Business Modelling for the Quality Control and Commercialisation of Engineered Nano-materials

Submitted in fulfilment of the requirements of the Degree of Doctor of Philosophy: Operations and Quality Management in the Faculty of Management Sciences at the Durban University of Technology

Oladimeji Hezekiah

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Supervisor: ___

Prof. Shalini Singh

Abstract

Nanotechnology is viewed by many as the technology that will create new opportunities for wealth and job creation. Meanwhile, despite nanotechnology's shuddering of the global economy, breaking into the markets have been increasingly onerous for many reasons. This study investigates emerging applications and the commercialisation of nanotechnology materials. It also deals with the opportunities and challenges associated with the possible acceleration of the commercialisation of applications of nanotechnology materials. Significant factors influencing the acceleration of nanotechnology materials onto the markets were identified through a series of literature reviews and surveys conducted with nanotechnology researchers. Common characteristics for the achievement of the successful commercialisation of nano-induced products were identified.

This study adopted a purposive sampling technique. The study population for the survey was made up of active researchers. The reliability test of the survey items was internally consistent with a Cronbach's alpha index of $\alpha = 0.926$. Qualitative analyses entailed the researchers in nanotechnology who were interviewed through the Delphi technique. Quantitative results were obtained in the study through a hybrid technique of the Analytical Hierarchy Process and the Data Envelopment Analysis (AHP/DEA).

This research identified and evaluated several critical factors for the effective commercialisation of nanotechnology and engineered nano-materials (ENMs) through a review of recent and current literature, as well as suggestions of academic experts in nanotechnology through the Delphi method. Thirty-four (34) critical factors grouped into ten (10) dimensions were identified and evaluated for importance and subsequently for priority scaling. The framework for this research used a hybrid approach of the Analytical Hierarchy Process and the Data Envelopment Analysis (AHP/DEA) The Analytical Hierarchy Process (AHP) technique was implemented in the evaluation of these critical factors for effective nanotechnology commercialisation decision-making. Furthermore, the DEA was suitably used in validating the AHP priority model obtained.

This analytical approach provided support for quality control and the commercialisation of the decision-making process. The study concluded by proposing a framework to provide scientific knowledge that will help researchers, technology investors and managers in the commercialisation process of nanotechnology and engineered nano-materials. A strong recommendation was made for robust fundamental research for viable commercial production and improvement for the enhancement of a nano ethic.

1. I know and understand that plagiarism is using another person’s work and pretending it is one’s own, which is wrong.

2. This thesis is my own work.

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OLADIMEJI HEZEKIAH

Student Number: 21452297

Declaration

I, Oladimeji Hezekiah, hereby declare that this thesis is wholly my own work and that all the references to my best of knowledge, are accurately reported. This work has not been submitted for a degree at any other University, and that its only prior publication was in the form of conference papers and chapter of a book as listed below:

- **Oladimeji, H.** and Singh, S. 2013. Operations research modelling approaches for commercialisation of nano-engineered materials. In: Kanny, K. ed. *Advances in composites, biocomposites and nanocomposites*. Manipal: University Press.
- **Oladimeji, H.** Singh, S. and Kanny, K. 2018. *Critical factors for the commercialisation of nanotechnology* Being a poster presentation at the South African Nanotechnology Initiative (SANi) April 2018.
- **Oladimeji, H.** and Singh, S. 2018. Bionanocomposites in packaging: Business model for products' commercialisation. In: Ahmed, S. ed. *Bio-based materials for food packaging*. Singapore: Springer Nature Pte Ltd

____________________ 19 November 2021

Signature Date

Dedication

This study is dedicated to the *Arugbo-Ojo* – the Immortal, Invisible and Holy One indeed, and to the loving memory my late father – Pastor (Dr) David Oladimeji who never waited to benefit a ‘dime' of his labour from me. This dissertation was undertaken in your honour and I hope to do more.

Acknowledgement

"God will make a way, where there seems to be no way. He works in ways we cannot see (nor understand). He will make a way!" Today, once again, the assurances in my favourite song in times of challenges and difficulties are fulfilled. You are genuinely the *Way-Maker, Miracle-Worker, Promise-Keeper* and *the Lion-of-Judah* as You made this day a reality.

My heartfelt gratitude especially goes to my wife, Dr Motunrayo Oladimeji for standing by me through this tough period. You are indeed a BB – an epitome of *Brain & Beauty*. Many thanks to my two darling angels – Hephzibah Oladimeji & Esther Ola-Hezekiah. Dad should be able to create more time for you now.

I am profoundly thankful to my Supervisor, Prof. Shalini Singh. It has been a herculean task for me to coin words to describe you. All I know is that "God has been sending *Angels* to me at my cross-roads over time in my journey of life and you are the latest". You are not just a Supervisor to me but a Mentor, Source of encouragement, Motivator and a Challenger. Your several academic awards displayed in your office continue to challenge me to be the same or better. Thanks for believing in me, especially when you introduced nanotechnology to me, and you kept challenging towards a successful completion.

I will ever be grateful to my amiable HoD, Mr Rabindutt Ramlagan, for all your efforts at the 'cross-road'. I am grateful to the Librarian, Ms Sarah Mita for all her training. It was a privilege to use the DUT library while I was in South Africa. The extra effort you went through to get me any material I requested while I was in Nigeria is highly appreciated.

Many thanks also to my “nano partners” – those members of the Composite Research Group who supported me by sharing their times, thoughts and insights during the research of this study.

I want to express my appreciation to DUT every form of supports which made this degree programme a reality. I hope to work towards the development of nanotechnology in South Africa in return for this enormous gesture. Thanks for investing in me!

Finally, this acknowledgement would be incomplete without wholeheartedly appreciating God for those He used to make me feel at home during my short stays in South Africa. God shall reward your efforts.

Thanks all.

Abbreviations and Terminology

Within this study, several abbreviations and terminologies in the field of nanotechnology and operations research were used. These are outlined below:

Abbreviation

AHP	Analytical Hierarchy Process
CNT	Carbon nanotube
CRG	Composite Research Group
DEA	Data Envelopment Analysis
DM	Delphi Method
DMU	Decision Making Unit
DUT	Durban University of Technology
ENMs	Engineered Nano-materials
FAHP	Fuzzy Analytical Hierarchy Process
LINDO	Linear, Interactive, and Discrete Optimiser software package
LPP	Linear Programming Problem
MDCM	Multi-Criteria Decision Making
OR	Operations Research
SPSS	Statistical Package for Social Sciences
US-NNI	United States National Nanotechnology Initiative

Terminology

1. Model is described as a simplified representation of entity that is real (Taha 2017) with its functions illustrated to include envisaging a phenomenon (Maier, Eckect and Clackson 2017), making predictions, decision making (Roberts and Hutcherson 2019) and communication (Wynn and Clackson 2018)

2. Modelling comes from the Latin word *modellus* (Gerlee and Lundh 2016). The process of modelling assists the scientists representing ideas about the real world to one another, at the same time make changes to these depictions over time in response to new evidence and understandings (Wirtz *et al.* 2016)

3. Nanotechnology is any technology with the ability to control and reframe matter at the atomic and molecular levels in the range of approximately 1–100 nm and exploiting the distinct properties and phenomena at that scale as compared to those associated with single atoms or molecules or bulk behaviour. It is defined as science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers (Bhushan 2017). It is the study and application of extremely small things and can be used across all the other science fields (US-NNI 2019).

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CHAPTER ONE

INTRODUCTION

1.1 Overview of the Chapter

Advanced quality control systems have encouraged the demand for optimum quality products with cutting-edge technological innovations in the global competitive markets (Singh, Singh, Singh and Kumar 2019). Only an average of 10 out of 30,000 innovative ideas, according to Datta, Mukherjee and Jessup (2014), meet required quality standard. This, they believe, can be ascribed to the varying and challenging entrepreneurial activities involved in the complex linkage between the two ends of commercialisation of technological innovation which are generation of ideas and product launch.

Maresova, Stemberkova and Fadeyi (2019); and Chebo and Wubatie (2021) argue that there has been continuous interest in technological commercialisation as evident from peer-reviewed research of innovation. Dehghani (2015) identified three indispensable parts of research of innovation as market demand identification, technological development and effective commercialisation. Effective commercialisation is mooted to be a critical sector of the technological innovation chain with novel ideas being generated, nurtured, transformed and subsequently commercialised.

Meanwhile from time to time, new technologies with the potential to change the configuration of the micro and macro economies are continuously being developed and nanotechnology is described as one of the technologies with such immense potential. National Academies of Sciences Engineering and Medicines (2020) cites it as a technology with a compelling future impact. To this effect, this research is intended to propose a framework for the quality control and effective commercialisation of nanotechnology applications. This is novel as no such model has been presented, to the best of the Reseacher's knowledge.

In realising this intention, this chapter of the study reveals the infinite potential of innovations with focus on nanotechnology. The chapter also considers the aim and the various objectives of the study. The research methodology adopted for the study, the scope and delimitation, amongst others will be succinctly discussed.

1.2 Background and Context of the Study

Nanotechnology is rapidly becoming a fact of life and of business with major relevance for all human endeavours. Although it is a relatively new discipline in traditional sciences, this emerging technology possesses the immense potential of contributing to sustainable innovation (Omidiora 2014). Meanwhile, scientists have made some progress at building devices, including computer components, at nanoscales. Faster progress has occurred with the incorporation of nano-materials into other products (Hutchison 2016) and in various industrial areas such as food safety and packaging (Berekaa 2015; Singh, Shukla, Shukla, Kumar, Wahla, Bajpai and Rather 2017; Enescu, Cerqueira, Fucinos and Pastrana 2019); sustainable biofuel production (Rodríguez-Couto 2018); global agricultural development (Shang, Hasan, Ahammed, Li, Yin and Zhou 2019; Lowry, Avellan and Gilbertson 2019; Kah and Kookana 2020); thermal and insulation materials in the building industry (Gholami-Rostam, Mahdavinejad and Gholami-Rostam, 2015); and cancer diagnosis and treatment delivery (Jin, Kim, Hwang, Han, Kwak and Lee 2020). Extensive nanotechnology-based applications are also known to include environmental remediation (Wen *et al*. 2019; Aithal and Aithal 2021), sports, fashion, cosmetic products and medical equipment to improve modern lifestyle products (Joubert *et al* 2020; Idumah 2020) and lately, the management of COVID-19 (Rai *et al.* 2020; Idumah, 2020). Exploring the significant impact of nanostructures in biomimetics or biomimicry, Garg, Ghatmale, Tarwadi and Chavan (2017) opined that there are yet more nanostructures and their applications and commercialisation to be explored. Espinosa, Teran and Ortega (2021) assert that the intermediary processes between investments in research and development and gainful output are the quality control processes. According to Aithal and Aithal (2016), the business potential of this technology is expected to alleviate global social challenges. Nanotechnology is also expected to serve as a significant driving force in modernistic agriculture for sustainable food production (Alfadul, Altahir and Khan 2017).

This chapter considers the primary aim, the objectives and the justification for this study. Basically, evidence is presented on the commercialisation and quality control of nanotechnology enabled products and materials throughout the study. Subsequently, and based on the review of literature and research respectively conducted qualitatively and quantitatively, critical factors will be identified and a business framework developed for the successful commercialisation of engineered nano-materials.

1.2.1 Introduction to nanotechnology

The United States National Nanotechnology Initiative (US-NNI) (2019) views nanotechnology as the term used to describe new methods that have been developed to manipulate and build materials at the molecular level, as well as engineered materials at a scale of less than 100 nanometers. Nobel Prize Laureate Richard Feynman, in "There is Plenty of Rooms at the Bottom" (Feynman 1960 cited in Mangematin and Walsh 2012), technically first pointed out the potential quantum benefits of miniaturisation as a major advancement at nanoscales. Thus, nanotechnologists are always looking to exploit the properties of new materials at the nanoscale.

Typically, the availability of raw materials that could be practically exploited is the technologically distinctive feature of all civilisations. The most important part of the development of these materials involves the design and manipulation of structure, functionality and properties of the materials (Khan, Saeed and Khan 2019). Meanwhile, in several cases, the design and manipulation process are a function of the occurrence of the operational consequences of the atomic-scale (Kawai, Foster, Canova, Onodera, Kitamura and Meyer 2014).

Nanotechnology is interdisciplinary in that it cuts across traditional science and engineering fields, including life sciences, chemistry, physics, materials, computer science, electrical and mechanical engineering (Idumah 2020). It has also shown some applications in sustainable agriculture (Usman, Farooq, Wakeel, Nawaz, Cheema, Rehman, Ashraf and Sanaullah 2020). Drug delivery is also being proposed as a form of Deoxyribonucleic Acid (DNA) nanotechnology in medical technology (Dunn 2020). This emerging field of science is known to be disruptive and has a wide range of general purpose applications in any discipline (Masara, Poll and Maaza 2021). Therefore, several challenging bottlenecks in developing nanotechnology research, including its commercialisation success, require solution approaches that are quantitative and multidisciplinary.

1.2.2 Engineered Nano-materials (ENMs)

This sub-section focuses on the contextualisation of ENMs. Engineered nano-materials are extensively defined by Kaur, Gill and Jeet (2019) as materials with one or more essential dimensions below a hundred nanometers which uniquely possess magnetic, optical and electrical properties. Garduño-Balderas, Urrutia-Ortega, Medina-Reyes and Chirino (2015) confirm that the synthesis of ENMs has only been recent although there has been the existence of natural nano-materials long before the existence of humans. Furthermore, several consumer products are being manufactured with the use of ENMs (Vance, Kuiken, Vejerano, McGinnis, Hochella, Rejeski and Hull 2015).

These materials are adjudged as the archetype products of nanotechnology (Benelmekki 2019). According to Kaur, Gill and Jeet (2019), these engineered materials are of enormous commercial importance in novel drug delivery formulations. Furthermore, the concerns for their commercialisation and quality control in industrial productions have been rapid and at a higher pace when compared with the potential risk assessment and the development of evaluation techniques for the safe use of ENMs (Johnston, Gonzalez-Rojano, Wilkinson and Xing 2020).

1.2.3 Nanotechnology as Disruptive Innovation

Nanotechnology, in the Fourth Industrial Revolution, is described as a disruptive technology (Schulenburg 2012) as it exhibits a radical innovation by destroying existing processes in the market with immense economic and technical performance, thereby generating changes industrially, economically, socially and technologically (Reinhardt and Gurtner, 2015). Coccia (2020) argues that nanotechnology more often than not destroys established technologies in the market. This disruption is due to the dominant and dynamic attributes of emerging technologies over the established ones (Coccia and Watts 2020). There are theories associated with disruptive technologies for industrial and corporate dynamics as described in Figure 1.1 and extensively discussed in the following chapter of this study.

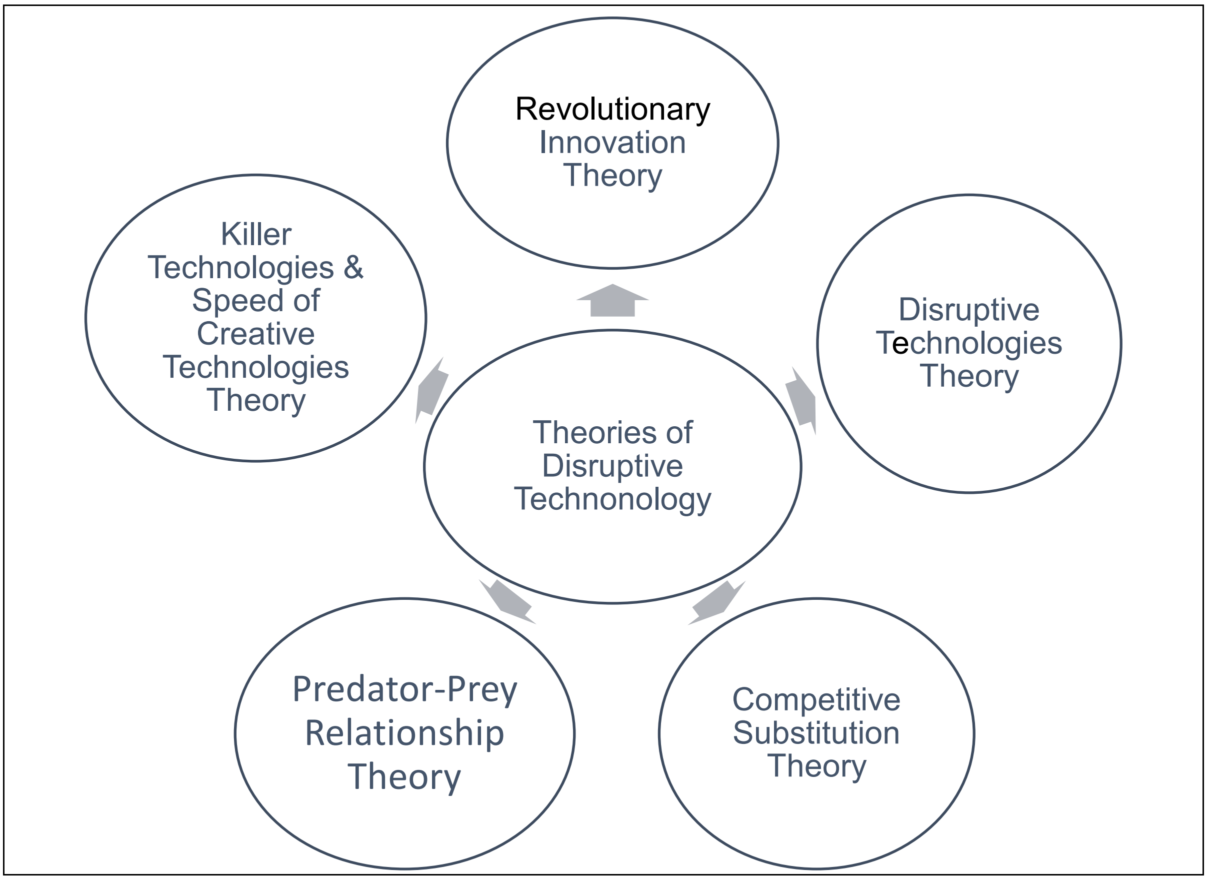


Figure 1.1 Theories of disruptive technologies in industrial dynamics

Source: Coccia (2020)

1.2.4 Commercialisation of Nanotechnology

Lewin (2014) asserts that the principal driver for the commercialisation of nanotechnology is its potential to tackle important global bottlenecks. Potentially, the commercialisation of nanotechnology has a great impact on daily living and on all areas of micro and macro economies (Kaur *et al*. 2014) as it has various applications in every field (Lewin 2014). The concept of 'Commercialisation' is termed as the conversion or transfer of 'technology' to a position of profit-making (Jafarizadeh-Malmiri, Sayyar, Anarjan and Berenjian 2019).

Kaur *et al*. (2014) posit that alhough the technology is gaining much attention from various stakeholders especially donors, the commercialisation of nanotechnology has been at its infancy stage and is still not getting the attention of nanotechnology researchers, especially in South Africa, as evident in figure 1.2.

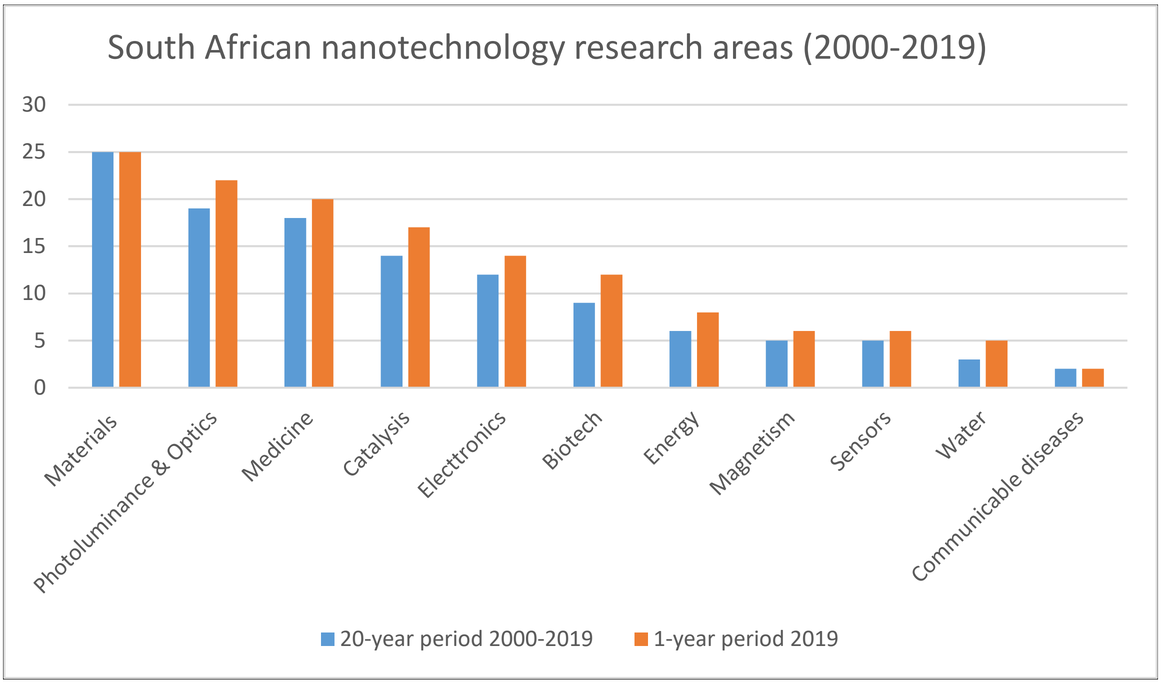


Figure 1.2 Strategic socio-economic nanotechnology research areas for South Africa

Source: Masara, Poll and Maaza (2021)

Masara, Poll and Maaza (2021) opine that South Africa is in an advantageous position to benefit from this emerging field, being one of the countries that have implemented the National Nanotechnology Initiative (NNI). Others are the United State of America, the United Kingdom, India, Japan, Germany and South Korea (Grassian *et al.* 2016). To this end, the framework for commercialisation could be viewed and delineated in three perspectives (Shakeel 2019), namely:

i) the development of emerging engineered materials possessing the potential to serve the demands of the market;

ii) adopting a commercialisation framework that is suitable for emerging technology and the manufacturing industry; and

iii) launching the enabled product in such a manner that it is receptive to the consuming populace and also self-sustaining in the market

This is the motivation for this study as it seeks to contribute to current discussions addressing nanotechnology commercialisation.

1.2.5 Quality Control and Assurance for ENMs

According to Krug (2014), it is generally acknowledged that the quality control and quality assurance of ENMs are greatly impacted during their production as a result of an inadequate description of the distinctive nature of the materials. Hence, the necessity for the characterisation of ENMs (Johnston, Gonzalez-Rojano, Wilkinson and Xing 2020) and its consideration in this section of the work. As depicted in Figure 1.3, the characterisation techniques that are often used are categorised into intrinsic properties which include the primary particle size, the composition and the specific surface area, while the aggregation, dispersion tendency and the shape are extrinsic properties.

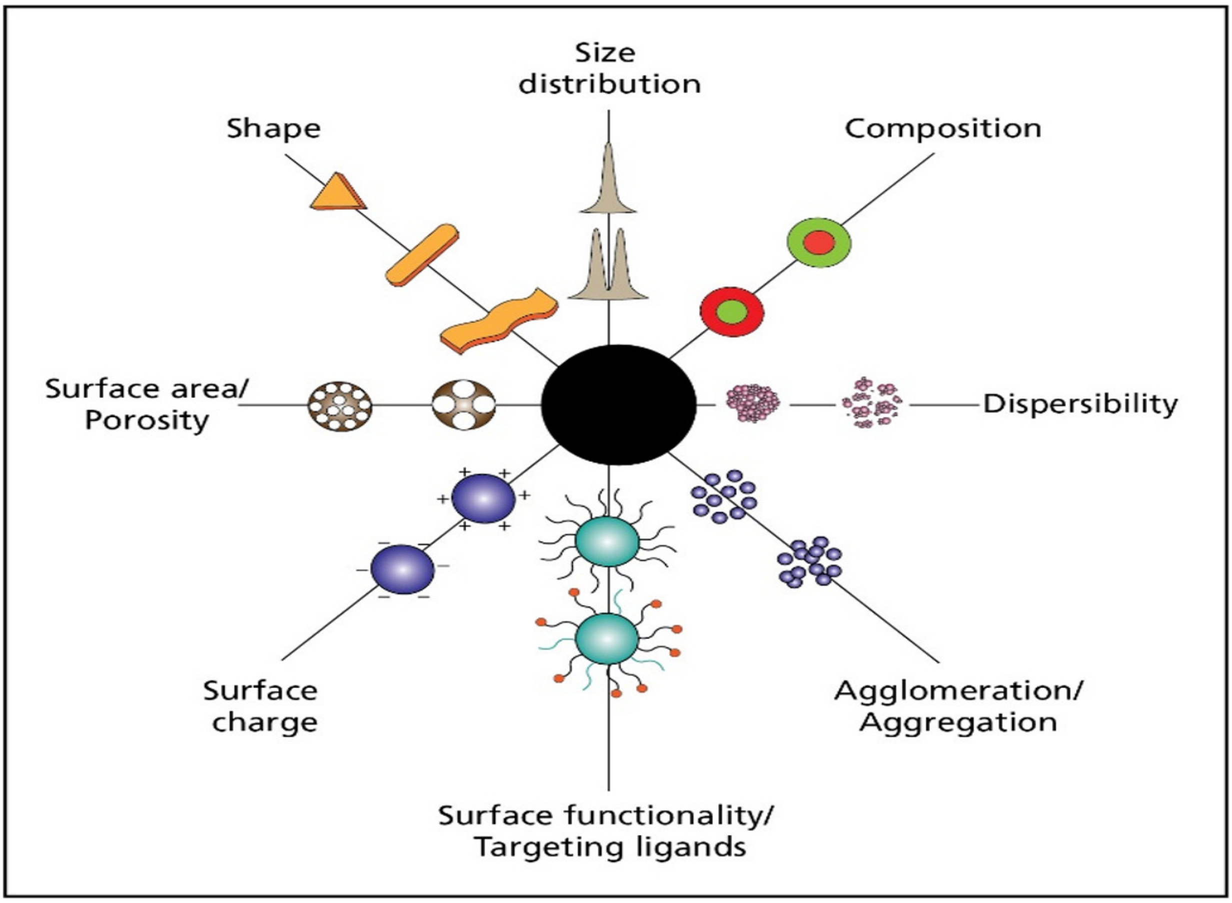


Figure 1.3 Considerable properties in the characterisation of ENMs for quality control

Source: Johnston, Gonzalez-Rojano, Wilkinson and Xing (2020)

Mitra (2016) equates quality with fitness for purpose. The author further succinctly describes the quality of a product or an engineered material as the fitness of the material to attain and exceed consumers' intended use and requirements. A modern definition of the quality of a product or an engineered material was proposed by Montgomery (2020) as the inverse proportionality to variability. This definition implies that quality is critically linked to variability in such a way that a decrease in the variability of the characteristics of a product will lead to a corresponding increase in the quality of the product. Quality is metaphorically viewed as 'moving targets' (Šedžiuvienė and Tamutienė 2016) and in an epithetical view, quality is described by Elassy (2015) to be elusive as it is based on agreement with approved standards and hence there exists no global definition of quality (Paulauskaitė, Zuzevičiūtė and Starkevičiūtė 2016). The critical properties for the quality of a product are as shown in Figure 1.3 and these are essential for market acceptability of nano-enabled products.

