluster papers into research areas, i.e., possible key research alternatives that are in line with government policy needs.
    c. Calculate the scientometric indicators for each cluster/alternative per success factor.
3. **Determine an MCDM based nanotechnology key technologies foresight model.**
    a. Combine factors supporting successful nanotechnology with AHP in an MCDM foresight decision-making model.
    b. Assign scientometric indicators that can closely measure each Critical Success Factor, e.g., multidisciplinarity success factor measured by the degree of collaboration scientometric indicator.
4. **Rank identified research alternatives using the MCDM foresight model.**
    a. Use the MCDM foresight model with inputs from scientometric analysis to rank the research alternatives.

5. **Benchmark the results with expert survey key technologies method.**
    1. Identify possible nanotechnology alternatives.
    2. Perform an experts' survey where nanotechnology experts can rank the research alternatives for socio-economic importance and scientific feasibility.
    3. Plot the survey results on a scatter plot such that research areas that possess an excellent scoring for both importance and feasibility are identified as critical research areas.
    4. Compare these results with those obtained in step 4 above.

The chapter which follows, chapter 4, presents and discusses the results of this research.

Chapter 4: Results and Discussion

The previous chapter, chapter 3, presented the methodology, research design, and activities that were followed in answering the research questions, addressing the research objectives and developing a nanotechnology specific foresight model. Chapter 4 presents and discusses the results emanating from this research.

4.1 Introduction

This research aimed to determine a nanotechnology-specific key technologies foresight model. In order to achieve that aim, chapter 3 presented the methodology which has four broad steps, namely, nanotechnology experts' survey to validate the proposed CSF for successful nanotechnology R&D, technology-mining and scientometric analysis of nanotechnology publications, and, finally, foresight model development using the analytical hierarchical process multi-criteria decision making (AHP-MCDM) model.

This chapter summarises and discusses the results of carrying out the steps listed above. The chapter starts by presenting the demographic statistics of South Africa's nanotechnology experts. This is followed by a section on descriptive statistics on successful nanotechnology and the six nanotechnology critical success factors. Results on CSF and successful nanotechnology correlation analysis are then reported. Next, results from the CFA analysis of the proposed Nanotechnology Innovation Diamond. A foresight perspective of South Africa's nanotechnology is presented through tech-mining and scientometric analysis. The chapter then uses the results to develop the AHP-MCDM nanotechnology-specific foresight model. Results from an expert-survey foresight method are also reported. Chapter 4 is concluded by reporting the benchmarking of the AHP-MCDM model compared to the experts' key-technology survey method.

4.2 Expert Survey and demographic information

Participants in this part of the study to identify CSF are nanotechnology experts. The sampling frame was composed of six hundred and thirty-two (632) experts distributed within 245 organisations. Proportional stratified random sampling was used to select 478 experts for the study sample. Data was collected through an online electronic questionnaire. The survey generated 171 responses, representing a response rate of 36%. Due to insufficient data, four responses were excluded from the study, leaving 167 responses for further analysis.

This section reports on the demographic information of the nanotechnology experts from South Africa. The job descriptions of the respondents are shown in Figure 4.1.

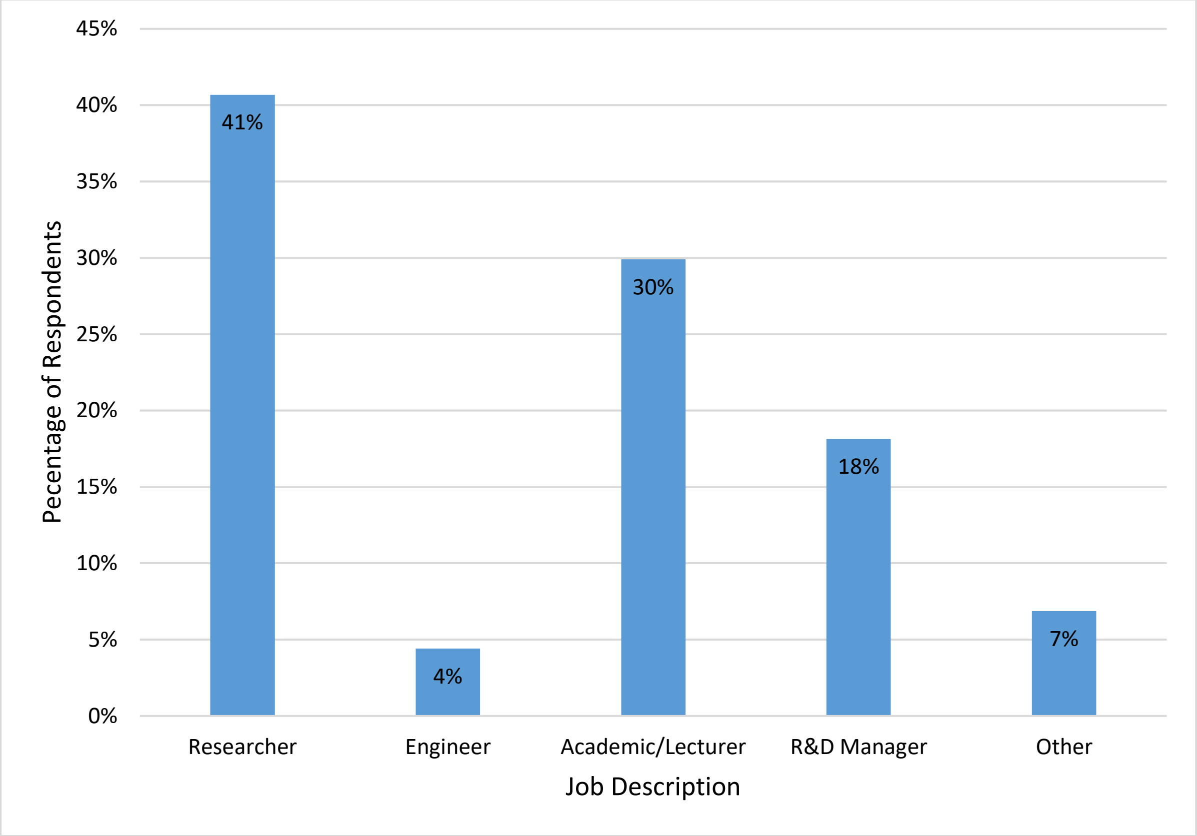


Figure 4.1: Job descriptions of respondents

Researchers and academics/lecturers make up most respondents at 41% and 30%, respectively. Only 4% of participants are engineers. This lack of participation of engineers in nanotechnology may affect the nanotechnology value chain because engineers are primarily responsible for producing nano-enabled products.

Figure 4.2 shows the economic sectors in which the respondents are working. The three most prevalent sectors are material science 31%, energy 16% and university 13%.

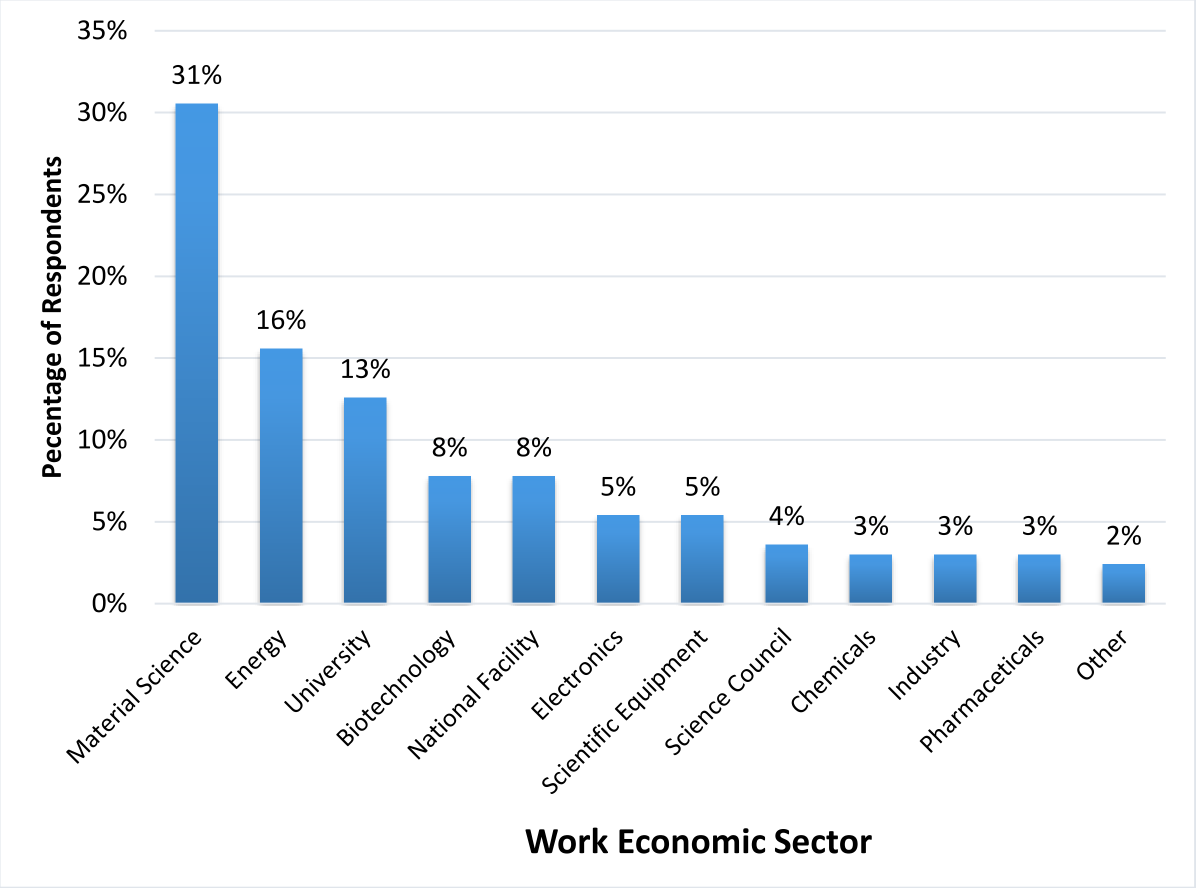


Figure 4.2: Sector of the economy in which respondents work

The respondents were also analysed according to the stage in the nanotechnology value chain at which they are employed. Figure 4.3 shows that most of the survey respondents, 47%, are engaged in the initial and primary stage of the nanotechnology value chain, that is in nano-materials, 17% work in nano-intermediaries, 16% in nano-enabled products, and 12% in nano-tools.

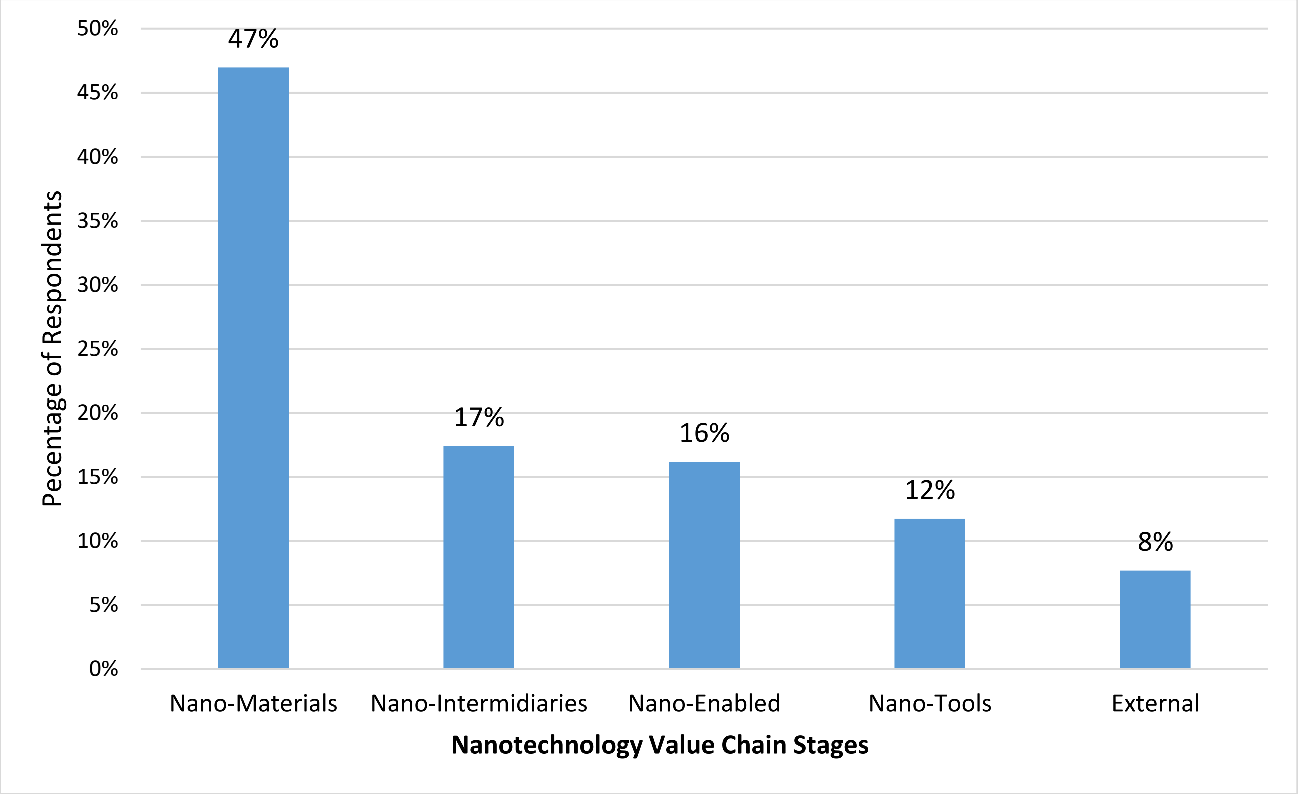


Figure 4.3: Nanotechnology value chain stage at which respondents work

4.2.1 Discussion of the demographic information of respondents

The "nanotechnology value chain" is a three-step process that takes nanotechnology ideas from concept to commercialisation (Shapira, Youtie and Kay, 2011; Wang and Guan, 2012; Gkanas *et al.*, 2013). At the bottom of the value chain are nanomaterials, which serve as primary inputs for nanotechnology. Nanomaterials include nanotubes, nanowires, thin films, nanopowders and quantum dots. The demographic data indicate that 71% of the respondents are employed as researchers, academics or lecturers primarily engaged in the initial stage of the nanotechnology value chain. This finding is supported by the fact that two of the most prevalent industry sectors selected by the respondents are material science and university, which constitute 44%. Only 4% of participants are engineers, 17% work in nano-intermediaries, and 16% in nano-enabled products.

Results from comparing South African nanotechnology publications to patents between 2000 and 2019 supports the finding that nanotechnology experts in South Africa focus primarily on nanomaterials rather than on more innovative nanotechnology stages, such as nano-intermediates and nano-enabled products. There were 11 265 publications on WoS for South Africa, whereas only 43 patents were identified from the EPO records. Since engineers are more likely to file patents than academics, this simple comparison also confirms that most South African nanotech experts are researchers and academics instead of industry engineers who are more likely to file patents.

In the results and discussion above, it is evident that the majority of South African nanotechnology experts are academics and researchers; there are very few engineers. Thus, from a technology management and foresight perspective, there is a need for more engineers in nanotechnology to support the development of nano-enabled products from South African nanotech R&D research outputs.

4.3 Descriptive statistics

This section presents the descriptive statistics for the constructs on successful nanotechnology and the critical success factors for nanotechnology.

4.3.1 Successful nanotechnology

Table 4.1 presents the descriptive statistics on the construct of successful nanotechnology and its related variables. The top variable identified was that successful nanotechnology leads to the improvement of existing products and services. The lowest-ranked variable was that successful nanotechnology results in the commercialisation of R&D outputs. All the six variables had a mean score between

3.6407 and 3.886, implying that, on average, respondents agreed that these variables are related to successful nanotechnology innovation.

Table 4.1: Descriptive statistics for successful nanotechnology

Variable	N	% Strongly Disagree	% Disagree	% Undecided	% Agree	% Strongly Agree	Mean	Std. Deviation	Mean Rank
5 (b) Successful nanotechnology R&D results in the improvement of existing products and services	167	2.4	7.2	24.0	32.3	34.1	3.8862	1.03795	1
5 (d) Successful nanotechnology R&D leads to new technology licensing opportunities	167	5.4	6.0	16.8	45.5	26.3	3.8144	1.06207	2
5 (c) Successful nanotechnology R&D results in the production of patents and/or trade secrets	167	3.0	11.4	18.6	37.1	29.9	3.7964	1.08405	3
5 (a) Successful nanotechnology R&D results in the development of new products and services	167	3.6	9.6	23.4	34.1	29.3	3.7605	1.08777	4
5 (f) Successful nanotechnology R&D leads to the formation of new companies and/or spin-off companies	167	4.2	8.4	24.0	35.3	28.1	3.7485	1.08505	5
5 (e) Successful nanotechnology R&D leads to commercialisation of research results	167	7.2	6.6	25.7	35.9	24.6	3.6407	1.13659	6

4.3.2 Descriptive statistics on nanotechnology CSFs

This section presents the descriptive statistics for the six identified critical success factors. The section is concluded by testing hypothesis 1 to determine whether all the critical success factors have equal mean scores.

4.3.2.1 Conducive innovation environment

Table 4.2 presents the descriptive statistics for a conducive innovation environment. The two most important variables are strategic partnerships (62.2% agreeing) and government-supported infrastructure (61.6% agreeing). The respondents ranked the alignment of nanotechnology to government strategy as the least important variable. All four variables had a mean score between 3.4970 and 3.8144, implying that respondents agreed that they are essential.

Table 4.2: Descriptive statistics for conducive innovation environment

Variable	N	% Strongly Disagree	% Disagree	% Undecided	% Agree	% Strongly Agree	Mean	Std. Deviation	Mean Rank
6(c) Strategic partnerships between government, industry, academia and research institutions are important for successful nanotechnology innovation.	167	4.2	4.8	28.7	29.9	32.3	3.8144	1.07335	1
6(d) Government-supported research infrastructure and skills development are critical for successful nanotechnology innovations.	167	3.6	7.2	27.5	31.1	30.5	3.7784	1.07211	2
6(a) The primary factor driving successful nanotechnology innovations is a conducive innovation environment created by government policies.	167	5.4	9.0	25.7	31.7	28.1	3.6826	1.13589	3
6(b) Most successful R&D innovations in nanotechnology are those aligned with government priorities.	167	8.4	12.0	24.0	32.9	22.8	3.4970	1.20678	4

4.3.2.2 Consumer perceptions and needs

Table 4.3 presents the descriptive statistics on consumer perception variables. The most essential variable is that nanotechnology products must be accepted by the final consumer. All the four variables had a mean score between 3.6527 and 3.7365, implying that, on average, respondents agreed that they are important.

Table 4.3: Descriptive statistics on consumer perceptions and needs

Variable	N	% Strongly Disagree	% Disagree	% Undecided	% Agree	% Strongly Agree	Mean	Std. Deviation	Mean Rank
07(a) In order for Nanotech innovations to be successful, they must be accepted by the final consumer.	167	5.4	7.2	25.1	32.9	29.3	3.7365	1.12048	1
7 (d) Most consumers of nanotechnology products are not aware that they are using nanotechnology-based products.	167	4.8	9.0	24.0	34.7	27.5	3.7126	1.10912	2
7 (b) Market perceptions of nanotechnology products by the public is a key success factor for nanotech innovations, especially those with applications in medicine, environment, cosmetics and food.	167	6.6	10.2	24.0	29.9	29.3	3.6527	1.19198	3
7 (c) Successful nanotechnology research must incorporate consumer and market needs early in the research.	167	6.0	8.4	26.3	32.9	26.3	3.6527	1.13503	4

4.3.2.3 Agglomeration and clustering

Table 4.4 presents the descriptive statistics on agglomeration and clustering variables. The four variables had a mean score between 3.3892 and 3.7186. The top-ranked variable is that working in a cluster increases the success rate of nanotechnology. The second top-ranked variable is that the research institutions' location is vital for nanotechnology R&D success.

Table 4.4: Descriptive statistics agglomeration and clustering

Variable	N	% Strongly Disagree	% Disagree	% Undecided	% Agree	% Strongly Agree	Mean	Std. Deviation	Mean Rank
8(c) Working within a nanocluster enables sharing tacit knowledge, specialised infrastructure, and resources. Hence it increases the success rate of nanotechnology innovations.	167	4.8	10.2	22.2	34.1	28.7	3.7186	1.12949	1
8(a) The physical location of nanotechnology R&D facilities is a major factor that contributes to innovation success; some locations present a competitive advantage in facilitating successful nanotech innovations.	167	4.2	10.8	21.0	38.3	25.7	3.7066	1.09386	2
8(d) Nanotechnology clusters and nanotech centres of excellence provide a conducive environment for entrepreneurs and nanotech start-up companies.	167	7.2	8.4	20.4	38.9	25.1	3.6647	1.15441	3
8(b) There is a higher success rate for nanotechnology research conducted within nanotech research centres, science parks, and clusters.	167	7.2	14.4	28.1	32.9	17.4	3.3892	1.14519	4

4.3.2.4 R&D skills and capabilities

Table 4.5 shows the descriptive statistics for R&D skills required for successful nanotechnology. Innovation management and commercialisation skills were ranked the most important with an average of 3.7126. Intellectual management skills were ranked the lowest, with an average of 3.5509.

Table 4.5: Descriptive statistics on R&D, innovation and commercialisation skills

Variable	N	% Strongly Disagree	% Disagree	% Undecided	% Agree	% Strongly Agree	Mean	Std. Deviation	Mean Rank
9(b) Successful nanotech innovations emanate from R&D teams that possess innovation management and commercialisation skills.	167	3.6	11.4	25.1	29.9	29.9	3.7126	1.11993	1
9(d) Successful nanotech innovations emanate from R&D teams that have technological entrepreneurship skills.	167	6.6	9.0	18.6	39.5	26.3	3.7006	1.14868	2
9(a) Successful nanotechnology innovations emanate from R&D teams with high skills in scientific research, e.g., teams that have a high number of publications, a high number of citations, etc.	167	6.6	10.2	23.4	34.1	25.7	3.6228	1.16483	3
9(c) Successful nanotech innovations emanate from teams with intellectual property management skills such as the ability to patent and license innovations.	167	8.4	7.2	31.1	27.5	25.7	3.5509	1.19062	4

4.3.2.5 Nano-hybridisation

Table 4.6 shows the descriptive statistics on nano-hybridisation variables. The top two variables are strategic partnerships between industry and research facilities. The second is that nanotechnology must align with social and economic requirements such as nanoenergy, nanomedicine, etc. All the four variables had a mean between 3.6587 and 3.7605.

Table 4.6: Descriptive statistics on nano-hybridization

Variable	N	% Strongly Disagree	% Disagree	% Undecided	% Agree	% Strongly Agree	Mean	Std. Deviation	Mean Rank
10(e) Strategic R&D partnerships between industry and national research facilities are important for successful nanotechnology research.	167	3.6	9.0	22.2	38.3	26.9	3.7605	1.05972	1
10(d) Successful nanotechnology innovations must be aligned to socio-economic needs, e.g., energy security, clean water, medical needs, among others.	167	4.2	8.4	25.1	38.3	24.0	3.6946	1.05689	2
10(a) Successful nanotechnology innovations must be aligned to existing industry sectors, for example, nano-energy, nanobiotechnology, nano-electronics, nano-agriculture, and nanomedicine.	167	4.8	9.0	24.6	35.9	25.7	3.6886	1.09712	3
10(b) Industry and academia collaboration is important for successful nanotechnology innovations.	167	6.6	8.4	23.4	35.9	25.7	3.6587	1.14478	4

4.3.2.6 Multi-and interdisciplinarity

Table 4.7 presents the descriptive statistics on multidisciplinary and interdisciplinarity in nanotechnology. The top two variables are that nanotechnology is immerging as the core of interdisciplinary research, and nanotechnology is a multi-disciplinary field. All four variables had a score between 3.6527 and 3.7246.

Table 4.7: Descriptive statistics on multi-and interdisciplinarity

Variable	N	% Strongly Disagree	% Disagree	% Undecided	% Agree	% Strongly Agree	Mean	Std. Deviation	Mean Rank
11(d) Due to its multidisciplinary and interdisciplinary nature, nanotechnology is emerging as the core for the convergence of several disciplines.	167	6.6	7.2	23.4	32.9	29.9	3.7246	1.15990	1
11(a) Nanotechnology is a multidisciplinary field.	167	5.4	9.0	26.9	29.9	28.7	3.6766	1.14213	2
11(c) Nanotechnology cannot be viewed as a stand-alone discipline but combines several cross-cutting scientific skills.	167	5.4	12.6	20.4	34.1	27.5	3.6587	1.16563	3
11(b) Successful Nanotechnology innovations are produced by interdisciplinary teams.	167	7.2	7.8	25.7	31.1	28.1	3.6527	1.17672	4

4.3.3 Summary on critical success factor means

Figure 4.4 shows the summary mean scores of the six critical success factors. All the CSFs had a mean between 3.9356 and 4.4162. Multi- and interdisciplinarity and consumer perceptions were ranked as the top two, while R&D skills were ranked last.