From all considerations in this and the preceding section, it is evident that quality tools are essential for the successful commercialisation of nanotechnology, more especially required for ENMs.

1.2.6 Operations Research, Models and Modelling

It is mooted by Akbari, Akbari and Yavari (2014) that Operational Research techniques can play a perfect role to boost the development, quality control and commercialisation of products and materials based on nanotechnology. The authors posit that, in collaboration with some areas of specialisation, nanotechnology has made significant impacts on countries' industrial sectors through achievements in the optimisation of production and maintenance costs, efficiency, energy generation and consumption. Since Operations Research is about optimisation, this study seeks to identify the redundant importance of commercialisation of nano products or services, and it intends to explore and develop a commercialisation technique in Operations Research.

To reiterate the relevance of Operations Research methods in nanotechnology, Aslani, Eftekhari, Hamidi and Nabavi (2015) identified factors in the selection of commercialisation methods to include the costs of minimisation and maximisation of technology transfer time. Technological attraction and market access were also identified in Hassan, GolAfshani, Gholami and Keshavarsi's (2012) work. According to Barbieux and Padula (2018), for any organisation to survive with new technology, there is the need for innovativeness in the enabled-products or a high degree of novelty in the market. Davoodi, Farsi and Naseri (2012) opine that traditionally in any organisation, commercialisation forms part of a business framework that is vital to the development and continued survival of technology. Due to nanotechnology being a new science, this is not yet evident. These authors concluded that organisations which were successful had suitable and precise business frameworks for themselves thus alluding to the importance of commercialisation in nanotechnology.

Based on expert opinion, nano-materials exhibit promising use as they are cost-effective and eco-friendly (Rana, Kour, Yadav and Yadav, 2020). Meanwhile, according to Rai, *et al*, (2020), nanotechnology-based research is at the preliminary stage. To this end, decision making assumes scientifically supported processes, which in most cases encompasses several decision makers and interest groups including the producers and consumers. More importantly, quality decisions are determinants of quality products (Alimohammadzadeh, Bahadori and Hassani, 2016) suggesting the importance of quality as every decision to produce or embark on commercialisation is influenced by product quality. Meanwhile, in order to successfully deal with the varying attitudes and opinions of different people, a variety of methods are in use and adopted in this study including those involving quantitative, qualitative and semi-qualitative attributes or qualities.

1.3 Statement of the Research Problem

Several potential activities of ENMs have yielded enormous outputs in the advanced applications of nano-enabled products in the market (Nile *et al.* 2020). Critical to twenty-first century global scientific advancement, product and social innovations and extensive technological development is nanotechnology advancement (Hao, Hui and Lau, 2020). However, Cerrillo *et al*. (2020) state that this is not without some key challenges. These 21st century challenges are viewed as being convergent, and the required solutions to these bottlenecks lie in the adoption and advancement of technology with the capacity of creating new product prototypes at the intersecting and interacting points with diverse technologies. Meanwhile, the bottlenecks in the technological advancement of nanotechnology include technology commercialisation and quality control (Marassi *et al.* 2018). Aithal and Aithal (2016) decried the global failure to attain the earlier timeline predicted for nanotechnology commercialisation. Meanwhile, Zivic, Grujovic, Ahad and Brabazon (2017) described the market as an emerged, one with huge investments and promising scientific outputs.

The commercialisation of any technology application is a complex process (Manoukian, Hassab-Elnaby and Odabashian 2015). Just like every other emerging technology, nanotechnology commercialisation is difficult (Seidenstricker and Antonino 2018), challenging (Páez-Avilés 2017) and more complex during its very nascent phases (Mattila, Yrjölä and Lehtimäki 2019). Many studies (for example, Aithal and Aithal 2016) in different fields in the commercialisation of technology are conceptual rather than empirical. Meanwhile, assessing the current status of nanotechnology commercialisation, Allan *et al*. (2019) opine that the creation of consumer awareness of technological applications or products in nanotechnology is seen over time as one being slow and arduous. This laborious task is observable in the transition of research laboratory's ideas to the admiration of the consumers in the market, even for the best managed business organisations (Jafarizadeh-Malmiri, Sayyar, Anarja and Berenjian 2019). Seidenstricker and Antonino (2018) advocate the adoption of business modelling framework in addressing this transition.

Meanwhile, Aithal and Aithal (2016) had earlier proposed business model building in a study that could only highlight the steps to successful nanotechnology commercialisation. For future studies, the authors subsequently recommend the use of data collection from a focus group. Consequently, Marassi *et al.* (2018) highlighted the urgent demand for robust analytical tools to ascertain sustainable commercialisation and quality control. Hence, towards achieving an efficient and effective business framework for the commercialisation of ENM applications, this study seeks to fill this gap as there exists an immediate and critical necessity to identify critical factors or facilitators essential for business organisations to be successful. Based on this business perspective, a new framework of ENM commercialisation will be developed and analysed through the adoption of the Operations Research tools.

To this end, through model adoptions, this study seeks to identify and evaluate the main critical factors essential for the effective and efficient commercialisation of engineered nano-materials. This thesis also sets out to explain the challenges to commercialisation faced by advanced materials ventures, especially engineered nano-materials, and how these challenges can be addressed by using a quantitative business framework.

1.4 Aim of the Study

The primary aim of this research is to seek and study the factors necessary for the successful commercialisation of applications containing engineered nano-materials

(ENMs). It is envisaged that this will increase the Operations Research knowledge-base with regards to nanotechnology commercialisation.

1.5 Objectives of the Study

Sequential to the strong need to adopt Operations Research modelling techniques in applications in emerging technology like nanotechnology is the identification and evaluation of the critical factors for the effective and efficient commercialisation of applications containing engineered nano-materials. The objectives of this study are:

Objective 1: To identify the critical factors and sub-factors necessary for the effective commercialisation of engineered nanotechnology materials.

Objective 2: To develop a framework for modelling the commercialisation of nanotechnology materials in general and carbon nanotubes in particular.

Objective 3: To determine if there is a significant difference between the priority rankings obtained through the Analytical Hierarchy Process (AHP) and Data Envelopment Analysis (DEA).

This present study, therefore, attempts to adopt and apply hybrid algorithm of the Delphi technique and Analytical Hierarchy Process (AHP) to the commercialisation of applications of engineered nano-materials. The mathematical framework of the AHP modelling technique has been extensively used for several and different purposes (Mishura and Chatterjee 2018) including atomic scale's optimisation of processing parameters and experimental interpretation involving advanced data management (Salari, Rakhshandehroo and Nikoo 2018). As an emerging technology with a stochastic nature and dearth of empirical evidence, according to Garcia *et al*. (2020), the Delphi technique has exhibited enormous relevance and flexibility in determining the priorities of the factors through consensus of experts.

1.6 Research Questions

Question 1: What are the critical factors and sub-factors necessary for the effective commercialisation of engineered nanotechnology materials?

Question 2: What strategy is available for the developement of the commercialisation framework and procedure of nanotechnology materials in general and carbon nanotubes in particular?

Question 3: Is there a significant difference between the priority rankings obtained through the Analytical Hierarchy Process (AHP) and Data Envelopment Analysis (DEA)?

1.7 Developing a proposed framework for the commercialisation of engineered nano-materials (ENMs)

The systematic analysis for prioritisation of factors for successful commercialisation is supported by models (Nielsen, Lund, Montemari, Paolone, Massaro and Dumay 2018), especially the business modelling framework (Bagnoli, Massaro, Ruzza and Toniolo 2020). Shariati *et al*, (2017) are experts in Operational Research and technology commercialisation that proposed a framework for effective ENMs commercialisation. The third chapter of this study presents a detailed discussion on the contributions of these scholars, amongst others, including those of Ghorshi-Nezhad (2015) and Abdullah and Najib (2016). Their proposals contributed immensely to the study generally as further discussed in Chapter Three.

Figure 1.4 depicts the analytical approaches identified in literature. According to Wohlin and Aurum (2015), these techniques are designed towards the improvement of decision-making. Aithal and Aithal (2016) and Masondo and Makunga (2019) confirm the applications in the commercialisation and quality control materials that are technologically engineered materials.

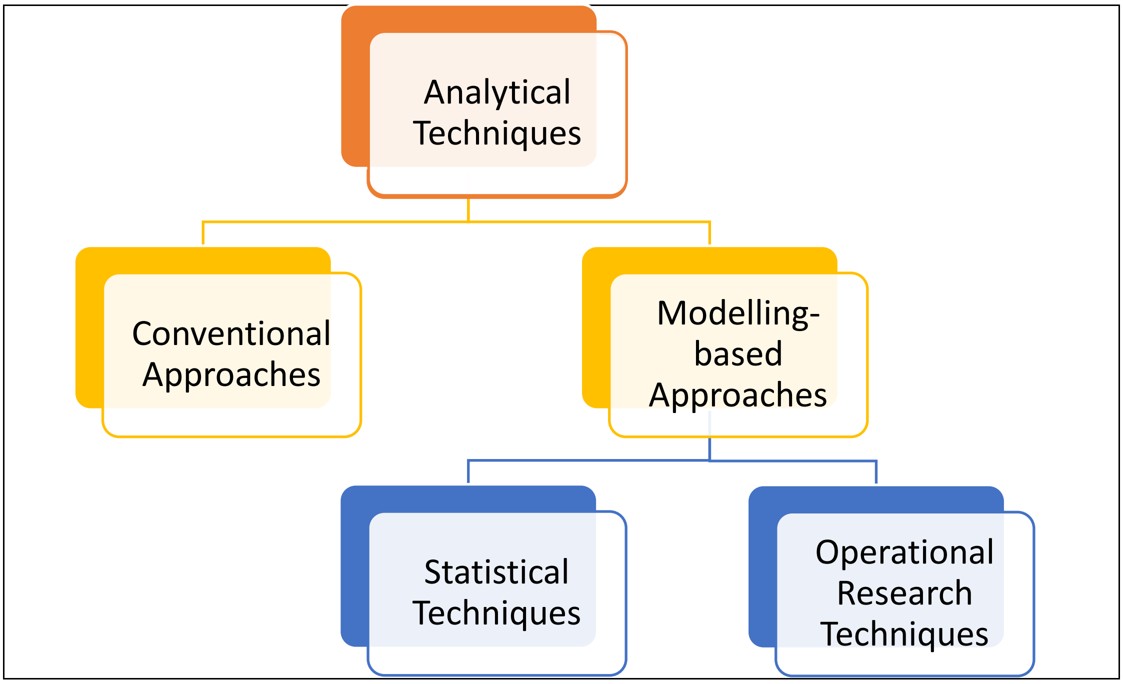


Figure 1.4 Analytical approaches providing support for quality control and commercialisation decision-making process

Source: Wohlin and Aurum (2015)

The Conventional approaches are analogue-based but fail to provide a relationship between the critical factors for commercialisation decision-making. They are designed to only provide the algorithm for the commercialisation decision (Oladimeji, Singh and Kanny 2018). An example is the checklist method. The Statistical techniques are designed as an improvement to the conventional approaches. An example is the Delphi method (DM). The DM is able to provide a step-by-step procedure for the commercialisation decision and likewise identifies the relationship between the critical factors for commercialisation decision-making. The deficiency of these approaches is resolved by using the Operational Research techniques. The Analytical Hierarchy Process (AHP) is an Operational Research technique, a process that effectively helps the organisation in commercialisation decision-making by prioritising the available decision factors. As a result of this limitation of the conventional approaches, this study adopts the modelling-based approaches and the Delphi method to identify the weight coefficients of the evaluation factors, while the AHP will be used to identify the collection of the weights for priority scaling.

1.8 Research Methodology

The research criteria adopted for this study are both quantitative and qualitative. Quantitative research is a scientific investigation that includes both experiments and other systematic methods that emphasize control and quantified measures of performance (Creswell and Creswell 2017; Saunder, Lewis and Thornhill 2015; Queirós, Faria and Almeida 2017). Quantitative researchers are concerned with the development and testing of hypotheses and the generation of models and theories that explain behaviour (Creswell and Creswell 2017), largely between related variables (Aspers and Corte 2019). From a quantitative perspective, this study will adopt the Delphi Method and Analytical Hierarchy Process for optimal decision-making in the commercialisation of ENMs applications.

In broad terms, qualitative research is conceptualised as an approach that allows one to examine people's experiences in detail (Archibald, Radil, Zhang and Hanson 2015) by using a specific set of research methods, such as in-depth interviews, focus group discussions, observation, content analysis, visual methods and life histories and biographies (Ngulube 2015). The qualitative methodology perspective of this study will be based on literature review approach as recent publications are reviewed for the purpose of determining the critical factors essential for the commercialisation of ENMs applications.

Furthermore, the study adopts the purposive sampling method. The purposive sampling technique, also called judgment sampling (Etikan, Musa- Alkassim 2016), is the deliberate choice of a respondent due to the characteristic qualities that the respondent possesses (Turner 2019). Creswell and Creswell (2017) state that it is a non-random technique that does not need underlying theories or a set number of respondents.

Ogbeifun, Agwa-Ejon, Mbohwa and Pretorius (2016) and Kumar, Singh, Mishra, Reddy, and Bajpai (2017) argue that an average of ten (10) to fifteen (15) experts is needed in a Delphi panel to produce good results. Meanwhile, several studies have been conducted using the integration of the Delphi group decision approach and AHP in a single study. Poompipatpong and Kengpol (2013) designed an empirical study with the aid of AHP using 12 study respondents to derive the weightages of selected parameters. This evaluation factor system was developed by employing an expert investigation into the web-based Delphi method. The authors opine that the Delphi method is an appropriate approach when determining evaluation factors and the opinions and experiences are to be taken into important consideration. Taking the opinions of 5 experts (with other respondents), Moslem, Alkharabsheh, Ismael and Duleba (2020) adopted a combination of AHP and the Best Worst Method (BWM) in designing a decision support model for quality evaluation. Based on an exponential scale, Poompipatpong and Kengpol (2013) concluded that AHP is the most appropriate technique to obtain the best assessment of weights for the set of factors identified. In establishing the quality evaluation system, Yonghong, Bohan, Fan and Gang (2012) adopted the Delphi method in integrating expert views. They designed a quality assessment model by adopting the AHP to determine the weights of the factors identified. Several other studies with respect to the combination of the Delphi method and AHP are reviewed in Arof (2015). These justify the choice of respondents participating in the study comprising of members of the Composite Research Group (CRG) which is domiciled at the Department of Mechanical Engineering, at DUT. In-service trainees, postdoctoral research fellows and postgraduate students from various area of specialisation (Engineering, Chemistry, Material Science and Management) are members of the CRG. To this end, it is observed that no previous work has carried out an analysis of the commercialisation of engineered nano-materials.

Nanotechnology researchers from the CRG make up the study population. Ten members of the CRG who are researchers in nanotechnology form the sample. The goal of surveying the researchers is to gain an understanding of the variables or factors that must be taken into account during the development of a framework. The framework is proposed to build roadmaps for different nanofields specifically, ENMs, nanomedicine, nanoelectronics and nanoenergy. It is expected that the framework developed will be used by policy makers and scholars and serve as input for the Science and Technology platform development.

1.9 Research Instruments:

For this study, the opinions of researchers on technology selection factors are collected through the use of questionnaires. The first phase of the survey is a pre-test conducted at the early stage of the research. The questionnaire development was to acquire a thorough understanding of the views and contributions of nanotechnology researchers and to identify the most relevant and important factors.

The questionnaire was structured into four sections after the introduction (see Appendices I and 2). Section I considered the respondents' technical expertise; Section II sought to rate the critical factors for nanotechnology commercialisation while Section III sought to rate the sub-critical factors for nanotechnology commercialisation and Section IV considered the personal characteristics of the respondents. The respondents were requested to rate the level of importance of each factors (section II) and sub-factors (section III) using a five-point Likert scale.

Based on the input from the first round, the AHP questionnaire was revised. The revised questionnaires (see Appendices 3 and 4) were resent to the respondents for the second round of inputs for the AHP prioritisation modelling. This survey, which consists of a number of questions sets for the purpose of pair-wise comparison, was structured into two sections. Section 1 aimed to determine the relative importance of critical factors for successful nanotechnology commercialisation, while the second section determined the relative importance of sub-factors for successful nanotechnology commercialisation.

1.10 Scope of the Study

The main focus of this study is to develop a framework for the quality control and commercialisation of ENMs. The study develops this framework by determining the critical factors necessary for the successful commercialisation of the ENMs. Researchers in the field of nanotechnology were considered for this purpose. These are active members of the Composite Research Group of the Durban University of Technology (DUT) who were also present at the International Conference of Composite, Biocomposite and Nanotechnology (ICCCBN) 2015, Durban, South Africa. These researchers are currently conducting research in nanotechnology.

1.11 Limitation of the Study

The following are the limitations of this study:

- The Delphi Method and AHP were used in this study. The Delphi method is often preferred as it provides minimum datasets that are equally representative of the variables (Cherubin, Karlen, Cerri, Franco, Tormena, Davies, and Cerri 2016; Vasu *et al*. 2016). According to Cherubin *et al*. (2016), this method allows the use of a small sample size for studies requiring only expert knowledge, but might be constrained by biases in the process of decision making. These biases are however, reduced by checking the consistency of the evaluations of the decision-maker through the application of the AHP technique (Kumar 2017).

- The quality framework is informed in accordance with Technical Reports TR/ISO 12885 and TR/ISO 13121.

1.12 Significance of the study

Scientifically, this study is essential and significant. Several studies (Lan and Sheng 2014; Hassanali and Zahra 2015; and Kumar *et al*. 2015) have been conducted using the integration of the Delphi group decision approach and AHP in a single study, but none in the field of nanotechnology and its commercialisation. This is addressed in the current study as it traces how the process of commercialising an application containing ENMs requires the alignment of a variety of different stakeholders namely the university, hospital, industry, administration and society. This study will progress the knowledge on nanotechnology commercialisation by revealing different commercialisation processes for start-ups to large organisations in collaboration with public sector research.

This study is important for addressing the non-scientists on scientific issues that may very well affect their employment, health, education, finances and security. Importantly, there exists several innovative implications for managers as regards the commercialisation of ENMs especially as ENMs, are being metamorphosed into mass production. More importantly and being a novel one, it focuses on business and operations research modelling of nanotechnology for the optimum improvement of nano-materials for research and development (R & D) and manufacturing uses. It is therefore expected that the ouputs of this study will provide scientific knowledge that will help researchers and manufacturers in the commercialisation process of ENMs.

1.13 Contributions of the study

This study is applicable in the field of nanotechnology ‘wars’ towards the extensive use of ENMs. It can also be used to estimate the possible time taken for the commercialisation of a nano-material application. The strategy of an organisation for the commercialisation and implementation of a novel nano-material can be affected by other organisations’ efforts to do the same. Therefore, the need for strategic decision-making emerges. In such strategic conditions, the framework developed in this study will assist organisations in their decision-making. In addition, the results of this thesis will provide scientific knowledge that will help researchers and manufacturers in the commercialisation process of ENMs.

Nanotechnology possesses the unique properties of creating new devices with the ability to improve the quality of life (Khan, Saeed and Khan 2019). This unique property of nanotechnology sets it above other general-purpose technologies. Organisations are known to explore new ways of addressing the needs of consumers. This organisational characteristic is made possible by the unique property of Nanotechnologies through significant transformations within existing fields, from microelectronics to nano-electronics, from biotechnologies to nano-biotechnologies, and from energy to nano-energy (Páez-Avilés 2017). Transformations within the existing industries are efficiently enabled through the development of effective business frameworks which, is displayed in this study towards transforming industry logic.

The basic concept of this research was presented at the International Conference on Composites, Biocomposites and Nanocomposites (ICCBNM 2013) and its publication was also included in the Conference Proceedings. The intent of this presentation was achieved as critiques and comments from peer reviewers had a helpful impact towards the advancement of this study.

The results of this study will be of great value and relevance for further academic research purposes, especially for the Operational Research discipline. The academics will receive insights into new concepts and empirical Operational Research modelling as applied to the commercialisation of nano-engineered products.

1.14 Outline of research

This study comprises of seven chapters. Chapter Two will be devoted to presenting a review of the literature related to conceptual, theoretical and empirical issues addressed in this thesis. Chapter Three provides an overview of the methodological approaches employed and the methods used to collect data for this research. The modelling and implementation with the statistical analysis will be presented in Chapter Four, while the fifth chapter will cover the AHP priority modelling and analysis of the data gathered and will also provide an interpretation and discussion of these data. Chapter Six considers the validation of the AHP priority model. The final chapter will assess the findings of this study, draw relevant conclusions and make important recommendations.

Meanwhile, this current chapter introduced the aim and scope of this research, as well as the background to the nanotechnology, its functions, uses and applications. Consequently, the following concepts emerged in this chapter:

- The introductory role of Statistical and Operational Research (S&OR) techniques in addressing challenges faced in the nanotechnology commercialisation process and boosting the development of nanotechnology.
- The existence of a need between the two factions in nanotechnology commercialisation (that is, the investment community and scientific researcher) to lead nano-based inventions to a successful market position.

CHAPTER TWO

REVIEW OF RELATED LITERATURE

2.1 Overview of the Chapter

Various innovations in nanotechnology are rapidly becoming a fact of life as discussed in Chapter One. The initial chapter also revealed the infinite potential of these innovations. Chapter Two comprises twelve sections. The first section highlights the need for technological adoption (commercialisation) after technological innovation (invention). It focuses on the business perspective of the commercialisation of nanotechnology-based products. The second section discusses the role of models and model building in nanotechnology commercialisation. The following section discusses the conceptual background of nanotechnology and reviews its potential applications in a wide range of sectors. Fourthly, various literature on the concept, properties and the commercialisation of engineered nano-materials will be reviewed. The ensuing sections will discuss the need for a multidisciplinary solution approach to the commercialisation of ENMs. The sixth section is set out to achieve Objective One of this study as various commercialisation factors are identified from literature. The subsequent three sections respectively review statistical, operational research, business modelling of ENMs as well as the *pros* and *cons* of these forms of frameworks are finally reviewed.

Succinctly, the overall goal of this chapter is to garner insights into the business modelling of engineered nano-materials for quality optimisation and control. It reviews currently available literature on nanotechnology, carbon-nanotubes, their commercialisation and current development and applications in Operations Research.

2.2 Business Perspective of Nanotechnology-Based Products

Considering the transversal description of nanotechnology, Allan *et al*. (2019) riterate the importance of the development of business and investment frameworks for the successful commercialisation of nanotechnology and its enabled products. To this end, the current section discusses the necessity for inventions such as materials, products and processes from nanotechnology to be commercialised and adopted by users. This section further examines the critical elements for the successful commercialisation of engineered nano-materials, especially nanotechnology-based products, notwithstanding the possible associated risks.

As evident in Section 1.2 of Chapter One, there are novel application prospects of nanotechnology. Nanoparticles further exhibit unusual physical, chemical and mechanical properties as outlined in Section 2.4. Bilal and Igbal (2020) opine that nanotechnology exhibits unique features that change the physical properties of products towards their improvement. Through these technological innovations, new products and nano-materials are engineered by making revolutionary contributions in various developmental fields ranging from manufacturing (Aithal and Aithal 2016) to energy and telecommunication (Abdullah and Najib 2016) to the health care industry (Salari, Rakhshandehroo and Nikoo 2018; Catalan-Figueroa and Morales 2021). To most experts, optimal applications of nanotechnology and its materials will keep re-modelling the way in which humans live (Nasrollahzadeh, Sajadi, Sajjadi and Issaabadi 2019). Meanwhile, Faddel *et al.* (2018) postulate that there are potential risks associated with these materials as a result of their toxicity effects particularly arising from their physiochemical properties.