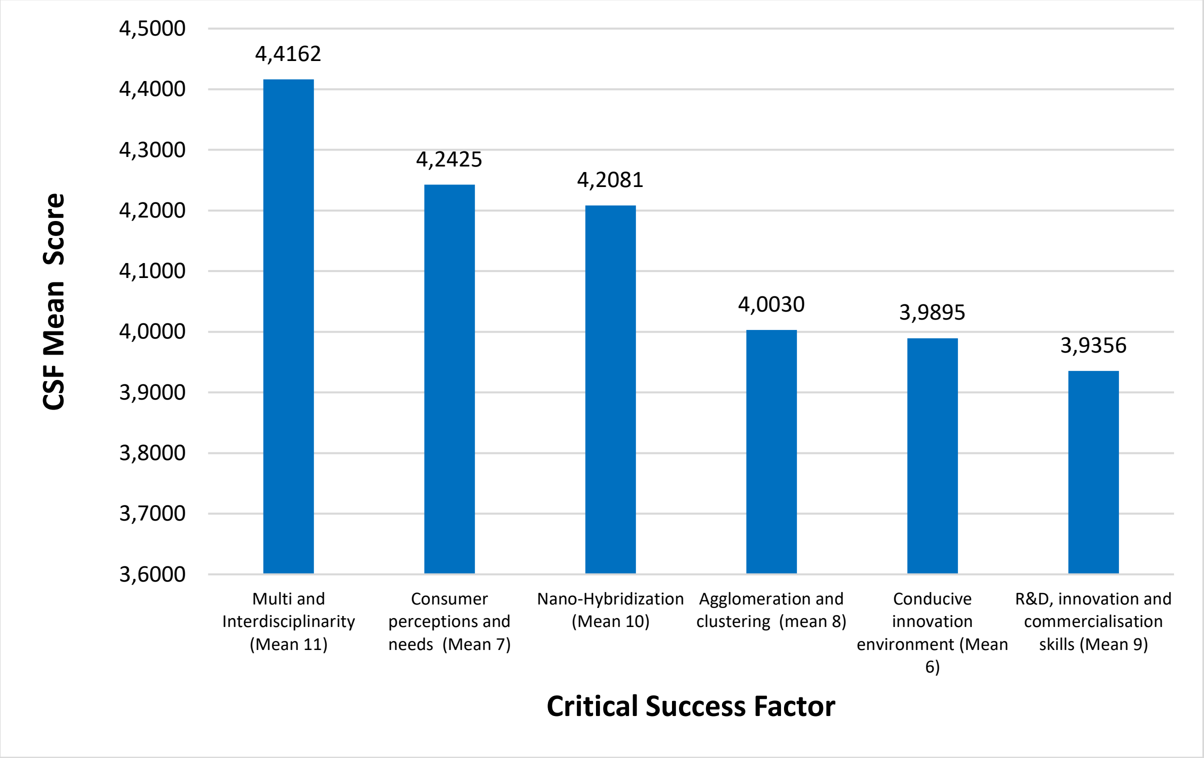


Figure 4.4: Critical success factors mean rankings

The next step was to identify if there was a statistical difference between the means of the six CSFs. Table 4.8 shows the paired-samples t-Test at a 95% confidence level for the critical success factors of nanotechnology innovation. The results were used in evaluating hypothesis 1 restated below:

Hypothesis 1: There is no statistical difference between the means of nanotechnology innovation and diamond critical success factors.

H_o: $\mu_1 = \mu_2$ (the paired population means are equal for all six CSFs)

Alternate Hypothesis 1: There is a statistical difference between the means of nanotechnology innovation and diamond critical success factors.

H_a: $\mu_1 \neq \mu_2$ (the paired population means are not equal for all six CSFs)

Table 4.8: Paired samples t-Test for critical success factors

Pair	Paired Differences					t	df	Sig. (2-tailed)	Result
	Mean Difference	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference					
				Lower	Upper				
mean6 - mean7	-0.25299	0.81310	0.06292	-0.37722	-0.12877	-4.021	166	0.000	Significant
mean6 - mean8	-0.01347	0.96171	0.07442	-0.16040	0.13346	-0.181	166	0.857	Non-significant
mean6 - mean9	0.05389	0.93586	0.07242	-0.08909	0.19687	0.744	166	0.458	Non-significant
mean6 - mean10	-0.21856	0.89895	0.06956	-0.35591	-0.08122	-3.142	166	0.002	Significant
mean6 - mean11	-0.42665	0.81787	0.06329	-0.55160	-0.30169	-6.741	166	0.000	Significant
mean7 - mean8	0.23952	0.66900	0.05177	0.13731	0.34173	4.627	166	0.000	Significant
mean7 - mean9	0.30689	0.68530	0.05303	0.20219	0.41159	5.787	166	0.000	Significant
mean7 - mean10	0.03443	0.62208	0.04814	-0.06061	0.12947	0.715	166	0.475	Non-significant
mean7 - mean11	-0.17365	0.53402	0.04132	-0.25524	-0.09207	-4.202	166	0.000	Significant
mean8 - mean9	0.06737	0.55049	0.04260	-0.01674	0.15147	1.581	166	0.116	Non-significant
mean8 - mean10	-0.20509	0.60762	0.04702	-0.29792	-0.11226	-4.362	166	0.000	Significant
mean8 - mean11	-0.41317	0.68379	0.05291	-0.51764	-0.30870	-7.809	166	0.000	Significant
mean9 - mean10	-0.27246	0.73725	0.05705	-0.38509	-0.15982	-4.776	166	0.000	Significant
mean9 - mean11	-0.48054	0.65858	0.05096	-0.58116	-0.37992	-9.429	166	0.000	Significant
mean10 - mean11	-0.20808	0.67197	0.05200	-0.31075	-0.10542	-4.002	166	0.000	Significant

Note: The yellow highlighted mean pairs have no statistically significant difference

Significance levels key

- Significant means $p < 0.05$, hence there is a statistically significant difference between the means
- Non-significant means $p > 0.05$, hence there is no statistically significant difference between the means

Pairs Key

mean6 - mean7	“Conducive innovation environment” & “Consumer perceptions and needs”
mean6 - mean8	“Conducive innovation environment” & “Agglomeration and clustering”
mean6 - mean9	“Conducive innovation environment” & “R&D, innovation and commercialisation skills”
mean6 - mean10	“Conducive innovation environment” & “Nano-Hybridization”
mean6 - mean11	“Conducive innovation environment” & “Multi and Interdisciplinarity”
mean7 - mean8	“Consumer perceptions and needs” & “Agglomeration and clustering”
mean7 - mean9	“Consumer perceptions and needs” & “R&D, innovation and commercialisation skills”
mean7 - mean10	“Consumer perceptions and needs” & “Nano-Hybridization.”
mean7 - mean11	“Consumer perceptions and needs” & “Multi and Interdisciplinarity”
mean8 - mean9	“Agglomeration and clustering” & “R&D, innovation and commercialisation skills”
mean8 - mean10	“Agglomeration and clustering” & “Nano-Hybridization”
mean8 - mean11	“Agglomeration and clustering” & “Multi and Interdisciplinarity”
mean9 - mean10	“R&D, innovation and commercialisation skills” & “Nano-Hybridization”
mean9 - mean11	“R&D, innovation and commercialisation skills” & “Multi and Interdisciplinarity”
mean10 - mean11	“Nano-Hybridization” & “Multi and Interdisciplinarity”

The results in Table 4.8 show that out of the 15 possible mean combinations, only four highlighted yellow pairs have statistically insignificant differences in their mean p>0.05. Most of the pairs, which is 11 pairs, have a statistically significant difference in their means. Therefore, the null hypothesis, which states that the paired population means are equal for all six CSFs is rejected, and the alternate hypothesis is accepted.

4.4 Pearson correlation analysis

This section reports on correlation analysis on the nanotechnology foresight critical success factors (CSFs) and “successful nanotechnology”.

4.4.1 Correlation between nanotechnology critical success factors

Table 4.9 presents Pearson linear correlations between the CSFs pairs. All the 15 pairs have a significant positive linear correlation with each other. Only one pair - innovation environment and agglomeration - have a weak correlation. The other 14 pairs have a moderate to strong correlation with each other.

Table 4.9: Paired Pearson correlations between the critical success factors

Pair	Correlation Test Means	N	Correlation (r)	Sig.(p)	Level of Correlation
1	“Conducive innovation environment” & “Consumer perceptions and needs”	167	0.344	0.000	Moderate correlation
2	“Conducive innovation environment” & “Agglomeration and clustering”	167	0.280	0.000	Weak correlation
3	“Conducive innovation environment” & “R&D, innovation and commercialisation skills”	167	0.380	0.000	Moderate correlation
4	“Conducive innovation environment” & “Nano-hybridisation”	167	0.369	0.000	Moderate correlation
5	“Conducive innovation environment” & “Multi and interdisciplinarity”	167	0.378	0.000	Moderate correlation
6	“Consumer perceptions and needs” & “Agglomeration and clustering”	167	0.545	0.000	Strong correlation
7	“Consumer perceptions and needs” & “R&D, innovation and commercialisation skills”	167	0.607	0.000	Strong correlation
8	“Consumer perceptions and needs” & “Nano-hybridisation”	167	0.612	0.000	Strong correlation
9	“Consumer perceptions and needs” & “Multi and interdisciplinarity”	167	0.588	0.000	Strong correlation
10	“Agglomeration and clustering” & “R&D, innovation and commercialisation skills”	167	0.780	0.000	Strong correlation

Pair	Correlation Test Means	N	Correlation (r)	Sig.(p)	Level of Correlation
11	“Agglomeration and clustering” & “Nano-hybridisation”	167	0.699	0.000	Strong correlation
12	“Agglomeration and clustering” & “Multi and interdisciplinarity”	167	0.547	0.000	Strong correlation
13	“R&D, innovation and commercialisation skills” & “Nano-hybridisation”	167	0.601	0.000	Strong correlation
14	“R&D, innovation and commercialisation skills” & “Multi and interdisciplinarity”	167	0.649	0.000	Strong correlation
15	“Nano-Hybridization” & “Multi and interdisciplinarity”	167	0.561	0.000	Strong correlation

Correlation Level Key

- 1 < | r | < .3 … small / weak correlation
- .3 < | r | < .5 … medium / moderate correlation
- .5 < | r | ……… large / strong correlation

4.4.2 Correlations between critical success factors and successful nanotechnology

Table 4.10 shows the correlation results between the CFSs and “successful nanotechnology”. The results indicate that all the six CSFs have a statistically significant positive linear correlation to “successful nanotechnology”.

Table 4.10: Paired correlations between the “Successful nanotechnology” and “CSFs”

Pair	Correlation Test Means	N	Correlation (r)	Sig.(p)	Level of Correlation
1	“Successful Nanotechnology” & “Conducive innovation environment”	167	0.552	0.000	Strong correlation
2	“Successful Nanotechnology" & “Consumer perceptions and needs”	167	0.475	0.000	Medium correlation
3	“Successful Nanotechnology” & “Agglomeration and clustering”	167	0.323	0.000	Medium correlation
4	“Successful Nanotechnology” & “R&D, innovation and commercialisation skills”	167	0.331	0.000	Medium correlation
5	“Successful Nanotechnology” & “Nano-hybridisation”	167	0.396	0.000	Medium correlation
6	“Successful Nanotechnology” & “Multi and interdisciplinarity”	167	0.337	0.000	Medium correlation

Correlation Level Key

- 1 < | r | < 0.3 … small / weak correlation
- 0.3 < | r | < 0.5 … medium / moderate correlation
- 0.5 < | r | ……… large / strong correlation

4.5 Confirmatory factor analysis (CFA)

This section discusses how CFA was carried out to validate the proposed Nanotechnology Innovation Diamond model. AMOS Graphic version 26 was utilised to assess the proposed model's validity based on CFA model fit indicators.

4.5.1 Reliability and validity of measurement

Reliability analysis is done to ascertain if a model reliably measures the intended latent construct. Before processing with CFA model fit, reliability and validity were evaluated by Cronbach's alpha and the composite reliability (CR). The minimum acceptable value of Cronbach's alpha is > 0.7 and composite reliability is CR > 0.6 (Connell, 1987). Table 4.11 below shows that all the constructs met the minimum reliability requirements.

Table 4.11: CFA construct reliability analysis results

Latent Construct	Cronbach's Alpha (>0.7)	Composite Reliability (>0.6)
Successful nanotechnology	0.847	0.848
Conducive innovation environment	0.733	0.753
Consumer perceptions of nanotechnology	0.759	0.733
Agglomeration and clustering	0.746	0.720
R&D, innovation and commercialisation capabilities	0.786	0.754
Nano hybridisation	0.701	0.749
Multi and interdisciplinary	0.762	0.676

4.5.2 CFA model fit indices

There is a large number of CFA fit indices, which leads to two challenges. To begin with, there is no agreement on the fit indices to use, and the cut-off values for accepting model fit are also up for debate. The three kinds of CFA model fit indices are absolute fit indices, parsimony fit indices and incremental fit indices. Hooper, Coughlan, and

Mullen (2008) present a CFA analysis reporting guideline in which they recommend including the Chi-Square statistic, its degrees of freedom, the Root Mean Square Error of Approximation (RMSEA), the Standardised Root Mean Square Residue (SRMR), the Comparative Fit Index (CFI), and one parsimony fit index (NFI) or Tucker-Lewis Index (TLI). On the other hand, Hu and Bentler (1999) suggest a two-index reporting approach that includes three options: TLI and SRMR, RMSEA and SRMR, or CFI and SRMR.

The cut-off values for the various indices start at a low of greater than or equal to 0.80 for CFI/TLI/RNI and RMSEA less than 0.08 (Matsunaga, 2010). The upper limits for cut off are RMSEA less than 0.07, SRMR less than 0.08, and CFI/TLI/RNI greater than or equal to 0.95 (Hooper, Coughlan and Mullen, 2008; Hu and Bentler, 1999). Table 4.12 below reports the fit indices adopted to validate the proposed model.

Table 4.12: CFA Model fit indices adopted for the research

Fit Index Class	**Name**	**Model fit recommended level from literature** (Matsunaga, 2010; Hooper, Coughlan and Mullen, 2008; Fan *et al*., 1999; Marsh *et al*., 2004; Hu and Bentler, 1999; Connell, 1987)
Absolute fit indices	*Minimum Discrepancy Chi Square* *Chi-square (**X^2**)*	• P< 0.05 Good fit accept model, • P >0.05 reject model • Ignore the fit index of minimum discrepancy chi-square if the sample size obtained for the study is greater than 200
	Relative normed chi-square ***(X^2)*****/DF**	• <3 Good fit accept the model
	Goodness of Fit ***(GFI)***	• >0.9 Satisfactory fit • >0.8 Good fit accept
	Root Mean Square Error of Approximation ***(RMSEA)***	• < 0.05 Good fit accept • < 0.08 Acceptable • > 0.10 Poor fit

Fit Index Class	**Name**	**Model fit recommended level from literature** (Matsunaga, 2010; Hooper, Coughlan and Mullen, 2008; Fan *et al*., 1999; Marsh *et al*., 2004; Hu and Bentler, 1999; Connell, 1987)
	Standardised Root Mean Square Residual ***(SRMR)***	- <0.08 Satisfactory fit
Incremental fit Index	*Comparative Fit Index* ***(CFI)***	- >0.95 Satisfactory fit - >0.90 Good fit
Normed fit index	*Tucker-Lewis Index* ***(TLI)***	- >0.95 Satisfactory fit - >0.90 Good fit

4.5.3 Nanotechnology Innovation Diamond model fit analysis

The Nanotechnology Innovation Diamond comprises six CSFs that work together to form the construct of successful nanotechnology. This section reports on the CFA and validation of the proposed Nanotechnology Innovation Diamond. SPSS Amos Graphic was used for CFA to calculate standardised model fit estimates. In the standardized model, the standardized regression weights, correlation and squared multiple correlations are displayed. The section is concluded by presenting results on testing hypothesis 2 which proposed that all the six identified success factors significantly contribute to successful nanotechnology.

4.5.3.1 Non-optimised initial model

Figure 4.5 below shows the initial non-optimised model and how the six CSFs interact to result in successful nanotechnology.

Source: Synthesised by the researcher.

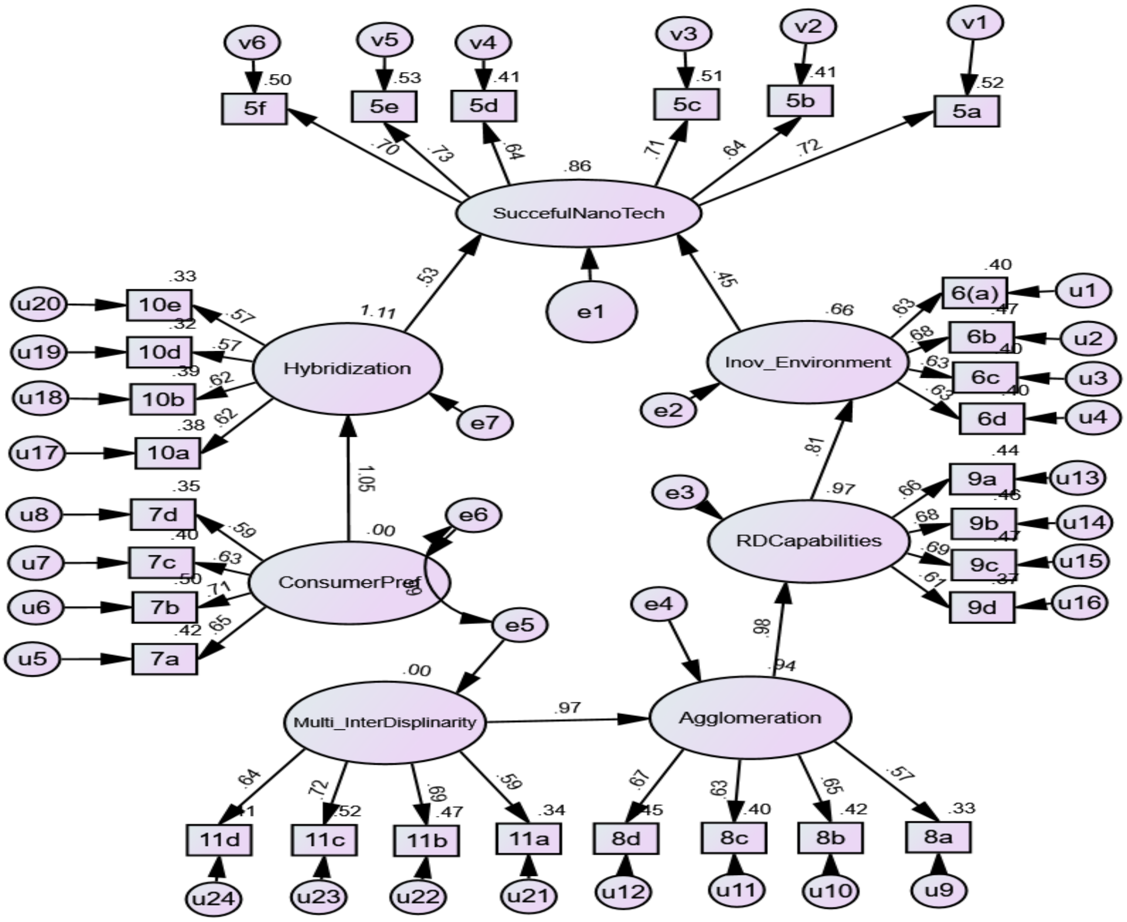


Figure 4.5: Nanotechnology Innovation Diamond non-optimised model

Table 4.13 below shows the model fit indices evaluation for the non-optimised initial model. The model showed a good acceptable fit; however, AMOS Graphic was used to further improve the fit indices by looking at construct correlations.

Table 4.13: Model fit indices for non-optimised model

Chi-Square (X^2)	Degrees of Freedom (DF)	*P (<0.05)*	*(X^2)/DF* (<3.0)	GFI (>0.80)	RMSEA (<0.08)	SRMR (<0.08)	TLI (>0.90)	CFI (>0.90)	Comment
522.963	398	0.000	1.314	0.832	0.043	0.064	0.937	0.942	1. All set fit criteria achieved 2. Model fit was achieved based on two-index criteria (Hu and Bentler, 1999)

4.5.3.2 Optimised final model

The optimised Nanotechnology Innovation Diamond model is shown in Figure 4.6.

Source: Synthesised by the researcher

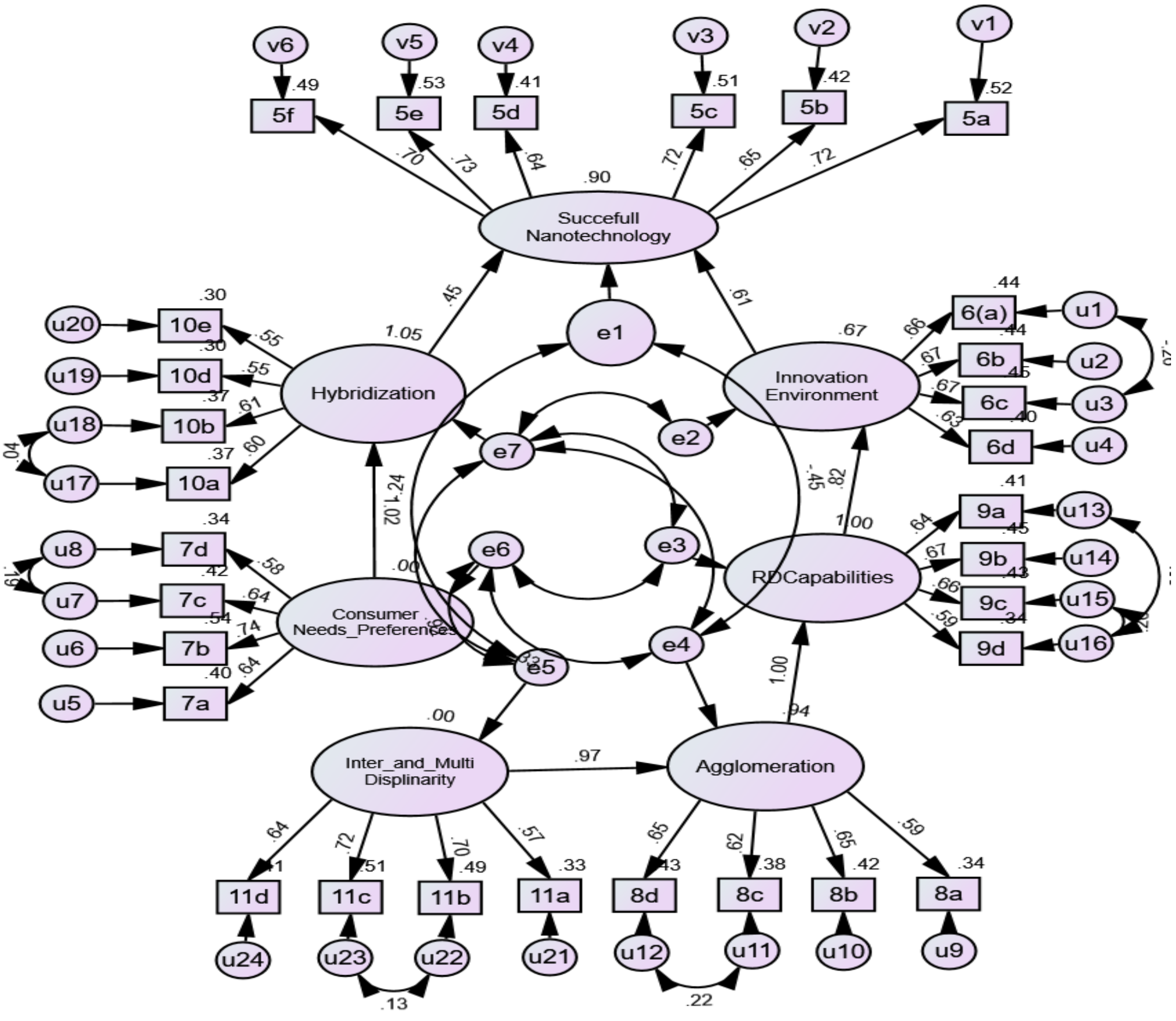


Figure 4.6: Nanotechnology Innovation Diamond optimised model

Table 4.14 shows the model fit indices for the optimised model. The results show that after optimisation and adding the correlations, the model has improved fit performance as compared to the non-optimized model.

Table 4.14: Model fit indices for Nanotechnology Innovation Diamond optimised model

Chi-Square (X^2)	Degrees of Freedom (DF)	*P (<0.05)*	(X^2)/DF (<3.0)	CFI (>0.80)	RMSEA (<0.08)	SRMR (<0.08)	TLI (>0.90)	CFI (>0.90)	Comment
464.068	383	0.003	1.212	0.850	0.036	0.059	0.957	0.962	1. Model fit achieved based on set criteria, 2. Model fit is achieved based on two-index criteria (Hu and Bentler, 1999).

The next step was to determine if all the six critical success factors had a statistically significant contribution to successful nanotechnology according to hypothesis 2.

Null hypothesis 2: The six critical success factors proposed by the Nanotechnology Innovation Diamond are not significant for a successful nanotechnology research and development model.

Alternate hypothesis 2: The six critical success factors identified by the Nanotechnology Innovation Diamond are significant for a successful nanotechnology research and development model.

The relationship between the six factors shown in Figure 4.6 was analysed, and the results are reported in Table 4.15 below which presents the standardised regression estimates (SE), the critical ratio (CR) and the p-value (P) between the critical success factors as proposed in the Nanotechnology Innovation Diamond.

Table 4.15: Regression weights between success factors in the model

Nanotechnology Innovation Diamond			S.E	C.R	P	Result / Conclusion
Multi & Interdisciplinarity	→	Agglomeration	0.162	5.861	***	Significant
Agglomeration	→	R&D Capabilities	0.176	6.669	***	Significant
Consumer needs	→	Market Hybridisation	0.141	6.773	***	Significant
R&D Capabilities	→	Conducive Innovation Environment	0.124	6.617	***	Significant
Conducive Innovation Environment	→	Successful Nanotechnology	0.162	3.900	***	Significant
Market Hybridisation	→	Successful Nanotechnology	0.156	3.422	***	Significant

An evaluation of the level of significance of the relationship between the factors was based on the critical ratio (CR) of the regression estimate (Byrne, 2013), with CR > 2.58 indicating a 99% level of significance. Based on the analysis results in Table 4.15, each factor contributed significantly to the Nanotechnology Innovation Diamond model in Figure 4.6. A p-value = (***) indicates a highly significant relationship $p < 0.001$; therefore, null hypothesis 2 is rejected, and alternate hypothesis 2 is accepted.

These results demonstrate that the Nanotechnology Innovation Diamond model achieves minimal criteria for the CFA model fit requirements. Therefore, the six identified CSFs make a statistically significant contribution to the success of nanotechnology R&D, innovation and technology transfer.

In the model, consumers' needs lead to hybridization between nanotechnologies and existing socioeconomic needs, resulting in industries such as nano-textiles, nanoelectronics, nanocosmetics, nanomedicine, and nanoagriculture. In nanotechnology, the need for interdisciplinary teams and establishing partnerships with other economic sectors make the agglomeration/clustering of nanotechnology

R&D vital. This clustering of institutions will improve nanotechnology research and commercialisation capabilities. Companies gain from clusters because of expert-knowledge spillover effects across firms, industry alliances, sharing technical knowledge, localised specialised equipment, and skilled workforce availability. Finally, it is critical to operate in an environment that promotes innovation, such as the Triple Helix, a model that supports public-private collaborations in R&D to harness resources and talents.

The covariance analysis of the residual values for the latent contracts denoted by values e1 to e7 in Figure 4.6 shows that only three latent construct relationships have a statistically significant covariance at 95% confidence level. These three covariances are discussed below.

Significant covariance 1: e6←→e5: There is a statistically significant covariance between "Consumer needs and preferences" and "Multidisciplinary skills in nanotechnology" and a strong positive linear correlation of 0.588. The possible explanation could be that, as more disciplines understand and participate in nanotechnology, consumers also become aware of the benefits derived from nanotechnology, hence driving consumer needs and acceptance of nanotechnology products.

Significant covariance 2: e7 ←→e5: There is a statistically significant covariance between "Market hybridisation" and "Multidisciplinary skills in nanotechnology" and a strong positive linear correlation of 0.561. The possible explanation is that as more disciplines gain skills and competence in nanotechnology, such as scientists from medicine, biotechnology, and electronics, they take back the skills to their research and industry domains. Hence, nanotechnology will hybridise with these existing industries, creating nanomedicine, nanobiotechnology, and nanoelectronics, among others. Therefore, as nanotechnology becomes more interdisciplinary, more enterprises are created that use nanotechnology.

Significant covariance 3: e7 ←→e4: There is a statistically significant covariance between “Market hybridisation” and “Agglomeration in nanotechnology” and a strong positive linear correlation of 0.699. Agglomeration results from different companies working together in a cluster or single location. The cluster results in knowledge transfer and skills; hence, as cross-pollination of ideas happen in a cluster where different technological industries are located, the benefits of nanotechnology are identified by other sectors. Therefore, it becomes incorporated into their products and services since nanotechnology is a general-purpose technology. For example, if a cosmetics company, an energy company, and a nanotechnology company are located in a single cluster, a discovery in nanotechnology focusing on selective solar absorber materials can be adopted by the cosmetics company in producing sunscreen creams and at the same time adopted by the energy company in making selective solar absorbers. Hence, nanotechnology will be hybridised into nanocosmetics and nanoenergy through knowledge spillovers occurring in the cluster.

4.6 Analysis of nanotechnology publications from South Africa

The results of the scientometric analysis of nanotechnology academic publications from South Africa are presented in this section. The research done in this subsection aimed to provide a foresight viewpoint on nanotechnology in South Africa based on the tech-mining of nanotechnology publications released between 2000 and 2019.

The first stage in performing a technology-foresight study is to scan the research environment and gain a thorough understanding of significant scientific and technological advances and major research domains and alternatives. The second phase in the foresight process is to identify major stakeholders who would be engaged during the foresight exercise. As a third step in foresight, the generation phase analyses and evaluates identified research areas and determines favourable futures supporting socioeconomic development. The foresight steps described above were conducted based on publication analysis, and they are reported in this section.

4.6.1 South Africa nanotechnology publication trends

Table 4.16 summarises the trends in nanotechnology publishing in South Africa from 2000 to 2019 from the Web of Science Core Collection database. There were 68 publications in 2000 which increased to 1672 publications in 2019, showing a 2458% growth rate. In contrast, total publications for all disciplines rose from 4950 in 2000 to 25163 in 2019, which is an increase of only 508%. Hence, the growth of nanotechnology-related research publications outpaced that of all other areas, as shown in Figure 4.7 below.

Table 4.16: Nanotechnology publication trend for South Africa

Year	Nanotech Publications	Total Publications	Nanotech Share %	Annual Nanotech Growth %
2000	68	4950	1.4%	
2001	83	4979	1.7%	22%
2002	84	5384	1.6%	1%
2003	96	5156	1.9%	14%
2004	135	5767	2.3%	41%
2005	163	6062	2.7%	21%
2006	170	6955	2.4%	4%
2007	245	8138	3.0%	44%
2008	276	8931	3.1%	13%
2009	337	9881	3.4%	22%
2010	417	10218	4.1%	24%
2011	476	11686	4.1%	14%
2012	628	13652	4.6%	32%
2013	726	14104	5.1%	16%
2014	830	15422	5.4%	14%
2015	983	20044	4.9%	18%
2016	1199	21982	5.5%	22%
2017	1289	22946	5.6%	8%
2018	1388	23782	5.8%	8%
2019	1672	25163	6.6%	20%
Total	**11265**	**245202**		

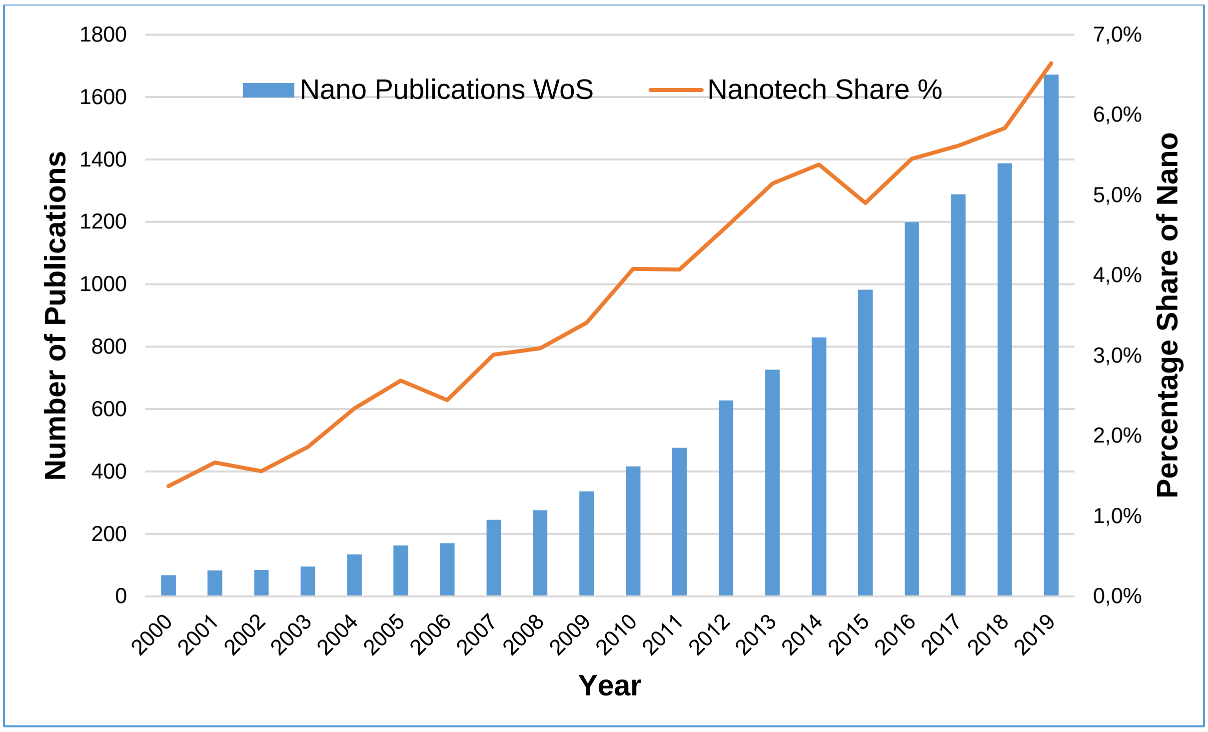


Figure 4.7: South Africa nanotechnology publications

Figure 4.7 indicates that the overall contribution of nanotechnology articles rose from 1.4% in 2000 to 6.6% in 2019, representing a 0.52% annual growth. These results suggest that nanotechnology research in South Africa grew exponentially from 2000 to 2019. This agrees with results reported in literature (Islam and Miyazaki, 2009).

4.6.2 South Africa nanotechnology output compared to BRICS

There are five leading emerging economies: Brazil, India, China, and South Africa. These five are collectively known as BRICS countries. The performance of South Africa in nanotech R&D was evaluated against that of the BRICS countries using the nanotechnology activity index. Rousseau (2018) defines the activity index (AI) as the ratio between the country's share of publication output in an area and its share of worldwide publications. The world activity index is assumed to be one (1); so, the AI of country X over period P can be approximated by equation (4.1).

$$AI\ (Nano, Country\ X) = \frac{Country\ X\ ratio\ of\ nanopublications\ in\ period\ P}{World\ ratio\ of\ nanopublications\ in\ period\ P} \quad (4.1)$$

In Table 4.17, South Africa's performance is compared to BRICS countries over 20 years and in a 1-year snapshot.

Table 4.17: South Africa nanotechnology publications compared to BRICS

20-Year Period 2000 - 2019					1-Year Period 2019				
Country	Nano Publications	Total WoS	Nano Ratio	Activity Index	Country	Nano Publications	Total WoS	Nano Ratio	Activity Index
World	2 718 619	40 331 494	0.067	1.00	World	260675	3168362	0.082	1.00
China	664 787	4 939 513	0.135	2.00	China	94059	607574	0.155	1.88
India	165 351	1 312 591	0.126	1.87	India	22399	140491	0.159	1.94
Russia	93 394	876 138	0.107	1.58	Russia	9447	91764	0.103	1.25
Brazil	45 656	874 857	0.052	0.77	Brazil	5211	87818	0.059	0.72
South Africa	11 264	245 202	0.046	0.68	South Africa	1672	26190	0.064	0.78

In the last 20 years, South Africa, with an activity index of 0.68, had the lowest productivity in nanotechnology amongst the BRICS countries. With an AI of 2.0, China had the highest nanotech productivity amongst BRICS nations. Even if one considers only a single year (2019), the situation remains roughly the same: South Africa ranks second from the bottom with an AI of 0.78, while India and China remain the most productive countries. These findings suggest that South Africa can gain from working with the more productive BRICS nations. South Africa can benchmark on R&D infrastructure, education systems, innovation support systems, and policies implemented by the more productive BRICS countries so that it improves its nanotechnology productivity.

4.6.3 Institutions publishing in the nanotechnology field in South Africa

Table 4.18 outlines the most active nanotechnology research institutions in South Africa based on publications output.

Table 4.18: Nanotechnology publishing institutions in South Africa

20-Year Period 2000 – 2019				1- Year Period 2019		
Institutions	**Publications**	**Share %**		**Institutions**	**Publications**	**Share %**
1) South Africa	11 264	100 %		South Africa	1672	100%
2) University of Johannesburg	1583	14%		University of Johannesburg	355	21%
3) University of Witwatersrand	1370	12%		University of KwaZulu Natal	242	14%
4) University of KwaZulu Natal	1286	11%		University of South Africa	202	12%
5) Council Scientific & Industrial Research (CSIR)	1044	9%		National Research Foundation (iThembaLABS)	165	10%
6) University of Pretoria	959	9%		University of Witwatersrand	152	9%
7) University of Free State	940	8%		University of Pretoria	134	8%
8) University of Stellenbosch	905	8%		University of The Free State	129	8%
9) University of South Africa	867	8%		Tshwane University of Technology	118	7%
10) National Research Foundation (iThembaLABS)	789	7%		Council Scientific & Industrial Research (CSIR)	116	7%
11) University of Cape Town	748	7%		University of the Western Cape	105	6%
12) Rhodes University	665	6%		North West University South Africa	92	6%
13) University of the Western Cape	642	6%		University of Stellenbosch	80	5%
14) Tshwane University of Technology	494	4%		University of Cape Town	79	5%
15) North West University	492	4%		Rhodes University	62	4%
16) Nelson Mandela University	327	3%		Durban University of Technology	56	3%

20-Year Period 2000 – 2019			1- Year Period 2019		
Institutions	**Publications**	**Share %**	**Institutions**	**Publications**	**Share %**
17) University of Zululand	260	2%	Nelson Mandela University	55	3%
18) Durban University of Technology	206	2%	University of Zululand	42	3%
19) Vaal University of Technology	174	2%	Vaal University of Technology	33	2%
20) University of Fort Hare	142	1%	University of Fort Hare	31	2%
21) Cape Peninsula University of Technology	121	1%	University of Limpopo	19	1%
22) MINTEK	87	1%	University of Venda	17	1%
23) University of Limpopo	82	1%	Cape Peninsula University of Technology	16	1%
24) University of Venda	75	1%	Sefako Makgatho Health Sciences University	11	1%
25) SASOL Technology	24	0.21 %	National Institute of Theoretical Physics (NITheP)	11	1%

Table 4.18 shows that universities account for the bulk of publications. With 14%, the University of Johannesburg is the most prolific publisher, followed by the University of the Witwatersrand (12%) and the University of KwaZulu-Natal (11%).

National research facilities, consisting of just three institutions: the Council for Scientific and Industrial Research (CSIR), iThembaLABS, and MINTEK, are the second group of most productive institutions. CSIR produces 9% of all publications, making it fourth on the national ranking. Nanotechnology publications produced by iThembaLABS and MINTEK are 7% and 1%, respectively.

When the single year 2019 is compared to the last 20 years, results show that the University of South Africa, iThembaLABS and Tshwane University of Technology have increased their share of nanotechnology publications relative to other institutions. On the other hand, WITS University dropped from third to sixth place, while CSIR improved from fifth to tenth.

SASOL Technology was the only private company identified with 24 publications, which is a mere 0.21% of the total publications. These results suggest that the private sector in South Africa is not participating in nanotech R&D and innovation. The lack of industry participation can negatively influence nanotechnology innovation, commercialisation, and technology transfer for South Africa. The limited number of private sector academic articles can be attributed to several factors. Firstly, a few nanotechnology experts work in the private sector, which is evident from the survey results where only 3% of the respondents work in the industry compared to 75% who work in research and academia. In addition, only 4% of survey respondents are employed as engineers, and engineers are the ones who generally work in the industry. Secondly, in South Africa, the industry does not have an incentive to publish because the government policy does not incentivise the private sector to publish academic articles. The DHET incentive scheme only pays universities a publication subsidy. Low industry participation in scholarly publishing is also supported by Porter and Cunningham (2005a), who argue that an academic scientist or engineer is 45 times more likely to publish their research than an industrial scientist/engineer. In terms of foresight strategic planning, these findings suggest that the South African government must develop policies that support industry participation in R&D activities to promote technology transfer and uptake of innovations by industry.

4.6.4 The Hirsch-index analysis of South African nanotech publications

The H-index is a metric that measures the effectiveness of a researcher's research papers. It is a crucial scientometric indicator produced via publication analysis (Hirsch, 2005). Researchers, national R&D facilities and universities are now routinely evaluated using the H-index or its modified form, the five-year H-index, abbreviated as H5-index (Karpagam *et al.*, 2011).

By discounting disproportionate weight from highly cited publications and papers that have not been cited yet, the H-index attempts to correct for bias when measuring publications' impact. The H-index is determined by reviewing the list of publications by individuals or institutions ranked in descending order by the number of times cited. An H-index is equal to the number of papers (N) in a list with N or more citations.

The 5-year Hirsch index (H5-index) was analysed for South Africa and the top ten publishing institutions over the last five years (2015 - 2019). South African nanotechnology papers have received a total citation rate of 12.76 per paper during the previous five years, with an H5-index of 94. The 10 top publishing organisations produced articles with H5-indexes ranging from 58 to 32, with an average citation rate of 16.17 to 10.46, as indicated in Table 4.19 below.

Table 4.19: H5-index for top ten South Africa nanotechnology publishing institutions 2015 - 2019

Institutions	H5-index	Average Citations per item
South Africa	94	12.76
1. University of Johannesburg	58	16.17
2. University of South Africa	55	14.54
3. National Research Foundation (iThemba Labs)	45	15.55
4. Council Scientific & Industrial Research (CSIR)	44	14.88
5. University of KwaZulu-Natal	43	10.89
6. University of Witwatersrand	40	11.21
7. University of Cape Town	39	15.92
8. University of Pretoria	38	11.66
9. University of Stellenbosch	34	13.22
10. University of Free State	32	10.46

4.6.5 South Africa's most prolific nanotech authors

The top ten authors for nanotechnology papers in South Africa are shown in Table 4.20.

Table 4.20 Top ten researchers (authors/co-author) for nanotechnology publications in South Africa

20-Year Period 2000 – 2019				1-Year Period 2019		
Researcher Name	Number of Publications	Share %		Researcher Name	Number of Publications	Share %
1) NYOKONG T	445	3.95%		1) MAAZA M	56	3.35%
2) SWART HC	388	3.44%		2) SWART HC	45	2.69%
3) MAAZA M	326	2.89%		3) NYOKONG T	39	2.33%
4) RAY SS	260	2.31%		4) RAY SS	34	2.03%
5) GUPTA VK	178	1.58%		5) VAN DER BRUGGEN B	34	2.03%

20-Year Period 2000 – 2019				1-Year Period 2019		
Researcher Name	**Number of Publications**	**Share %**		**Researcher Name**	**Number of Publications**	**Share %**
6) COVILLE NJ	172	1.53%		6) OLUBAMBI PA	33	1.97%
7) NTWAEABORWA OM	167	1.48%		7) KAVIYARASU K	27	1.61%
8) REVAPRASADU N	166	1.47%		8) EZEMA FI	26	1.56%
9) MAMBA BB	153	1.36%		9) DEJENE FB	25	1.50%
10) EBENSO EE	151	1.34%		10) MAMBA BB	22	1.32%
Total percentage contribution		**21.35%**		**Total percentage contribution**		**20.39%**

Based on the WoS core collection South Africa had 30 614 researchers who authored or co-authored a total of 11 265 articles related to nanotechnology between 2000 and 2019. One would expect the publications to be evenly distributed among these authors, but, in contrast, the top 10 authors listed below account for 21.35% of all articles published. One finds that the result remains the same even when the single year of 2019 is considered. In the year 2019, 20.39 % of the total publications were also contributed by the top ten researchers. This result is also in line with Lotka's Law (Phillips, 2013), which states that the distributions of scientific publications are substantially asymmetrical. Leaders tend to produce large amounts of articles, whilst the remainder appears in "ones and twos".

When the names of authors/co-authors are analysed for the last 20 years compared to the 2019 one-year snapshot, one finds that the top four authors have not changed. On the other hand, some new names are emerging in the list of top authors. One can observe that the system is playing host to both new researchers and researchers with years of experience. This combination of old and new authors/co-authors is important in nanotechnology foresight and strategic planning because it shows continuity and succession management within the system.

4.6.6 South Africa's international nanotechnology collaborations

South Africa's cooperation with other countries was analysed based on its co-authorships with other countries. Figure 4.8 shows the top 20 nations with which South Africa collaborates. With 1241 (11%) publications, India is South Africa's most prominent collaborator, followed by the USA which produced 919 (8.2%) co-authored articles with South Africa. Nigeria is South Africa's most prolific collaborator among African countries, with 585 academic papers.

When the single year 2019 analysis is done, one finds that India remained South Africa's biggest collaborating partner. On the other hand, Nigeria was ranked number two in 2019 and Botswana was number 16. These figures suggest an increase in intra-Africa nanotechnology collaboration for South Africa. Another point to note is that, in comparison to the preceding two decades, South Africa's cooperation with the BRICS nations grew in 2019. According to this research, Russia, a member of the BRICS, is ranked 17th among the top 20 nations in 2019, but it did not feature on the top 20 list in the last two decades analysis. This can be explained by the initiatives made under the BRICS international collaboration.

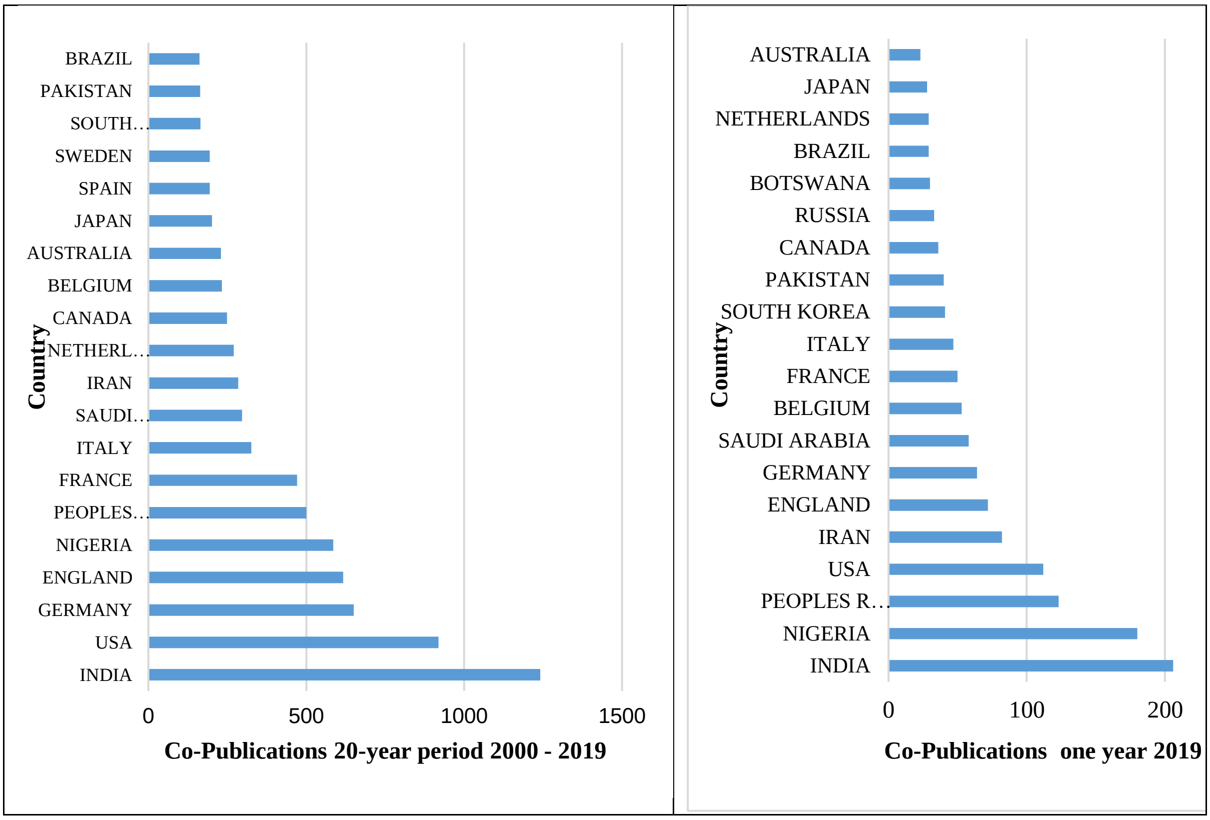


Figure 4.8: South Africa nanotechnology international collaborations

4.6.7 Nanotech subject focus areas for South Africa

The Web of Science subject classification system was utilised to analyse the different subject areas in which South Africa is involved. Presented below, Table 4.21 lists the top 20 subject areas for nanotechnology R&D publications in South Africa.