Jun *et al.* (2021) elucidated that much is yet to be discovered about these potential adverse health and ecological effects of exposure to ENMs. Catalan-Figueroa and Morales (2021) contend that the numerous benefits engineered nano-materials potentially offer have associated risks. Despite these exposures, the commercial applicability of ENM components have been on the increase (Nasrollahzadeh, Sajadi, Sajjadi and Issaabadi 2019). The commercialisation of engineered nano-materials, as will be explored subsequently in this section of the study, is expected to expand business opportunities thereby creating more jobs and leading to global economic growth and scientific development (Aithal and Aithal 2016).

Nanotechnology has two technological roles (Nasrollahzadeh, Sajadi, Sajjadi and Issaabadi 2019). According to the authors, this dual role is disruptive and enabling technologically with disruptive market potential can result in vital developments in active commercial and technological ventures. Nasrollahzadeh *et al.* (2019) further point out that nanotechnology has applications in a variety of fields. In a similar manner, the commercialisation of nanotechnology has applications in many product sectors, inclusive of medical applications (Hobson 2016) as depicted in Figure 2.1.

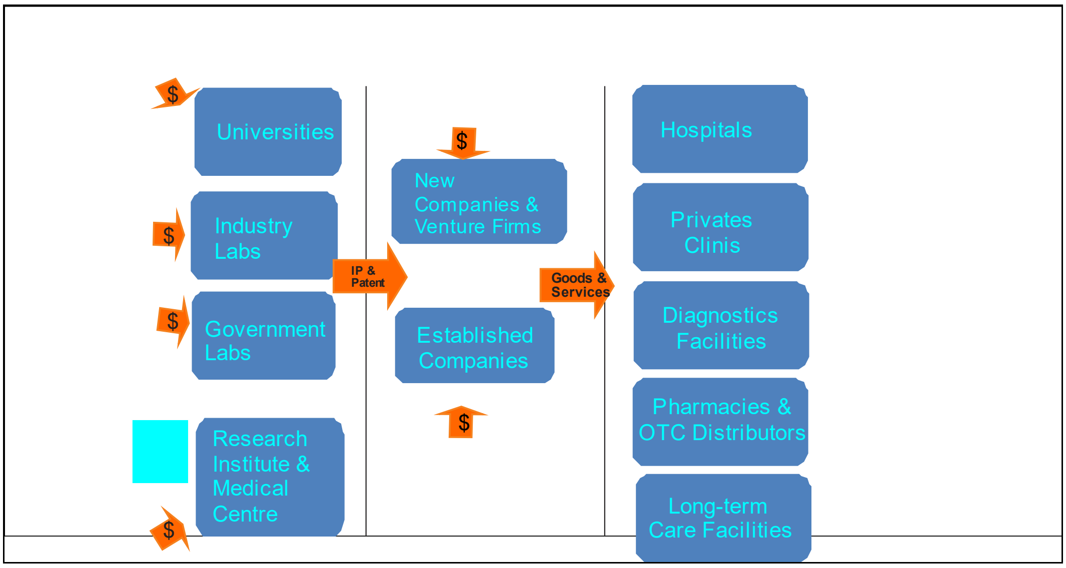


Figure 2.1: Typical nanotechnology commercialisation stages.

Source: Hobson (2016)

The three stages are scientific discoveries, development and the markets which are involved in advancing the progress of scientific knowledge applications as they have interfaces with the advantage of having a direct impact on the daily lives of the product consumers (Hobson 2016; Oladimeji and Singh 2018). These interfaces thereby allow the market to assist in the impactful move of scientific research (Inshakova and Inshakov 2017; Inshakova and Inshakova 2020). The markets in the commercialisation of nanotechnology-enabled products, are contended by Ostapchuk (2017) to have a direct link or dependence on the development of innovation/discovery. The author argued that the essence of commercialising emerging technology was to determine the interaction and interest or probable loyalty of consumers to a new product. This process is carried out to determine the functionality of the product through a systematic flow or linkage of innovational interfaces (Oladimeji, Singh and Kanny 2018).

Aithal and Aithal (2016) emphasise that the prevailing economic and business environment, market potential, market share and innovative engineered materials, among others, are essential elements required to initiate the successful commercialisation of engineered nano-materials. Figure 2.2 depicts a summary of the innovation interfaces identified by Hobson (2016). Anadon *et al.* (2016) considered a business perspective as the intersection between the technological invention stage of innovation and technological adoption, which forms the motivation for this study.

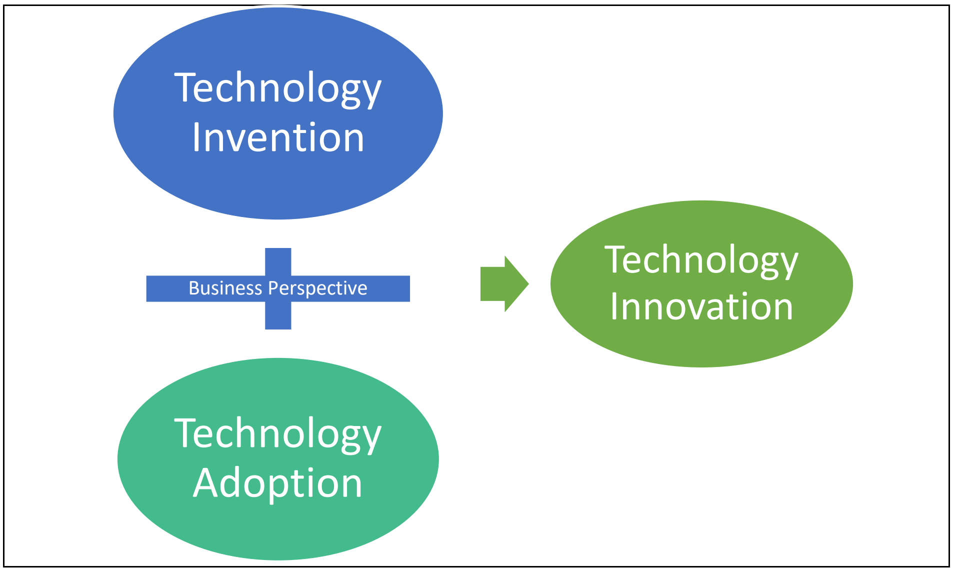


Figure 2.2: A schematic diagram illustrating a business perspective of technology commercialisation.

Source: Adapted from Anadon *et al.* (2016)

Considering materials engineering, new scientific and technical advances are generated at the invention stage of innovation. Practically, these new advances are exhibited at the adoption stage, and for the purpose of business investment and policy, these advances are important to business decision-makers. Shapira, Gök and Salehi (2016) assert that the interface linkage of the technology invention and commercialisation for the innovation of engineered nano-materials is likewise important to business development. Aithal and Aithal (2016), corroborating the assertion of Shapira, Gök and Salehi (2016), confirmed the involvement of diverse organisation in nanotechnology developments. These organisations, according to the authors, benefit from the economic edge of developments in nanotechnology the optimum commercialisation of nanotechnology and its applications. This study, thereby, draws its interest by understudying the business perspective of innovations in nanotechnology and critically identifying and prioritising the factors required for ENMs' successful commercialisation.

2.3 Models and Model Development in Nanotechnology Commercialisation

Models and model development are critical implementations for the successful commercialisation of emerging technology (Flammini, Arcese, Lucchetti and Mortar 2017). Absolute importance has been attached to the improvement of understanding and applications of models and model developments in the commercialisation of nanotechnology. This trend had been substantially observed for every technology, particularly at its emergence. Outlined in Section 1.4 in Chapter One, one of the objectives of this study is to introduce the applications of modelling-based approaches to the commercialisation of engineered nano-materials. It is therefore important that a wider perspective on models and modelling be explored in order to achieve nuanced understandings of models and model development for the commercialisation of engineered nano-materials, which is a focal point of this study.

Towards the management of current uncertainties, models and modelling are critical tools of financial markets (Rhodes, Lancaster and Rosengarten 2020). The terms ‘model’ and ‘modelling’ are described by Alsoudani (2016) as the developmental foundation of operations management and oriented towards solving real-life problems. According to Alsoudani (2016), modelling was coined from “modellus” which is a Latin word. In the same vein, a model is described by the author as a simplified categorisation of a real object, including its characteristics, described to illustrate an existing event, exchanging of information, predictions and decision-making. In the words of Stefanovska, Polenakovikj and Dzidrov (2016), modelling is a process through which scientists, over time, make changes to a process in order to respond to new evidence and understandings. These changes are made possible by representing ideas about the real world (Alsoudani 2016). Through the structural provision of the task’s behavior and effectual predictions of actions taken, models are primarily used to analyse data in line with the scientific understanding of processes (Khayyat 2015).

Models are divided into two categories, namely quantitative and qualitative models. Quantitative models are functions that are structurally developed to include the behavioral processes of real-life operations (Martinez-Luengo, Kolios and Wang 2016; Oladimeji and Singh 2018). They are structured to assist decision-makers by partly including decisional problems in real-life operational processes (Siebert, Kunz and Rolf 2020). Research study based on quantitative models are rational knowledge generation approaches (Green and Thorogood 2018). Symbolically, the causal relationship between two variables (dependent and independent) is explained with the use of a quantitative model. As a result, observational explanations are made possible through the classical features of the obtained relationship for future state forecast purposes (Green and Thorogood 2018). These classified models will be used in the next chapter of this research to lead the discussion on the relevance and possible contributions in the development and manipulation of statistical methods and modelling of ENMs' commercialisation. Meanwhile on these discourses, the findings made by Martinez-Luengo, Kolios and Wang (2016) form a basis for the point of departure for this section.

Stefanovska, Polenakovikj and Dzidrov (2016) provided reports and critiques of a number of commercialisation models, which were confirmed by Amadi-Echendu (2021). The Functional Models and the Linear Models were discussed heuristically. According to Stefanovska, Polenakovikj and Dzidrov (2016), the Linear Model is an R&D model and is referred to as the Assembly-line model, Bucket model, Ladder model or the Pipeline model. For any successful commercialisation, Figure 2.3 describes the innovation pipeline with the process from the research level to the product sales level. In support as depicted in Figure 2.3, the core intermediary activities between research and product sales are identified by the linear model as development, production and marketing.

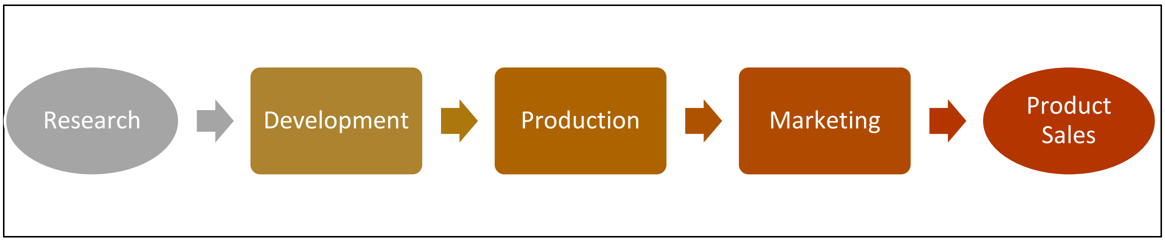


Figure 2.3: A Classic Linear Model

Source: Adapted from Stefanovska, Polenakovikj and Dzidrov (2016)

Amadi-Echendu (2021) hypothesised the frameworks of innovation models as classified into two generations and illustrated in Figure 2.4. Stefanovska, Polenakovikj and Dzidrov (2016) described the innovation (linear) model's first generation as the "technology push", and the "market pull" as the second generation. (Appendices 3 and 4)

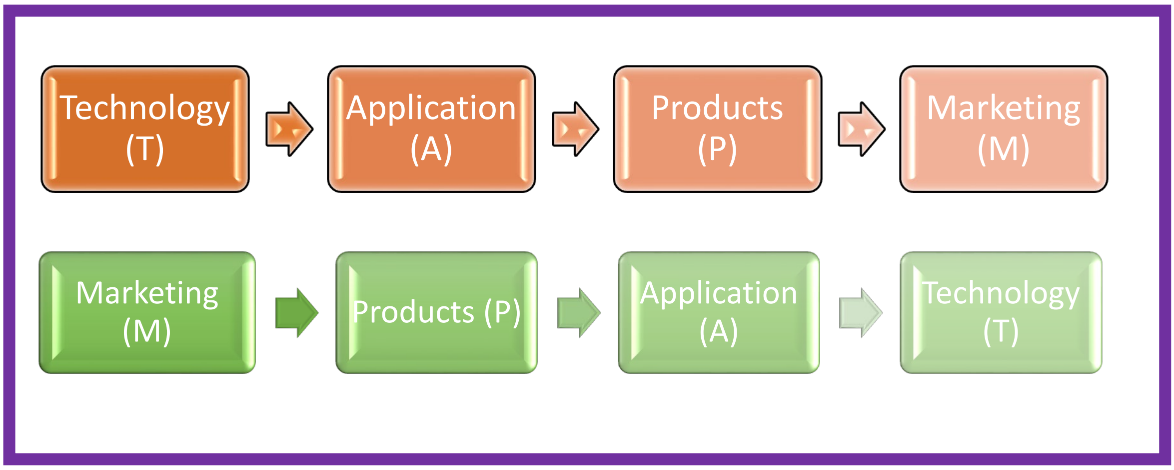


Figure 2.4: Framework of the 1st and 2nd generations' linear (Innovation) models

Source: Adapted from Amadi-Echendu (2021)

Due to the lack of feedback loops, the linear model does not have the support of the present reality of the state of technology commercialisation (Schummer 2014). Innovation models are made up of six generations (Stefanovska, Polenakovikj and Dzidrov 2016). The authors confirmed that there are four generational innovation models of the six that are non-linear and are functionally integrated with several feedback loops. Aithal and Aithal (2016) identified that at every commercialisation process stage of emerging technology, there are feedback loops. The integration of the feedback loops feature makes those models more relevant for the emerging technology commercialisation process, consequently making them more relevant for quality control.

Stefanovska, Polenakovikj and Dzidrov (2016) confirmed the necessity for feedback loops in an invention-commercialisation process for quality control. The authors suggest that feedback from consumers is an essential element of any innovational technology. This finding by these authors will form part of the basis of this study towards determining the essential feedback factors for quality control and the process of commercialisation of ENMs.

Remarkably, Aithal and Aithal (2016) commented that there exists a highly risky point of a "Valley of Death" within the research stage and market stage of the product development of technology. The "Valley of Death" point within the marketplace is used in illustrating the linkage between academic-based innovations and their commercial applications. It is evident that the focus and development and market engagement are the reasons for the existence of the high risk. Figure 2.5 is a schematic illustration of the "Valley of Death" point of commercialisation. Meanwhile, Allan *et al*. (2019) opined that the commercialisation experiences in the "Valley of Death" in other technological domains are similar to that of nanotechnology but with some distinct characteristics, considering its context and the enabled-materials.

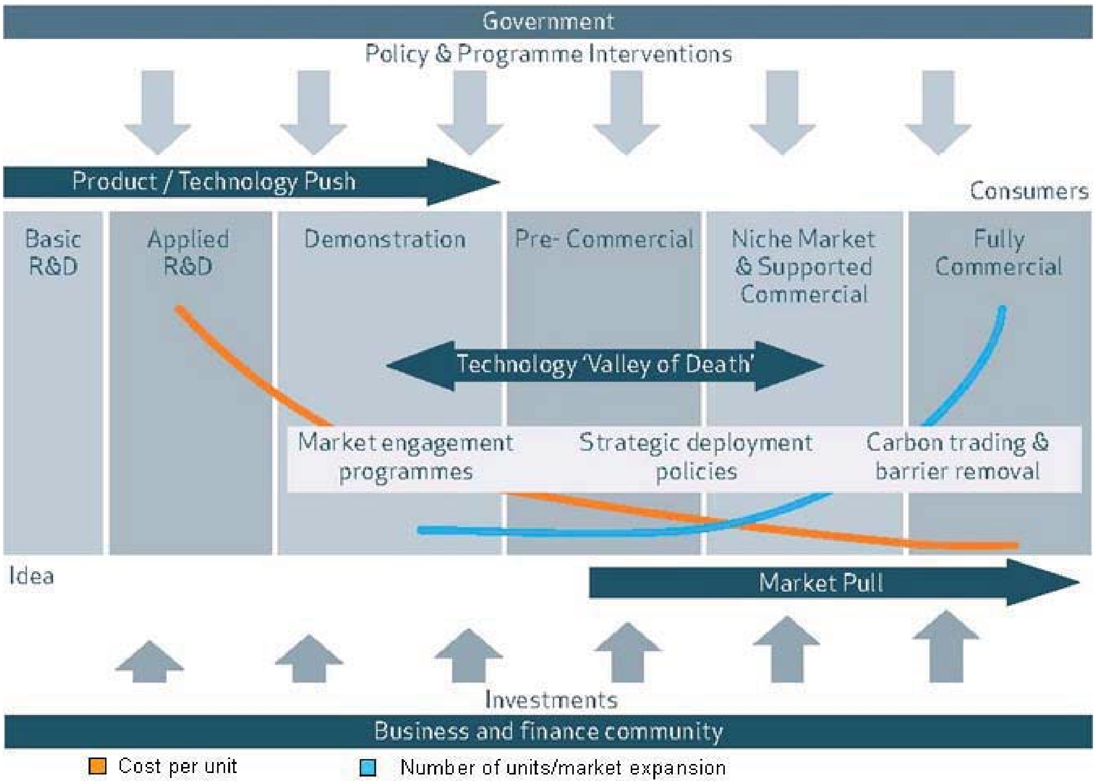


Figure 2.5: "Valley of Death" Point of Commercialisation

Source: Amadi-Echendu (2021)

In creating a linkage for this "Valley of Death" for the improved process of nanotechnology commercialisation, the present will take into consideration the research design adopted to articulate the factors critical for the successful commercialisation of ENMs.

2.4 Nanotechnology: Conceptual Framework

Classified by Bayda *et al*. (2020) to include Nanochemistry, Nanophysics and Nano-materials science, amongst others, nanotechnology is *a* complex interdisciplinary science. Contributing to most disciplines under science and engineering, the interdisciplinary approach of communication is discovered as necessary for market penetration (Allan *et al*. 2019). The study seeks to use existing and current literature to introduce the applications of modelling-based approaches to nanotechnology commercialisation. This section sets out to review the concepts of Nanotechnology as available in the literature for a clearer understanding of the nanoworld for relevant applications and commercialisation.

Clearly ambiguous by definition, the term *nanotechnology* has caused core problems for policy-makers (Allan *et al*. 2019). The existence of numerous and conflicting definitions has been core to the problems (Akbari, Akbari and Yavari 2014). However, Schummer (2014) identified three different approaches to define nanotechnology as depicted in Figure 2.6. Accordingly, these approaches are obviously indefinite and are currently in use.

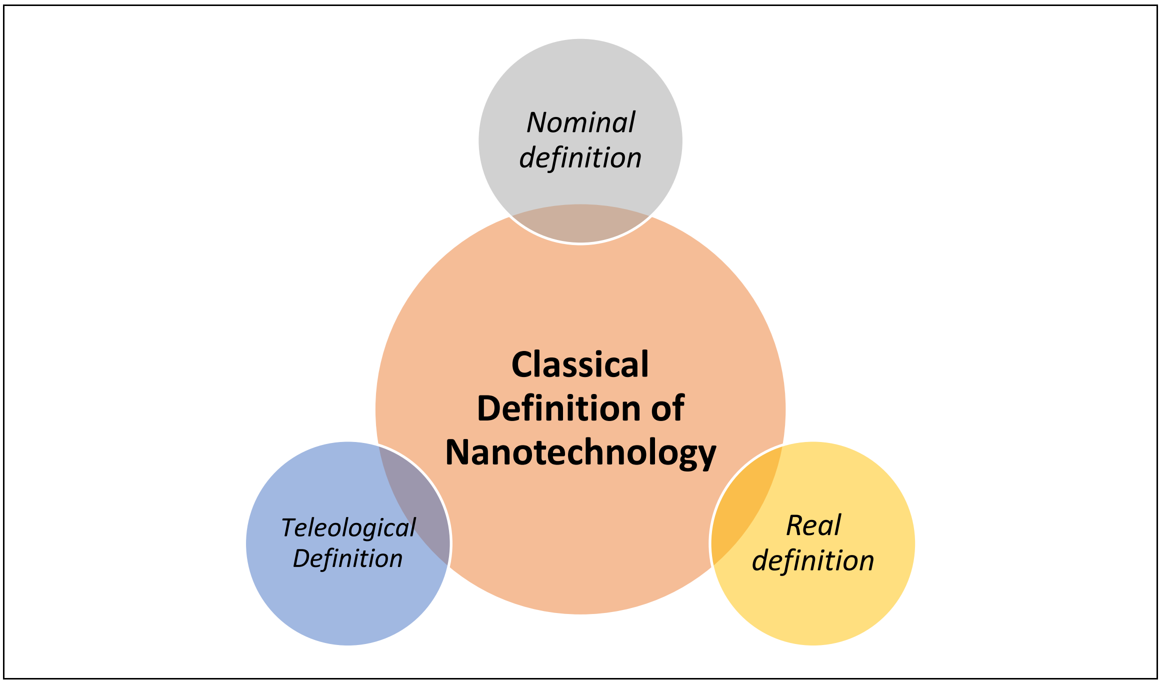


Figure 2.6: Classical Definition of Nanotechnology

Source: Adapted from Schummer (2014)

Firstly, the Nominal definition approach satisfies the necessary and sufficient conditions for any technology that must be adopted for the investigation and manipulation of material objects in the nanoscale equivalence for the development of new devices and functionalities. This definition is confirmed in Thiruvengadam, Rajakumar and Chung's (2018) work, where nanotechnology is termed as any phenomena in Science or Engineering taking place at a scale of 10^{-9}m and utilised in the design, manufacturing and application of materials, structures, systems and devices which exhibit different features and properties (biological, physical and chemical) at the nanoscale. The second approach is referred to as the Teleological definition. Here, the future goals of nanotechnology are considered, which are to provide generic values (health, wealth and security) and relative attributes (size, speed, toughness and economical). The Real definition is the third definitional approach. This refers to some listed specific and unrelated technological research areas which include molecular biotechnology, molecular modelling, nanoparticle research and nanostructured materials, amongst others. Common to all these approaches is that nanotechnology is an area of technology that adopts materials which are very small. This classical definition clears any form of ambiguity or vagueness in the understanding of the roles and properties of nanotechnology.

Thiruvengadam, Rajakumar and Chung (2018) posit that the diversification in the definitions is an indication that nanotechnology has a wide gamut of applications. As Judy and Bertsch (2016) argued, engineered nano-materials are being integrated into various products, including cosmetics and water-repellant clothing (Part, Berge and Huber-Humer 2016). According to Mackevica, Revilla, Brinch and Hansen (2016), many of these engineered nano-materials, due to their biocidal effect of preventing any kind of survival of organisms possibly harmful to human health, are being applied to nano-enabled consumer products. Hansen *et al*. (2016) confirmed the current consumer market is characterised by nearly three thousand products that are nanotechnology-enabled as they are composed of engineered nano-materials.

Meanwhile, “nano” indicates midget (Akbari, Akbari and Yavari 2014) and nanotechnology is any technology with a controlling ability to reframe a physical substance that is atomic and molecularly structured and of approximately 1–100 nm, and adopts the unique feature and occurrence at a scale comparably associated with single atoms or molecules or bulk behaviour (Thiruvengadam, Rajakumar, and Chung 2018). Nanotechnology, as widely described by the United States National Nanotechnology Initiative (US-NNI), is the conduct of science, engineering and technology at the nanoscale, approximately equivalent to between 1 and 100 nanometers. Nanotechnology practically makes use of atomic molecules and structures at nanoscales (Bayda 2020). Nanotechnology is the study of extremely small things and applications, which can be adopted across all the natural science and management science fields (Aithal and Aithal 2015). The ultimate frontier of this emerging technology is that with new functions and properties through the re-engineering of their small structure, it creates applications in the form of devices, materials and systems. Fundamentally, at the nanoscale, it economically changes the properties of a material at the most efficient level for applications in science, manufacturing, engineering, molecular medicine and technology. Nanotechnology exploits the threshold of natural transition encountered from single atoms or molecular behaviour to the collective behaviour of atomic and molecular assemblies (Thiruvengadam, Rajakumar and Chung 2018).

Meanwhile, nanometer scaling has been suggested by Thangadurai, Manjubaashini, Thomas and Maria (2020) to be nomenclature *Feynman* (*Φ*nman) named after Feynman, the scientist for his enormous nanotechnology discoveries and contributions. To this end,

$$1\ \Phi\text{nman} \equiv 1 \text{ nanometer } (10^{-9})$$

and $$1 \text{ nanometer } (10^{-9}) = 1\ \mu\ (10^{-3}\ \textit{Micron}).$$

In a succinct manner, nanotechnology at the atomic level can be seen as R&D at a molecular level or macromolecular level of 1–100 nanometers, at which new or existing structures, appliances or systems are used in a controlled setting in order to give them new characteristics and functions due to their small size (Thangadurai, Manjubaashini, Thomas and Maria 2020).

As noted, defining nanotechnology is complex and abstract (Joubert *et al*. 2020), and is characterised by uncertainty (Allan *et al*. 2019). The early phase of development is science-driven with scientists exploring different approaches, materials and observations (Bayda 2020). This development is typically only applicable to spiral structured engineered nanotechnology particles (ENPs) with 60 carbon atoms and not those naturally occurring nanotechnology particles under 100 nm. Examples of ENPs are carbon nanotubes, metal oxides and bucky-balls, while those of the latter include other processes' by-products like carbon black, welding fumes or fire smoke (Poudel and Li 2018).