Table 4.21: South African nanotechnology papers by subject area

20-year period 2000 - 2019				1- year period 2019		
Subject Area	**Publications**	**Share %**		**Subject Area**	**Publications**	**Share %**
1) Chemistry	3832	34.02		Chemistry	577	34.51
2) Materials Science	2733	24.26		Materials Science	434	25.96
3) Physics	2558	22.71		Physics	316	18.90
4) Engineering	1358	12.06		Engineering	308	18.42
5) Science Technology Other Topics	1259	11.18		Science Technology Other Topics	252	15.07
6) Electrochemistry	637	5.66		Electrochemistry	80	4.78
7) Polymer science	610	5.42		Environmental Sciences Ecology	75	4.49

20-year period 2000 - 2019				1- year period 2019		
Subject Area	**Publications**	**Share %**		**Subject Area**	**Publications**	**Share %**
8) Biochemistry Molecular Biology	464	4.12		Polymer Science	71	4.25
9) Optics	355	3.15		Energy Fuels	62	3.71
10) Environmental Sciences Ecology	354	3.14		Biochemistry Molecular Biology	59	3.53
11) Pharmacology Pharmacy	324	2.88		Pharmacology Pharmacy	59	3.53
12) Energy Fuels	291	2.58		Optics	46	2.75
13) Crystallography	277	2.46		Metallurgy Metallurgical Engineering	44	2.63
14) Metallurgy Metallurgical Engineering	253	2.25		Biotechnology Applied Microbiology	27	1.61
15) Biotechnology Applied Microbiology	216	1.92		Instruments Instrumentation	27	1.61
16) Water Resources	169	1.50		Thermodynamics	27	1.61
17) Instruments Instrumentation	161	1.43		Mechanics	25	1.50
18) Thermodynamics	145	1.29		Water Resources	23	1.38
19) Genetics Heredity	143	1.27		Crystallography	22	1.32
20) Biophysics	137	1.22		Computer Science	21	1.26

Chemistry is the most dominant subject, accounting for over 34% of publications. In the last two decades, chemistry, materials science, physics, and engineering were the top four subjects with a contribution of 93.05% publications. When one-year 2019 is considered, these four subjected accounted for 95.34% output.

When viewed from a 1-year window, it becomes evident that computer science, which had not previously been listed among the 20 most prolific subjects publishing in nanotech, is now among the top disciplines. In the year 2019, computer science contributed 1.26% of publications. The fact that computer science now ranks among the top twenty subjects in publications on nanotechnology may indicate a convergence of nanotechnology and computing science, for example, in areas such as artificial intelligence (AI), machine learning, and the drive towards a fourth industrial revolution (4IR). Computer science publications on nanotechnology can also indicate convergence in nanotechnology (Roco, 2020). Nevertheless, there must be further investigations in the South African context to determine the extent and existence of the convergence of nanotechnology, biotechnology, information technology, cognitive sciences, and artificial intelligence (NBICA).

4.6.8 A foresight analysis of South Africa's nanotechnology research areas

The discipline of technology foresight is centred around systematically considering the longer-term futures of science, technology, the economy, and society to identify and develop the strategic emerging research areas that are most likely to result in socio-economic development in the medium to long term period (Martin, 1995). In this research, possible research areas were generated from the analysis of South Africa’s National Development Plan (NDP) Vision for 2030 (Department of Trade & Industry - South Africa, 2015), the 10-Year National Innovation Plan (DST, 2007), and the Nanotechnology Strategy 2006 (DST, 2005). Combining nanotechnology subfields found in literature and the above-mentioned government policy documents, the following possible socio-economic relevant nanotechnology research areas were identified: water, energy, communicable diseases, sensors, textiles, nanofibers, magnetism, nanotools, photoluminance, biotechnology, catalysis, material science, mining, automotive, nanofluids, medicine, agriculture, optics, electronics, food, and cosmetics.

In order to determine if the above-mentioned research areas exist in the South African nanotechnology publications, related research has to be classified and categorised together. On the other hand, since nanotechnology is an emerging research area, a method of categorising nanotechnology research is not yet well developed, so there is no readily available look-up database for categorising nanoscience research areas (Tanaka, 2013). There was an attempt by Tanaka (2013) to formulate a classification system, but it is not comprehensive. It just gives science disciplines, for example, nanophysics, nanochemistry, and nanoengineering, which is almost the same as those in WoS. Vantage Point was used to create an automatic categorisation protocol for nanotechnology publications using the thesaurus function and relevant keywords for each research area. Detailed search term classification developed for this research is provided in Appendix 3.

The South African publications were automatically grouped into the foresight research areas based on the developed algorithm. The developed algorithm uses a one-to-many mapping. Hence in using this system, papers can span more than one research area; for instance, an article on photovoltaics can sometimes also belong to electronics, and a paper on biotechnology can sometimes also belong to medicine.

4.6.8.1 Foresight-oriented research areas for South Africa

According to research publications output shown in Table 4.22 below, the top research areas in nanoscience in South Africa over the past 20 years were nanomaterials (25%), photoluminescence and optics (19%), and nanomedicine (18%). Only 3% of nanoscience research output focuses on water and 2% on infectious diseases.

Table 4.22: South Africa's prominent research areas

20-Year Period 2000 – 2019				1-Year Period 2019		
Nanotechnology Research Area	Number of Publications	Ratio		Nanotechnology Research Area	Number of Publications	Ratio
1) Materials	2845	25%		1) Materials	415	25%
2) Photoluminance & Optics	2172	19%		2) Photoluminance & Optics	367	22%
3) Medicine	2008	18%		3) Medicine	329	20%
4) Catalysis	1606	14%		4) Catalysis	287	17%
5) Electronics	1390	12%		5) Electronics	237	14%
6) Biotech	1021	9%		6) Biotech	194	12%
7) Energy	655	6%		7) Energy	135	8%
8) Magnetism	587	5%		8) Sensors	102	6%
9) Sensors	553	5%		9) Magnetism	99	6%
10) Water	328	3%		10) Water	79	5%
11) Communicable Diseases	243	2%		11) Engineering Applications	38	2%

Comparing the 20-year history to the recent one year, 2019, a snapshot of top research areas shows that the leading research areas are not significantly different. However, in the last one-year, 2019, engineering applications of nanotechnology now appear in the top research areas accounting for 2% of output. The list of potential strategic research areas for South Africa initially included food, textiles, and automotive research, but each of these other fields had contributions that were less than 0.05%. Therefore, these research areas with a tiny contribution were not analysed further in this research.

4.6.9 Experts in the top research areas of South Africa

Nanotechnology experts need to be mobilised and engaged early in any foresight process, and this should be done in advance of developing the identified strategic research area for South Africa. Table 4.23 lists the top 10 nanotechnology experts based on the number of publications they produced per research area. Table 4.23

shows the top three researchers per field highlighted in yellow. One can also see the top publishers per research area; for example, Ray Suprakas is the most prolific publisher in materials, Nyokong Tebello in medicine, while Maaza Malik in electronics and energy, and Mamba Bhekie for water research. When it comes to photoluminance and optics, it is Swart Hendrik. In preparation for further consultations, nanotech foresight planners can use Table 4.23 to assemble teams of experts in each field.

Table 4.23: Top ten most active nanotechnology researchers in South Africa

South Africa Research Area	Researcher Name									
	Nyokong, Tebello	Maaza, Malik	Swart, Hendrik C	Gupta, Vinod Kumar	Ray, Suprakas Sinha	Kasinathan, Kaviyarasu	Agarwal, Shilpi	Ntwaeaborwa, Odireleng M	Covill, Neville J	Mamba, Bhekie Brilliance
Materials	107	116	55	68	150	31	30	17	47	71
Photoluminance & Optics	87	185	309	25	47	56	13	149	15	13
Medicine	98	48	17	25	29	27	17	9	2	12
Catalysis	123	39	14	53	35	36	25	3	67	43
Electronics	30	60	26	4	27	9	3	8	21	11
Biotech	35	23	6	13	11	14	6	0	0	8
Energy	23	45	16	1	6	11	0	8	6	2
Magnetism	41	19	8	7	34	3	6	3	17	10
Sensors	20	18	11	19	7	7	7	4	7	10
Water	1	0	1	18	12	0	7	0	0	36

Note: The top three researchers per research area are highlighted in yellow

4.6.10 Areas of specialisation by South African research institutions

Any planning process that seeks to develop a foresight strategy should include the participation of institutions as stakeholders. One can identify these stakeholders based on their publications output. The top publishing organisations per research area are shown in Table 4.24. The top three institutions are highlighted in yellow and the most prolific publishing organisation in red text. For example, foresight planners can identify possible stakeholders for nanomedicine are the University of KwaZulu Natal, the University of Witwatersrand and the University of Cape Town; then for photoluminance and optics, the University of Free State, and for electronics, the University of Pretoria.

Table 4.24: Research focus areas in South African institutions based on publications during 2000-2019

	Institution Name														
South Africa Research Area	University of Johannesburg	University of Witwatersrand	CSIR	University of KwaZulu Natal	University of Free State	University of Stellenbosch	University of Pretoria	University of Western Cape	University of Cape Town	University of South Africa	Tshwane University of	North West University of	Rhodes University of	Nelson Mandela University of	iThemba LABS
Materials	**555**	371	368	295	232	169	153	149	92	257	186	118	171	100	87
Catalysis	**348**	197	168	187	60	47	78	211	91	168	42	80	142	20	49
Photoluminance & Optics	262	232	230	192	**518**	52	128	111	41	302	77	50	117	106	147
Medicine	199	255	116	**276**	55	192	181	117	240	96	65	103	170	36	41
Electronics	190	203	131	147	122	64	**221**	66	50	172	38	48	43	56	40
Magnetism	120	68	54	**128**	33	89	19	16	20	72	13	9	28	6	18
Water	**116**	30	44	13	8	13	16	7	6	53	62	11	8	6	1
Biotech	112	128	71	**156**	30	94	90	62	96	63	28	65	89	9	24
Sensors	**102**	55	68	40	29	30	44	71	26	51	29	19	45	10	12
Energy	50	70	113	86	49	17	53	**121**	21	62	26	27	31	21	34
Communicable Diseases	5	40	19	44	5	**47**	29	11	40	4	2	15	8	2	1

4.6.11 South Africa international collaborators by research area

Collaboration with other countries is crucial to foresight planning. Table 4.25 identifies South Africa's top collaborating countries by research area based on the papers the country co-authored with South Africa. Highlighted in yellow are the top collaborating countries, while the top collaborators are highlighted in red. In seven of these research areas, India is the number one cooperating country; however, in the field of medicine and communicable diseases, the top collaborating country is the United States. For energy, China is the top cooperating country, and Belgium is the top collaborating country in water research.

Table 4.25: South Africa collaboration based on co-authorship between 2000 and 2019

Area	India	USA	UK	China	Germany	Nigeria	France	Iran	Saudi Arabia	Italy	Belgium
Photoluminance & Optics	363	114	139	67	94	143	98	32	48	69	17
Materials	323	119	106	68	106	208	75	73	76	54	36
Catalysis	200	54	56	142	47	63	34	48	52	17	14
Medicine	193	290	170	62	129	70	95	37	56	47	52
Electronics	136	82	85	52	94	92	40	19	47	48	13
Magnetism	116	23	27	28	44	17	20	22	26	21	6
Biotech	111	103	71	30	44	41	25	21	24	19	15
Sensors	78	31	30	29	25	21	33	27	18	12	18
Energy	43	27	49	87	35	31	16	3	8	14	7
Water	30	33	14	28	5	17	2	22	11	2	43
Communicable Diseases	22	77	41	5	17	3	14	1	6	6	15

4.6.12 South Africa nanotechnology research area clusters

Through the agglomeration and clustering of nano-tech institutions, research networks are created, access to skilled labour is provided, and local-level tacit knowledge is shared, thereby catalysing and accelerating nanotech innovations and commercialisation. In order to reap the future commercial benefits of nanotechnology clusters in a country, foresight planning must identify and understand each cluster's characteristics. A clustering system for nanotechnology institutions in South Africa was developed utilising Vantage Point software. Table 4.26 provides a breakdown of the number of publications by field of research within South Africa's nanotechnology research clusters. Yellow highlights the top two clusters for a particular research area, while red highlights the most prolific group. In Table 4.26, one can see that the Western Cape and Johannesburg are the best locations to develop nanomedicine; the KwaZulu-Natal region for communicable diseases research and Pretoria for nanoelectronics.

Table 4.26: Research clusters and their areas of focus in nanotechnology in South Africa

Area	**Pretoria**	**Johannesburg**	**Western Cape**	**Free State**	**KwaZulu Natal**	**North West**	**Eastern Cape**	**Limpopo**
Materials	865	**896**	571	242	452	145	237	38
Photoluminance & Optics	**692**	483	447	519	322	65	202	14
Medicine	414	457	**693**	55	342	121	189	41
Catalysis	394	**537**	440	104	221	105	135	22
Electronics	**504**	374	312	126	184	56	89	9
Biotech	225	240	**301**	30	202	73	90	24
Energy	**224**	116	209	50	102	36	46	24
Magnetism	135	174	**182**	38	145	12	32	8
Sensors	**163**	**163**	160	30	67	22	50	13
Water	**150**	140	45	10	30	12	12	11
Communicable Diseases	46	47	**101**	5	51	15	10	3

4.6.13 Degree of collaboration in South Africa's research areas

Teams made up of individuals from different functions or disciplines are considered a key success factor for successful technological innovation (Torkkeli and Tuominen, 2001; Connel *et al.*, 2001). Science policymakers frequently stress the importance of interdisciplinarity in nanoscale research (Schummer, 2004). The USA nanotechnology policy (Battard, 2012) and the South African nanotechnology policy (DST South Africa, 2006) both encourage more interdisciplinary research collaborations.

Analysis of co-authorship by individuals and organisations was used to evaluate collaborations in South Africa's research areas. Figure 4.9 illustrates the extent of co-authorship by research area. Three or four authors co-author most papers; only 2% are by single authors. Bimodal co-authorship distribution is observed. 19% of the papers have three co-authors, and another 19% have four co-authors.

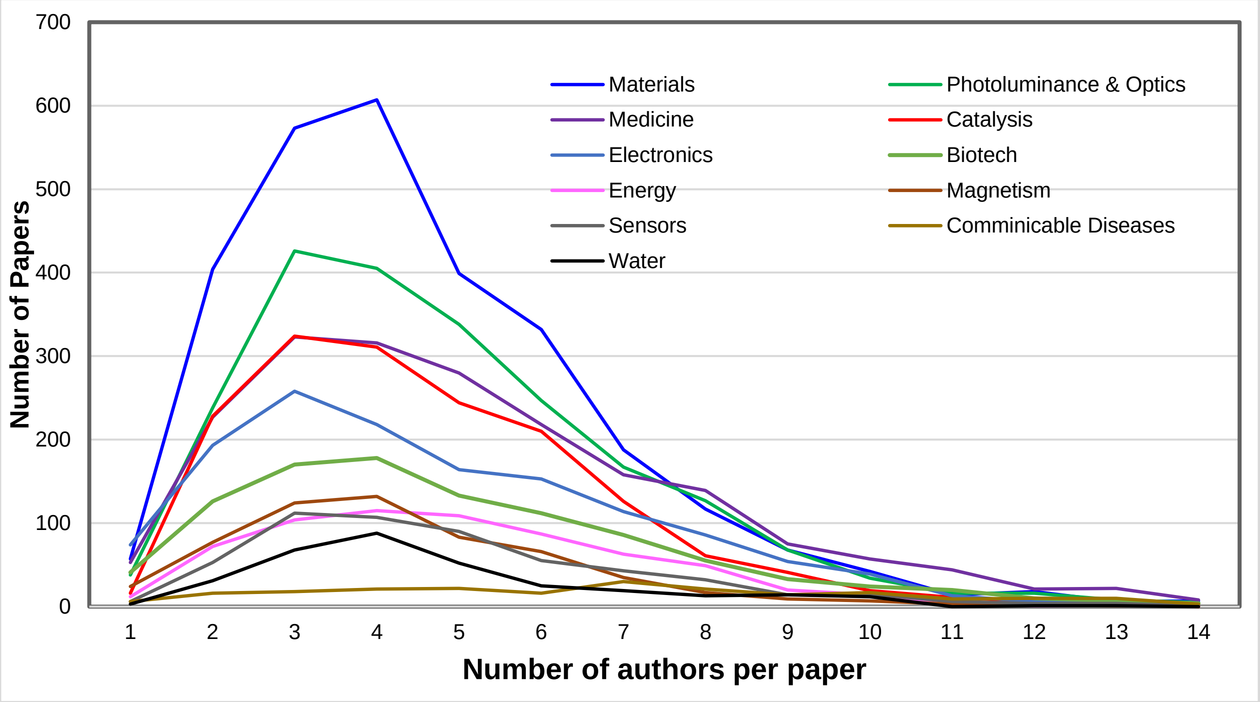


Figure 4.9: Collaboration between researchers within each research area

As shown in figure 4.10 below, institutional collaboration was examined using organisational co-authorship. Collaboration between organisations is lower than collaboration between researchers as most papers (30%) are authored by one organisation. The collaboration level reaches its highest at two organisations, then falls into exponential decline such that there is only 0.05% of mutual submissions between ten organisations.

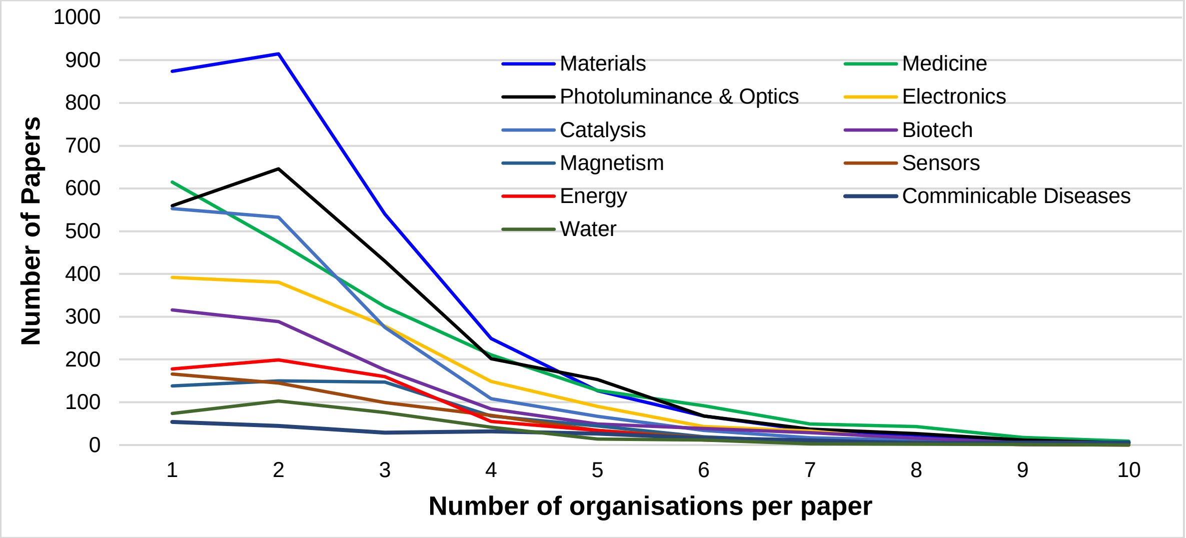


Figure 4.10: Organisational collaboration per research area

Table 4.27 below displays collaboration according to the research area. A high level of cooperation between researchers has been observed, ranging from 0.95 to 0.99. Collaboration between organisations is lower, ranging from 0.69 to 0.78.

Table 4.27: The extent of collaboration in research areas

Research Area	Total Number of papers	Single Researcher authored papers	Single Organisation authored papers	Researcher degree of collaboration	Organisational degree of collaboration
Materials	2845	57	874	0.98	0.69
Photoluminance & Optics	2172	38	560	0.98	0.74
Medicine	2008	53	615	0.97	0.69
Catalysis	1606	16	553	0.99	0.66
Electronics	1390	74	392	0.95	0.72
Biotechnology	1021	41	316	0.96	0.69
Energy	655	12	178	0.98	0.73
Magnetism	587	24	138	0.96	0.76
Sensors	553	6	166	0.99	0.70
Water	328	3	74	0.99	0.77
Communicable Diseases	243	6	54	0.98	0.78

The low number of collaborations can be attributed to the Department of Higher Education and Training (DHET) publications' incentive scheme, where publication subsidies are split based on the number of authors per institution and assigns a value of zero to any publication with more than 100 co-authors (DHET, 2003). Hence the scheme discourages institutional and international collaborations because, according to the procedure, the lower the number of collaborating institutions/authors, the higher the payment to individual institutions/authors; the more publications one produces per year, the more monetary reward one receives. As a result of this scheme, one finds that researchers in South Africa now choose financial publication rewards versus quality, high impact journals, and large collaborations (Hedding, 2019; Muthama and McKenna, 2020). South Africa may be losing out because publications from big collaborations usually have a high impact and attract many citations (Yolande X *et al.*, 2016). In addition, given that nanotechnology is a multidisciplinary field at the nexus of the convergence of several disciplines, large collaborations are critical for its success.

4.6.14 Publication citation rates for South African research areas

Citations per paper and research area citation index were used to analyse the citation rates of South Africa's main research areas. StatsNano estimates that South Africa receives 9.08 citations per nano-article (StatsNano, 2020). The research area citation index was calculated using this number. The citation rates are shown in Table 4.28. The results show that electronics has the lowest average citation rate of 13.3 citations per paper and communicable diseases has the highest average citation rate of 33.8.

Table 4.28: The relative citations of South Africa's research areas

Research Area	Total Citations	Number of papers	Citation per paper	Relative Citation
Electronics	18549	1390	13.3	1.47
Energy	10449	655	16.0	1.76
Photoluminance & Optics	36209	2172	16.7	1.84
Magnetism	10313	587	17.6	1.93
Sensors	9964	553	18.0	1.98
Materials	52593	2845	18.5	2.04
Catalysis	33952	1606	21.1	2.33
Medicine	42458	2008	21.1	2.33
Water	7013	328	21.4	2.35
Biotech	24644	1021	24.1	2.66
Communicable Diseases	8203	243	33.8	3.72

4.6.15 South Africa research areas according to Nanotechnology value chain

The nanotechnology value chain is a three-step process that transforms nanotechnology inventions from ideation to commercialisation (Shapira, Youtie and Kay, 2011; Wang and Guan, 2012; Gkanas *et al*., 2013). The value chain begins with nanomaterials, moves into nano-intermediaries and concludes with nano-enabled products. Foresight planners can classify nanotechnology research based on the nanotech value chain. Fundamental research produces nanomaterials, applied research offers intermediate materials, while innovation and commercialisation provide nano-enabled devices.

The stage of development within the South African nanotechnology research areas was evaluated using the nanotechnology value chain. In Figure 4.11, one notes that 49% of the papers published before 2013 dealt with nanomaterials. However, by

December 2019, many papers published fit within the nano-intermediaries stage. The graph also shows that nanotechnology research is evolving and moving into the more innovative value chain stages, as there was a 1% increase in papers reporting nano-enabled products.

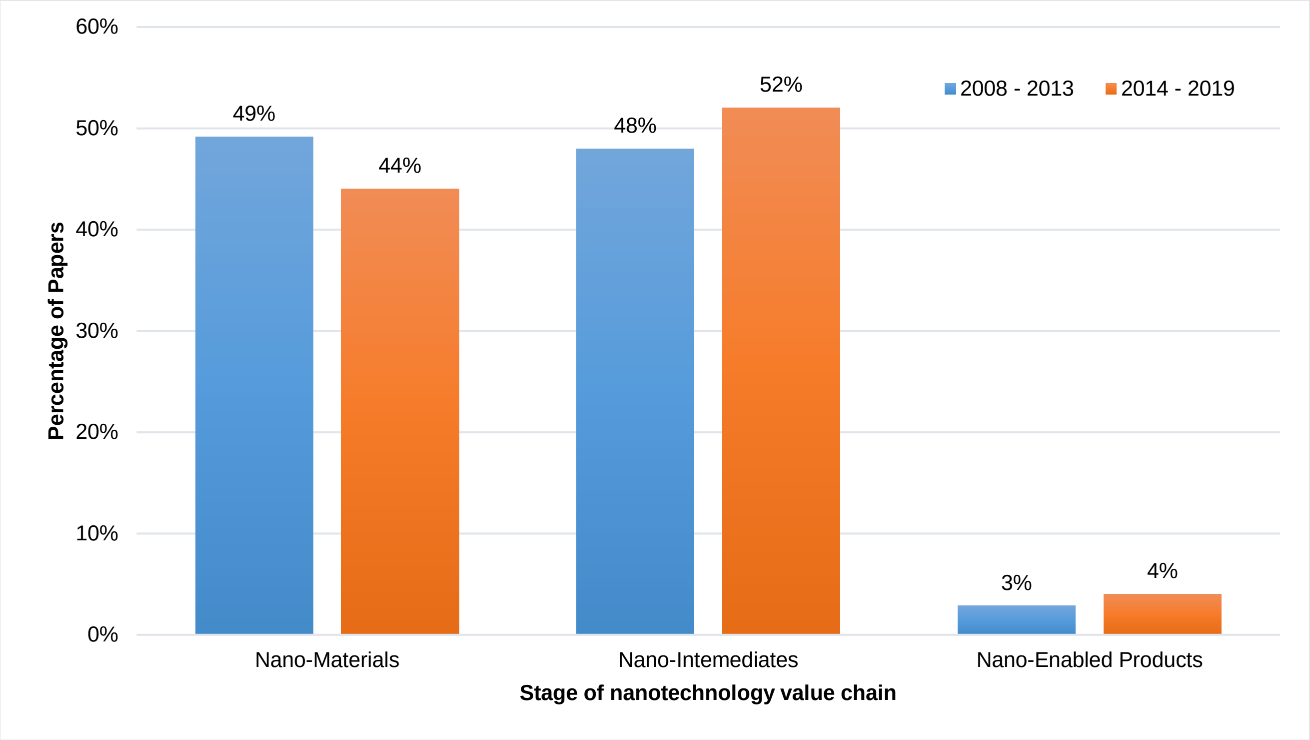


Figure 4.11: Two-period analysis of publications classified according to nanotechnology value chain

Science and technology's ultimate goal is to create nano-enabled goods that can be used to meet socioeconomic goals and improve people's quality of life. The number of publications on nano-enabled products by study area is depicted in Figure 4.12. Medicine, with 76 papers, is the most prominent field reporting on nano-enabled products. Medicine is followed by water, electronics, and energy in the second, third and fourth place, respectively.