Nanotechnology encompasses a series of atomic-based and molecular-based techniques which are capable of arranging atoms and molecules in specially designed and controlled positions. This ability facilitates the production of new structures and devices with, at least, one dimension in the nanoscale (Bayda 2020). Nanotechnology, therefore improves various aspects of society, thus improving the quality of life (Aithal and Aithal 2015). According to Zuo, Li and Wang (2019), the technically diverse definitions of nanotechnology indicate that a wide spectrum of research fields is embedded in nanotechnology. The contentions of these authors are essential for this study which is interdisciplinary and multidisciplinary in its research and applications.

Ramani and Niosi (2014) contend that nanotechnology is a form of generic technology. According to Zuo, Li and Wang (2019), a generic technology is a technology that, if, optimally exploited, will yield maximum benefits for a wide range of sectors of the economy and/or the society. Generic, radical technology is of interest because of its potential for value-creation across a broad range of industries and applications as elucidated by Poudel and Li (2018). Corroborating Zuo, Li and Wang (2019) on this standard definition, Azizi-Lalabadi, Hashemi, Feng and Jafari (2020) describe nanotechnology as the application of science on the nanometer scale. It is further described by Zuo, Li and Wang (2019) as a generic technology with potential applications in a wide range of sectors, from electronics and computing to sensors and catalysis. There are benefits associated with nanotechnology as a generic technology (Zuo, Li and Wang 2019). These benefits, more especially attributed to new ventures, are proposed as displayed in Table 2.1.

Table 2.1: Benefits of nanotechnology as a generic technology

Benefits	Description	References
Market applications	Nanotechnology-enabled products can serve as market alternative against previous unviable application.	Shapira and Youtie (2015); Bhushan (2017); Mitter and Hussey (2019); Shafiq *et al.* (2020)
Risks diversification	General purpose technology allows risks diversification and amortisation of costs associated with R&D.	Naseer *et al.* (2018)
Termed revenue opportunities	There is the provision of revenue opportunities in short, medium and long-terms due to market potentials at various maturity stages.	Aithal and Aithal (2016)
Investment opportunities	There is the attraction of investment opportunities in all possibilities.	Shapira and Youtie (2015); Aithal and Aithal (2016); Zivic, Grujovic, Ahad and Brabazon (2017)

Source: Generated by the researcher

Nanotechnology can be traced back for centuries as much has been written on the concept of and study on nanotechnology and materials in the nanometer scale (Aithal and Aithal 2015; Bhushan 2017; Thiruvengadam, Rajakumar and Chung 2018). According to Aithal and Aithal (2015), nanotechnology is the first major global research initiative of the 21st century.

Exploiting plant health management for the early detection of pests, diseases and nutrient deficiencies, Subramanian (2014) views nanotechnology as a fascinating field of science which manipulates atom by atom and thus the processes and products that evolved are the most precise ones, which are impossible to achieve by conventional systems. Basically, the continuous existence, development and applications of nanotechnology are simply a function of the continued existence and contribution of engineered nano-materials (Aithal and Aithal 2016). Hence, it is essentially fundamental to discuss what ENMs are, as critically reviewed in the subsequent sub-sections. The various types, properties, applications and commercialisation are also considered.

2.5 Engineered Nano-materials (ENMs)

Vollath (2013) argues that the conceptual understanding of engineered nano-materials is dependent on the rudimentary knowledge of four major pure and applied science disciplines, namely biology/medicine, material science, chemistry and physics. As presented in Figure 2.7, nano-materials application is related to the interface of biology/medicine, material science, chemistry and physics with respect to the understanding of the properties and behaviour of materials. This indicates a major difference between engineered nanotechnology materials and other conventional materials. Another major difference identified and explicitly explained, is the “bottom-up” and “top-down” approaches of materials synthesis (Bayda *et al*. 2020). While Patra and Gouda (2013) argue that these two are the main approaches adopted in nanotechnology, Vollath (2013) argues that the “bottom-up” approach is more favored in the synthesis of nano-materials against the “top-down” approach, which is preferred in the synthesis of conventional materials.

Nano-materials can be developed or synthesised biologically or chemically (Hasan 2015).

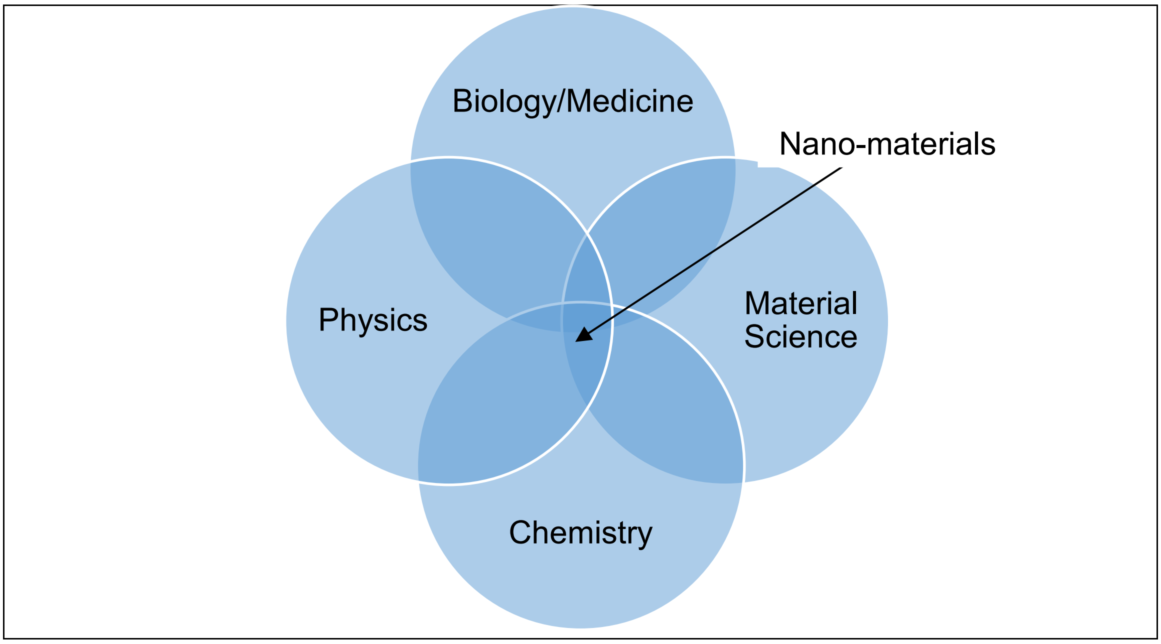


Figure 2.7: Interface relationship between nano-materials and other science areas
Source: Adapted from Vollath (2013)

At present, most commercial ENMs can be categorised as follows (Nurfatihah and Siddiquee 2019; Findik 2021)

- Nanotubes (primarily carbon and silicon, amongst others)
- Nanoclays
- Metal oxides
- Quantum dots

Table 2.2: ENM types and dimension characteristics

ENM TYPE	NUMBER OF DIMENSIONS	SIZE
Nanoparticle	3	1-100 nanometers range
Nanotubes/Nanowires	2	1-100 nanometers range
Nanofibers	3	50-300 nanometers range with diameter < 50nm
Nanofilms	1	1-100 nanometers range
Nanoplates	2	1-100 nanometers range

Source: Findik (2021)

Patra and Gouda (2013) and Findik (2021) reviewed some nanotechnology materials to include nanocomposite fibers, carbon nanofibers and carbon nanoparticles, clay nanoparticles, carbon nanotubes and nanocellular foam structures as depicted in Table 2.2. Nanocomposite fibres are amorphous ENMs which combine one-, two- and three-dimensional materials (Kaur, Gill and Jeet 2019). A carbon nanotube is a cylindrical form of carbon with a nanometer dimension (Patra and Gouda 2013; Kaur, Gill and Jeet 2019; Anzar *et al*. 2020). In attempting to understand the knowledge-base of ENMs towards the commercialisation of their applications, this section explores the conceptual framework of engineered nano-materials.

2.5.1 Carbon nanotubes

This section focuses on the carbon nanotube (CNT) which is coined by far as one of the strongest materials synthesized by mankind (Xu, Jie and Beyerlein 2014). In the words of Hulla, Sahu and Hayes (2015),

> *"…researches on nano-materials and nanotechnology are extensively sparked up as a result of the synthetic discovery of CNTs".*

CNTs create a complex problem because of the persistent uncertainties edging around their potential risks (Poudel and Li 2018). Carbon nanotubes, just like any other engineered nano-material, offer some unique properties, in mechanical (Ghasemi *et al*. 2016) electronic (Anzar *et al*. 2020) and latent physical features (Kaur *et al*. 2019). These properties are important in understanding complex processes like growth and cutting processes in the measurement of the attributes and dimensions of these materials (Hulla, Sahu and Hayes 2015). According to Hasan, Tyagi, Yadav and Narang (2020), the tools and methods of statistics traditionally deal with the study of variability, which is typically exhibited by all natural processes. Hence, these complex processes can be better simplified with the application of these tools and methods.

Statistical concepts and tools, as suggested by Stolojan and King (2018), assist in the conduct of efficient scientific investigation thereby increasing the likelihood of identifying new ways of enhancing productivity and product quality towards optimum customer satisfaction. This suggestion is a confirmation of the idea that in administering the manufacturing of consumer products that are of high-quality, there would be a need to understand the cause-and-effect relations by using the scientific method of experimentation and observation. This novel idea is noted to have emanated not long after the Scientific Revolution days by the mutual inventiveness of industrialists and pragmatic scientists. However, according to Stolojan and King (2018), the statistical application would require much more complex problem-solving and trouble-shooting and is time-consuming.

The measurement and manipulation of matter at the atomic/molecular scale have generated the discovery of novel materials (Sathiyapriya *et al*. 2019). In a list of the most captivating nano-materials, the CNTs possess strong measurement characteristics, potential applications and some fundamental properties, hence giving CNTs significant attention, and are the ultimate outstanding inventions of nanotechnology (Jha, Singh, Sharma and Fuloria 2020). As indicated earlier, CNTs offer unique properties in the mechanical, electronic, chemical and physical disciplines (Dong, Park, Leonhardt, Zhang and Liang 2020). They can be conceptualised to be rolled-up tubes in the form of sheets of graphite and covered at one end, thereby forming a seamless cylinder, called single-walled CNTs (SWCNTs) (Jha, Singh, Sharma and Fuloria 2020). A form of many cylinders heaped up one inside the other, described as multi-walled CNTs (MWCNTs), could also be generated (Susantyoko, *et al.* 2017). Mohammed and Chen (2020) succinctly argued that the arrangement of SWCNTs in a concentric manner will result in the formation of a MWCNT.

The knowledge of the science and technology of carbon nanotubes is essential in this study as this will contribute to the frontier of commercialisation of ENMs application.

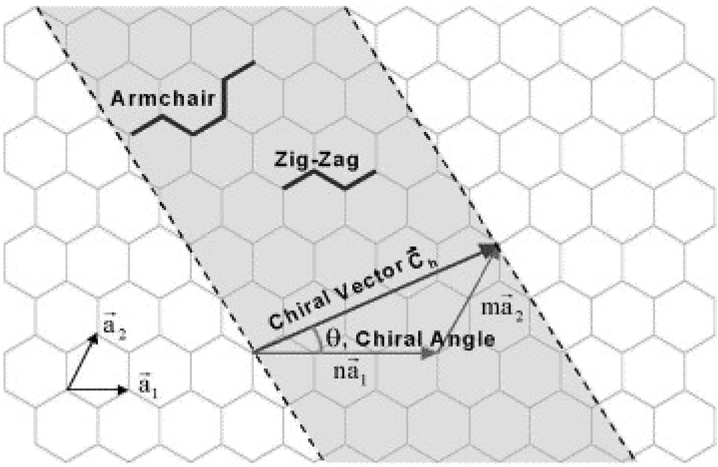
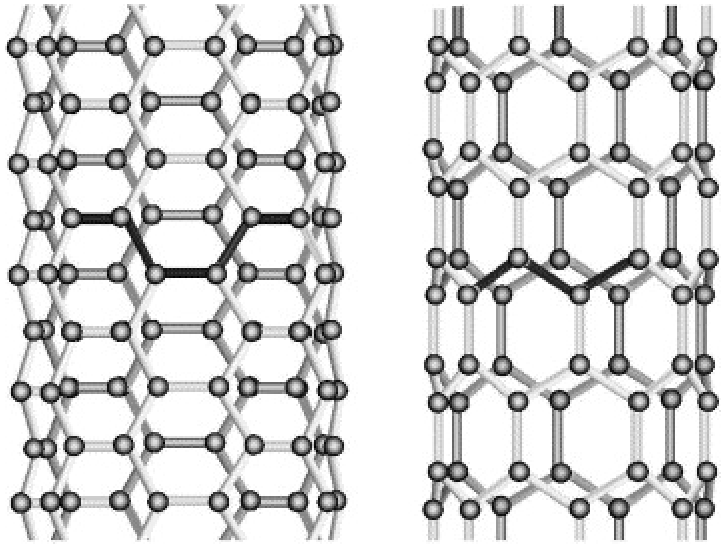


Fig. 2.8: **Symbolic depiction presenting how a hexagonal sheet of graphite is ‘rolled’ to form a CNT**
Source: Lamberti *et al.* (2015)



(a) (b)

Fig. 2.9: Depictions of the atomic structure of (a) an armchair and (b) a zig-zag CNT
Source: Lamberti *et al.* (2015)

The atomic structure of nanotubes is described in terms of the tube chirality, or helicity, which is defined by the chiral vector, $\underset{C_h}{\rightarrow}$, and the chiral angle, *θ*. In Figure 2.8, the cutting of the graphite sheet along the dotted lines can be visualized, and the tube rolled so that the tip of the chiral vector touches its tail. The chiral vector, often known as the roll-up vector, can be described by the following equation:

$$\underset{C_h}{\rightarrow} = n\ (\underset{a_1}{\rightarrow}) + m\ (\underset{a_2}{\rightarrow}) \qquad (1)$$

where the integers (*n*, *m*) are the number of steps along the zig-zag carbon bonds of the hexagonal lattice and $\underset{a_1}{\rightarrow}$ and $\underset{a_2}{\rightarrow}$ are unit vectors. The chiral angle determines the amount of 'twist' in the tube. The two limiting cases exist where the chiral angle is at 0° and 30°. These limiting cases are referred to as zig-zag (0°) and armchair (30°), based on the geometry of the carbon bonds around the circumference of the nanotube. The difference in armchair and zig-zag nanotube structures is shown in Figure 2.9. In terms of the roll-up vector, the zig-zag nanotube is (*n*, 0) and the armchair nanotube is (*n*, *n*). The roll-up vector of the nanotube also defines the nanotube diameter since the inter-atomic spacing of the carbon atoms is known (Lamberti *et al.* 2015). This research intends to build on these actuator effects which CNTs exhibit which is essential for the commercialisation of their applications.

Meanwhile, carbon nanotube materials, amongst other ENMs, are beginning to exhibit significant progress towards the commercialisation of several applications, as evident in years of a series of research and development (Valavanidis and Vlachogianni 2016). Their productions at a commercial scale and prospective industrial applications are possible with minimal defects (Mohammed and Chen 2020). The notable features of these materials make them relevant cases for this study especially due to their commercial availability and affordability as their unique properties are also considered.

2.5.2 Unique Property of Carbon Nanotubes

Ogunsona *et al*. (2019) argued that the advent of several nano-made consumer products is a result of the unique properties and economic applications of engineered nano-materials. The appropriate advantageous properties of the carbon nanotubes make this element have several applications in different technologies (Anzar *et al.* 2020). Experimentally, carbon nanotubes are the strongest of all the engineered nano-materials (Kinloch *et al*. 2018) and possess more applications in consumer products (Singh 2017; Jha, Singh, Sharma and Fuloria 2020), although these opportunities of the innovative products could pose enormous challenges (Devasahayam 2019). Dong, Park, Leonhardt, Zhang and Liang (2020) identified and confirmed three highly exceptional properties (chemical, electrical and mechanical). The special properties of carbon nanotubes are succinctly reviewed below since the general understanding of nanotechnology is synonymous with the knowledge of the design, characterisation, properties and applications of engineered nano-materials (Dong *et al*. 2020).

2.5.2.1 Chemical Property of Nanotubes

The essence of this property or characterisation is to know the rate and spatial distribution of atoms and molecules within the surface of engineered nano-materials (Bayda *et al*. 2020).

2.5.2.2 Electrical Property of Nanotubes

The electrical property of carbon nanotubes has been remarkably exhibited in several experiments (Pourfayaz *et al*. 2014) and products (Lekawa-Raus *et al*. 2014).

2.5.2.3 Mechanical Property of Nanotubes

Exceptionally strong in terms of in-plane deformations, the carbon nanotubes possess high mechanical properties since they can be seen as “rolled-up” graphene sheets (Monthioux *et al*. 2017). These properties are unique abilities in carbon nanotubes and they are potential game-changers in the commercialisation prospects of carbon nanotube-based materials as improvement in the properties (chemical, electrical and mechanical) of these ENMs will have revolutionary impacts on the global environment, industries, economies and competitiveness (Henderson, Whitman and Meador 2015). Moreover, it is expected that the broader perspective of nanotechnology and engineered nano-materials explored would aid in achieving a distinct understanding of their operational structures. It is therefore anticipated that this understanding would serve as the basis for their quality control and commercialisation modelling, which is an underpinning focal point of this study.

2.5.3 Commercialisation of Engineered Nano-materials

Commercialisation, in technology, is often interchangeably used as technology transfer. Technology commercialisation is alluded to be the logical and transitional process of scientific innovations, scientific inventions and scientific discoveries into profitable products and services having to do with organisations, companies or even a state in its entirety (Mohannak and Samtani 2014). As highlighted in preceding sections, there has been an increase in the application of engineered materials from nanotechnology commercialised products. Although nanotechnology currently remains an immature technique in some industries (He, Deng and Hwang 2019), authors have opined that several novel products have been discovered every year in the process of focusing on the implementation of nanotechnology and there has been an increasing number of these products available commercially.

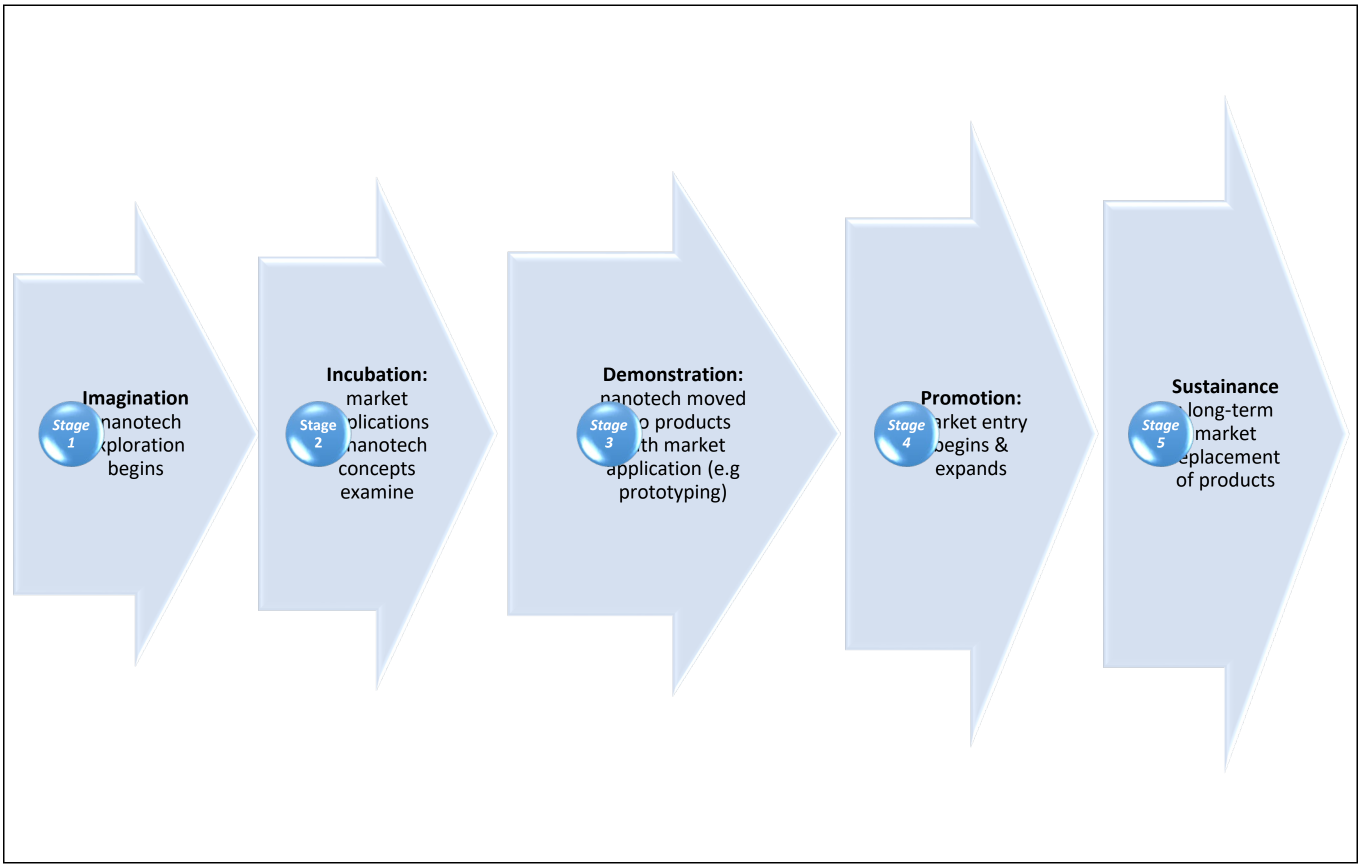


Figure 2.10: Commercialisation Levels for Maximum Market Entry (*Culled by the researcher*)

Source: Khan and Asmatulu (2013)

Khan and Asmatulu (2013) illustrated a sequence of stages to achieve optimum entry of nanotechnology materials into the market. Figure 2.10 describes these as necessary and sufficient stages for the effective commercialisation of scientific innovations. This description serves as motivation for the development of commercialisation theories in the course of this study.

According to Nogueira, Paino and Zucolotto (2013), ENMs have expectantly had an impact on the global economy through the volumes of their market, thereby requesting an urgent need for an in-depth study and analysis of commercialisation of ENMs, which is the main interest of this study. Inshakova and Inshakov (2017) argued that any state of the world desiring to economically and technologically advance must imperatively embark on the development and industrial application of ENMs. Despite its commercial prospects, according to Siddique and Numan (2021), the commercialisation of products of ENMs is long and hard. Interestingly, the commercialisation of products of ENMs has generated much attention (Khan and Asmatulu 2013). Meanwhile, carbon black is perhaps the earliest nanotechnology-based product, which for centuries has been in commercial use (Siddique and Numan 2021). Thereafter to date, according to Singh (2017) there has been an increase in the current acceptance of nanotechnology as the potential “next great commercial opportunity”.

Shapira, Youtie, and Arora (2013) iterated the importance of nanotechnology commercialisation as its adoption makes it possible for nanotechnology to achieve the technology requirement of performance, reliability and economic standard, thereby satisfying the causal-effect hypothesis that consumers’ acceptance has a significant effect on the success in its commercialisation processes.

2.6 Commercialisation of Engineered Nano-materials: The Need for a Multidisciplinary Solution Approach

Maine (2013) advocates that nanotechnology has essentially adjourned from the current growth of entrepreneurial innovation. The potential of the commercialisation of engineered nano-materials is to sustain the competitive and innovative industry to change by enabling major progress in several sectors of manufacturing, including biotechnology, automotives, energy, aerospace, electronics and construction.

In the meantime, Sia (2019) asserted that the observed retarded progress in this field was unconnected with the dearth of statistical, mathematical and Operations Research models. Shapira, Youtie and Arora (2013) opine that several challenges inhibiting the progress of nanotechnology research demand solutions from a multidisciplinary view point. Furthermore, the authors confirmed that with the application of techniques in statistics, significant impacts have been made in many other technology fields in the past. Therefore, this field of science is expected to address the challenges inhibiting the progress of nanotechnology research and boost the development of nanotechnology.

Statistics and statistical models occupy important and central positions in business and industry. Models in statistics are applied to quality designs and processes of engineered products, thereby creating improvements in technological processes (Mawaddah, 2013). According to Silva, Hassani, Madzen and Lee (2019), statistical models could also be used to forecast the behaviour of the marketing of a new brand to prepare its launch as well as to manage existing brands.

Vesely, Vesely and Vesely (2017) identified some challenges capable of providing opportunities for applications of statistical techniques in nanotechnology, as highlighted below:

- The analytical procedures in Statistics afford the user with the opportunity to learn further about the formation processes of nanocomposites;
- Statistical modelling assists in dealing with special types and processes of data;
- Analytical techniques in Statistics aid in the improvement of processes with high-defect and low-quality; and
- Statistics assist in enhancing product reliability of a low and unpredictable nature.

Oladimeji and Singh (2013) attest that interfacing techniques in Statistics and Operational Research are important in dealing with the challenges confronting the development of nanotechnology research as multidisciplinary features exists between the two disciplines. Sia (2019) confirmed the urgency of the need for the development of new and intrinsic techniques of these disciplines for a better understanding of the behaviour of ENMs. Towards accelerating the development of nanotechnology research, innovational rates and the commercialisation of nanotechnology, Maine (2014) advocates that much attention is required in academic and research institutions with the aids of interdisciplinary collaboration.