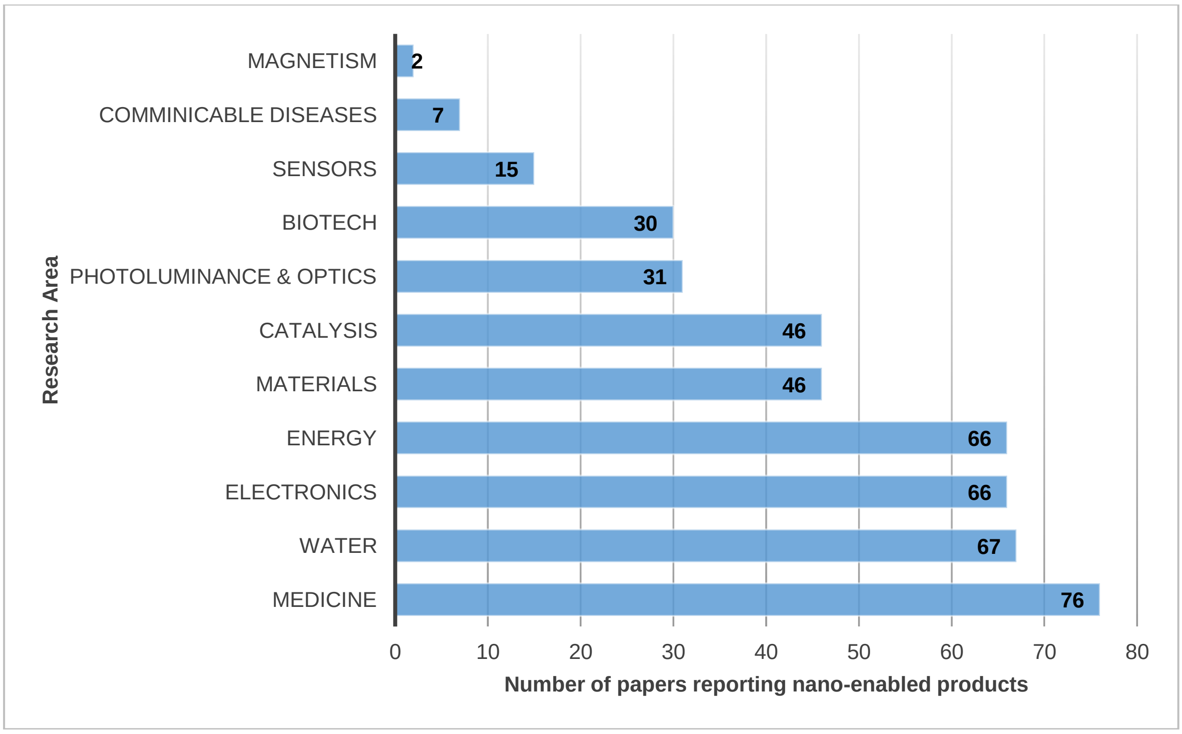


Figure 4.12: Number of papers reporting nano-enabled products by research area

4.6.16 A comparison between South Africa's nano-enabled-products papers to BRICS

Using the last 5000 publications until December 2019, an analysis was done to compare South Africa's performance to BRICS countries. An analysis of the publications within medicine, electronics, and energy is provided in Figure 4.13 below. The least number of publications on nano-enabled products was published by South Africa, followed by Russia. China has published the most papers on nano-enabled products, followed by India. When one considers energy and electronics, China's dominant position in the field of electronic devices reported in the literature is reinforced by these results (Investopedia, 2019; Intrepidsourcing, 2018; Gangnes and Van Assche, 2008).

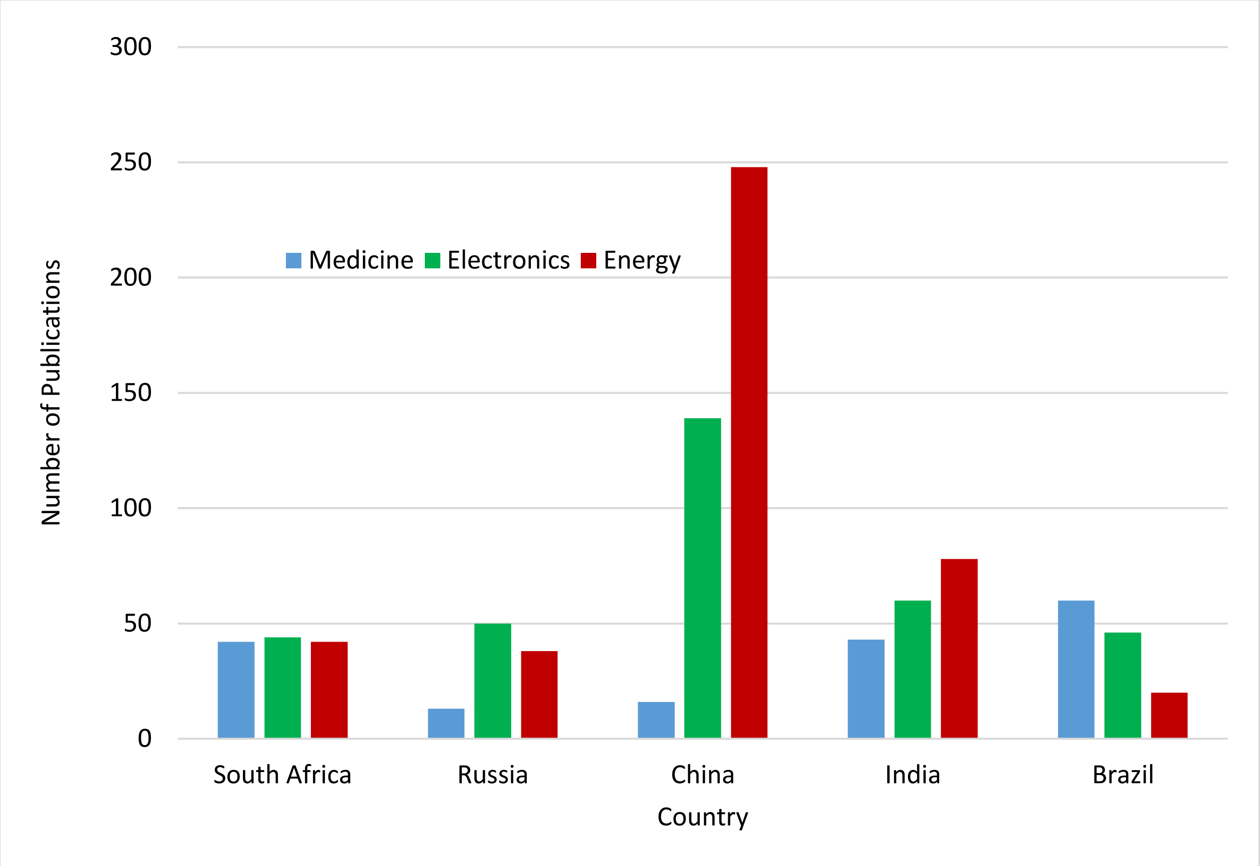


Figure 4.13: A comparison of South Africa's papers on nano-enabled products with those from BRICS countries

4.7 Nanotechnology-specific foresight model

This section reports on the determination of the mathematical model to rank key research areas in nanotechnology. The model combined results from the previous sections, and these are: the Nanotechnology Innovation Diamond CSFs as criteria in the AHP model, research alternatives from the technology mining process, and performance of each area from scientometric analysis of publications in each research alternative.

4.7.1 Validity and reliability

Cronbach's alpha and Composite Reliability (CR) were used to assess the reliability of the critical success factors model. This research achieved reliability values above the minimum acceptable reliability values of 0.7 for Cronbach's alpha and CR > 0.6 (Connell, 1987). The Cronbach's alpha value for the complete 30-variable measurement scale is 0.95, indicating that the measuring equipment is internally consistent and reliable.

The following procedures were taken to assure the validity and reliability of this study's tech-mining results. To extract target records for this research from the Web of Science core collection, a well-established Boolean nanotechnology search approach (Porter et al., 2008) was adapted. Additionally, data cleaning was performed to ensure that the search technique was accurate in extracting nanotechnology-specific records for the study. Secondly, a large sample of publications was analysed (11 265), thereby minimising sampling error. Sampling error increases when the number of objects being measured is small; in this situation, the number of objects being measured is enormous.

For the MCDM AHP model, a quality control check was done by assessing the consistency of the pairwise comparison of weights. The consistency ratio was calculated to be 0.0013, which is less than the maximum acceptable threshold of 0.10 (Saaty, 1980); hence the weights determined in the CFA can be reliably used. Finally, the results from the developed MCDM foresight model were benchmarked with results from an expert survey key technologies method which gave closely similar priority fields of research.

4.7.2 MCDM nanotechnology foresight model

4.7.2.1 CSF weights on successful nanotechnology

Table 4.29 shows the nanotechnology CSFs weights on the successful nanotechnology construct calculated from the optimised CFA model. The table also shows corresponding scientometric indicators that can be used to measure the CSFs.

Table 4.29: Criteria weights calculated from the CFA model and corresponding scientometric indicators

Criteria	Weight (*Wj*)	Measurable Scientometric Indicator
1) R&D competency	0.132	Combine two indicators which are the Number of publications (% share) Ratio or Activity Index and the Relative Citation Rate (%) Ratio
2) Multi and Inter-disciplinarity	0.252	Combine two indicators, the degree of collaboration by authors and degree of collaboration by organisations
3) Agglomeration	0.062	The percentage of papers in cluster identified
4) Consumer preferences/needs	0.206	**Assumption:** All identified research alternatives were assumed to have similar consumer preferences/needs because they are fields identified by government economic policies.
5) Industry and Market Hybridisation	0.040	Number of nano-enabled papers (% share)
6) Conducive Innovation environment	0.308	**Assumption:** All projects will be done in a similar innovation environment
Total Combined Weight	**1.000**	

Before the weights, *Wj,* were used in the AHP foresight model, a quality control check was done by assessing the consistency ratio of the pairwise comparison of weights. The consistency ratio was calculated and found to be 0.0013, which is less than the maximum allowed threshold of 0.10 (Saaty, 1980). Hence the weights determined in the CFA can be reliably used in AHP.

4.7.3 Analytical hierarchical process (AHP)- MCDM model

Figure 4.14 below shows the MCDM foresight model developed by combining CSFs from the Nanotechnology Innovation Diamond and the analytical hierarchical process (AHP) to rank key research areas in nanotechnology.

Source: Synthesised by the researcher.

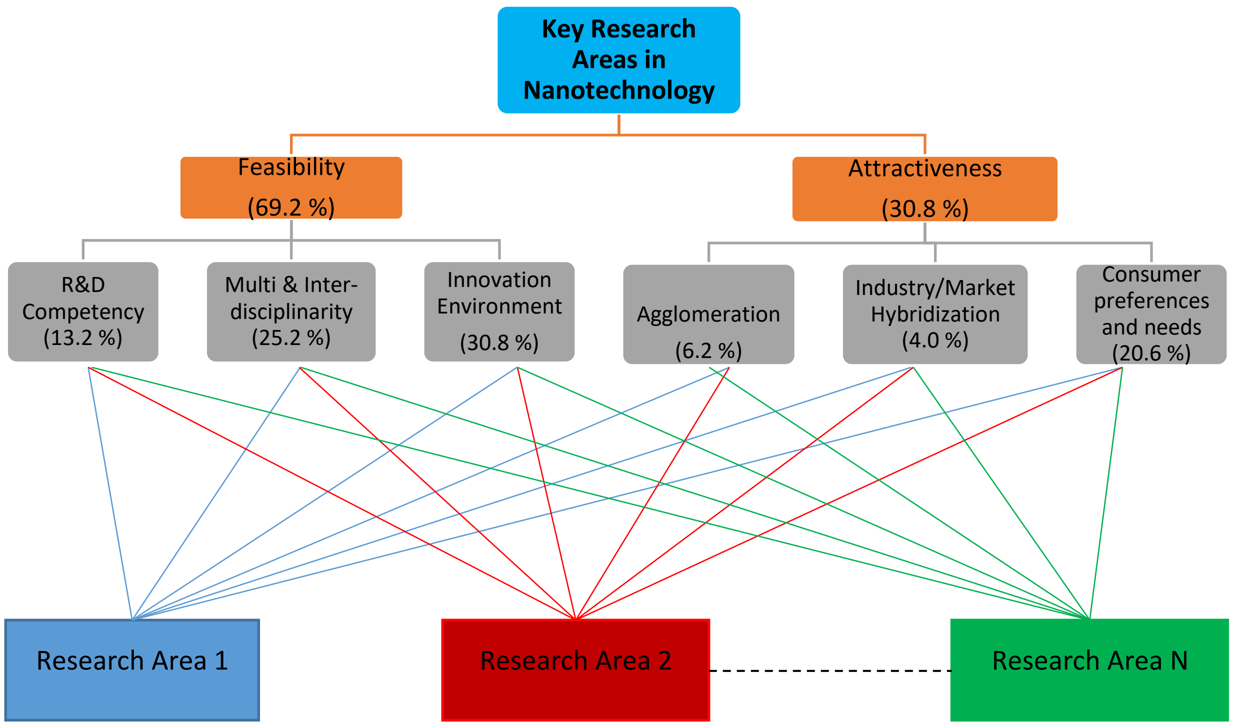


Figure 4.14: AHP based nanotechnology foresight model

The model in Figure 4.14 shows that the experts surveyed regarded scientific feasibility as more critical, giving it a weight of 69.2% as compared to socio-economic attractiveness, which has a weight of 30.8%.

4.7.3.1 AHP scientometric indicator inputs

Table 4.30 below shows the top 11 nanotechnology research areas and their corresponding scientometric indicators. Food, textiles, and cosmetics were among the other prospective foresight study fields identified in this study, but their contribution ratios were too low to be considered for further examination. The identified top 11 research areas were then used as the research alternatives from which key technologies were determined.

Table 4.30: Top 11 research areas for South Africa and related scientometric indicators

Research Area	Number of Publications	Ratio of Activity	Researcher degree of collaboration	Organisational degree of collaboration	Research Area Relative Citation	Nano-Enabled Products Ratio
Materials	2845	25%	0.98	0.69	2.04	0.102
Photoluminance & Optics	2172	19%	0.98	0.74	1.84	0.069
Medicine	2008	18%	0.97	0.69	2.33	0.168
Catalysis	1606	14%	0.99	0.66	2.33	0.102
Electronics	1390	12%	0.95	0.72	1.47	0.146
Biotechnology	1021	9%	0.96	0.69	2.66	0.066
Energy	655	6%	0.98	0.73	1.76	0.146
Magnetism	587	5%	0.96	0.76	1.93	0.004
Sensors	553	5%	0.99	0.70	1.98	0.033
Water	328	3%	0.99	0.77	2.35	0.148

Table 4.31 below shows the top 11 nanotechnology research areas and their activity levels for the nine provinces of South Africa.

Table 4.31: Top 11 Research area specialisations comparisons per province

Research Area	South Africa	Pretoria	Joburg	Western Cape	Free State	KZN	North West	Eastern Cape	Limpopo
Materials	21%	23%	25%	16%	20%	21%	22%	22%	18%
Photoluminance & Optics	17%	18%	13%	13%	43%	15%	10%	18%	7%
Medicine	14%	11%	13%	20%	5%	16%	18%	17%	20%
Catalysis	12%	10%	15%	13%	9%	10%	16%	12%	11%
Electronics	10%	13%	10%	9%	10%	9%	8%	8%	4%
Biotechnology	7%	6%	7%	9%	2%	10%	11%	8%	12%
Energy	5%	6%	3%	6%	4%	5%	5%	4%	12%
Magnetism	4%	4%	5%	5%	3%	7%	2%	3%	4%
Sensors	4%	4%	4%	5%	2%	3%	3%	5%	6%
Communicable Diseases	2%	1%	1%	3%	0%	2%	2%	1%	1%
Water	3%	4%	4%	1%	1%	1%	2%	1%	5%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

4.7.3.2 Key nanotechnologies research areas ranking using AHP-MCDM foresight model

The scientometric data was then fed into the AHP model to rank the identified areas of research. Table 4.32 shows the identified research areas ranked using the AHP foresight model. A research area with AHP a score greater than or equal to 0.09 was considered critical. However, foresight planners can decide to set their own cut-off values. The ranking was done according to the provinces of South Africa to enable planners to identify a province's vital nanotechnology research areas. Ranking nanotechnology according to provinces or clusters is essential because nanotechnology research tends to cluster into some regions. Entities located within a cluster progress faster because they can share resources, access skilled labour, and share local tacit knowledge, thus accelerating innovation and commercialisation.

Table 4.32: South Africa key nanotechnology research areas AHP ranking per province

Research Area	Pretoria	Joburg	Western Cape	Free State	KZN	North West	Eastern Cape	Limpopo
Materials	0.099	0.100	0.095	0.097	0.098	0.099	0.099	0.096
Photoluminance & Optics	0.096	0.093	0.093	0.112	0.094	0.091	0.096	0.089
Medicine	0.091	0.093	0.097	0.087	0.095	0.096	0.096	0.097
Catalysis	0.091	0.094	0.093	0.090	0.091	0.095	0.092	0.091
Electronics	0.093	0.091	0.090	0.091	0.090	0.090	0.090	0.087
Biotechnology	0.088	0.089	0.090	0.086	0.091	0.092	0.090	0.092
Energy	0.088	0.086	0.088	0.087	0.087	0.088	0.087	0.092
Sensors	0.087	0.087	0.087	0.086	0.086	0.086	0.087	0.088
Magnetism	0.087	0.087	0.088	0.086	0.089	0.085	0.086	0.087
Water	0.087	0.087	0.085	0.085	0.085	0.085	0.085	0.088

Note: A research area with an AHP score ≥ 0.09 is considered critical. However, foresight planners can decide to set their own cut-off values.

Mobilising and engaging key stakeholders is an essential step of the foresight process. The top researchers, institutions and countries collaborating with South Africa in the identified key research areas were identified based on the number of publications in the research area. Table 4.33 below shows the key research areas and their respective top researchers, institutions and collaborating countries. For example, under materials science Suprakas Ray is the leading researcher, the University of Johannesburg is the leading institution, and India is the top collaborating country; under energy, Maaza Malik is the top researcher, the University of the Western Cape is the top institution and China the top collaborating country.

Table 4.33: Key research areas and corresponding top researchers, institutions and collaborating countries

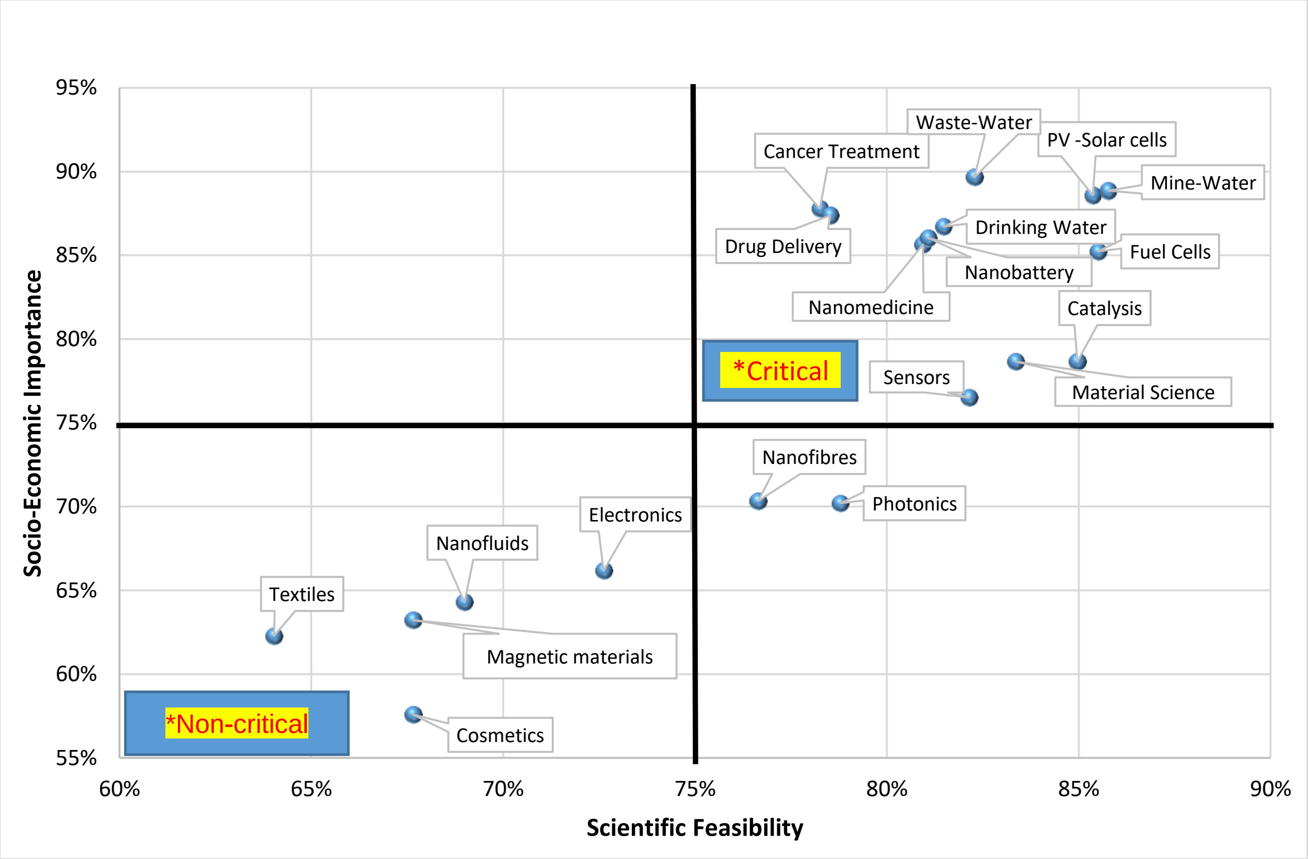
Research Area	Top Researchers	Top Institutions	Top Collaborating Countries
Materials	1) Ray, Suprakas Sinha 2) Maaza, Malik 3) Nyokong, Tebello 4) Mamba, Bhekie Brilliance	1) University of Johannesburg 2) Wits University 3) Council for Industrial and Scientific Research (CSIR)	1) India 2) United States of America
Photoluminance & Optics	1) Swart, Hendrik C 2) Ntwaeaborwa, Odireleng 3) Maaza, Malik	1) University of the Free State 2) University of South Africa 3) University of Johannesburg	1) India 2) United Kingdom
Medicine	1) Nyokong, Tebello 2) Maaza, Malik 3) Ray, Suprakas Sinha 4) Kasinathan, Kaviyarasu	1) Wits University 2) University of Cape Town 3) University of KwaZulu-Natal	1) United States of America 2) India
Catalysis	1) Nyokong, Tebello 2) Covill, Neville J 3) Gupta, Vinod Kumar 4) Mamba, Bhekie Brilliance	1) University of Western Cape 2) University of Johannesburg 3) Wits University	1) India 2) China
Electronics	1) Maaza, Malik 2) Ray, Suprakas Sinha 3) Nyokong, Tebello 4) Swart, Hendrik C	1) University of Pretoria 2) University of Johannesburg 3) Wits University 4)	1) India 2) Germany
Biotechnology	1) Nyokong, Tebello 2) Maaza, Malik 3) Kasinathan, Kaviyarasu 4) Gupta, Vinod Kumar	1) University of KwaZulu-Natal 2) Wits University 3) University of Johannesburg	1) India 2) United States of America
Energy	1) Maaza, Malik 2) Nyokong, Tebello 3) Swart, Hendrik C 4) Kasinathan, Kaviyarasu	1) University of Western Cape 2) Council for Industrial and Scientific Research (CSIR) 3) University of KwaZulu-Natal	1) China 2) United Kingdom

4.7.4 Expert survey key technologies foresight

An expert survey was conducted to rank identified research areas according to two criteria, which were “Scientific and Technological Feasibility” and “Socio-Economic Importance”. Under scientific and technological feasibility, the experts were requested to consider the R&D stage of the technology, i.e., whether it is still theoretical, or if it is now in applied stages of development, and the availability of skills and resources in South Africa. To rank socio-economic importance, experts were asked to consider how important the research area is for South Africa’s socio-economic development needs. The experts ranked the identified technologies using a 5-point Likert scale where scientific and technological feasibility had ranks from 1 = Very unlikely to 5 = Very likely. Socio-economic importance started at 1= Not important to 5 = Very important.