Expectantly, Nunes *et al*. (2015) iterate that statistics will increasingly feature in various research and industrial fields of any technology. By extension, an important role is expected to be played in nanotechnology development and production of nano-devices. Meanwhile, according to Shelke and Jajoo (2014), the adoption of appropriate statistical models will aid quality improvement activities in nanotechnology development. To this end, a combination of Statistical Averages and Analytic Hierarchy Process in Operational Research will be adopted in the development of prioritization modelling in the study.

2.7 Factors for Nanotechnology commercialisation: Conceptual framework

Various critical factors have been proposed in the conduct of several studies, towards effective commercialisation processes of emerging technologies. Several of these critical factors are reviewed in this section of the study by setting out to achieve Objective One of this study. The present section corroborates the propositions of Luthra, Garg and Haleem (2014) that the review of related literature has been discovered to be a valid viewpoint and necessary procedure in structuring the research field appropriately. As outlined in Section 1.7, this study sets out to present nanotechnology critical factors for engineered nano-materials through literature in order to form a general model of technology evaluation. It is required that the essential critical factors should be identified for the successful and effective implementation of technology commercialisation strategies by technologists and business managers. In the words of Luthra, Garg and Haleem (2015), the identified critical factors are essential enablers which are important for success. Therefore, this section of the study is devoted to broadening the empirical concept of the essential critical factors and the process of modelling for the successful commercialisation of nanotechnology enabled-products. Adopting the work of Kumar, Luthra, Haleem, Mangla and Garg (2015) on this discourse as the point of departure of this section and as succinctly outlined in Table 2.3 several studies have been conducted on these concepts, the critical factors and the framework.

Kumar *et al*. (2015) recognised the important role being played by these important enablers or critical factors, which technologists and managers require for successful technology commercialisation. Corroborating Luthra, Garg and Haleem (2015), these critical factors or enablers are conceptualised as essential factors for the successful adoption of technology inventions. Inshakova and Inshakov (2019) argued that these factors have had a significant impact on the global steady growth of the key market indices of ENMs. Luthra, Garg, and Haleem, (2015) identified and evaluated five critical dimensional factors and grouped them into twenty-four sub-factors, which were categorised from the literature review and experts' inputs.

Table 2.3: A brief overview of studies on the technology commercialisation process

Source: Adapted from Lan and Sheng (2014); Hassanali and Zahra (2015); Kumar *et al*. (2015)

AUTHOR(S) & YEAR	MODEL TYPE USED	FACTORS CONSIDERED
Kumar and Jain (2003)	Descriptive statistics, Correlation and Regression Analyses	• Funds availability • Support for technology supplier • Product engineering to market needs • Commitment of entrepreneur/company • Technical/Market staff training • Product and packaging aesthetics • Pricing, product positioning and launch • Longer and low interest rate loan re-payment
Bandarian (2007)	Delphi and Fuzzy Logic	• Technology area (Process evaluation, Technical evaluation) • Market area (Economic evaluation, Market evaluation, Perception evaluation) • Legal area (Regulatory/Policy evaluation)
Mahboudi and Ananthan (2010)	AHP	• Cultural factors (Information development, Diffusion of scientific attitude) • Global factors (Training in international companies, Employment of expatriates in technological field) • Recipient organisation factor (Investment in R&D, Technology development strategic planning, Managerial and organizing skills' development in the organisation) • Structural factors (Standard creation, localization of importing technology) • Absorption and Application factors (Creating research and production relationship, Absorption potential of importing technology, Expertise training) • Infrastructural factors (Personnel infrastructure, Informational and organisational infrastructure) • Technological factors (Commercialized technology price, Technology's complicity and simplicity level, Technology's development and improvement level)
Shen, Chang, Lin and Yu (2010)	Delphi, AHP and Patent co-citation approach (Hybrid model)	• Technological merit (Advancement of technology, Innovation of technology, Key of technology, Propriety of technology) • Generics of technology (Technological connections, Technological extendibility) • Business effect (Potential return on investment, Current market share effect, New market potential, Market size potential, Technology timing)

		• Technology development potential (Technical resources availability, Equipment support, Opportunity for technical success) • Risk (Technical risk, Technical difficulties, Commercial risk)
Amadi-Echendu and Rosetlola (2011)	Delphi	• Finance related issues • Marketing strategy issues • Intellectual property issues • Commercialisation environment issues • Technology management issues • Innovation development issues
Borzouei, Mirdamadi and Hosseini (2011)	Kaiser-Meyer-Olkin (KMO) & Bartlett's test and Kaiser criterion for Factor Analysis	• Infrastructural factors (Government investment interest, Support for researchers, Motivation for producers, …) • Economic factors (Budget provision, Income security improvement, Dynamic market existence, …) • Cultural factors (Creating consumer belief, Nano-awareness creation, …) • Informative factors (Private sector investment in nanotechnology, Media attention, Social culture creation) • Financial factors (Research budget provision, Research organisations' finance system)
Lo, Wang, Chen and Hung (2012)	Importance-Performance Analysis	• Compatibility • Complexity • Relative advantage • Trialability • Observability • Brand • Price • Country-of-origin effects • Quality
Lee, Lee, Jhon and Shin (2013)	Literature and Logistic & Tobit Regression models	• Field of technology (nanoequipment, nano-materials, nanodevices and nanobios) • Feature of technology (Convergence between nanotechnology and other emerging technologies like Information & Communication Technology (ICT) or Biotechnology (BT), Toxicity and Energy & environmental relevance) • R&D strategy (R&D intensity, explorative/exploitative R&D, Government R&D support and Research partnership with universities) • Feature of organisation (Size, Age)
Lan and Sheng (2014)	Delphi and Fuzzy AHP	• Personal factors (Gender and Age, Education, Income, Level of consumption, Awareness, Stakeholders' crucial opinions) • Environment factors (Cultural value, Government environmental protection policy, Government subsidy measures, Economic circumstances)
Mohannak and Samtani (2014)	Delphi and Mean, Standard Deviation &	• Technological readiness (Technology stage of development, Possible replicability, Technological nature & sophistication, Proof of application, Potential to combine with other technologies, Prototype availability,

	Inter-Rater Agreement (IRA)	Technical feasibility, Uniqueness of technology, potential for further development) • Economical and Market factors (Growth contribution, Market needs, Financial risk, Market impact, Time to market, Level of competition, Potential for attracting required resources) • Social benefits (Employment provision, Knowledge spillover, Social networks, Environmental impact, Brand creation, Cost advantage to users) • Legal and Regulatory (Exclusive patent, Protection of IP rights, Open innovation, New areas of application, Need for complimentary technologies)
Hassanali and Zahra (2015)	Delphi and AHP	• Environmental factors (Government legislation, Legal/regulatory, Government support) • Marketing factors (Customer need, Advert, Pricing policy, Competition strategy) • Technology factors (R&D capabilities, Market oriented, Timely innovative) • Management factors (Management, Management Skill, Management acceptance)
Kamolkittiwong and Phruksaphanrat (2015)	Delphi and AHP	• External factors (Suppliers, Regulation, Consumer/Market, Competitors, Social/Stakeholder) • Internal/Organisational factors (Organisation strategy, Top management support, Reverse logistics, Economic benefits)
Koç and Burhan (2015)	AHP	• Environmental Factors (Land Mass security, Transportation, Climate, Urbanization Rate) • Cost of Investment • Sectoral Factors (Customer Potential, Market Proximity, Warehouse Proximity, Regional Commercial Activity, Possible Competitors) • Human Resources Potential • Regional Potential (Facilities available in the region, Automobile insurance rate)
Kumar *et al.* (2015)	Delphi and AHP	• Economic relative advantage (Cost effectiveness, Higher profits margins, Expected sales' increase) • Marketing benefits and forces (New areas' penetration, Use of existing customers, End users support, Market demand, Competition, Timing judgment) • Technical features (Scientific changes, Suppliers' technical strength, Local suitability of technology, Compatibility , Functionality, Reliability, Trial-ability, Observe-ability) • Regulatory concerns (Government authorities, Environmental concerns, International bodies) • Management strategic issues (Strategic implications, Training and development , Human resources, Commitment)

Lee, Lee, Jhon and Shin (2013) reviewed some studies and recognised four related categories relevant to the identification of the factors which are critical for the successful commercialisation of nanotechnology:

- The Nanotechnology Field carried out this classification and further prediction for the commercialisation period. The author identified that the four fields were nano-equipment, nano-materials, nano-bios and nano-devices.
- The Features of Nanotechnology- The classification include Toxicity and Energy and Environmental Relevance. Also identified is the convergence between nanotechnology and Information and Communication Technology (ICT) or Biotechnology (BT).
- R&D strategy of nanotechnology organisations In order to ease commercialisation, four critical factors are considered. These are governmental support of R&D, exploitative/explorative strategies to develop new markets, high R&D intensity and Research partnerships with universities.
- Age and size of the nanotechnology organisations

Successful commercialisation is the most profitable form of new product development activity, but it is risky due to the existence of considerable uncertainty in characterising the type of consumer needs that can be satisfied by new technology (Goswami, Daultani and De 2021). The biggest challenge that nanotechnology is facing on its route to the markets is its innovativeness or novelty (Barbieux and Padula 2018). Meijer, Huijben, van Boxstael and Romme (2019) confirmed that three features are potential barriers that could inhibit the successful commercialisation of ENMs. These are:

- The necessity for extensive research on the relevant discipline. Meijer, Huijben, van Boxstael and Romme (2019) opined that there exists several fields and sub-areas of nanotechnology that need more critical scientific investigations to gain entrance into the consuming markets, which notably demand more interdisciplinary collaborations.
- Peculiar to developing countries is the limited financial resources of operations for start-ups and Micro, Small and Medium Enterprises against the larger investments. Meijer, Huijben, van Boxstael and Romme (2019) confirmed that this may continue to be a big hurdle.

- The opinion and acceptance of the public towards nanotechnology products are linked to issues like safety and toxic effects. However, it is observed that this public concern is vague and without basis, but based on insufficient and inaccurate information on the knowledge of safety and toxicity. Categorically, Joubert *et al.* (2020) mentioned that the knowledge and perceptions of the public towards nanotechnology-enabled products have a direct impact on their commercialisation. Meanwhile, Yaqoob, Parveen, Umar and Ibrahim (2020) recommended that the scientific communities should critically investigate the potential self-toxicity effects of ENMs on human health.

The present study, as displayed in Figure 2.11, proposes the process of a functional input-output model on technology commercialisation. The motivation for the current research was the need to carry out an evaluation of the importance of the critical factors as depicted in the Modified Input-Output Model.

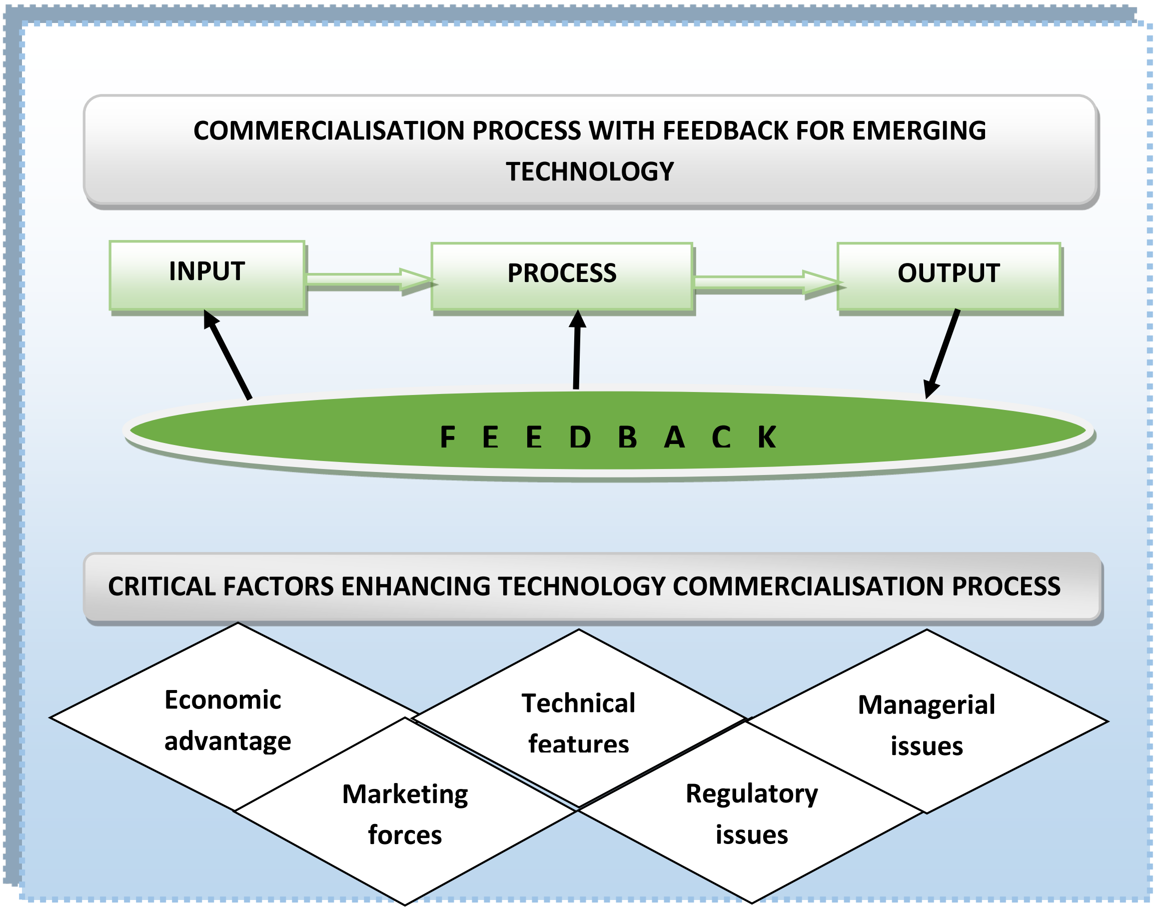


Figure 2.11: Modified Input-Output Model on the Technology Commercialisation Process *Source:* Adapted from Luthra, Haleem, Mangla and Garg (2015)

The critical factors were identified and categorised into ten factors with corresponding sub-factors. These categories were influenced by the factors considered in the overview of studies on the technology commercialisation process outlined in Table 2.3 and the modified input-output model on the technology commercialisation process depicted in Figure 2.11, which are listed as follows:

- **Technical and Technological features of the nano product (TT)**
  - Intersection of nanotechnology with biotechnology
  - Convergence of nanotechnology with information and communication technology (ICT)
  - Scientific changes through high levels of technological support and technology management effectiveness
  - Technical abilities of suppliers
  - Local suitability of nanotechnology based on the country's environmental and socio-economic state
  - Technological functionality, trial-ability and reliability
- **Economic factors (EF)**
  - Cost-effectiveness
  - Profit margins
  - Increase in sales turnover
- **Production factors (PF)**
  - Production cost issues
  - Labour intensity
- **Informative factors (IF)**
  - Publicity through press and media
  - Private-Public Partnership
- **Cultural factors (CF)**
  - Researchers-Investors constructive collaboration
  - Awareness and emphasis of the national ministry of technology towards nanotechnology commercialisation
  - Acculturation with respect to the commercialisation of nanotechnology
- **Social benefits (SB)**
  - Enhancement of social infrastructure/networks
  - Employment creation

- Product branding and brand recognition
- Cost advantages to customers

- **Regulatory policies (RP)**
    - Patent and legal issues
    - Governmental fiscal policies' regulations
    - Grant support and climate control by the international community
- **Marketing potentiality and forces (MF)**
    - Price suitability for sales facilitation
    - Product aesthetic and packaging
    - Product positioning and launch
    - Market potential for end-products
    - New market penetration for new and emerging technology
- **Organisation's strategic issues and features (FS)**
    - Organisational strategic implications
    - Organisation's business policies
    - Training and development support for technical and marketing staff
    - Personnel resources with generic and specialized nano-commercialisation knowledge
- **Health and Safety (HS)**
    - Public opinion about toxic issues
    - Safety issue

The factors above outlined for the commercialisation of applications of ENMs were distinctively selected from Table 2.3 because factors are found to be important to this study. While the factors considered in Table 2.3 are relevant to new technologies, the above factors outlined are essentially critical for the commercialisation of applications of ENMs.

2.8 Priority Modelling of Factors for Nanotechnology commercialisation: Empirical Framework

A critique of Table 2.3 as adapted in Figure 2.11 indicates that the Delphi method and Analytic Hierarchy Process (AHP) were more popular in the priority modelling of factors for successful technology commercialisation. As evident in Table 2.12, 9 of the 14 articles considered, made use of Delphi only, AHP only or a combination of the two methods in their analysis. Basically, the Delphi method was used for expert input for for the analysis and validation of the factors. Evaluation and prioritisation of the critical factors of nanotechnology commercialisation are treated with AHP. Based on the recommendation and validation of experts, the importance of these critical factors for nanotechnology commercialisation was rated towards developing quantitative models essential for facilitating new technological commercialisation decision-making. These factors and sub-factors were derived through an extensive review of the literature.

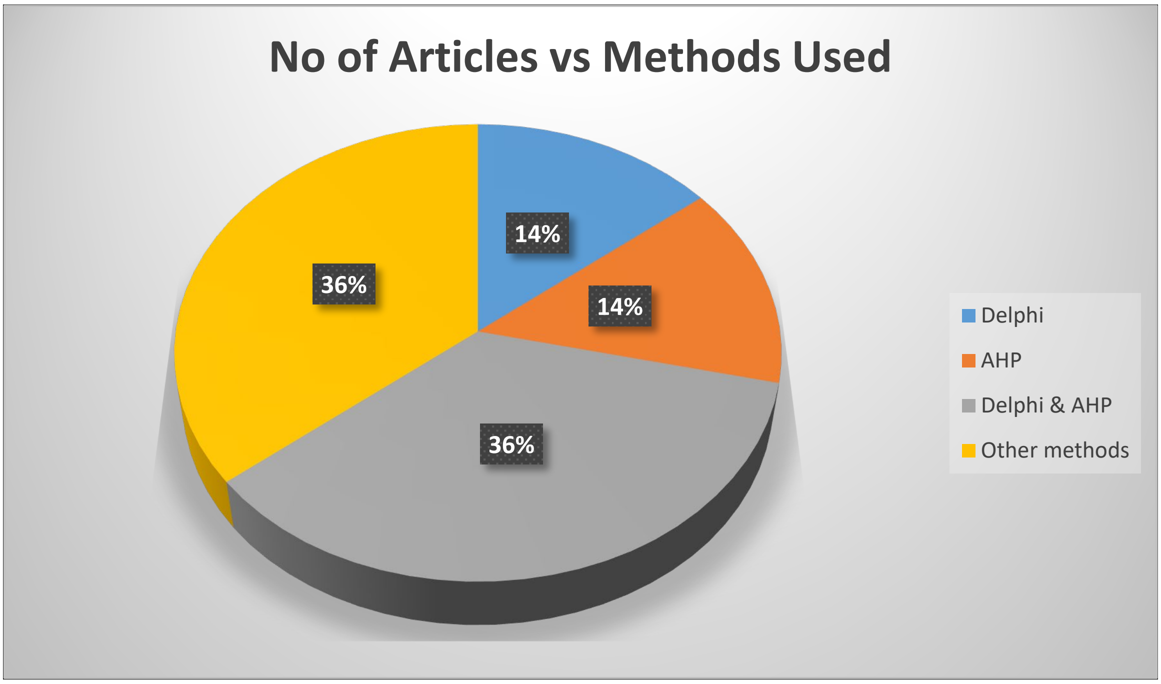


Figure 2.12: Graphical summary of methods adopted in reviewed articles

Source: Adapted by the researcher

Other analytical methods adopted for technology commercialisation among the articles reviewed include Kaiser-Meyer-Olkin (KMO) and Bartlett's test and Kaiser criterion for Factor Analysis (Khalilzadeh *et al.* 2017); Importance-Performance Analysis (Azma, Safarzad, Saeidi and Aghajani 2020); Logistic and Tobit Regression models (Lee, Lee, Jhon and Shin 2013) and Mean, Standard Deviation and Inter-Rater Agreement (IRA) (Mohannak and Samtani, 2014). Jou and Yuan (2015) adopted a hybrid model which combined Delphi and AHP with the Patent co-citation approach.

Furthermore, various studies, including that of Lin *et al.* (2020), have revealed that the Analytic Hierarchy Process, often in combination with the Delphi Method, is a popular technique relevant to the modelling of subjective decision-making processes with multiple attributes, with respect to the following application instances:

- Developing optimal strategies for the nanotechnology industry (Barbieux and Padula 2018)
- An efficient appraisal of technological innovation capabilities of enterprises (Detcharat, Pongpun and Tarathorn 2013)
- An analysis of factors influencing consumers' purchasing decisions, as related to marketing issues (Lan and Sheng 2014)
- Hybrid selection and the management of emerging technology for the competitive advantage of manufacturing industries (Mohannak and Samtani 2014).

Therefore, this study focuses on the prioritisation of the critical factors which are responsible for the commercialisation of engineered nano-materials and will be adopting a combination of the Delphi Method and the Analytical Hierarchy Process to achieve this focus. The justifications for these approaches and the research methodology are discussed in the next chapter of this study.
Making reference to the introductory method and theoretical foundations as described in Saaty (1980), Darko *et al*. (2018) noted that a major advantage of AHP is that it involves a variety of tangible and intangible goals by reducing complex decisions to a series of pair-wise comparisons, implementing a structured, repeatable and justifiable decision-making approach. The study will take this major advantage in the development of the data collection instruments as pair-wise comparisons are considered amongst the factors.

Krishnamoorthy and Kunasekaran (2014) combine state-of-the-art research in Multi-Factor Decision Analysis methods applicable to nanotechnology with a hypothetical case study for nano-material management. Of all the methods, AHP is a compensatory optimisation approach. According to the authors, the appropriate use of AHP prevents the wastage of resources (for example, time, materials and money). AHP uses a quantitative comparison method that is based on pair-wise comparisons of decision factors rather than utility and weighting functions. The goal of AHP is to select the alternative that results in the highest value of the objective function (Darko *et al*. 2018). This study adopts the

AHP in the evaluation and ranking of the critical factors essential for successful commercialisation of engineered nano-materials. Through the DM, these factors will be sorted by a thorough review of the literature and validated from the opinions of researchers in the field of nanotechnology. The next sub-section of the study discusses the decision to support modelling for the commercialisation of ENMs using the Analytical Hierarchy Process (AHP) based on selected factors and sub-factors validated by nanotechnology experts.

2.8.1 The Delphi panel process

Generally, according to Avella (2016), the Delphi method is categorised as a consensus development approach which is suitable for research interest with insufficient and contradictory evidence. Yang, Zeng and Zhang (2012) amongst others, noted that the Delphi panel process is applicable for studies which are complex in nature and multidisciplinary, with considerable elements of uncertainty. Habibi, Sarafrazi and Isadyar (2014) view the Delphi method as an approach that can be used for the effective structure of the communication process of a set of respondents while dealing with a complex problem. This technique is particularly relevant for the development of theoretical models through consensus amongst experts (Fink-Hafner *et al.* 2019). Lopes, Rosário and Varela (2020:148) reiterate the argument of Landeta (1999) that emerging fields of research could adopt the Delphi process using a composed panel of experts. To this end, this study adopts this technique, considering that nanotechnology commercialisation is an emerging field of research.

2.8.2 Priority Modelling with AHP

For credible and quality decision-making, the AHP is a tool that can be used for reliable sourcing of experts' opinions on salient application domains (Macharia, Mundia and Wathuo 2015). The basic essence of adopting the AHP is to construct an n-dimensional matrix (where '[n' represents the number of factors under consideration) showing the relative importance of these factors and thereby expressing their priority ranking (Kumar *et al.* 2015).

The following approaches (see Figure 2.13) are identified in the literature to aid in realising the research objective for the AHP nanotechnology commercialisation model:

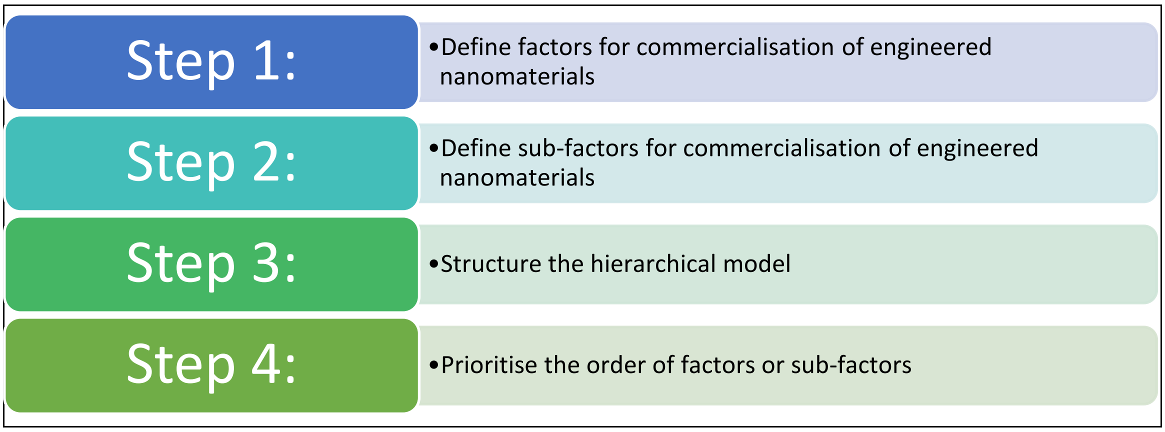


Figure 2.13: The Study's Approaches for AHP Model Development

Source: Adapted by the researcher

Furthermore, the AHP technique is adopted to rank these critical factor dimensions and sub-factors under each dimension. As depicted in Figure 2.14, the AHP framework of evaluation of nanotechnology commercialisation critical factors is structured to include three levels, namely:

Goal: To Prioritise Nanotechnology Commercialisation Critical Factors;

Factors: Ten dimensions of critical factors of nanotechnology commercialisation; and

Sub-factors: Sub-factors under each dimension of critical factors.

.

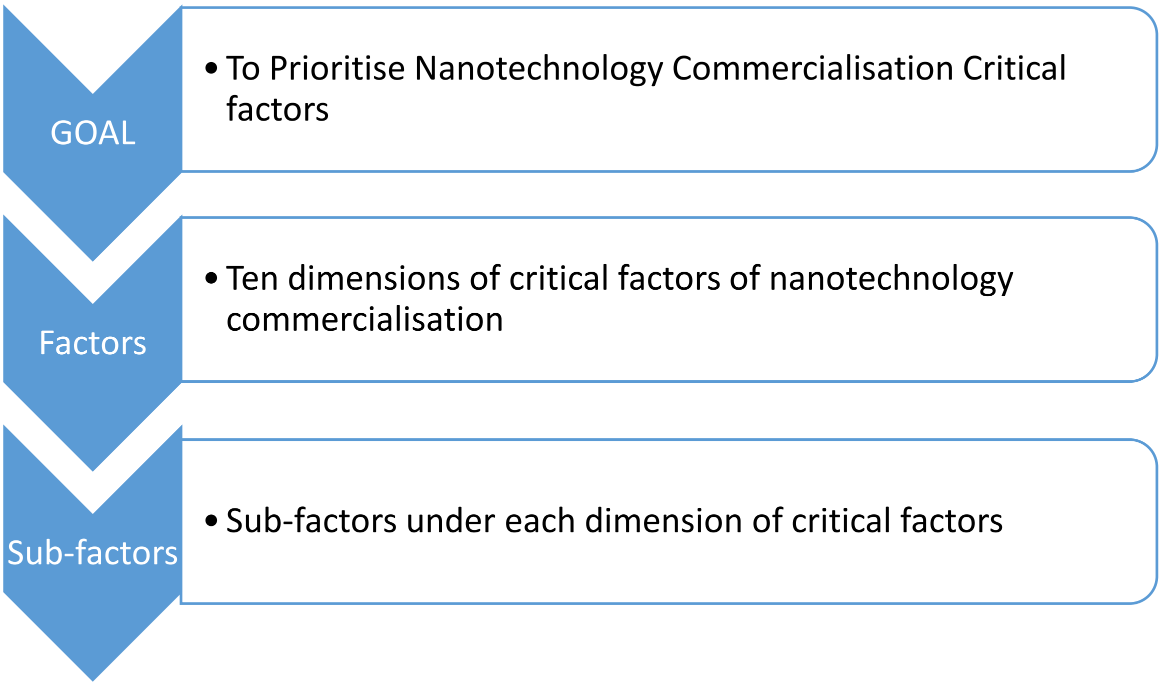


Figure 2.14: AHP framework for evaluation of technology the commercialisation

Source: Adapted by the researcher

The first step in any AHP model development, as illustrated in Figure 2.14, is the establishment of the factors to be considered. Hence, based on the consideration of literature, ten factors were identified for the purpose of this study as depicted in Figure 2.15.

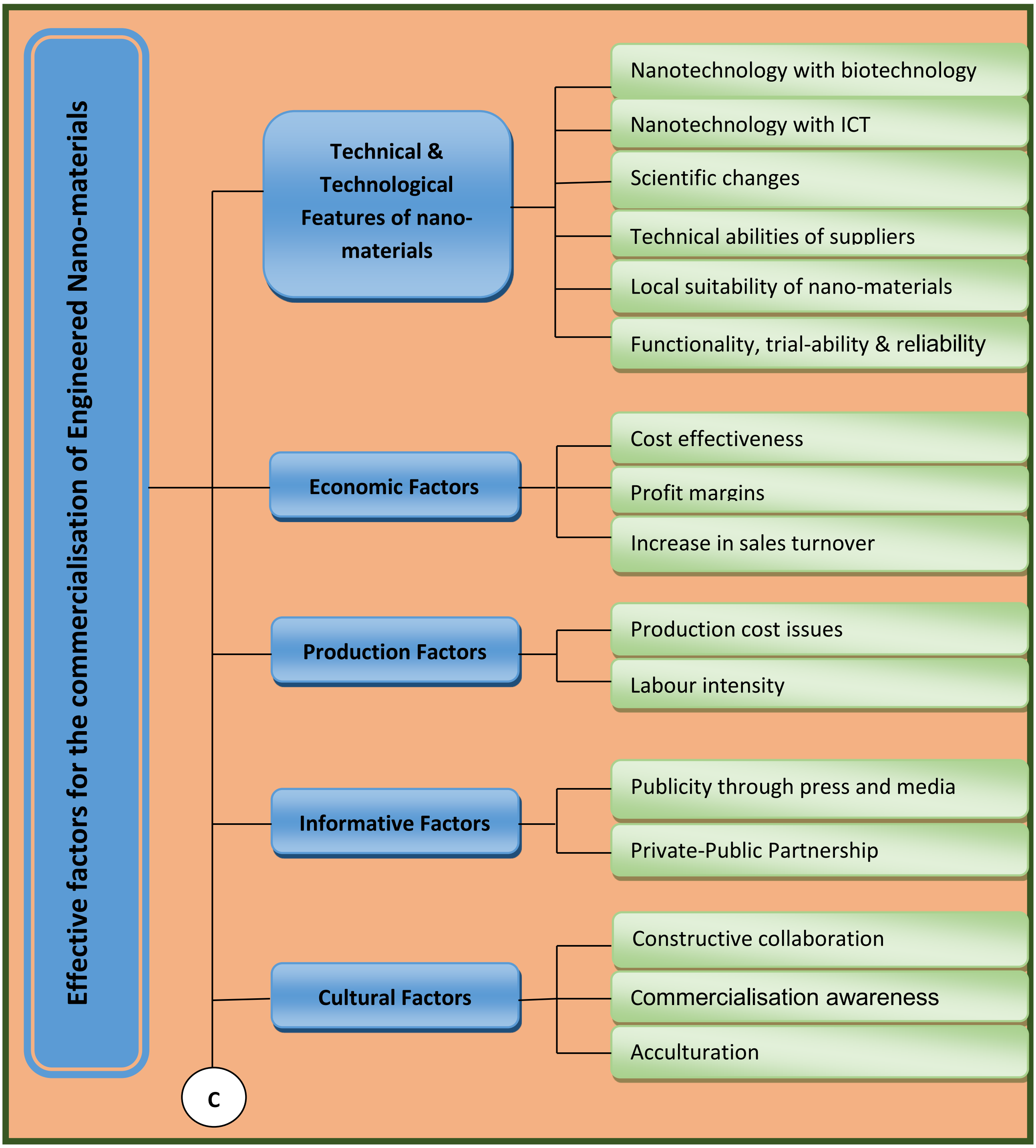


Figure 2.15: AHP model of effective factors for the commercialisation of ENMs

Source: Hassanali and Zahra (2015); Kumar *et al.* (2015)

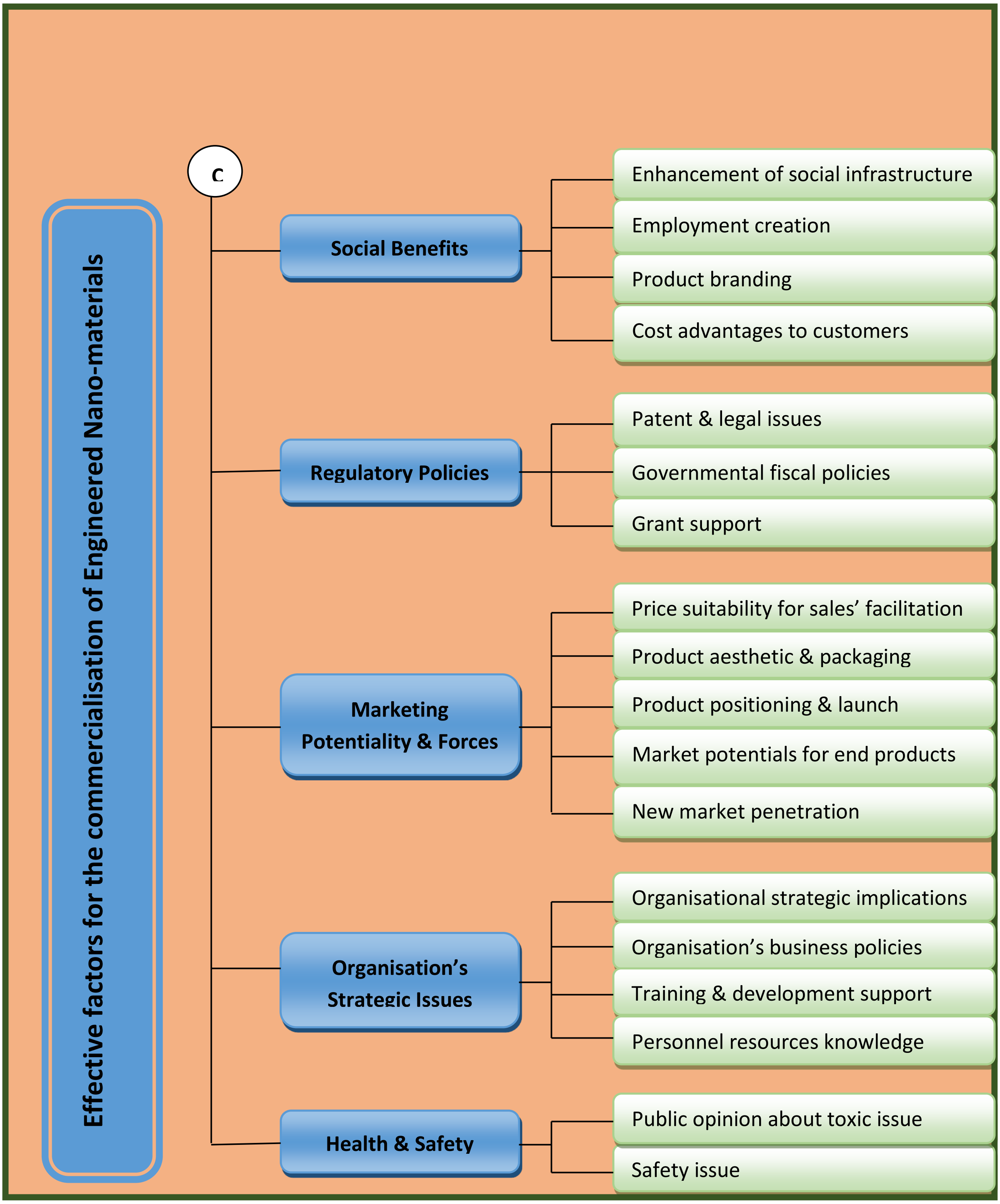


Figure 2.15(continued): AHP model of effective factors for the commercialisation of ENMs

Source: Hassanali and Zahra (2015); Kumar *et al.* (2015)

The connector symbol © indicates a continuation of the process

Table 2.4 expresses the standard judgmental scaling for pairwise comparisons of factors in an AHP exercise, as proposed by Saaty (2016). The standardised scaling has been widely used for over four decades (Luthra, Haleem, Mangla and Garg 2015).

Table 2.4: The Standard Judgmental Scale for Pair-wise Comparisons of Factors in AHP

Source: Saaty (2016); Luthra, Haleem, Mangla and Garg (2015)

Scale	Intensity of Importance	Explanation	Notation
1	Equal Importance	Two activities contribute equally to the objective	E
2	Weak		W
3	Moderate Importance	Judgment and experience moderately favour one element over the other	M
4	Moderate Plus		M+
5	Strong Importance	Judgment and experience strongly favour one element over the other	S
6	Strong Plus		S+
7	Very Strong Importance	Judgment and experience very strongly favour one element over the other. Practical dominance is demonstrated	VS
8	Very, very Strong		VVS
9	Extreme Importance	One element is favoured over the other evidently with the highest possible order of arguedation	Ex

This study uses the AHP for the analysis and ranking of the critical success factors and sub-factors for the commercialisation of nanotechnology ENMs, as well as the step-by-step methodological procedure of these analyses and rankings indicating the modelling flowchart adapted for this study.

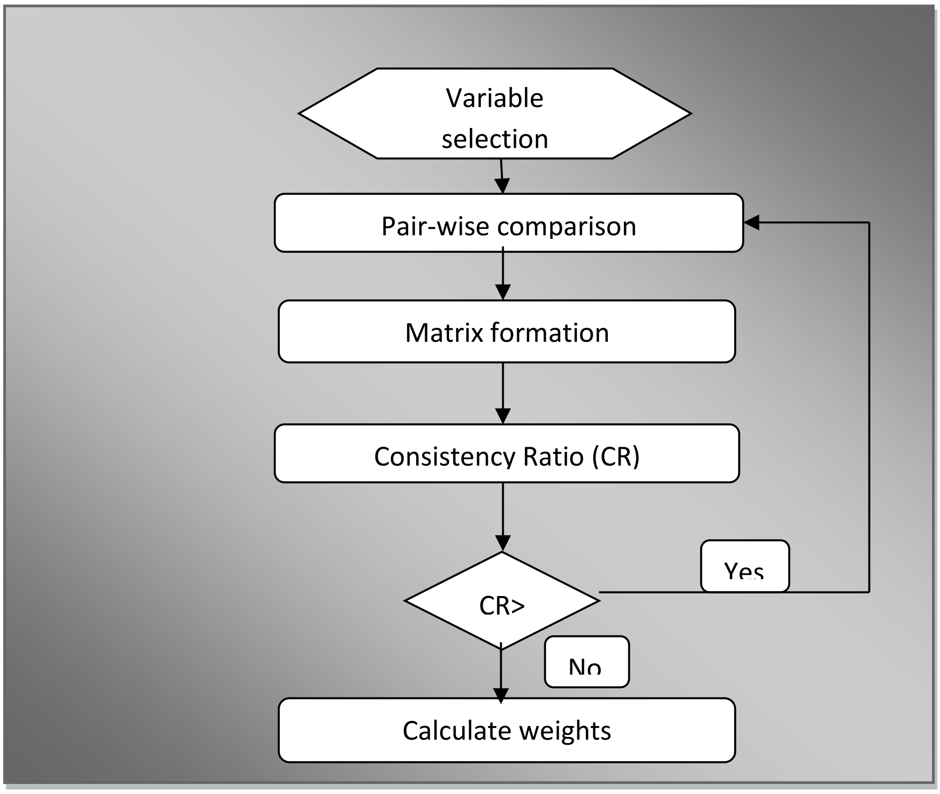


Figure 2.16: AHP modelling flowchart

Source: Adapted from Zhu (2014)

The consistency ratio (CR) is computed after the matrix formation. It is a critical value derived from the matrix for the evaluation of the judgements of the decision makers (Peláez, Martínez and Vargas 2018).The essence of the CR is to determine the trustworthiness, in terms of the consistency of the respondents' judgments. From Figure 2.16, it is expected that every resulting CR would be a maximum of 10%. Otherwise, it can be concluded that the whole ranking process is unreliable. The process of pairwise comparison is consistently repeated until a CR less than or equal to 0.1 is obtained. Subsequently, the weight or priority ranking is carried out. The pair wise comparison technique is commonly used to handle subjective and objective judgments in multi-factors decision making (Zhü 2014). This process helps this present study in improving the reliability of data obtained for optimal decision-making.

2.8.3 Strengths, weaknesses and challenges of AHP and the Delphi method

The Delphi Method has its strengths and weaknesses (Fink-Hafner *et al.* 2019). Seker (2015), in an attempt to identity the strengths and weaknesses, elucidated that the Delphi Method is sufficient for gathering data for a comprehensive and complex problem possessing a history of insufficient information. He further identified that the methods of summarising and presenting the responses are necessary.

The AHP has the following strengths and weaknesses:

Strength 1: Compared to other multi-factor methods, the AHP has some advantages over these methods. These advantages include its flexibility, intuitive appeal to decision-makers and the possibility of checking for inconsistencies (Ansah, Sorooshian and Bin-Mustafa 2015). In many instances, researchers find the pairwise comparison form of data input uncomplicated and appropriate (Sum 2018).

Strength 2: The decomposition feature of a decision problem into its corresponding parts and construct hierarchies of factors is another distinct advantage of the AHP method. Here, the consequence of each element becomes apparent (Frikha and Moalla 2015; Saaty 2016).

Strength 3: AHP aids in the capturing of both subjective and objective evaluation measures. The AHP method reduces bias in decision-making while providing a useful mechanism for checking the consistency of the evaluation measures and alternatives (Sum 2018).

Strength 4: Another basic feature of the AHP method is observed in Ansah, Sorooshian and Bin-Mustafa (2015). Through the calculation of the geometric mean of the individual pairwise comparisons, this method supports group decision−making through consensus.

Strength 5: AHP is uniquely positioned to assist in the modelling of risky and uncertain environments as it has the capability of deriving scales where measures ordinarily do not exist (Saaty 2016).

Weakness 1: The Analytical Hierarchy Process could be referred to as a complete aggregation method of the additive form. The aggregation methods have a peculiar challenge, which is the occurrence of compensation between good scores on some factors and bad scores on other factors. This problem could cause the loss of detailed, and often important information (Ansah, Sorooshian and Bin-Mustafa 2015).

Weakness 2: The Analytical Hierarchy Process contains the approach that the decision problem is broken into a number of sub-systems, within which and between which a substantial number of pairwise comparisons would have to be completed. The disadvantage of this approach is the number of pairwise comparisons to be completed, hence resulting in a voluminous task (Frikha and Moalla 2015).

Weakness 3: The artificial limitation of the use of the 9−point scale is another significant disadvantage of the AHP technique. There are instances whereby the decision−maker might find it difficult to distinguish amongst them and which one is more important than the other (Sum 2018).

AHP, with the several limitations of this methodology, has been popularly used in many applications of the public and private sectors. The methodology is adopted in this study because it is the leading approach used for MCDA methods.

2.9 Overview of Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a relatively new non-parametric approach for measuring comparative or relative efficiency (usually a real number ranging between 0 (or 0%) and 1 (or 100%) (Asandului, Roman and Fatulescu 2014). DEA is described as a mathematical technique (Ehsanifar 2014) and a data-oriented approach (Kumar, Shankah and Debnath 2015) based on linear programming, as originally proposed by Charnes, Cooper and Rhodes (1978). Basically, adopted in finding optimum weights to maximise the efficiency of variables under evaluation, DEA as depicted in Figure 2.17, is grouped into four basic models (Visbal-Cadavid, Martínez-Gómez and Guijarro 2017; Mirmozaffari *et al.* 2020)

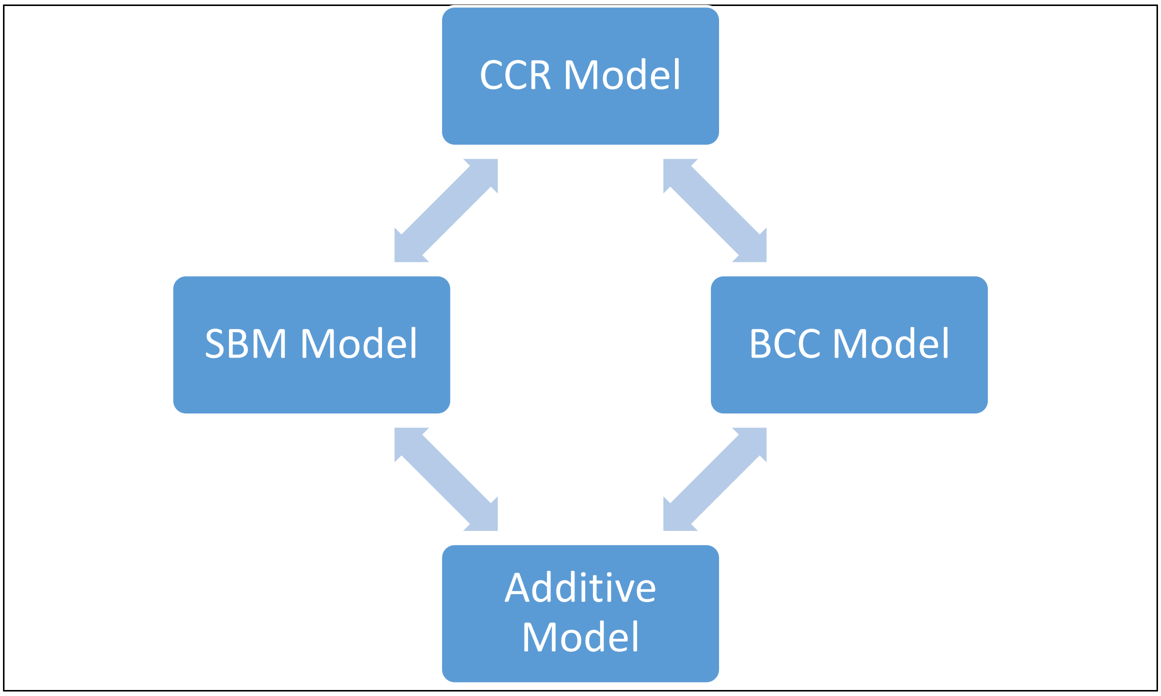


Figure 2.17: Four Basic DEA Models

Source: Adapted from Stiakakis and Sifaleras (2013)

This study adopts the CCR model to validate the hierarchical structure as obtained using AHP. According to Jablonsky (2014), there have been several attempts from previous studies (Adler, Friedman and Sinuany-Stern 2002; Zarei, Mehdiabadi, and Javindia 2012; Ehsanifar 2014) to combine AHP and DEA models purposely to evaluate efficiency. In recent periods, more studies (Keskin, and Köksal 2019; Popovic, Savic, Kuzmanovic and Martic 2020) considered a combination of the techniques.

2.10 DEA Model for Cross-Weights Evaluation

Considering a comparison matrix A, such that

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{a_{11}} & \cdots & \boldsymbol{a_{1n}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{a_{n1}} & \cdots & \boldsymbol{a_{nn}} \end{bmatrix} \quad (1)$$

The matrix is such that, for every, $i \neq j,\ a_{ij} = \frac{1}{a_{ji}}$ otherwise $a_{ij} = 1$.

Let $W = (w_1,\ w_2,\ \ldots,\ w_n)^T$ be a priority vector. The comparison matrix A is said to be perfectly consistent if $a_{ij} = a_{ik}.a_{jk}$ for every $j, k \in \{1,\ 2,\ \cdots,\ n\}$. Otherwise, it is said to be an inconsistent comparison matrix. In Data Envelopment Analysis models, each row is viewed as a Decision-Making Unit (DMU) and each column is viewed as an output (Wang, Luo and Xu, 2013). Sun, Wu and Guo (2013) and Moeini, Karimi and Khorram (2015) developed the following Linear Programming model for the purpose of generating weights with each DMU having n outputs. The objective is to:

$$Maximize\ w_0 = \sum_{j=1}^{n} a_{0j} v_j \tag{2}$$

$$subject\ to \begin{cases} w_i = \sum_{j=1}^{n} a_{ij} v_j \leq 1, \ \ i = 1, \cdots, n \\ w_j/\beta \ \leq \ v_j \ \leq \ w_j/n, \qquad j = 1, \cdots, n \end{cases}$$

$$Maximize\ w_0 = s_0 / \sum_{j=1}^{n} s_k \tag{3}$$

$$subject\ to \begin{cases} s_i = \sum_{j=1}^{n} a_{ij} v_j \leq 1, \ \ i = 1, \cdots, n \\ 0 \ \leq \ v_j \ \leq \ s_j/n, \qquad j = 1, \cdots, n \end{cases}$$

Where v_j are decision variables

Subscript 0 is the decision criterion, DMU_0

β is the upper bound for the maximum eigenvalue of matrix A

such that $\beta = min \left\{ \max_i \left(\frac{1}{r_i} \sum_{j=1}^{n} a_{ij} r_j \right), \ \max_i \left(\frac{1}{c_i} \sum_{j=1}^{n} a_{ij} c_j \right), \right\}$ (4)

where $r_i\ and\ c_i$ are respectively row sums and column sums of the matrix A.

Alternatively to model (3), the linear programming model below is applicable for as a possible solution to the priority ranking of decision criteria with perfectly consistent pairwise comparison matrices. This is obtainable through the variable transformation of model (3) as proven in Sun, Wu and Guo (2013) and Moeini, Karimi and Khorram (2015):

$$Maximize\ w_0 \tag{5}$$

$$subject\ to \begin{cases} w_i = \sum_{j=1}^{n} a_{ij} z_j \leq n z_i, \ \ i = 1, \cdots, n, \\ \sum_{j=1}^{n} \left(\sum_{i=}^{n} a_{ij} \right) z_j = 1, \\ z_j \geq 0, \qquad j = 1, \cdots, n. \end{cases}$$

Hosseinian, Navidi and Hajfathaliha (2012) proposed an extension of the linear programming model. According to the authors, DMUs in DEA models are arranged in rows, while the outputs (representing the inputs this time around) are arranged in columns purposely to maximize outputs or minimize inputs.