4.7.4.1 Key-research areas identified from experts’ survey

The results of the survey are shown in figure 4.15 below. Research areas scoring 75% and above on both importance and feasibility were considered as critical. However, it is essential to note that this was the researcher’s choice of a cut-off point. Other foresight planners can choose their own cut-off criteria for criticality. The 75% cut-off was chosen because most of the ranks in the two aspects were 50% and above, so taking a cut-off of 50% would have meant most research areas would have ranked as critical.



Note: Research areas scoring 75% and above on both economic importance and scientific feasibility were considered critical. However, foresight planners can choose their own cut-off criteria for criticality.

Figure 4.15: Expert survey-based key research ranking scatter plot

4.7.4.2 Regional nanotechnology fabrication facilities in South Africa

In line with the finding that nanotechnology clusters, agglomeration and shared facilities are essential for successful nanotechnology innovation, the researcher wanted to find out if the establishment of regional nanotechnology fabrication facilities is key to the success of nanotechnology innovation in South Africa. This question could not be answered by scientometric analysis. Results of the expert survey shown in Figure 4.16 indicate that 75% of respondents considered that regional nanotechnology fabrication facilities are required for success.

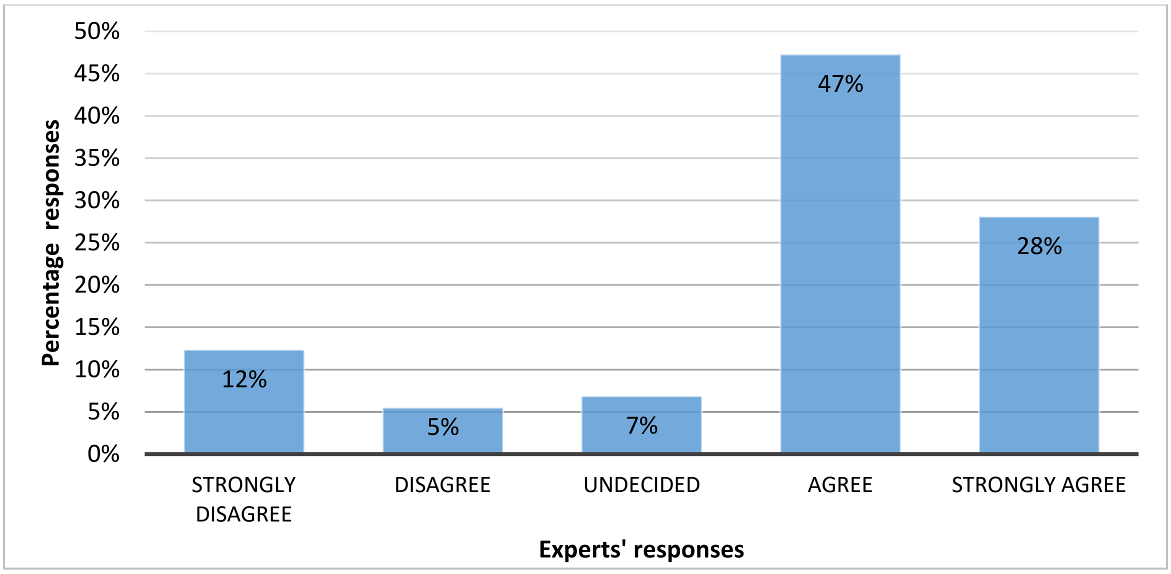


Figure 4.16: Responses on the need to set up regional nanotechnology fabrication facilities in South Africa

4.7.4.3 Nanotechnology fabrication techniques required in South Africa

The research also aimed to understand which fabrication techniques are considered essential for South Africa. This data can be used to support the establishment of regional nanotechnology fabrication facilities. Figure 4.17 shows the distribution of required fabrication techniques. The top three required techniques are chemical vapour deposition, laser deposition and sputtering.

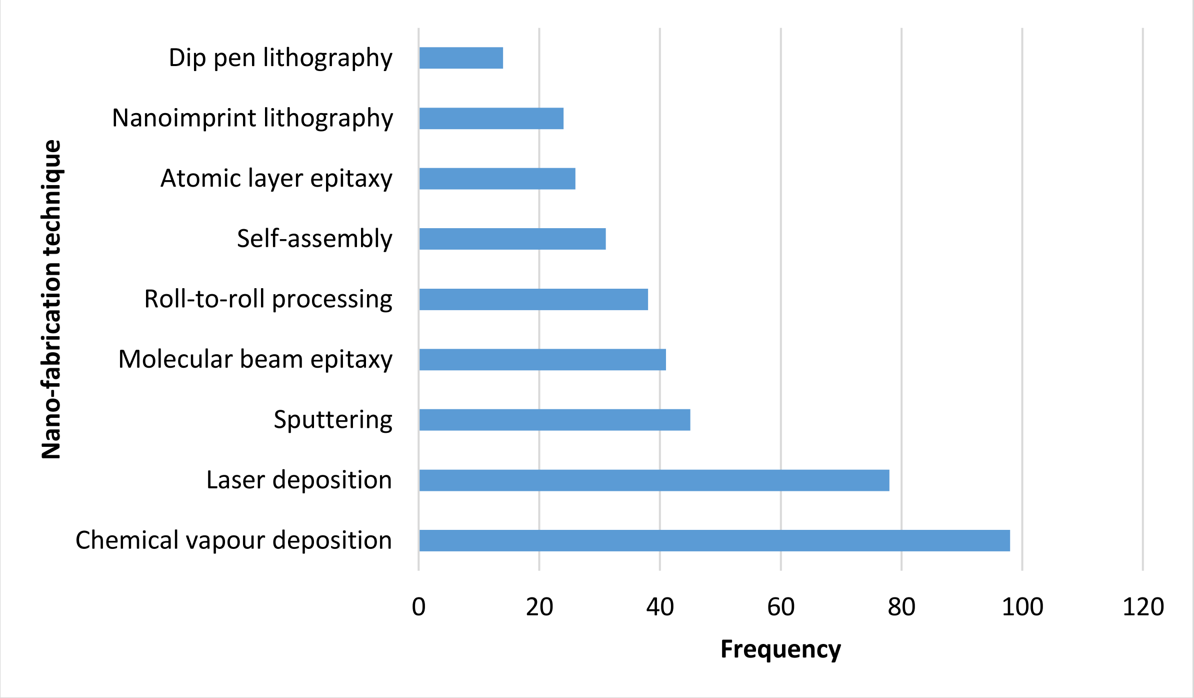


Figure 4.17: Nanotechnology fabrication techniques required in South Africa

4.7.5 Benchmarking expert survey versus the AHP-MCDM foresight method

A comparison of the results of the AHP method versus the expert survey method reveals the following key findings:

1) The majority of research areas identified as critical technologies using the AHP foresight model were also identified by experts as essential. These include materials science, medicine, catalysis, and energy.
2) Nano cosmetics, food and nano textiles were dropped in the early stages of analysis because they had less than 0.05% publications. However, the expert survey also ranked these areas as non-critical research areas for South Africa.
3) A significant difference between the two methods is in water research. The AHP did not rank water as a critical research area. However, the experts' survey ranked water research in areas such as acid mine water treatment and drinking

water nanotechnologies as a critical research area. The reason could be that this is an upcoming research area with few publications by South Africa on the ISI Web of Science database. Hence this can be a weakness of the AHP scientometric based model such that it does not readily identify green fields of research that have few publications.

4) The expert survey foresight method does not rank the critical research areas, but the AHP model provides a numbered and clear ranking.
5) The AHP model cannot answer some key foresight questions that can only be answered through an expert survey; for example, in this research, the need for fabrication facilities and the types of fabrication techniques required were investigated using the expert survey.
6) AHP-MCDM and the expert survey agreed on 70% of the research areas.

4.8 Results summary

This chapter has presented the results emanating from this research. These results presented the steppingstones upon which the nanotechnology-specific key-research area foresight model was built. The chapter started by reporting on the demographic information of South Africa's nanotechnology experts. A total of 167 experts participated in the survey, 71% are academics and researchers, and only 4% are engineers. The majority of professionals (47%) work in the initial stages of the nanotechnology value chain, developing nanomaterials, 16% work in nano-enabled products and only 3% work in industry. From a foresight perspective, there is a need to promote more nanotechnology research by engineers, participation of industry, and support nano-enabled products sectors.

Section 4.3 reported on the descriptive statistics for the research constructs. The construct variables were ranked using a five-point Likert scale rated from 1 to 5. Section 4.3.1 reported on the “successful nanotechnology” construct. Successful nanotechnology has six variables. The six variables have a mean score between 3.6407 and 3.886, implying that on average respondents agreed that these variables are related to successful nanotechnology innovation.

Section 4.3.1 presented the descriptive statistics for the six CSFs proposed in the Nanotechnology Innovation Diamond. These were also evaluated using the five-point Likert scale; each CSF was composed of four observable variables. The CSFs had a mean between 3.9356 and 4.4162. Multi- and interdisciplinary and consumer perceptions were ranked as the top two, while R&D skills and capabilities were ranked lowest. The next step was to identify if there was a statistical difference between the means of the six CSFs. At 95% confidence, it was found that out of the 15 possible paired-mean combinations, four pairs have statistically insignificant differences in their mean $p>0.05$. In contrast, 11 pairs have a statistically significant difference in their means. Therefore, the null hypothesis, which states that the paired population means are equal for all six CSFs is rejected, and the alternate hypothesis is accepted.

Results on the Pearson linear correlation analysis of the Nanotechnology Innovation Diamond CSFs showed that all the six CSFs have a significant linear correlation with each other. The results also showed that all the six CSFs have a statistically significant positive linear correlation to the “successful nanotechnology” construct.

Section 4.5 reported on the Nanotechnology Innovation Diamond validation using CFA, and the results show that the model met the minimum model fit requirements with a 95% confidence level. The critical ratio (CR) of the regression estimate was used to analyse the significance level of the CSFs' relationships (Byrne, 2013).

Results showed that all CSF make a highly significant contribution in the model with all factors having a p-value = (***) which indicates a highly significant relationship $p < 0.001$. Therefore, all the six CSFs are statistically significant, correlated to “successful nanotechnology”, and are significant for the Nanotechnology Innovation Diamond model.

The next set of results in section 4.6 gave a foresight-based analysis of the South African nanotechnology environment based on technology mining of nanotechnology publications produced between 2000 and 2019. South Africa is experiencing an exponential rise in nanotechnology publications. Publications per year increased from 68 in 2000 to 1672 in 2019, representing a 2 458% increase. However, compared to BRICS countries, South Africa has the lowest productivity index of 0.68.

In South Africa, universities publish the majority of nanotechnology research. Only one private company, SASOL Technology, was recognised as having 24 publications, accounting for 0.21% of overall production. This lack of private sector participation will negatively affect nanotechnology research innovation and commercialisation. With 1241 (11%) publications, India is South Africa's most prolific collaborating partner, followed by the United States with 919 (8.2%). With 585 (5.2%) publications, Nigeria is South Africa’s most prominent collaborator on the African continent.

Nanotechnology research fields with a socioeconomic advantage for South Africa include materials science, photoluminance and optics, medicine, catalysis, electronics, energy, biotech, magnetism, sensors, water, and communicable diseases. India is the top collaborating country in seven out of nine key nanoscience research areas. However, the United States is the top collaborating country in medicine and communicable diseases. China is the top collaborating country in energy, and Belgium is the top collaborating country in water. Based on regional clustering of research areas, the Free State is dominant in photoluminance and optics research, Pretoria leads electronics research, the Western Cape or Johannesburg are most active in nanomedicine research, and the Western Cape or Kwa-Zulu National are prominent in communicable disease research.

The degree of collaboration between researchers varies from 0.95 to 0.99 in all research areas, with most papers produced by three or four authors. On the other hand, organisational cooperation is lower, ranging from 0.69 to 0.78. A single organisation writes the majority of papers (30%). With 13.3 citations per manuscript, electronics has the lowest citation rate, while communicable diseases research has the highest citation rate with 33.8 citations per article. The nanotechnology value chain was used to analyse the level of innovation in the research domains, and only a small fraction of articles (3.5%) reported on nano-enabled products. Most articles on nano-enabled products have been published in nanomedicine, followed by water, electronics, and energy respectively.

The last set of results came from combining the presented results and feeding them into the AHP-MCDM foresight model. The model determined the following as critical nanotechnology research areas: material science, photoluminance and optics, medicine, catalysis, electronics, biotechnology, and energy. The model was benchmarked against an expert-survey key technologies foresight method. The results indicate that experts also identified research areas identified as critical using the AHP-MCDM foresight model to be critical, for example, materials science, medicine, photonics, catalysis, and energy. In summary, the AHP-MCDM and expert survey agreed on 70% of the research areas.

The AHP model has the following advantages over the experts' survey. Enormous amounts of data could be analysed, and critical technologies could be more clearly ranked in order of criticality, critical technologies could be identified for different provinces and clusters, essential stakeholders in developing identified research areas could be easily identified, for example, top researchers per area, top institutions per area and top collaborating international countries. However, the AHP=MCDM foresight model has some weaknesses. It cannot answer certain types of questions. For example, the question of whether the establishment of regional nanotechnology fabrication centres is critical for the success of nanotechnology innovation in South Africa could only be answered through the experts' survey. The experts can also identify some essential research areas with only a few publications, and green fields cannot be picked up from tech-mining publications. However, the AHP model can be improved by incorporating an experts' survey component. Alternatively, a module to run webometrics to search for websites and news can also capture green fields' research areas and socio-economic needs.

The next and last chapter, chapter 5, will present the conclusions from this research, highlight contributions made, list the limitations, and make recommendations for further investigation.

Chapter 5: Conclusions and Recommendations

The results of this study were presented in the previous chapter, Chapter 4. The reported results included an expert survey, a CFA of the proposed Nanotechnology Innovation Diamond, a foresight perspective of South Africa based on tech-mining, the AHP-MCD critical technologies foresight model, and benchmarking of the AHP-MCDM model with the experts' survey foresight method.

5.1 Introduction

This chapter presents the conclusions and recommendations of the research journey in the quest to develop a nanotechnology-specific key-research areas foresight model. It starts by recapping the research problem, questions, objectives and how they were addressed. The next section summarises the key contributions to knowledge emanating from this research, reports on the study's limitations, and makes recommendations for further research in improving nanotechnology innovation management and foresight. The chapter is then concluded by recapping contributions of this research to innovation management and how the results will impact and enhance socio-economic development.

5.2 Research background

Nanotechnology is an emerging field of science that has grown exponentially since the year 2000. From a business management perspective, it is crucial to understand that the market for nanotechnology-enabled commercial products is expanding exponentially, mainly because nanoscience discoveries have so many practical uses (Islam and Miyazaki, 2009). By the year 2013, the market for nanotechnology-enabled commercial products had surpassed US$1 trillion (NSF, 2014), and it was predicted to reach US$3 trillion by 2020, creating six million jobs (Roco, 2017). From an economics perspective, nanotechnology is anticipated to drive the next Schumpeterian wave of economic growth (Mangematin *et al*., 2012; Linton and Walsh, 2008; Tuncel, 2015). As a result, most countries have initiated nanotechnology research programmes to benefit from this tremendous opportunity. Nanotech is a general-purpose technology that has widespread applications in every industry such that governments cannot invest in all possible nanotechnology research areas. Countries need to carry out technology foresight exercises to determine critical strategic research areas in nanotechnology on which they can focus and concentrate.

However, there is a lack of nanotechnology-specific foresight methods. According to Firat, Woon and Madnick (2008), there is currently little research on matching the technology foresight methods to a particular technology. This knowledge gap is supported by Salerno *et al*. (2008), who contend that, whereas foresight studies to establish priority research areas at a macro level are commonly available, studies to determine where to focus within these identified priority research topics are still in their infancy of development. In addition, while the critical technologies foresight exercises discussed in the literature (Wagner and Popper, 2003; Grebenyuk and Shashnov, 2012; Durand, 2005; Keenan, 2003) are macro-key-technologies, none of them is technology-specific.

The research problem is that, to the best of the researcher's knowledge, no effective technology foresight method exists for determining and ranking a country's key strategic research areas in nanotechnology.

Identifying, selecting, and ranking critical strategic research areas in nanotechnology helps a country to cost-effectively utilise limited resources by focusing and concentrating resources on those nanotechnology areas of research with the greatest prospects for innovation and technology transfer success. Hence this research aimed to develop an effective nanotechnology specific foresight model.

However, the quest to develop a nanotechnology specific foresight model identified several knowledge gaps which include the lack of a nanotechnology innovation management model and associated critical success factors, inadequate methods to classify nanotechnology publications into research areas, minimal application of quantitative and MCDM techniques for technology foresight exercises.

5.2.1 Addressing research questions and objectives

A quantitative research approach was used to address the study questions and objectives and build a nanotechnology foresight model. The research was implemented in four steps which were experts' survey, technology mining of nanotechnology publications, scientometric analysis, and finally developing an AHP – MCDM nanotechnology-specific foresight model.

Table 5.1 re-summarises the research questions and their associated objectives:

Table 5.1: Research questions and objectives

Research Questions	Research Objectives
1. What are the critical success factors (CSF) that promote nanotechnology research that results in successful innovations?	1. Establish the Critical Success Factors for successful innovation and technology transfer in nanotechnology and how they interact.
2. What are the relative weights of the identified CSF when used as criteria in multi-criteria decision-making models?	2. Estimate the numerical weights for identified criteria for successful nanotech innovations.
3. How does one categorise and characterise nanotechnology publications into nanotechnology research alternatives for a particular country?	3. Determine how to categorise the nanotechnology research areas and access their respective properties.
4. What scientometric indicators can measure CSF that promotes nanotechnology research that results in successful innovations?	4. Determine the set of scientometric indicators to measure CSF for nanotech research areas.
5. How can one develop a multi-criteria decision-making based foresight model for effectively ranking a country's strategic key research areas in nanotechnology?	5. Develop a MCDM based foresight model to rank strategic key research areas in nanotechnology effectively.

The first research question was, what are the critical success factors (CSF) that promote nanotechnology research that results in successful innovations? The question aimed to understand the CSFs for successful nanotechnology and determine a successful nanotechnology innovation management model. The Nanotechnology Innovation Diamond with six critical success factors was proposed through an extensive literature review. The six identified interrelated critical success factors are consumer needs and preferences, nanotechnology-hybridisation with existing industries and market needs, multi- and interdisciplinarity, technological agglomeration, availability of the right R&D skills (scientist-entrepreneurship), and a conducive innovation environment. Survey data from nanotechnology experts based in South Africa was then used to validate the model using CFA. The analysis showed that at 95% confidence level, the Nanotechnology Innovation Diamond model satisfied the minimum CFA requirement for model fit, that all six CSFs are linearly related to each other, and that their linear correlation to successful nanotechnology constructs is high. In conclusion to the CFA test, it was observed that the six CSFs identified make a statistically significant contribution to successful nanotechnology.

The second research objective was to estimate the numerical weights for identified criteria for successful nanotech innovations and evaluate if is there is a statistical difference in the numerical means of these CSFs and assess their weight on successful nanotechnology. The results indicated that at 95% confidence level, there is a statistical difference between the paired means of Nanotechnology Innovation Diamond CSFs, that is $\mu_1 \neq \mu_2$ the paired population means are not equal for all six CSFs. The CSFs' weights on successful nanotechnology were then determined from the optimised Nanotechnology Innovation Diamond model using CFA, and the quality of the weights was checked using the pairwise comparison consistency ratio. The consistency ratio was 0.0013, which is less than the maximum acceptable threshold of 0.10 (Saaty, 1980); hence the weights were found to be acceptable and reliable.

The third research question was, how does one categorise and characterise nanotechnology publications into nanotechnology research alternatives for a particular country? The related objective aimed to find a way to organise nanotechnology publications into research areas. The identified research areas can then be used as research alternatives in foresight exercises. Vantage Point was used to create an automatic categorisation protocol for nanotechnology publications using the thesaurus function combined with the appropriate research area search terms and keywords. The developed algorithm uses a one-to-many mapping. The South African publications were automatically grouped into the foresight research areas based on the developed algorithm.

The fourth objective sort to determine scientometric metrics that can be used as metrics to evaluate the CSFs identified in the Nanotechnology Innovation Diamond. R&D capabilities and skills can be determined by the total number of publications using percentage share or activity ratio. R&D skills and capabilities can also be measured using the relative citation ratio. More skilled groups are expected to have higher activity ratios and high citation rates. The level of inter-and multidisciplinary research can be measured using the degree of collaboration for both authors and institutions. The degree of research agglomeration can be measured by the number of publications produced from clusters or their activity index. The number of patents and papers reporting on nanotechnology-enabled products can be used to evaluate market and industry hybridisation.

The fifth research question was, how can one develop a MCDM based foresight model for ranking a country's strategic key research areas in nanotechnology effectively? The related objective was to determine a MCDM based foresight model to rank strategic key research areas in nanotechnology.

A nanotechnology-specific foresight model was developed by combining the results from objectives one to four. The model integrates the critical success factors of nanotechnology research from the Nanotechnology Innovation Diamond, technology-mining, scientometric analysis, and the analytical-hierarchical process (AHP). The model was empirically tested in South Africa. The results were benchmarked with an expert-survey foresight method which gave closely similar priority fields of research.

5.3 Contributions of the study

This section summarises how this research has contributed to the discourse and contributed to closing some knowledge gaps on nanotechnology foresight and innovation management. The section starts by reporting how this research has contributed to nanotech innovation management and technology transfer through the Nanotechnology Innovation Diamond. It next discusses how this research has contributed to closing the gap on the lack of use of quantitative methods in foresight. The nanotechnology specific foresight model contribution is then presented, and the model and results from this research contribute to the nanotechnology foresight perspective of South Africa. Finally, the section presents and contributes a generic procedure that can be used in developing technology-specific foresight methods in other technological areas such as biotechnology or information technology.

5.3.1 Nanotechnology innovation model

Although considerable research has been done on technological innovation strategies, little research is published on innovation and technology transfer specific to nanotechnology (Meyer, 2007; Linton and Walsh, 2008). Therefore, there is a lack of frameworks for successful nanotechnology management. This research proposed the Nanotechnology Innovation Diamond with six critical success factors to address this gap. The six critical success factors are consumer needs and preferences, nanotechnology hybridisation with existing industries and market needs, multi- and interdisciplinarity, technological agglomeration, availability of the right R&D skills (scientist-entrepreneurship), and a conducive innovation environment. A CFA was then used to validate the model, and the results showed that the model satisfied the minimum CFA model fit requirements at a 95% confidence level.

The Nanotechnology Innovation Diamond presents six CSFs that are fundamental for nanotechnology R&D success. According to the model, consumer needs and socio-economic demands drive the integration of nanotechnologies into current industries and create hybrid markets such as nanoagriculture, nanomedicine, nanoengineering, nanoelectronics, nanocosmetics, etc. Hybridisation implies that a single innovation in nanotechnology can be integrated into several industries. For example, an innovation in nano-based selective light absorber can be used in cosmetics for sunscreen creams (nano-cosmetics), in medicine for the sunburn medication (nano-medicine), in photovoltaic cells for efficient solar panels design (nano-energy), in electronics for light/solar sensor design (nano-electronics) and radiative cooling paint for automobiles and buildings (nano-engineering). This example shows how pervasive a single nano-technology innovation can be to many industries. Hence a single nanotechnology innovation has the potential to disrupt several existing technologies concurrently.

The clustering of organisations also identified as a CSF will enhance nanotechnology research and development capabilities. Companies gain from clusters because of expert-knowledge spillover effects across firms, industry alliances, sharing technical knowledge, localised specialised equipment, and skilled workforce availability. Finally, it is critical to operate in an environment that promotes innovation, such as the Triple Helix, a model that supports public-private collaborations in R&D to harness resources and talents.

The developed model is suitable for nanotech R&D and innovation management. As an example, for nanotechnology innovations to succeed, research leaders need to establish interdisciplinary teams; work in a research cluster, and view nanotechnology as a GPT whereby one discovery or invention has numerous potential technological applications. To put it another way, they need to examine how a nanotechnology invention can integrate with existing industries and social needs.

Nanotechnology foresight exercises and portfolio management can also be carried out using the model. For example, a project with a good chance of succeeding must be multidisciplinary, addressing a market/consumer need for existing industries. Ideally, the research team should be an integral part of an R&D cluster.

5.3.2 Quantitative methods use in foresight methods

The use of quantitative foresight methods in developing the AHP-MCDM foresight model in this research helped close the gap on the lack of use of quantitative methods in foresight. Based on the literature review, although key technologies identification is a MCDM decision-making problem (Keenan, 2003), none of the key technologies foresight methodologies that were reviewed (Wagner and Popper, 2003; Grebenyuk and Shashnov, 2012; Durand, 2005; Keenan, 2003) used MCDM. Salo *et al*. (2003) also observed that MCDM methods' possible applications in foresight have not yet been thoroughly explored. This is also supported by Popper (2008), who reported that MCDM use in foresight exercises constituted only 1.2%. Popper’s (2008) research further shows a lack of the use of all quantitative and semi-quantitative methods in foresight models, which implies a need to contribute to foresight models that use evidence-based, quantitative semi-quantitative methods.