Given a pair-wise comparison matrix $A = (a_{ij})$ with n-dimensions as provided by a decision-maker, with the ith criteria (alternative) of the comparison matrix A being taken as DMUi for $i = 1,2, \dots, n$, and the jth criteria being taken as an output for $j = 1,2, \dots, n$. For derivation of priority weights, Hosseinian Navidi and Hajfathaliha (2012) proposed the following model:

$$Maximize\ Z \tag{6}$$

$$subject\ to \begin{cases} w_i \ \geq \ Z, & i = 1, \cdots, n, \\ \sum_{j=1}^{n} a_{ij} v_j - w_i = 0, & i = 1, \cdots, n, \\ \sum_{i=1}^{n} w_i = 1, & i = 1, \cdots, n, \\ v_i - \frac{1}{\beta} w_i \geq 0, & i = 1, \cdots, n, \\ v_i - \frac{1}{n} w_i \leq 0, & i = 1, \cdots, n, \\ w_i \geq 0; \ v_i \geq 0, & i = 1, \cdots, n. \end{cases}$$

This study adopts the DEA models' extension for the computation of the priority weights of the decision criteria to validate the AHP models. The DEA models' extension is an alternative designed for DEA without input, as investigated by Paradi and Zhu (2013); Emrouznejad and Tavana (2014); Najafi, Saati and Tavana (2015) and Paradi, Sherman and Tam (2017). This section of the study was inspired by the works of Fülöp and Markovits-Somogyi (2012); Sinuany-Stern, Mehrez and Hadad (2000) and Wang, Luo and Xu, (2013), who found the results appreciative and applicable towards the possibility of obtaining a more accurate and validated hierarchical evaluation. Meanwhile, according to Kumar and Gulati (2014), the strength of DEA is the value-free system and the point is that it does not require a priori weights for inputs and outputs.

2.11 Theoretical Framework

This section considers the various theories that underpin quality control and commercialisation as a disruptive technology.

2.11.1 Theories relevant to quality control and commercialisation of ENMs

This section discusses some theories which are relevant to technology commercialisation. These theories are available in studies of technology commercialisation literature (Sithole and Rugimbana 2014) and have been adopted in the determination of critical factors of successful commercialisation and quality control of emerging technologies (Farsi and Kalatehael 2013). From traditional academic literature on technological innovation, Wynarczyk (2013) noted the existence of three theoretical frameworks which are inter-related but distinct and form the basis for this study. These schools of thought are the Agency Theory, Resource-Based Theory and Optimising the Transaction Costs, which are discussed below.

Agency Theory

Assessing the impact of the Agency Theory on factors for technology commercialisation, Farsi and Kalatehael (2013) argued that there is a scarcity of studies considering the variables. This was corroborated by Calvo, López, Pazos and Gulías (2019) as they also identified a dearth of studies relating the Agency Theory to critical factors for the successful commercialisation of technological products. The authors stated the Agency Theory as goal conflicting, arising when there is an engagement of mutual efforts between individuals having different interests and varying information of the other part.

According to Wynarczyk (2013), this theory is designed to evaluate arrangements within the organisation and governance between the participating parties in the event of uncertainty. These arrangements are listed to include board decision-making, profit sharing and risk-sharing.

Resource-based Theory

According to Hitt, Xu and Carnes (2016), the Resource-based Theory is broadly applicable in several areas of application, including the commercialisation of technology products. The theory proposes that organisations have capacities in creating and sustaining competitive advantages by adopting valuable and rare resources (tangible or intangible). Marozau and Guerrero (2016) adopted the Resource-based Theory in determining predictive factors for the commercialisation of technological services. The Resource-based Theory was also used by Sithole and Rugimbana (2014) to identify the critical factors for successful innovations and the commercialisation of technology and research.

Transaction Costs Optimisation Theory

This theory is an economic-based one with a primary focus on the minimisation of costs amongst transacting parties through mutual relationshis (Cecchini, Leitch and Strobel 2013). Mwai, Kiplang'at and Gichoya (2014) opined that the Transaction Cost Theory can be adopted by organisations involved in technological commercialisation in making predictions on the optimum time to perform some economic activities and the most realistic time that these activities could be carried out on the market, subject to certain levels of uncertainty.

2.11.2 Theories relevant to disruptive technologies in industrial dynamics

Theory of Disruptive Technologies

This theory that was suggested by Christensen (1997) argues that disruptive technologies undergo a commercialisation process through market niches but can rise in competition with existing technologies and penetrate established markets. The author identified five characteristics of disruptive innovations, as succinctly explained below and as summarised by Liu, Liu, Chen and Mboga (2020).

- **Attributes at the initial stage:** In all incidences, an emerging disruptive technology is known to exhibit retarded performance compared with incumbent technology at the initial point because much value is not placed on it as a mainstream technology by mainstream customers.
- **Target customers:** New customers, also referred to as marginal customers, often appreciate disruptive technologies. Nanotechnology, a disruptive technology, provides access to affordable and uncomplicated products when compared with mainstream technologies.
- **Target markets:** The commercialisation of emerging and disruptive technologies is usually initiated in non-critical and emerging markets since the established customers of mainstream technologies do not demand products enabled through disruptive technologies.
- **Strategy:** Disruptive technologies are emerging technologies that steadily improve their performance, thereby achieving the standards of functionality demandable by mainstream markets.
- **The final stage:** This is a point of replacement where mainstream technology is displaced by the emerging disruptive technologies. At this point in the dominant market, mainstream products are displaced by the new entrants.

Theory of Revolutionary Innovation

According to Coccia (2019), this theory was propounded by Abernathy and Clark (1985). The Theory of Revolutionary Innovation claims that an innovation is 'revolutionary' if it possesses a disruptive tendency to render obsolete any existing competences while being adopted amongst mainstream customers within existing markets. Coccia (2020) argues that innovation is a divided phenomenon. While some innovations are disruptive by destroying and rendering obsolete existing competences, others are known for the improvement and refining of established technologies.

Theory of Competitive Substitution

This was first discussed and established by Fisher and Pry (1971) to explain technological evolution in the economics of technology (Coccia 2019). According to Utterback, Pistorius and Yilmaz (2019), the theory states that the adoption of an emerging technology is associated with the nature of a related established one in existence, in such a way that there is an improvement in the older technology. This interaction which exists in turbulent markets, is identified as competition for the dominance of one technology over another (Berg, Wustmans and Bröring 2019; Moehrle and Caferoglu 2019).

Theory of Predator-prey Relationship

A Predator-prey Relationship is generated when there exists a competition between technologies (Pistorius and Utterback 1997). As such, the market share of an established and mature technology may be gradually retarded, as explained by Farrell (1993) through the Lotka-Volterra equations and confirmed in Utterback, Pistorius and Yilmaz (2019).

Theory of Killer Technologies

Coccia (2019) proposes the concept of Killer Technology, also known as the Speed of Creative Disruption Theory, in the economics of innovation in an attempt to generate disruptive technological innovations for radical market changes in society. The author, in an attempt to understand the reactions and effects of the Killer Technology Theory, proposes a model showing the relationship in terms of a differential equation of logistic function between an established technology (Victim Technology *V*) and an emerging technology (Killer Technology *K*).

For the following analytical assumptions:

K evolves based on some *S*-shaped technological growth's pattern

V evolves based on some *S*-shaped technological growth's pattern

The initial equation for the Victim Technology, *V*, is given as

$$\frac{1}{v}\frac{dV}{dt} = \frac{b_1}{K_1}(K_1 - V)$$

The above expression can be re-written as

$$b_1 dt = \frac{K_1}{V(K_1 - V)} dV$$

So that

$$\int b_1 dt = \int \frac{K_1}{V(K_1 - V)} dV$$

$b_1 t + A = logV - \log(K_1 - V)$, so this can be re-written as $\log(K_1 - V) - logV = a_1 - b_1 t$

$\log\left(\frac{K_1 - V}{V}\right) = a_1 - b_1 t$ (1)

Considering the Killer Technology K_L in a similar manner and *mutatis mutandis*,

$\log\left(\frac{K_1 - K_L}{K_L}\right) = a_2 - b_2 t$ (2)

Solving for *t* in equations (1) and (2),

$\frac{V}{K_1 - V} = e^{b_1(t_2 - t_1)} \left(\frac{K_L}{K_2 - K_L}\right)^{\frac{b_1}{b_2}}$ (3)

Taking $B = \frac{b_1}{b_2}$ and $= \frac{K_2}{(K_1)^{\frac{b_1}{b_2}}} e^{b_1(t_2 - t_1)}$, in a simplified form, equation (3) is expressed as

$K_L = AV^B$ (4)

The following simple linear relationship is obtained by taking the logarithmic form of equation (4):

$log\ K_L = log\ A + B\ log\ V$ (5)

The following possibilities are witnessed in the markets for various values of *B,* which is the growth coefficient determining the evolution of the emerging (Killer) technology with respect to the established (Victim) technology:

For a value of B = $\begin{cases} < 1, & successful\ commercialisation\ of\ the\ emerging\ technology \\ = 1, & proportional\ development\ of\ the\ emerging\ (killer)\ technology \\ > 1, & under - development\ of\ the\ emerging\ (killer) technology \end{cases}$

The Theories extensively enumerated above are those related to the quality control and commercialisation of emerging technology. By extension, this is also expected to be applicable to the adoption and development of nanotechnology and ENMs.

2.12 Summary of the Chapter

Overall, this review of selected literature has outlined nanotechnology and nano-materials with particular reference to their commercialisation and the growing body of knowledge and research on Operational Research application in nanotechnology. In exploring the concepts of multi-disciplinary modelling, this chapter has linked Statistical and Operational Research techniques to nanotechnology commercialisation. As evident in the literature, this chapter has described the theoretical and empirical potential of the application of the Analytic Hierarchy Process, amongst other Operational Research techniques, in the commercialisation of nanotechnology and nano-materials. Meanwhile, it is evident from the literature review that there are still gaps to be filled in this application in an emerging technology. As a result, Chapters Four and Five systematically explore the classical potential of quantitative and qualitative techniques in the commercialisation of nanotechnology and nano-materials. Chapter Six presents a structural framework that could guide the developmental process of operational business modelling for the commercialisation of nanotechnology, especially that of ENMs. Chapter Three describes the methodological rationale and philosophical paradigms.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Overview of the chapter

This chapter is an exposé of the justification of the methodological rationale and research design used in this study. It introduces the methodology of the study. The preliminary and Delphi pilot studies conducted are reviewed and the main study introduced. The empirical investigations examine business modelling for the quality control and commercialisation of nano-engineered materials. Literature suggests that information on the commercialisation of nanotechnology is very scant and that of its products crucial (Sharma and Hussain 2018). According to Barbieux and Padula (2018), its innovativeness is complex, especially in a market characterised by competition and instability. Hence, this chapter intends to achieve the following:

- Integrate the opinions of nanotechnology researchers towards the multi-factors of ENM by adopting the Delphi Method. Expert opinion for technology selection factors were sourced through the administration of a questionnaire. The Delphi Method, in essence, is used in this study, to achieve consensus amongst the experts on the subject being evaluated. The method serves to draw on a large body of opinions and also meets the requirement for independence in the experts' judgment. This study therefore applies the Delphi Method to the selection process of system variables to increase the confidence of the proposed quantitative model;
- Propose a methodology that will involve quantitative, qualitative and semi-qualitative factors in the process. Hence, the Analytic Hierarchy Process (AHP) was selected as this method possesses this attribute. The AHP is useful when dealing with rational multi-decision-making for technological, commercial innovation especially with the involvement of the assessment of various factors (Sumrit and Anuntavoranich 2012). In nanotechnology business modelling, especially in the evaluation of potential suppliers and consumers, decisions most frequently have to be made as a group, by several decision-makers. The Analytic Hierarchy Process is one of the most popular and relevant multi-factor decision-making techniques for the formulation and analysis of decisions (Gupta, Dangayach, Singh and Rao 2015), especially in Operations Research and

Operations Management (Gupta, Dangayach, Singh and Rao 2015) and in various other fields (Koç and Burhan 2015). The Analytic Hierarchy Process meets both of these requirements as earlier pointed out in the review of the literature in Section 2.12. Hence, this study considers the choice of this Operations Research modelling method, which Ramaj-Desku, Berisha, Latifi and Loka (2020) proposed has been widely used by researchers in various disciplines.

The methodology is proposed to build roadmaps for different nanofields (nano-materials, nanomedicine, nanoelectronics, nanoenergy). It is expected that it will be used by policy-makers and scholars and serve as an input for Science and Technology Platform Development. Furthermore, the methodology is designed through the adoption of Statistical and Operational Research (S&OR) techniques which play an important role in approaching the numerous challenges confronting nanotechnology research. As stated earlier, challenges confronting nanotechnology research call for solutions from a multi-disciplinary approach. It is herewith envisaged that this approach will boost the development of nanotechnology.

3.2 Research design

Creswell and Creswell (2018) view research design as a procedure or plan for conducting a research study, spanning from the inception of research assumptions to the stage of comprehensive methods of data gathering, presentation and analysis. Summarising the views of Punch (2011), Wengraf (2002) and Van Wyk and Taole (2015), the evident definition of research design is a comprehensive arrangement of the process by which a researcher would conduct his/her research. According to Creswell (2013), it is a precise plan which makes available the structure for gathering data from the respondents, presenting the algorithms of the study and setting out the necessary steps for collecting information from the respondents.

Baran (2020) submits that research design is a blueprint that addresses the research questions in a study by presenting a pathway or structure displaying how the peculiar parts of the study perform together. This author concludes that decisions on the design must be done prior to the commencement of the study. In this particular study, questionnaires and surveys were adopted for collecting data to be processed and analysed. This process concluded with the development of a model for managerial decision-making.

The fundamental purpose of this study is to develop a strategy for the modelling of the commercialisation process and procedure of nanotechnology materials in general and carbon nanotubes in particular. It is estimated that in the United States of America (USA), for every one dollar invested in basic research, substantial funds of comparable worth must be invested for successful commercialisation (Hausman and Johnston 2014). Technologies are often lost due to a lack of interest of scientists in commercialisation (Mazumder, Sarkar and Puri 2014). In line with Bouzon, Govindan, Rodriguez and Campos (2016), a visual presentation of the procedures for the research design of this study is presented in Figure 3.1.

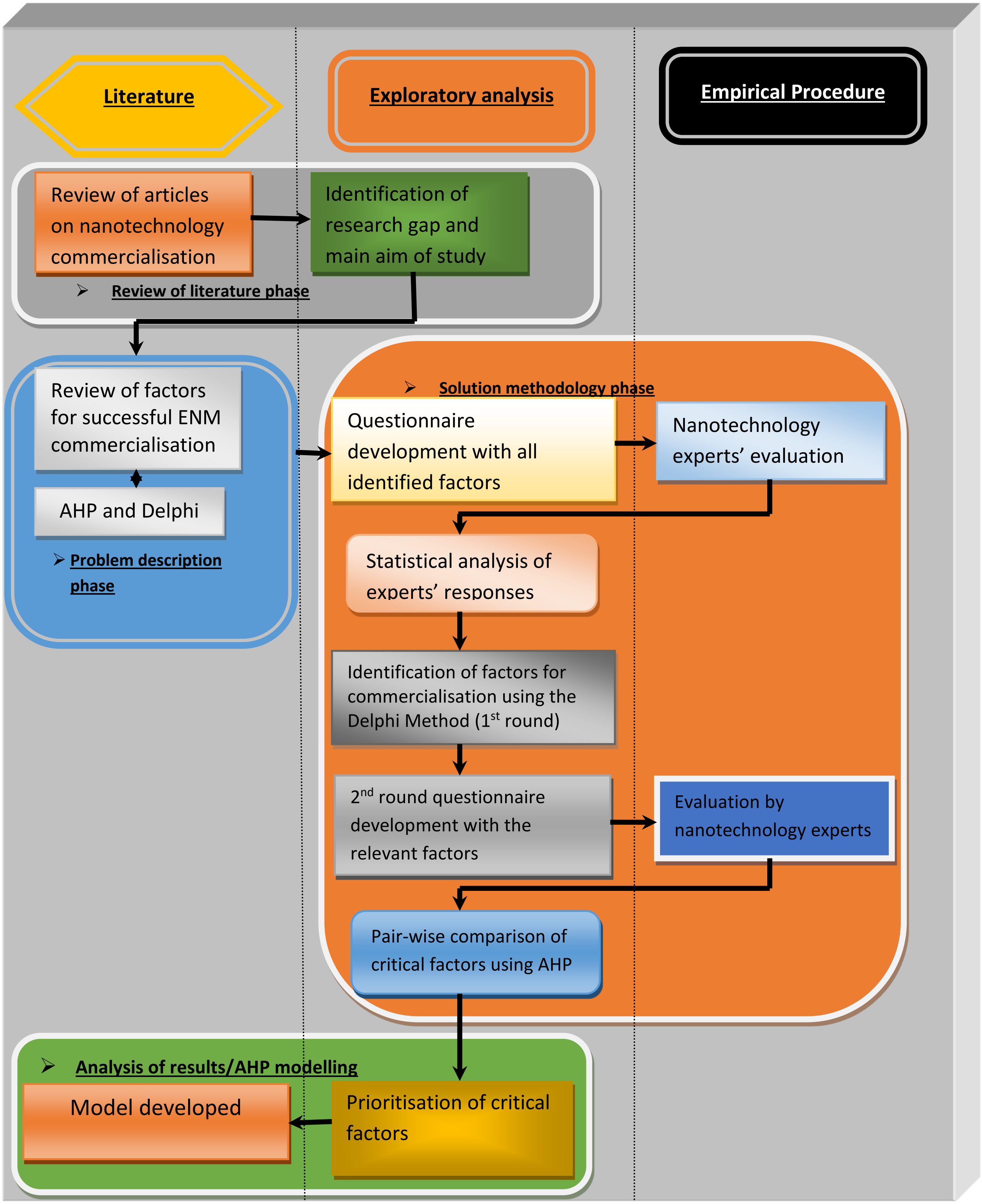


Figure 3.1: Research design of the proposed Delphi-AHP modelling for the study

Source: Adapted from Bouzon, Govindan, Rodriguez and Campos (2016)

Mazumder, Sarkar and Puri (2014) suggest that the success of the commercialisation of emerging technologies depends on the attributes of the products, the needs of the consumers and not only the R&D breakthroughs. Meanwhile, the commercialisation of these nanoproducts is a multi-factor decision-making challenge as this innovation involves the assessment of various factors. Advocates of the Delphi Method (DM) and Analytic Hierarchy Process (AHP) (Lan and Sheng 2014; Sharma, *et al.* 2020) have at different instances proposed a combination of the duo for various hybrid technology processes. In supporting Saaty (2016), Sharma, *et al.* (2020) reported that AHP is a widely used additive weighing method demonstrated in alleviating the difficulty that decision makers often are faced with when confronted with the determination of cardinal importance weights of a large set of attributes concurrently. These methods are therefore proposed for this study to determine relevant commercialisation critical factors through the DM and their relative importance through the AHP.

3.3 Research Methodology

Thomas (2021) views research methodology as the general process or framework that is adopted for conducting research, commencing from the planning stage to the reporting of the findings. Pillai and Kaushal (2020) opine that, with the goal of giving work structure, research methodology is the science of conducting a research and a methodical approach to tackle a problem.

According to Saunder, Lewis and Thornhill (2015), research methods are broadly classified under qualitative and quantitative research paradigms. Meanwhile, Nayak and Singh (2021) argue that the combination of the two research paradigms is considered a viable option by several researchers. This is referred to as the mixed-method research approach. These research approaches are enumerated in the subsequent sub-sections.

3.3.1 Research Philosophies, Worldviews or Philosophical Paradigms

Citing different authors (Guba 1990; Crotty 1998; Lincoln and Guba 2000; Neumann 2000) and Creswell (2013) confirmed worldviews to mean any of extensively defined research methodologies, paradigms, epistemologies and ontologies or, in a single phrase, a fundamental set of beliefs guiding an action. Theoretically, there are four philosophical worldviews, which can be fundamentally categorised under the three research methods available. As illustrated in Figure 3.2a and Figure 3.2b respectively, the three research approaches are qualitative, quantitative and mixed methods, while the four philosophical paradigms are positivism (or post-positivism), constructivism (or interpretivism), advocacy (or participatory) and pragmatism. The research paradigm adopted for this study is a combination of the quantitative and qualitative types of approaches.

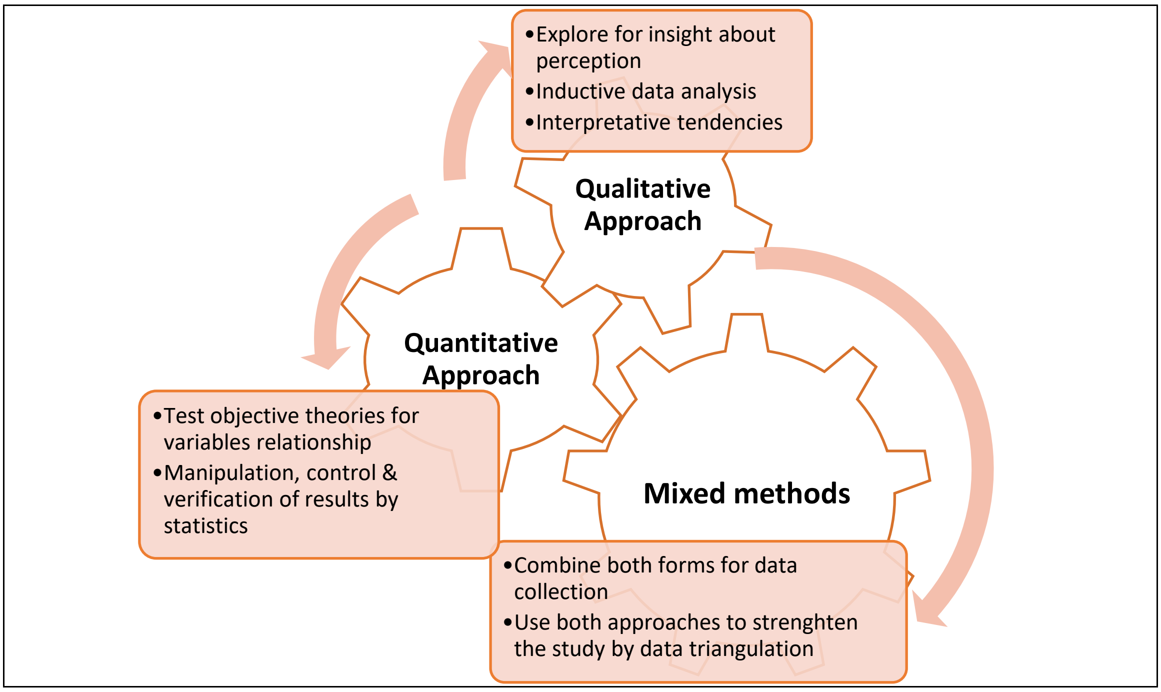


Figure 3.2a: The Research Designs Typologies

Source: Adapted from Lan and Sheng (2014)

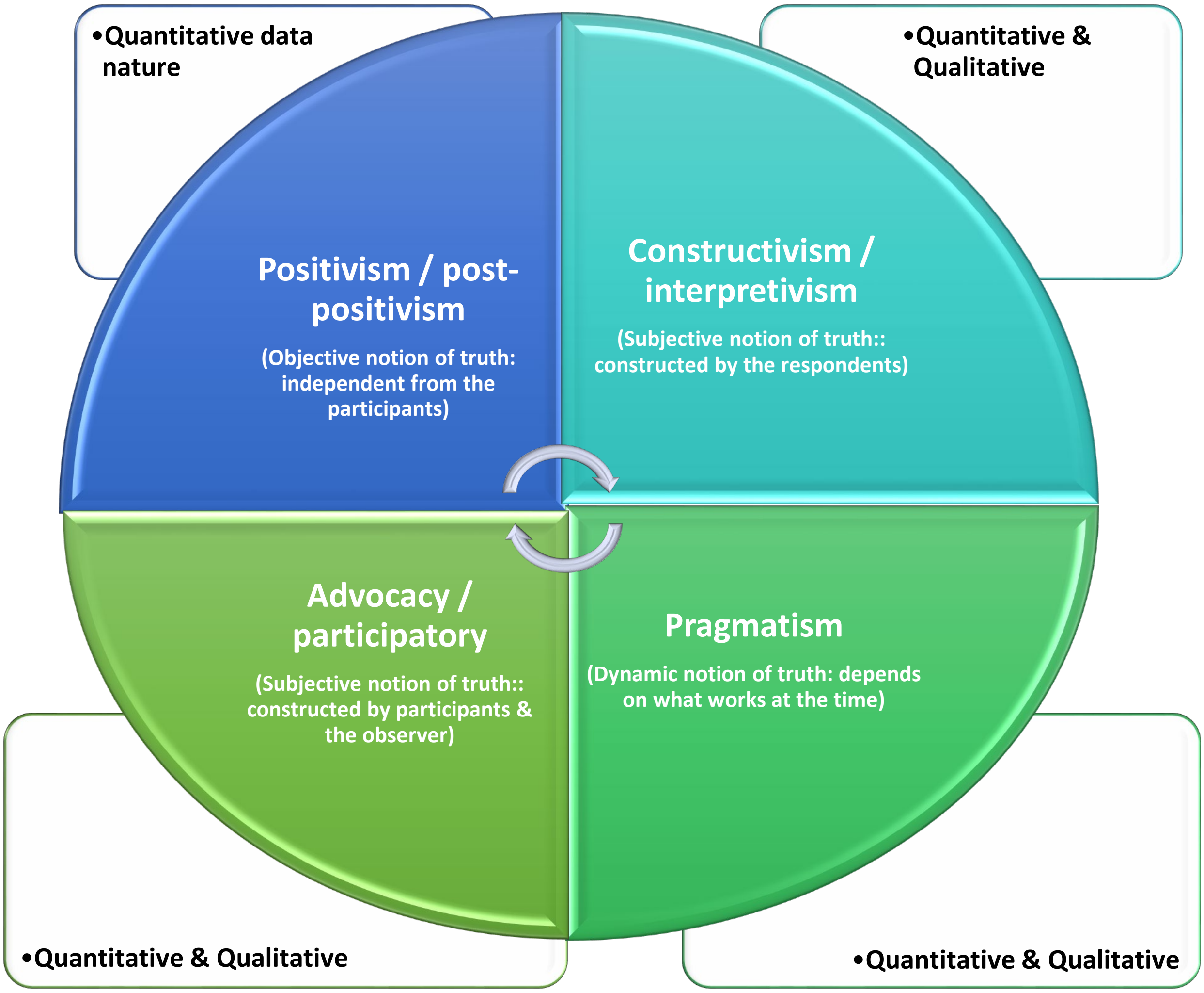


Figure 3.2b: The notion of truth and nature of data of the identified four worldviews
Source: Adapted from Peterson and Gencel (2013)

Essentially, these four worldviews have five different viewpoints which influence this study and the procedure through which it is conducted, as well as all enquiries reported. Creswell and Clark (2007) enumerated the five viewpoints as being categorised as ontology (nature of reality); epistemology (how knowledge of what one knows is gained); axiology (role of values in research); methodology (the research process) and rhetoric (the language of research).