The AHP-MCDM foresight model presented in this research follows a rational decision-making protocol and uses quantitative, evidence-based data. The model addresses some disadvantages of solely depending on qualitative and experts' opinion foresight methods. According to Shen *et al. (*2010), foresight results developed using groups of experts, for example, the Delphi method, suffer from specious persuasion, indifference to authority, reluctance to modify publicised opinions and bandwagon effects. The most vocal and persuasive participants may have an undue influence on the results. Also, experts are bound in their rationality due to varying degrees of expertise, limits to the amount of information, and the cognitive limitations of the mind, among other issues (Ronde, 2003). Therefore, like any other human, these experts may use heuristics and rules of thumb, particularly in complex decision-making problems like nanotechnology foresight, resulting in biased judgments and sub-optimal decisions (Turpin, 2004). This view is shared by Heraud and Cuhls (1999), who added that there could be a severe problem if one anticipates uncovering "the future" in the thoughts of a small group of "experts."

5.3.3 Nanotechnology specific foresight model

This research has addressed the lack of nanotechnology-specific foresight methods (Firat, Woon and Madnick, 2008; Salerno, Landoni and Verganti, 2008). It further presented a nanotechnology-specific foresight model, which was used to understand how nanotechnology has evolved in South Africa over the past 20-years. The model can be used in any country to understand historical nanotechnology growth and anticipate future development pathways for nanotechnology. Therefore, the foresight model developed presents a tool to support policy makers in understanding and influencing nanotechnology innovation trajectories according to a country's socio-economic needs.

The model developed in this research was empirically tested in South Africa and determined the following as critical nanotechnology research areas: material science, medicine, photoluminance and optics, catalysis, biotechnology, energy and electronics. The model was benchmarked against an expert survey key technologies foresight method. The results indicate that research areas identified as critical using the AHP-MCDM foresight model were also identified by experts to be critical, for example, materials science, medicine, photonics, catalysis, and energy. The AHP-MCDM model presented the following advantages over the experts' survey: enormous amounts of data could be analysed, critical technologies could be more clearly ranked in order of criticality, critical technologies could be identified for different provinces and clusters, and essential stakeholders in developing identified research areas could be easily identified, for example, top researchers per area, top institutions per area and top collaborating international countries.

However, the AHP-MCDM foresight model has the following weaknesses: it cannot answer certain types of questions, for example, the question of whether the establishment of regional nanotechnology fabrication centres is critical for the success of nanotechnology innovation in South Africa. The above question could be answered only through an experts’ survey. The experts can also identify some critical research areas with a few publications and green fields that cannot be picked up from publications tech-mining. However, the AHP-MCDM model can be improved by incorporating an experts' survey component. Alternatively, a module to run webometrics to search for websites and news can also capture greenfield research areas and socio-economic needs.

In conclusion, a micro-level, nanotechnology-specific key technologies foresight model was developed. The model developed is suitable for R&D strategic planning, R&D portfolio management and due diligence of projects. Finally, the model presented can form the basis of creating a nanotechnology foresight decision support system (DSS).

5.3.4 A nanotechnology foresight perspective of South Africa

This research also presented a foresight view on nanotechnology in South Africa based on a scientometric evaluation of South Africa's nanotechnology papers on the WoS over a 20-year period (2000-2019). In the first step of the foresight analysis, a scan of the South African nanotechnology R&D environment was conducted, followed by the determination of the possible nanotechnologies with social and economic benefits. An AHP-MCDM foresight model was then developed to analyse, evaluate and rank the critical strategic nanotechnology research areas for South Africa.

The majority of South African nanotechnology experts work as lecturers or scientists, with a primary concentration on material science, particularly the nanomaterials stage of the value chain, as evidenced by demographic statistics data. From a foresight and strategic management perspective, it is critical for South Africa to adopt policies and programs that encourage the development of nano-intermediate and nano-enabled products research.

South Africa has seen rapid growth in nanotechnology publications over the past two decades (2000-2019). The number of papers per year has grown tremendously, from 68 in 2000 to 1672 in 2019, thus a 2,458% increase in annual output. Research in nanotechnology grew more quickly than in other fields as well. Nanotechnology publications constituted 6.6% of South African scholarly publications on WoS in the year 2019 up from 1.4% in 2000. South Africa ranks lowest among the BRICS countries in terms of nanotechnology activities level. South Africa has a nanotechnology activity index of 0.68. On the other hand, with an activity index of 2, China is the most productive country among the BRICS countries. Together, the top four most prevalent subject areas: chemistry, materials science, physics, and engineering, produce 93.05% of nanotechnology publications for South Africa.

Researchers from universities publish most of the nanotechnology research for South Africa. The second biggest publisher is national research facilities. The University of Johannesburg is the most prolific university publisher with 14% of all publications, whereas CSIR is the most prolific national facility with 9% of all publications. South African private sector participation in nanotechnology research is very limited, which will negatively affect the technology transfer and market assimilation of nanotech innovations. From a futurist viewpoint, it is evident that the industry should be incentivised and persuaded to participate more in nanotechnology research.

The production of publications is strongly biased toward the most productive researchers, such that 21.35% of all publications are produced by the top ten researchers. India is South Africa's most dominant international collaborator, co-authoring 11% of its articles. Nigeria is South Africa's biggest African partner, accounting for 5.2% of all publications.

Several strategic nanotechnology research areas aligned to socio-economic needs for South Africa have been identified through this research. These include infectious diseases, water, medicine, photoluminescence and optics, catalysis, energy, electronics, materials science, magnetism, biotechnology, and sensors. The most prominent experts per strategic-research area were identified; for example, Ray Suprakas for nano-material science, Nyokong Tebello for nanomedicine, Maaza Malik for nano-electronics and nano-energy, Mamba Bhekie for water, and for photoluminance Swart Hendrik. Furthermore, the most prominent publishing organisations per research area were determined. For instance, the top three institutions for nanomedicine are the University of KwaZulu-Natal, University of Witwatersrand and University of Cape Town. The University of the Free State is the most prominent publisher of photoluminance and optics, and a leading nanoelectronics institution is the University of Pretoria.

The study also examined South Africa’s international nanotechnology collaboration links. The results show that with 1241 (11%) publications, India is the most prolific collaborating partner for South Africa, followed by the United States with 919 (8.2%). With 585 (5.2%) publications, Nigeria is South Africa’s most prominent collaborator on the African continent. In addition, India is the top collaborating country in seven out of the nine strategic research areas; however, the United States is the top collaborating country in infectious diseases and medicine. On the other hand, China leads in energy collaborations, and Belgium is the top collaborating country in water.

Because nanotechnology enterprises tend to cluster in certain places rather than being widely spread across the country, regional hubs for various nanotechnology fields were investigated, following which the most appropriate districts for each research area were identified. Photoluminance and optics companies, for example, must operate in Pretoria and the Free State. In contrast, nanomedicine companies must locate in the Western Cape and Johannesburg, and infectious disease research companies must locate in the Western Cape or KwaZulu-Natal.

South African collaboration by individual authors and across organisations was also analysed. The degree of cooperation between researchers varies from 0.95 to 0.99 in all research areas, with most papers produced by three or four authors. On the other hand, organisational collaboration is lower, with a degree of collaboration ranging from 0.69 to 0.78. The majority of papers, 30%, are written by authors from a single institution.

The nanotechnology research quality per research area was evaluated using citation rates. The citation rate for electronics is the lowest at 13.3 citations per manuscript, while the communicable diseases citation rate is the highest at 33.8 citations per article. The nanotechnology value chain was used to analyse the level of innovation in the research domains, and only a small fraction of articles (3.5%) reported on nano-enabled products. Most articles on nano-enabled products have been published in nanomedicine. Water came second, electronics was third, and energy was fourth.

In conclusion, this section of the study provided a 20-year foresight-oriented analysis of nanotechnology for South Africa. The study identified nanotech research areas that are socio-economically relevant to South Africa. Foresight strategists, entrepreneurs, legislators, and research managers can utilise this research to evaluate and select the potential nanotech focus areas to invest in South Africa.

5.3.5 Procedure for developing technology-specific foresight models

The positivism epistemology of foresight was followed in this research. Therefore, it is assumed that statistical data from nanotechnology publications and government policies can provide a basis to evaluate nanotech research and development performance against the nanotechnology innovation critical success factors and innovation models. Then, this data can be combined with MCDM techniques to determine the critical research areas in nanotechnology.

The methodology followed in this research can be adopted to develop other technology-specific foresight methods specific to different technology fields. For example, a similar procedure followed can be used to develop a foresight model for fields such as mobile applications, internet and communication technologies (ICT), metallurgy, mechatronics, robotics, and low-cost building technologies, among other technological areas.

Table 5.2 below summarises the methodology that can be followed and presents nanotechnology foresight as an example.

Table 5.2: Technology-specific critical technologies foresight methodology development process

Foresight Model Development Step	Activities for Nanotechnology
1. Determine the CSFs and model for successful R&D and innovation management.	• Determine the critical success factors for successful nanotechnology research. • Develop a model on how these factors contribute to successful nanotechnology. • Validate the critical success factors model using confirmatory factor analysis (CFA). • Calculate the weights of each on the successful nanotechnology from the optimised CFA model.
2. Determine an MCDM based technology foresight model.	• Combine factors supporting successful nanotechnology with AHP in an MCDM foresight decision-making model. • Assign scientometric indicators that can closely measure each critical success factor.
3. Perform tech-mining and scientometric analysis of publications on the technology.	• Identify a data source and extract nanotechnology publications for the country.

Foresight Model Development Step	Activities for Nanotechnology
	• Perform tech-mining and cluster papers into research areas, i.e., possible key research alternatives that are in line with government policy needs. • Calculate the scientometric indicators for each cluster/alternative per success factor.
4. Rank identified research alternatives using the MCDM foresight model.	• Use the MCDM foresight model with inputs from scientometric analysis to rank the research alternatives.
5. Benchmark the results of the MCDM foresight model with those from an expert survey key technologies method.	• Identify possible nanotechnology alternatives. • Perform an experts' survey where nanotechnology experts can rank the research alternatives for socio-economic importance and scientific feasibility. • Plot the survey findings on a scatter graph such that critical research areas are indicated as those with high scores in both importance and feasibility. • Compare these results with those obtained in step 4 above to validate the developed model.

5.4 Limitations of the study

1) The model was validated using the responses of 167 South African nanotech experts. Most of these experts specialise in nanomaterials. Therefore,

there is a need to test the model with a larger pool of experts working in diverse aspects of nanotechnology.

2) Due to time and resources constraints, a single publications database, the Web of Science Core collection, was used in this research to evaluate nanotechnology trends in South Africa. Publications not listed in the WoS core collection were not considered; therefore, there could be a substantial dataset of other nanotechnology publications missed in the analysis.

3) Even though scientometric metrics give quantifiable and evidence-based metrics for foresight research, they are not without limitations. These limitations are summarised below:

    a) Scientometric indicators have a time lag because it usually takes at least a year for an article to be published and several years for a patent to be awarded.

    b) Who, what, where, and when are some of the questions that tech-mining can answer? However, answers to queries about the process, how it works, and why it works almost always require expert judgement. (Porter and Cunningham, 2005b).

    c) Because some research is never published or patented, scientometrics does not capture all research in a given field; for example, an academic scientist or engineer is 45 times more probable to publish their work than their industry counterpart. (Porter and Cunningham, 2005b).

    d) Because not every research component can be evaluated or assessed using published articles to the same degree, scientometric metrics are partial indicators. "Research" or "knowledge generation" is a complicated concept that cannot be encapsulated in a single or small set of measurements based on publications.

e) At best, scientometric indicators are proxies for more “intangible” research dimensions like “research quality” or “research cooperation.” For example, “Research quality” is often equated with “citation impact,” and “research cooperation” is equated with “co-authorship” in scientometrics. As a result, present bibliometric approaches are simply insufficient to appropriately quantify such research metrics; hence, additional evaluation methods are required to support scientometric indicators.

f) Tech-mining is still new to technology managers; as such, it faces credibility issues. Hence many decision-makers may feel more comfortable using an expert opinion (Porter and Cunningham, 2005b).

g) The distributions of science and technology publications are substantially asymmetrical, according to Lotka's Law (Phillips, 2013). The top researchers are incredibly productive, while the others appear in "ones and twos," implying that significant contributions by less prolific authors who publish and patent less frequently may go unnoticed.

5.5 Recommendations for further research

The recommendations that follow can help direct additional research to further improve the proposed AHP-MCDM nanotechnology specific foresight model:

1) A total of 167 experts from South Africa participated in this study, most of whom specialise in nanomaterials. Hence, there is a need to test the model outside South Africa with a larger pool of experts, as CFA requires very large samples (Zainudin, 2012).

2) Improve the vantage point research area search and categorisation system developed in this research with a broader range of nanotechnology subfields. Detailed search term classification developed for this research is provided in Appendix 3. The categorisation system has 18 research areas. The number of research areas can be expanded by identifying additional research areas and related keywords. Secondly, the research areas already covered in Appendix 3 can be further improved by identifying additional keywords for each research area. The current categorisation system primarily uses publications keywords. Another dimension is to add patent search keywords so that the categorisations system can also be used for patents.

3) Test the AHP-MCDM foresight model in a different country, especially one with a large data set of patents to incorporate patent data into the model. The reported research was carried out using only publications data because South Africa has few patents. This research can be repeated using a country with a vast nanotechnology patents dataset. Target countries for the study can be selected from the StatNano database (StatNano, 2022).

4) Develop improved scientometric indicators that can closely measure all the nanotechnology CSFs for the Nanotechnology Innovation Diamond and the AHP-MCDM model. For example, “research capability ” was evaluated using the “number of publications ”and “citation impact”. However, a limitation exists that

research capability is more complex than the number of publications and citations. Thus, bibliometric indicators are insufficient to quantify such critical success factors appropriately. Hence, additional scientometric indicators ought to be developed to evaluate better these critical success factors using publications, patents and internet data.

5) The AHP-MCDM model presents a basis for developing an automated or semi-automated decision support system (DSS) for nanotechnology foresight planning, portfolio management and strategic management. Further work must be done to automate the AHP-MCDM foresight model presented in this study.

The next area in which further study is needed is nanotechnology convergence in South Africa. Computer science's rise as one of the top twenty disciplines publishing nanotechnology-related articles in 2019 suggests that convergence of nanotechnology is occurring in South Africa (Roco, 2020). In addition, in the field of nanoscience there was evidence of author collaboration in South Africa. However, based on the current results alone, one cannot say for certain at this point whether or not this is enough evidence to conclude the convergence of scientific fields in nanoscience research for South Africa. It is necessary to determine whether or not these collaborating authors collaborate across or within scientific areas. As a result, additional study is needed in South Africa to establish the prevalence and breadth of the integrated area of nanotechnology, biotechnology, information technology, cognitive sciences, and artificial intelligence (NBICA).

Suppose there is nanotechnology convergence (NBICA) in South Africa. In such a scenario, it is essential to figure out whether it is merely spanning disciplines and subjects (confluence phase), or if it is advanced to the integration phase where frameworks and systems are being built to tackle issues that individual fields cannot handle on their own (Roco, 2020). The additional study contributes to a better understanding among foresight planners on how nanotechnology convergence is developing in South Africa and how the country's national innovation system might look in the future.

5.6 Nanotechnology foresight recommendations to government

This section summarises foresight-related recommendations that the government can adopt to improve nanotechnology research in South Africa.

5.6.1 Improving the DHET incentive scheme to promote large-scale collaborations

The first foresight related recommendation relates to promoting a national system of innovation that is conducive to collaborative research. This research found that there is low institutional collaboration for nanotechnology in South Africa. The current DHET publications’ incentive negatively impacts scientific innovation and industrial development, as raised by the research community in South Africa (Hedding, 2019; Muthama and McKenna, 2020). Researchers now focus on quantity instead of quality, prefer non-collaborative research and even publish in predatory journals just to receive the monetary incentive (Mouton and Valentine, 2017). Recently, the South African Academy of Science (ASSAF) (Wingfield *et al.*, 2020) published some recommendations to the government proposing that the DHET formula for allocating research subsidy be modified to include publications with an excess of 100 co-authors. Therefore, it is suggested that the government establish a task team to review the DHET incentive scheme to promote a national innovation ecosystem conducive to large collaborations and industry participation in research. The task team can be guided by the tenants of the Triple Helix model (Choi *et al*., 2015; Yoon, 2015; Zhuang *et al*., 2021). Consultations must be done between concerned government departments (DHET, Department of Science and Innovation, Department of Trade and Industry), academia, research, and industry stakeholders. The task team has to develop and recommend a model that addresses the following key issues:

a) Promotes collaborative research both at the individual and institutional level, for example, an incentive scheme where research subsidy can be paid for institutional research, small collaborative research, and large-scale consortium research, and

b) A scheme that incentivises private-sector participation in research and hence encourages and promotes industry-academia collaboration in line with the Triple Helix model.

5.6.2 Strategies to increase patents, innovations and industry participation

The results in this study indicate that between 2000 and 2019, South Africa published 11 265 nanotechnology articles on the WoS core collection. On the other hand, the country produced a mere 43 nanotechnology patents as recorded on the European Patents Office (EPO) database. Hence, the second recommendation relates to how the government can boost the production of nanotechnology patents and innovations. The Department of Science and Innovation (DSI) can focus on two primary drivers, which are the development of scientist-entrepreneurs and providing an environment conducive to industry-academia collaborations. The fundamental aspect supporting scientific development is the availability of the right skills to lead the process. Hence it is essential to develop scientist-entrepreneurs first and then provide a conducive innovation environment for them to succeed. A key success factor identified in this research and reported in the Nanotechnology Innovation Diamond is that nanotechnology success depends heavily on scientist-entrepreneurs, i.e. human resources with skills in R&D, publishing academic articles, intellectual property management licencing, marketing, venture creation, and commercialisation of research. (Maine, 2014; Thomas *et al.*, 2020). The DSI can collaborate with the DHET to ensure that the university system in South Africa produces business survey scientists who can thrive in academia, research, innovation and entrepreneurship (Dance, 2019). Developing business survey scientist-entrepreneurs can be done in two ways as follows:

a) Incorporate business and entrepreneurship training right from undergraduate level for science and engineering students and/or

b) Offer a sandwich programme at the post-graduate level whereby students will graduate with two certificates/diplomas, one in the scientific discipline (masters/doctoral degree) and another in technology management and entrepreneurship, for example, a post-graduate certificate/diploma in Innovation and Technology Management.

The next aspect resulting in a few patents is linked to the country's innovation environment where poor industry-academia collaborations exist. In this research, it was observed that only 3% of respondents work in industry. In a closely related study by Patra and Muchie (2018), the lack of industry-academia collaboration in South Africa was observed through patents produced, whereby only 8% of patents were produced via industry-academia collaborations. The DSI must develop policy and incentives that promote industry-academia collaborations and promote patenting. For example, the following policy interventions are recommended:

a) Provide research grants dedicated to strengthening industry-academia collaboration. For example, the government can provide funding the following:
    i. Joint appointment of industry scientists/engineers as researchers/academics for universities
    ii. Joint research between academia and industry, and
    iii. Joint industry-academia supervision of postgraduate students.
b) Establish nanotechnology fabrication facilities accessed by both industry and universities as a means to promote networking and collaborative research. Such facilities will also act as nanotechnology agglomeration clusters because, in this research, it was observed that research agglomeration is critical for successful nanotechnology innovation.
c) Provide an incentive scheme similar to DHET publications incentive scheme where support is provided in filing patents, e.g. technical support, legal support and financial support, to reduce the cost of patenting (WEF, 2019).

In conclusion, training scientist-entrepreneurs and promoting an environment conducive to industry-academia collaborations will result in the proliferation of entrepreneurial universities in line with the Triple Helix model. Entrepreneurial-universities will in turn encourage an innovation culture, where students and academia work together with industry to patent new innovations with the ultimate objective of turning them into start-up companies. (Bodolica and Spraggon, 2021; Miller, Cunningham and Lehmann, 2021).

5.7 Summary

The research journey was summarised in this chapter. The chapter has reported how the research questions and objectives were addressed using quantitative research. The chapter summarised the conclusions on the “Nanotechnology Innovation Diamond”, a framework for managing successful innovation in nanotechnology and the AHP-MCDM foresight model for ranking key-research areas in nanotechnology.

The chapter also summarised how the research contributed to the nanotechnology innovation discourse and to closing gaps in knowledge. The study contributed to closing the following gaps:

- The lack of nanotechnology innovation management models by presenting the Nanotechnology Innovation Diamond,
- The lack of nanotechnology specific foresight models by developing the AHP-MCDM nanotechnology-specific foresight model,
- The lack of use of quantitative and semi-quantitative methods in foresight by developing a foresight model combining technology-mining, scientometric analysis and MCDM, and
- The lack of technology-specific foresight methods is addressed by presenting a generic procedure that can be adapted to develop other technology-specific foresight models.

From a practical innovation management perspective, the research has contributed three tools that innovation managers and policymakers can use. Firstly, the Nanotechnology Innovation Diamond can be used to manage nanotechnology R&D leading successful innovations and technology transfer effectively. Secondly, the AHP-MCDM nanotechnology-specific foresight model can be used in strategic planning and research portfolio management. The model helps in ranking strategic key research areas in nanotechnology to cost-effectively utilise limited resources by focusing on and concentrating resources towards those nanotechnology strategic areas of research that can contribute substantially to solving social and humanitarian problems, support economic development, and improve a country's competitive advantage.

Thirdly, this study has provided a 20-year foresight-based assessment and outlook on nanotechnology in South Africa. It assessed the sectors in which nanotechnology research is conducted in the country. Foresight strategists, entrepreneurs, public officials, and research and innovation managers can utilise the results of this study to determine prospective nanotechnology research areas in South Africa.

In conclusion to this research, it is paramount to remember that nanotechnology innovations create value through the development of new products and improving existing products and services in several economic sectors, for example, medicine, water, food security, energy, environmental protection, manufacturing, construction, electronics, and ICT, among others. This research will contribute to improving innovation management and increase the success rate of nanotechnology innovations and technology transfer. Hence ultimately, as more nanotechnology-based innovations find their way to the market, the research will contribute to improving the knowledge economy and economic competitiveness, solving developmental challenges such as the Sustainable Development Goals (SDGs) and improving society's quality of life.

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Appendix 1: Cover Letter

Survey Background and Informed Consent

Dear Respondent,

You are herewith invited to participate in an academic research study conducted by Brian Masara, a student in the Doctor of Business Leadership at UNISA's Graduate School of Business Leadership (SBL). For your own interest, I am also employed as the Executive Officer of the South African Institute of Physics (SAIP).

Title of the research: Nanotechnology strategic key research areas foresight model for improved innovation and technology transfer.

Purpose of the research: The purpose of the study is to investigate the critical success factors that promote nanotechnology research that leads to successful nanotechnology innovations. The survey results will feed into the development of a Multi-Criteria Decision Making (MCDM) based Key Technologies Foresight Model.

Aim of the research: The overall aim of this study is to develop an effective technology foresight model for selecting and ranking the key nanotechnology strategic research areas in which a country must focus and concentrate resources in order to increase its rate of successful innovations, technology transfer, and hence improve its competitiveness.

Confidentiality: All your answers will be treated as confidential, and you will not be identified in any of the research reports emanating from this research.

Consent: Your participation in this study is very important to us. You may, however, choose not to participate and you may also withdraw from the study at any time without any negative consequences. By selecting Yes below and continuing with the survey you indicate your willingness to participate in the study.

Participant Information Letter: Download the participant information here

Instructions:

Please answer the questions in this online questionnaire as completely and honestly as possible.

This should not take more than 30 - 45 minutes of your time. The study will involve the completion of four short questionnaires as follows:

SECTION A: Demographic information

SECTION B: Characteristics of Successful Nanotechnology Research and Development

SECTION C: Nanotechnology Innovation Critical Success Factors

SECTION D: South Africa's Key Research Areas in Nanotechnology

The results of the study will be used for academic purposes only and may be published in an academic journal. We will provide you with a summary of our findings on request.

Thank you for taking the time to read this and participate in this study.

* 1. I am willing to participate in this survey YES/NO

Appendix 2: Survey Questionnaire

SECTION A: Demographic Information

Please complete the questions below related to your area of work/expertise.

Question 2 Please select a category that closely describes your current job description place a tick against the closest job description.

Researcher	
Engineer	
Academic	
Both Researcher and Academic	
Research, Development & Innovation (RDI) Manager	
Policy Maker	
Both Researcher and RDI Manager	
Other (Specify)	

Question 3. The nanotechnology value chain has 5 main segments which are; nanomaterials industry, nano-intermediaries, nano enabled products, nanotools and the supporting external environment, as shown in figure 1 below;

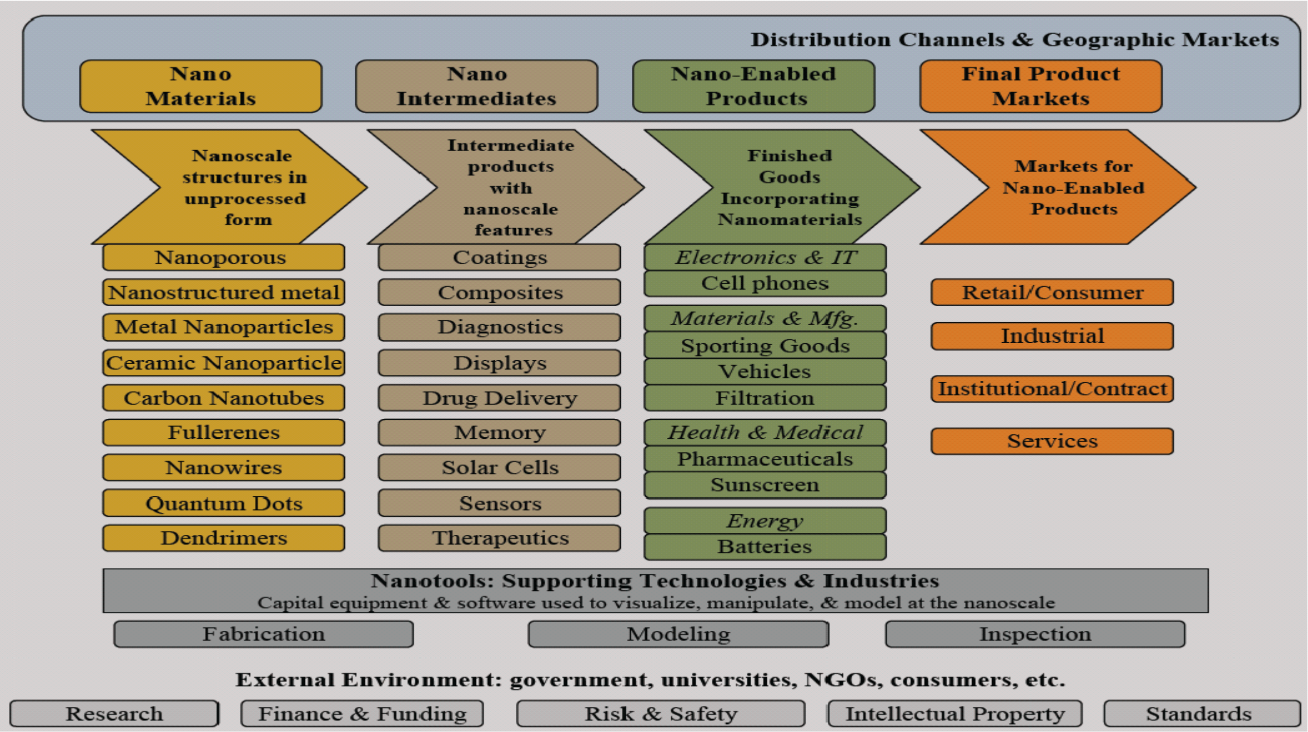

Figure 1: Nanotechnology Innovation Environment and Value Chain (Adopted from Frederick, 2009)

Please indicate the stages within the value chain that closely describe the nature of nanotechnology related industry you are involved in. Please tick appropriate box (s) below;

Nanomaterials		Nano-Intermediaries		Nano-Enabled Products		Nanotools		External Environment	

Question 4: Which of the following best describes the principal industry in which you work/research?

Aerospace	Forestry, Paper and Pulp	Packaging	Water
Agriculture	Government	Paint	
Automotive	Health Care	Petrochemical	
Biotechnology	Industry	Pharmaceutical	
Cement	Material Science	Photovoltaics	
Chemicals	Metrology	Science Council	
Cosmetics	Mining and Minerals	Scientific Equipment	
Electronics	National facility	Textile	
Energy	Optics	University	
Food and Beverages	Optoelectronics	Veterinary	

Section B: Characteristics of Successful Nanotechnology Research and Development.

Question 5: Successful nanotechnology research and development is said to possess several characteristics, please indicate whether you agree or disagree with the following statements by ticking the appropriate box below;

5(a) Successful nanotechnology R&D results in the development of new products and services

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

5(b) Successful nanotechnology R&D results in the improvement of existing products and services

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

5 (c) Successful nanotechnology R&D results in the production of patents and/or trade secrets

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

5 (d) Successful nanotechnology R&D leads to new technology licensing opportunities

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

5(e) Successful nanotechnology R&D leads to commercialisation of research results

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

5(f) Successful nanotechnology R&D leads to the formation of new companies and/or spin-off

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

SECTION C: Nanotechnology Innovation Critical Success Factors

There are several factors that can be considered as Critical Success Factors (CSF) that support nanotechnology research that leads to successful innovations. Please answer the questions 6 to 11 below by ticking the appropriate box.

Question 6: Please answer the following questions regarding nanotechnology innovation environment factors

6(a) The primary factor driving successful nanotechnology innovations is a conducive innovation environment created by government policies.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

6(b) Most successful R&D innovations in nanotechnology are those aligned with government priorities.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

6(c) Strategic partnerships between government, industry, academia, and research institutions are important for successful nanotechnology innovation.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

6(d) Government-supported research infrastructure, and skills development are critical for successful nanotechnology innovations.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

Question 7: Please answer the following questions regarding how consumer perceptions affect the success of nanotechnology R&D

7(a) In order for Nanotech innovations to be successful, they must be accepted by the final consumer.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

7(b) Market perceptions of nanotechnology products by the public is a key success factor for nanotech innovations, especially those with applications in medicine, environment, cosmetics, and food.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

7(c) Successful nanotechnology research must incorporate consumer and market needs early in the research.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

7(d) Most consumers of nanotechnology products are not aware that they are using nanotechnology-based products.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

Question 8: Please answer the following questions regarding clustering and agglomeration in nanotechnology R &D

8(a) The physical location of nanotechnology R&D facilities is a significant factor that contributes to innovation success; some locations present a competitive advantage in facilitating successful nanotech innovations.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

8(b) There is a higher success rate for nanotechnology research conducted within nanotech research centres, science parks, and clusters.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagree

8(c) Working within a nanocluster enables sharing tacit knowledge, specialised infrastructure, and resources. Hence it increases the success rate of nanotechnology innovations.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

8(d) Nanotechnology clusters and nanotech centres of excellence provide a conducive environment for entrepreneurs and nanotech start-up companies.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

Question 9: Please answer the following questions regarding the skills required for successful nanotechnology R&**D**

9(a) Successful nanotechnology innovations emanate from R&D teams with high skills in scientific research, e.g., teams that have a high number of publications, a high number of citations, etc.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

9(b) Successful nanotech innovations emanate from R&D teams that possess innovation management and commercialisation skills.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

9(c) Successful nanotech innovations emanate from teams with intellectual property management skills such as the ability to patent and license innovations.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

9(d) Successful nanotech innovations emanate from R&D teams that have technological entrepreneurship skills.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

Question 10: Please answer the following questions regarding nanotech R&D alignment to socio-economic needs

10(a) Successful nanotechnology innovations must be aligned to existing industry sectors, for example, nano-energy, nanobiotechnology, nanoelectronics, nanoagriculture, and nano-medicine.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

10(b) Industry and academia collaboration are essential for successful nanotechnology innovations.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

10(d) Successful nanotechnology innovations must be aligned to socio-economic needs, e.g., energy security, clean water, medical needs, among others.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

10(e) Strategic R&D partnerships between industry and national research facilities are important for successful nanotechnology research.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

Question 11: Please answer the following statements regarding inter- and multi-disciplinarity in nanotechnology

11(a) Nanotechnology is a multidisciplinary field.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

11(b) Successful Nanotechnology innovations are produced by interdisciplinary teams.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

11(c) Nanotechnology cannot be viewed as a stand-alone discipline but combines several cross-cutting scientific skills.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

11(d) Due to its multidisciplinarity and interdisciplinarity nature, nanotechnology is emerging as the core for the convergence of several disciplines.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagre

SECTION D: South Africa's Key Research Areas in Nanotechnology

There are various nanotechnology research areas in which South Africa is actively involved which are listed in questions 14 and 15 below. In technology foresight context these research areas can be evaluated with respect to two criteria, "Scientific and Technological Feasibility" and "Socio-Economic Importance". In addition, the country's "Nanofabrication Capabilities" must also be considered.

a) Scientific and Technological Feasibility: this takes into consideration the R&D stage of the technology, i.e., whether it is still theoretical, or, it is now in applied stages of development plus the availability of skills and resources in South Africa for the technology to be practically feasible.

b) Socio-Economic Importance: which considers how important the research area is for South Africa’s socio-economic development needs. For example, solving social and economic developmental problems, supporting existing industries, aligned to a country's development agenda etc.

c) Nanofabrication/Manufacturing Capabilities: which considers the availability of facilities and skills to provide scaled-up, reliable and cost-effective manufacturing of nanomaterials, structures and devices

Question 12: The establishment of regional nanotechnology fabrication facilities is key to the success of nanotechnology innovation in South Africa.

(i) strongly agree	(ii) agree	(iii) undecided	(iv) disagree	(v) strongly disagree

Question 13: Which of the following nanofabrication techniques do you consider as critical for South Africa’s nanotechnology innovation? You can choose more than one option.

Chemical vapour deposition	Roll-to-roll processing
Molecular beam epitaxy	Self-assembly
Atomic layer epitaxy	Sputtering
Dip pen lithography	E-beam evaporation
Nanoimprint lithography	Laser deposition
Other (please specify)	

Question 14: Please evaluate the following nanotechnology research areas with respect to their probable Scientific and Technological Feasibility in South Africa

RESEARCH AREA	**Scientific & Technological Feasibility**				
	1. Very Unlikely	2. Not Likely	3. Neutral	4. Likely	5. Very Likely
1) Nano Medicine					
2) Nano-based Fuel Cell Technology					
3) Nano-based High Capacity Battery Technologies					
4) Nano-based Photovoltaic Solar Cells					
5) Nano-based Targeted Drug Delivery					
6) Nano-based Cancer Treatment					
7) Nano-based Acid Mine Water Treatment					
8) Nano-based Wastewater Treatment					
9) Nano-based Drinking Water Purification					
10) Nano-based Photonic Materials					
11) Nano-based Electronic Devices & Components					
12) Nano-based Magnetic Storage and Memory					
13) Nano-based Photonic Devices and Components					
14) Nano-based Catalysis					
15) Nano-based Sensors and Detectors applications					
16) Nanofibers					
17) Nano-composite Materials					
18) Nanofluids					
19) Nano-based Cosmetics					
20) Nano-based Textiles					
21) Nano-based Engineering Materials					

Question 15: Please evaluate the following research areas with respect to their socio-economic importance to South Africa's socio-economic development needs.

RESEARCH AREA	**Socio-Economic Importance**				
	1. Not important	2. Slightly important	3. Moderately important	4. Important	5. Very important
22) Nano Medicine					
23) Nano-based Fuel Cell Technology					
24) Nano-based High Capacity Battery Technologies					
25) Nano-based Photovoltaic Solar Cells					
26) Nano-based Targeted Drug Delivery					
27) Nano-based Cancer Treatment					
28) Nano-based Acid Mine Water Treatment					
29) Nano-based Wastewater Treatment					
30) Nano-based Drinking Water Purification					
31) Nano-based Photonic Materials					
32) Nano-based Electronic Devices & Components					
33) Nano-based Magnetic Storage and Memory					
34) Nano-based Photonic Devices and Components					
35) Nano-based Catalysis					
36) Nano-based Sensors and Detectors Applications					
37) Nanofibers					
38) Nano-composite Materials					
39) Nanofluids					
40) Nano-based Cosmetics					
41) Nano-based Textiles					
42) Nano-based Engineering Materials					

THE END THANK YOU!

Appendix 3: Vantage Point Research Areas Categorization Protocol Terms

** Photoluminance & Optics 0 1 emission colour 0 1 lasers 0 1 light emission 0 1 light emitting 0 1 luminescence 0 1 luminescence properties 0 1 luminescent 0 1 Nano-Optics 0 1 Nanooptics 0 1 nanophosphors 0 1 optical 0 1 optics 0 1 optoelectronic 0 1 optoelectronic* 0 1 photoluminescence emission 0 1 photonic 0 1 photonics 0 1 photonics	**Electronics 0 1 ^electronic properties$ 0 1 ^electronic structure$ 0 1 band gap 0 1 band-gap 0 1 capacitance 0 1 device* 0 1 diode 0 1 dopped 0 1 dopping 0 1 conductivity 0 1 electric charge 0 1 electrical conductivity 0 1 electrical resistance 0 1 electrical resistivity 0 1 electronic 0 1 electronic excitation 0 1 electronic excitations 0 1 electronic-properties 0 1 magnetic random 0 1 memory 0 1 nanodevice* 0 1 nanoelectronics 0 1 p-type 0 1 quantum information 0 1 resistivity 0 1 semiconductor 0 1 transistor* 0 1 vacancies 0 1 voltage	**Medicine 0 1 ^neurological diseases$ 0 1 AIDS 0 1 antibacterial 0 1 antibodies 0 1 antibody 0 1 antimicrobial 0 1 bacteria 0 1 biomarker 0 1 biomarkers 0 1 Biopharmaceutics 0 1 biosensor 0 1 bone 0 1 Bone Repair 0 1 cancer 0 1 cancer- 0 1 cancer-cells 0 1 Cochlear 0 1 controlled-release 0 1 disease 0 1 DNA 0 1 drug 0 1 Drug Carriers 0 1 Drug Encapsulation 0 1 drug* 0 1 drug-delivery 0 1 E.coli 0 1 gene 0 1 Gene delivery 0 1 Genetic 0 1 HIV 0 1 Imaging Devices 0 1 implant 0 1 ImplanTable 0 1 in vitro 0 1 in-vitro 0 1 inflammation 0 1 medical 0 1 medicine 0 1 metallophthalocyanines 0 1 mRNA 0 1 nano-pharmac* 0 1 nanopharmac* 0 1 nanotoxicology 0 1 ntoxicology 0 1 pharmaceutical 0 1 photodynamic therapy	**Energy 0 1 batteries 0 1 Battery 0 1 Electrochemistry 0 1 Energy Storage 0 1 Energy-storage 0 1 fuel cell 0 1 fuel cells 0 1 fuel-cells 0 1 hydrogen energy 0 1 hydrogen removal energy 0 1 hydrogen storage 0 1 lamp 0 1 lamps 0 1 PEMFC 0 1 photovoltaic 0 1 proton exchange membrane 0 1 solar 0 1 supercapacitor 0 1 temperature reactor
**Catalysis 0 1 catalysis 0 1 catalyst 0 1 catalytic 0 1 electrocatalysis 0 1 Fischer-tropsch 0 1 nanocatalysis 0 1 photocatalytic 0 1 selective oxidation 0 1 surfactant 0 1 surfactants			**biotech 0 1 biolog* 0 1 biopersistence 0 1 biotechnology 0 1 enzyme* 0 1 toxicity 0 1 toxicity
**Materials 0 1 biopolymer 0 1 ceramics 0 1 Composites 0 1 copolymers 0 1 growth 0 1 mechanical properties	**Water 0 1 acid mine 0 1 Adsorption of Cr (VI) 0 1 adsorption of Cr(VI) 0 1 clean water		**Cosmetics 0 1 ^skin care$ 0 1 beauty 0 1 cosmetic* 0 1 lotion* 0 1 sun screen* 0 1 sun-screen*

<table>
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0 1 Nano-fibre
0 1 nanocomposites
0 1 nanofibres
0 1 nanotubes
0 1 polymers
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0 1 synthesis
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0 1 Cr(VI) from aqueous solution
0 1 desalination*
0 1 drinking water
0 1 drinking-water
0 1 groundwater
0 1 mine water
0 1 nanofiltration
0 1 removal of Cr(VI)
0 1 Removal of hexavalent chromium
0 1 removal of toxic
0 1 waste water
0 1 waste-water
0 1 waste-water treatment
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0 1 water filter
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0 1 water filtration
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0 1 water purification
0 1 water system
0 1 water treatment</td><td rowspan="2">0 1 Retina
0 1 surgery
0 1 Surgical
0 1 therapy
0 1 Tissue
0 1 Tuberculosis
0 1 virus</td><td>**Magnetism
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0 1 ^magnetic$
0 1 ^magnetization$
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0 1 pesticide*</td><td>**automotive
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0 1 aircraft*
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0 1 aviation
0 1 car
0 1 car manufacture
0 1 space craft*
0 1 vehicle parts
0 1 vehicle spares</td></tr>
</table>

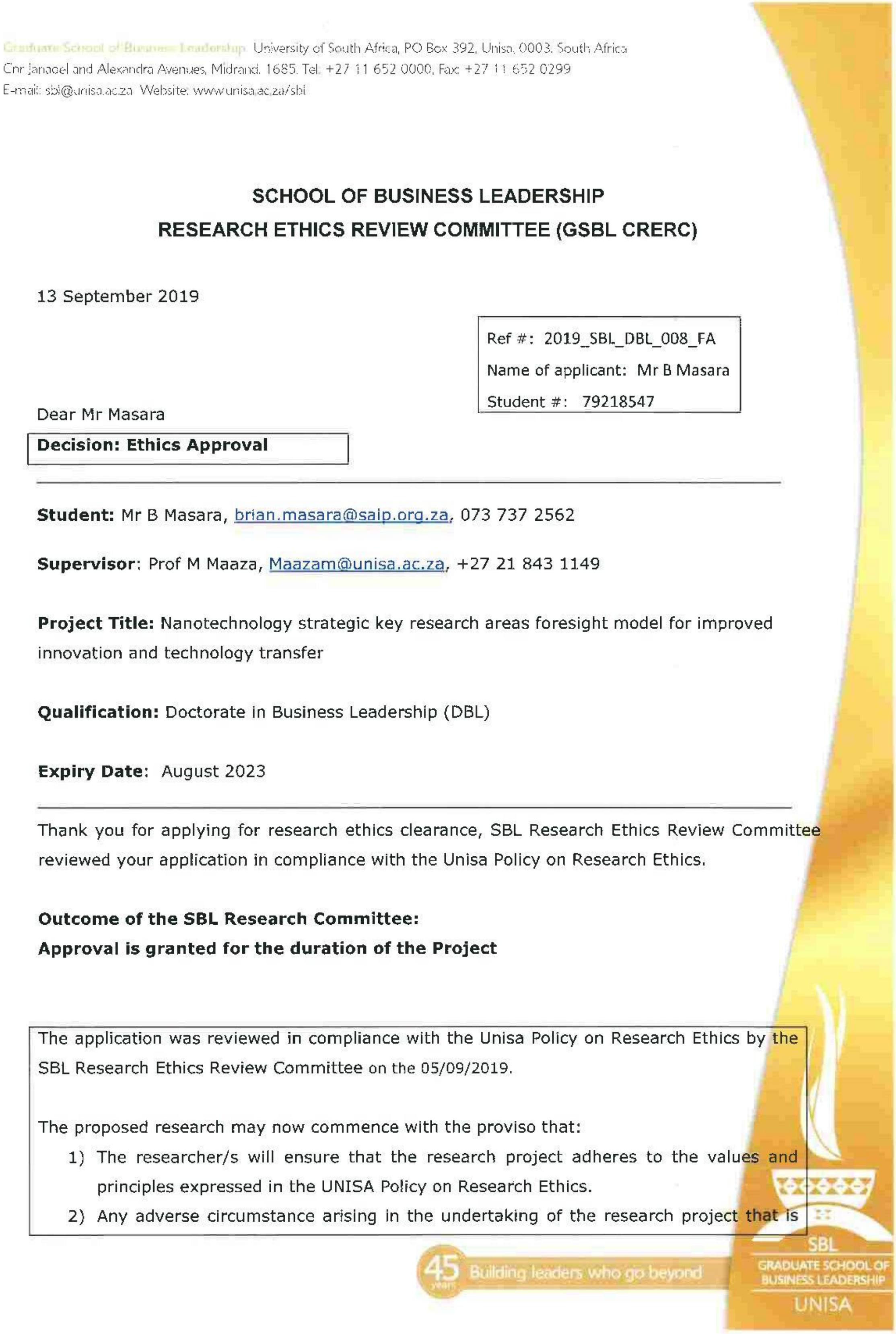
Appendix 4: Vantage Point Nanotechnology Value-Chain Categorization Protocol Terms

**Intermediates	**Materials	**Nano-Enabled Products
0 1 coat* 0 1 coating* 0 1 composite* 0 1 diagonostic* 0 1 display* 0 1 drug* 0 1 memory 0 1 nano intermidiat* 0 1 Nano Reinforce* 0 1 Nano-reinforce* 0 1 Nanofiller* 0 1 nanofillers 0 1 Nanofilter* 0 1 sensor* 0 1 solar cell 0 1 therapeutic*	0 1 ceramic nanoparticle* 0 1 crystal* 0 1 dendrimer* 0 1 fuller* 0 1 luminescence* 0 1 nanocluster* 0 1 Nanocrystal* 0 1 nanofuild* 0 1 nanoparticle 0 1 nanoporous 0 1 nanorod* 0 1 nanostructured 0 1 nanostructures 0 1 nanotube* 0 1 nanotubes 0 1 nanowire* 0 1 quantum dot* 0 1 quantum-dot*	0 1 batter* 0 1 cosmetics 0 1 electronics 0 1 filtration 0 1 lotion 0 1 nano-enabled 0 1 nano-filter 0 1 paint* 0 1 pharmaceutic* 0 1 photo voltaic panel 0 1 pv panel 0 1 solar panel 0 1 suncreen* 0 1 water filter

Appendix 5: Vantage Point South Africa Nanotechnology Clustering Protocol Terms

**Eastern Cape 0 1 mandela 0 1 Rhodes Univ 0 1 rodhes	**North West 0 1 mafikeng 0 1 North West Univ 0 1 nwu.ac.za	**KZN 0 1 ^Durban Univ Technol$ 0 1 ^Univ Zululand$ 0 1 natal 0 1 ukzn 0 1 ukzn.ac.za
**Joburg 0 1 ^Univ Johannesburg$ 0 1 ^Univ Witwatersrand$ 0 1 MINTEK 0 1 UJ 0 1 University of Johannesburg 0 1 wits	**Pretoria 0 1 ^UNISA$ 0 1 ^Univ S Africa$ 0 1 ^Univ South Africa$ 0 1 CSIR 0 1 Pretoria 0 1 Sefako Makgatho Hlth Sci Univ 0 1 Tshwane 0 1 TUT 0 1 Univ South Africa UNISA 0 1 University of Pretoria	**Western Cape 0 1 ^Cape Peninsula Univ Technol$ 0 1 ^Univ Cape Town$ 0 1 ^Univ Stellenbosch 0 1 ^Univ Western Cape$ 0 1 African Inst Math Sci 0 1 CPUT 0 1 Ilabs 0 1 iThemba 0 1 NRF 0 1 UCT 0 1 US 0 1 UWC
**Limpopo 0 1 ul.ac.za 0 1 Univ Limpopo 0 1 venda	**Free State 0 1 ^Univ Free State$ 0 1 SASOL 0 1 UFS	

Appendix 6: Ethical Clearance Letter



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RESEARCH ETHICS REVIEW COMMITTEE (GSBL CRERC)

13 September 2019

Ref #: 2019_SBL_DBL_008_FA
Name of applicant: Mr B Masara
Student #: 79218547

Dear Mr Masara

Decision: Ethics Approval

Student: Mr B Masara, brian.masara@saip.org.za, 073 737 2562

Supervisor: Prof M Maaza, Maazam@unisa.ac.za, +27 21 843 1149

Project Title: Nanotechnology strategic key research areas foresight model for improved innovation and technology transfer

Qualification: Doctorate in Business Leadership (DBL)

Expiry Date: August 2023

Thank you for applying for research ethics clearance, SBL Research Ethics Review Committee reviewed your application in compliance with the Unisa Policy on Research Ethics.

Outcome of the SBL Research Committee:
Approval is granted for the duration of the Project

The application was reviewed in compliance with the Unisa Policy on Research Ethics by the SBL Research Ethics Review Committee on the 05/09/2019.

The proposed research may now commence with the proviso that:

1) The researcher/s will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.
2) Any adverse circumstance arising in the undertaking of the research project that is

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relevant to the ethicality of the study, as well as changes in the methodology, should be communicated in writing to the SBL Research Ethics Review Committee.

3) An amended application could be requested if there are substantial changes from the existing proposal, especially if those changes affect any of the study-related risks for the research participants.
4) The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study.

Kind regards,

Prof R Ramphal
Chairperson: SBL Research Ethics Committee
011 – 652 0363 or ramphrr@unisa.ac.za

Prof RT Mpofu
Executive Dean (Acting): Graduate School of Business Leadership
011- 652 0256/mpofurt@unisa.ac.za

Appendix 7: Language Editor's Certificate

8 Nahoon Valley Place
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13 June 2021

TO WHOM IT MAY CONCERN

I hereby confirm that I have proofread and edited the following thesis using the Windows 'Tracking' system to reflect my comments and suggested corrections for the student to action:

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BM Carlson

Brian Carlson (B.A., M.Ed.)

Professional Editor

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Appendix 8: Turnitin Report

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