An extensive synopsis of the mixed method design as adopted in this study is illustrated in Section 3.3. Notably, a fundamental precept of a mixed methods strategy of inquiry is selected for this study to understand the realities of the world of nanotechnology commercialisation more fully. Furthermore, for nanotechnology business modelling, especially to evaluate potential suppliers' and consumers' interest, it is sensible to adopt a methodology that will involve quantitative, qualitative and semi-qualitative factors in the process (Lan and Sheng 2014) The Analytic Hierarchy Process meets both of these requirements as earlier pointed out in the review of literature. The choice of these Operations Research models is presented in the course of this study.

3.3.1.1 Qualitative research method

Creswell and Creswell (2017) reveal that the qualitative research method is designed to study social and cultural situations of interest in the social and management sciences. Taherdoost and Brard (2019), in a process analysis of criteria factors selection, submit that the qualitative research method is naturally exploratory as it can be adopted in developing a clear perspective of a scenario. Furthermore, the authors argue that due to the involvement of the researcher in the process, a high level of subjectivity is involved in the qualitative method.

This study adopted a review of literature in an extensive and explicit format during the course of the research. The literature review and the gathering of experts' opinions through the Delphi panel process have been discussed to be the most popular tools used in identifying critical factors for the effective commercialisation of nanotechnology products (Kumar, Luthra, Haleem, Mangla and Garg 2015). The literature review process was carried out basically to gather relevant and recent research materials (like research papers, conference proceedings, and text-books) through various databases like the Durban University of Technology (DUT) Summons, Google Scholar, Google books, Google search, Science Direct and the DUT online library. Through these sources, recent research papers, conference proceedings, research articles and text-books relevant to critical success factors for the commercialisation of nanotechnology materials were retrieved. Results of these findings are available in Sections 2.5 and 2.6.

Through the Delphi panel process, opinions were also sought from nanotechnology experts on possible factors responsible for the successful commercialisation of nano-materials. According to Avella (2016), the Delphi panel process is predominantly a qualitative research approach. In line with the views of Hennink, Hutter and Bailey (2020), this approach will make it possible to understand issues from the perspectives of the respondents of this study and to understand the meaning and interpretation of the criteria for nanotechnology commercialisation.

3.3.1.2 Quantitative research method

Creswell (2017) opines that in testing the theory of a relevant research problem, the quantitative research method is recommended as it features numerical values. Analytically, this study is developed to adopt statistical and Operational Research models for optimal decision-making of the commercialisation of selected ENMs. Applicable models include the Delphi Method (DM) and Analytical Hierarchy Process (AHP). The study adopts DM to integrate experts' opinions towards the multi-factors of ENMs. The experts' opinions for technology selection factors are collected through the use of questionnaires. The methodology of the AHP can be explained in the following steps (Mao *et al*. 2020):

- The problem is decomposed into a hierarchy of goal, factors, sub-factors and alternatives as depicted in Figure 3.3.
- Data are collected from experts. Experts can rate the comparisons.
- The pairwise comparisons of various factors are organised into a square matrix.
- The consistency of the matrix of order *n* is evaluated.
- The rating of each alternative is multiplied by the weights.

All comparisons and ratings, based on the AHP structure in Figure 3.3, were made using the Expert Choice 11.5 (Expert Choice, 2008) software. The descriptive and other analyses (means, frequency, percentage and standard deviations) of the responses were carried out using the Statistical Package for the Social Sciences (SPSS) 20.0 software. The AHP provides a means of decomposing the problem into a hierarchy of sub-problems as structurally modelled in Figure 3.3.

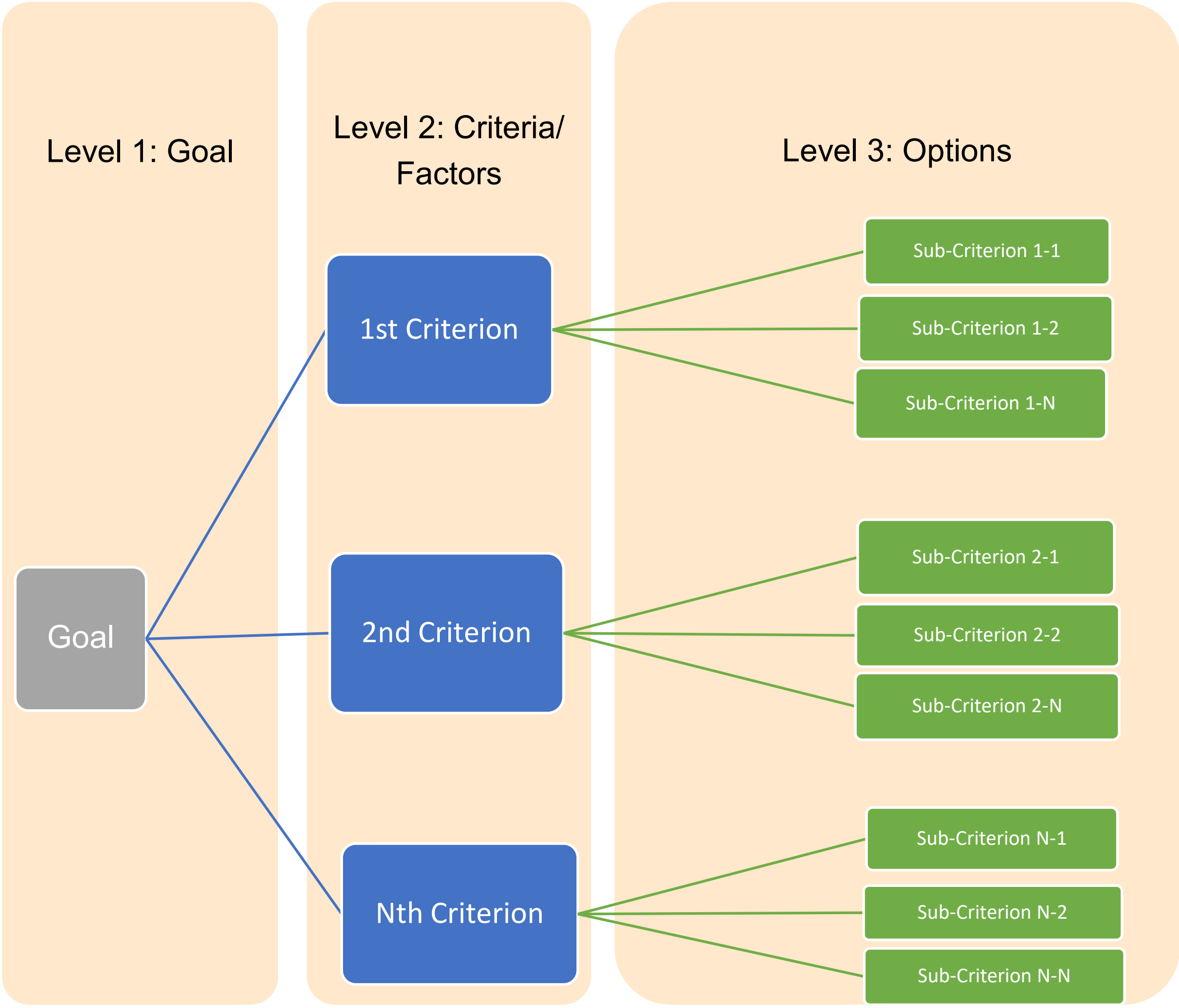


Figure 3.3: Structure of an AHP Model

Source: Mao, Zhou, Zhang, Du, Peng and Zhu (2020)

Decision-making nowadays assumes scientifically supported processes, which in most cases includes several decision-makers and interest groups (Yazdani, Zarate, Coulibaly and Zavadskas 2017). To successfully deal with the different attitudes and opinions of different people, a variety of methods are in use. Not many of them can involve quantitative, qualitative and semi-qualitative factors as AHP (Antoniou, Lappas, Leoussis and Nomikou 2017; Jhariya, Kumar and Pandey 2020), which requires a well-structured problem, represented as a hierarchy.

3.3.1.3 Mixed research method

There has been emphasis by methodologists on the combination of qualitative and quantitative methods as the focal point of mixed methods (Guetleman, Fetters and

Creswell 2015). Creswell (2017) views a study based on the mixed-method paradigm as a combination method study in which multiple (qualitative and quantitative) data collection and analysis strategies are adopted in a single study.

Although the qualitative research and quantitative research are respectively based on narration and statistics, Ling-Pan (2016) confirms that a mixed-method research assists in the following ways:

- Introduction and definition of key terms;
- Formulation of the significance of the research;
- Description of the conduct of the literature search; and
- Identification of the literature gaps.

Abro, Khurshid and Aamir (2015) used the mixed-method approach to ascertain the challenges of nanotechnology commercialisation. They found that a mixed-method study provided a reliable, valid and significant understanding of the challenges and processes of nanotechnology commercialisation. In a similar manner to the review above, this study combined both the quantitative and qualitative research strategies. The qualitative method was used to identify the critical commercialisation factors, while the quantitative approach was adopted in the analysis and development of a framework for the successful commercialisation of ENMs.

3.4 Research Process

The research process presents the integration of the various sections of this study into a methodological framework to explain the various research elements as developed in this research. As depicted in Figure 3.4, three phases were adopted during this research, which includes:

- the literature review phase;
- survey development phase; and
- the AHP model development phase.

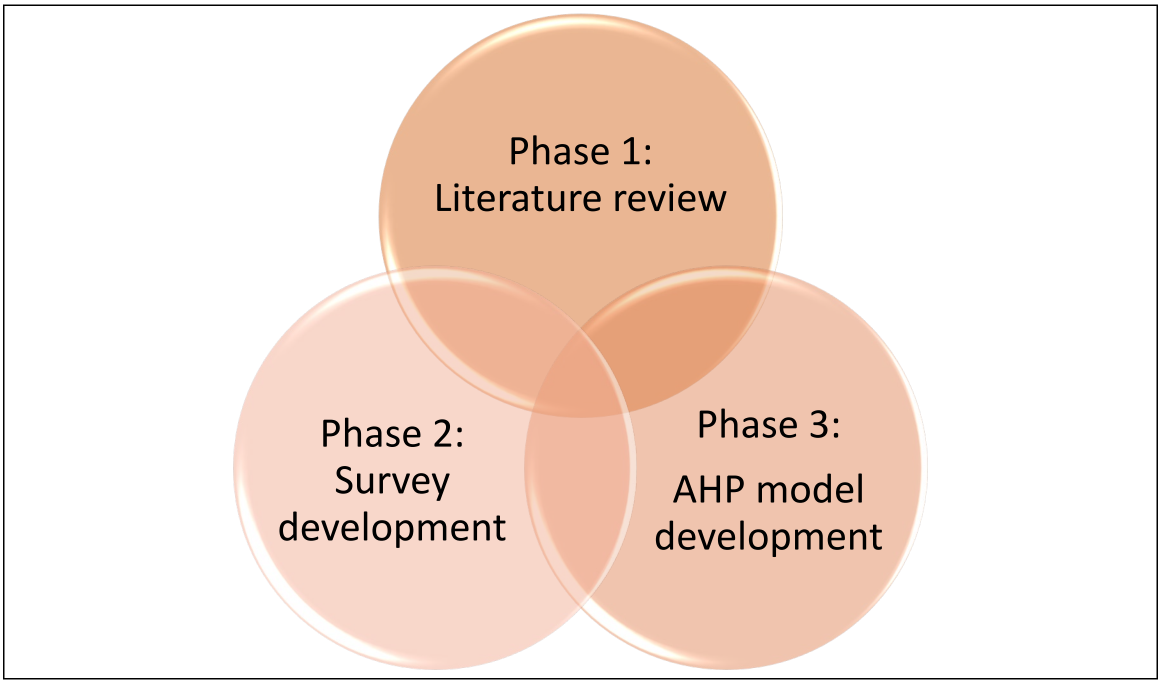


Figure 3.4: The study's research process

Source: Generated by the researcher

3.4.1 Phase 1: The Literature Review

The literature review was conducted to obtain a grasp of the extant knowledge. It was also conducted to identify the conceptual, theoretical and empirical contributions of various authors on this subject of nanotechnology commercialisation.

As stated earlier in Section 1.2, the commercialisation of any technology is a complex though interesting process (Manoukian, Hassab-Elnaby and Odabashian 2015). This study is motivated to understudy applications of nano-material and their commercialisation through a review of relevant literature, including academic journal articles and books on the various factors which are necessary and sufficient for the successful commercialisation of engineered nanotechnology materials. This review sufficiently provided the research with necessary background information, context and ideas for the study.

3.4.2 Phase 2: The Survey Development

Extensively, this study adopted a survey method which was questionnaire-based and designed to study a population with the purpose of conceptualising a sample from a population (Jespersen *et al.* 2018). A questionnaire was one of the data collection methods of survey research which supplied quantitative information on the drift, beliefs, opinions or attitudinal directions of a population (Creswell 2014). This method was purposely designed for the following reasons:

- To identify the critical factors and sub-factors necessary for the effective commercialisation of engineered nanotechnology materials.
- To develop a framework for modelling the commercialisation of nanotechnology materials in general and carbon nanotubes in particular.

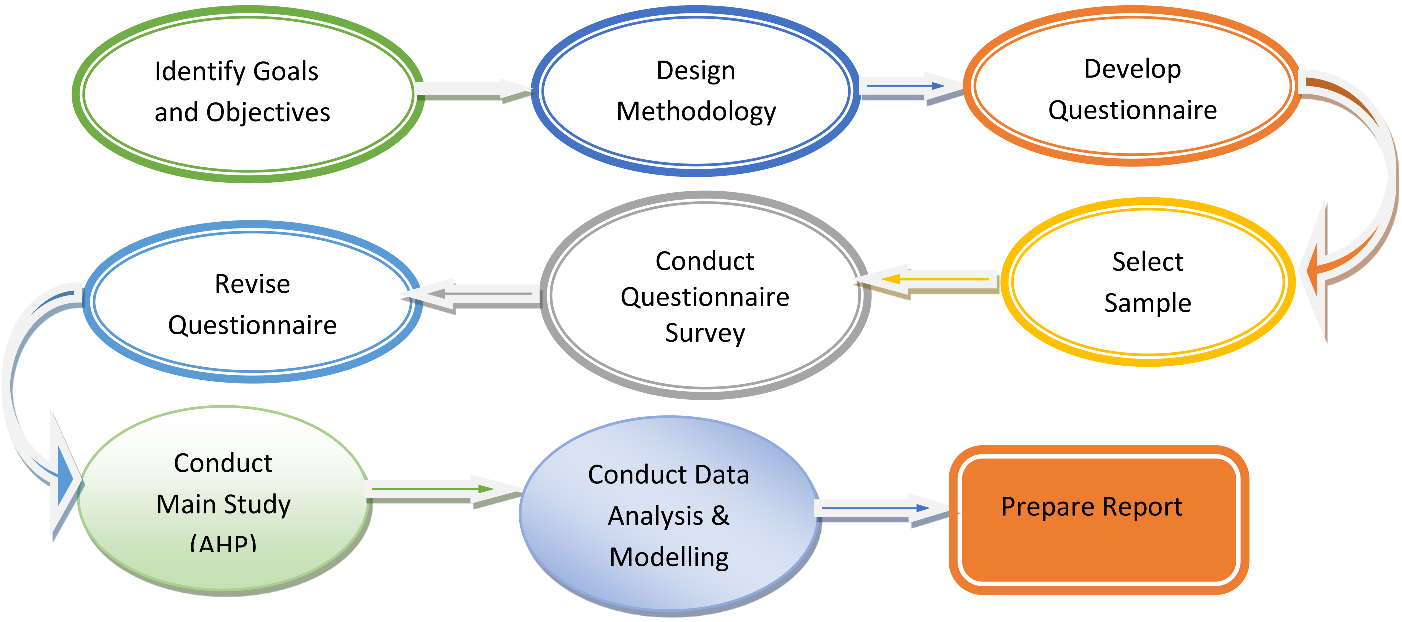


Figure 3.5: The activities conducted during the survey

Source: Generated by the researcher

Noting that the questionnaire survey design is viewed as a multistage process requiring detailed attention, the steps illustrated in Figure 3.5 were followed for research that yields an accurate assessment and measurement of opinions, beliefs and attitudinal directions of the population under study. The first round conducted at the early stages of the research questionnaire development helped to acquire a thorough understanding of the views and contributions of nanotechnology experts and to identify the most relevant and important factors. This survey was also aimed at effecting the feasibility of the questionnaire design.

The questionnaire was structured into four sections after the introduction (see Appendix I). Section I considered the respondent's technical expertise; Section II sought to rate the critical factors for nanotechnology commercialisation, while Section III sought to rate the sub-critical factors for nanotechnology commercialisation; and Section IV considered the personal characteristics of the respondents. A response rate of 60% was constituted which is in line with the finding of Nashir, Mustapha and Yusoff (2015) for the reliability of a sample size of between 5 and 10 members.

3.4.3 Phase 3: AHP Model Development

The main objective of this research was to develop an AHP model for the commercialisation of ENMs. The methodological framework of the study was discussed earlier in Section 3.2. The AHP is to aid in the development of a framework in realising the Objective two.

3.5 Population and Sample size

In the adoption of the Delphi Method, Habibi, Sarafrazi and Izadyar (2014) reported that there are various appropriate ranges of Delphi panel sizes. Engelman, Fuller and Steer (2018) indicated that 10 to 15 experts would form an appropriate Delphi panel to make sense in a concensus, while Nashir, Mustapha and Yusoff (2015) confirmed that a panel size of 5 to 10 experts could similarly produce realistic and reliable results. These justify the choice of respondents forming the study sample comprising members of the Composite Research Group (CRG) which is domiciled at the Department of Mechanical Engineering, DUT. In-service trainees, postdoctoral research fellows and postgraduate students from various areas of specialisation (Engineering, Chemistry, Material Science and Management) are members of the CRG.

Meanwhile, the technique of combining AHP and Delphi has been extensively adopted in several studies of policy determinations and technology transfer. In their study, Muhammad, Shaikh, Naveed and Qureshi (2020) adopted the Delphi method with the aid of a web-based survey technique, in the determination of critical factors as perceived by the limited experts in the field. The researchers conducted another round with the AHP integrated so as to prevent biased responses and prioritise the factors. To this effect, the study population for the current survey comprised the active researchers who are experts in nanotechnology from the Composite Research Group. At this stage, 10 members of the CRG formed the sample. According to Habibi, Sarafrazi and Izadyar (2014), there exist no accurate mechanism in determining the composition and sample size of the Delphi technique. The goal of administering the questionnaire survey to experts was to gain an understanding of the variables that must be taken into account within the study model. Furthermore, this Delphi study with the administration of the questionnaire survey aided the extensive evaluation and validation of the critical factors and sorted sub-factors. It has been observed that the Delphi study is essential for the validity of data (Staykova 2012) and it facilitates an understanding of the questionnaire, making it a helpful process for novice researchers (Belton, MacDonald, Wright and Hamlin 2019). In addition, the pilot sample is excluded from the main study (Staykova 2012).

3.6 Sampling Technique

The study adopted the purposive sampling technique. Also called judgment sampling, the purposive sampling technique is the deliberate choice of respondents due to the qualities that the respondents possess and it is a non-random technique that does not need underlying theories or a set number of respondents (Pandey and Pandey 2015). The researcher decides what needs to be known and sets out to find people who can and are willing to provide the information by virtue of knowledge or experience (Pandey and Pandey 2015). The judgment sampling technique is, especially, exemplified through the key respondent technique (Pandey and Pandey 2015; Kumar, Singh and Haleem 2015), wherein one or a few individuals are solicited to act as guides to a culture. Key respondents are observant and reflective members of the community of interest who know much about the culture and are both able and willing to share their knowledge (Pandey and Pandey 2015).

3.7 Validity and Reliability

Amongst other methods, the Cronbach's alpha is recommended for items consistency or the items' homogeneity in the scale which measures the same construct. The most frequently used method for testing reliability is Cronbach's alpha (Bolarinwa, 2015; Hazzi and Maldaon 2015). Schrepp (2020) presents a comprehensive categorised detail of the various alpha (α)-values as enumerated in Table 3.1.

Meanwhile, Hazzi and Maldaon (2015) further recommended Correlation Analysis between respective questionnaire items if SPSS software is used in conducting the reliability analysis. A revision or removal of weak items (that is items with a correlation of less than 3.0) is recommended (De Vaus, 2002: 401 as cited in Hazzi and Maldaon 2015). However, Hazzi and Maldaon (2015) suggest a cautious revision.

Table 3.1: Categories of Cronbach's α coefficients

Source: Hazzi and Maldaon (2015); Schrepp (2020)

Cronbach's α	Internal consistency
α ≥ .9	Excellent
α ≥ .8	Good
α ≥ .7	Acceptable
α ≥ .6	Questionable
α ≥ .5	Poor
α ≤ .5	Unacceptable

This study conducted a reliability test of the survey, and it was discovered that the questionnaire items were internally consistent as the Cronbach's α value fell within the excellent range as depicted in the Statistical Package for the Social Science (SPSS), version 20 software results presented in Section 3.9.

3.8 Preliminary (Pilot) Study – The Delphi first round

Research on nanotechnology commercialisation, being an innovation, requires a preliminary study as the prospects and imminence of the main study are fundamentally determined during this stage of the study (Geipele *et al.* 2014). More importantly, according to Hazzi and Maldaon (2015), preliminary studies are conducted purposely to:

- Enhance the efficiency of the main study;
- Improve the quality of the main study;

- Inform the researcher about the strengths and weaknesses of the scales used as well as the initial outcomes; and
- Examines the feasibility of the anticipated research method to be used in the course of carrying out the main study.

Centering attention on reporting a preliminary study using the questionnaire, Hazzi and Maldaon (2015) further accentuated that the following steps are necessary in conducting this kind of research:

- Tests for the reliability of the study using Cronbach's alpha;
- Cronbach's alpha reliability test similarly carried out on the main study;
- The results of the two tests should be compared; and
- Items in the questionnaire having common problems of reliability should be deleted.

Before the study commenced, an initial survey was conducted as a questionnaire which was administered to researchers in nanotechnology. The questionnaire (Appendices 1 and 2) was uploaded on a commercial online survey site (www.surveymonkey.com) and emails stating the website link were sent to the CRG members for completion and assessment for further usage in the main study. Thereafter, the experimental work validation was done using the validity of factors and sub-factors. Based on the input from the preliminary study, the AHP questionnaire was revised. The revised questionnaires (Appendices 3 and 4) were resent to the researchers for the second round of inputs for the AHP prioritisation modelling.

3.9 Results of Delphi (first round) study

The main study proceeded as the results for the reliability coefficients of the pilot study exceeded the Cronbach's alpha recommended value of 0.7 of acceptance. Table 3.2 displays the results of the Cronbach's alpha score.

Table 3.2: Reliability Statistics of the Delphi (first round) survey

Source: Study's survey

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardised Items	N of Items
0.926	0.938	33

3.10 Ethical Adherence

In the course of this study, the Researcher made every effort to strictly adhere to the acceptable ethical standards of the University. The Researcher considered the following:

- Prior to the questionnaire administration, consent was obtained from the respondents.
- The Researcher ensured that all data obtained from the Respondents was kept confidential.

3.11 Summary of the Chapter

Overall, this chapter considered the methods and approaches adopted in this research. It is an exposé of how the modelling and statistical analyses were carried out. In an attempt to determine the critical impacting factors for the successful commercialisation of nanotechnology engineered materials, questionnaires were developed in order to seek the opinions of selected experts in nanotechnology through a survey to determine the necessity of these factors. Specifically, this chapter has been able to address the second objective highlighted in Chapter One through the introduction of the applications of modelling-based approaches, which is the Delphi technique and the Analytical Hierarchy Process (AHP) for the commercialisation of engineered nano-materials. Conclusively, this chapter outlined the various measures that were adopted towards quality improvement and enhancement of this research.

Meanwhile, Chapter Four (Data Analysis and Modelling) structurally presents the detailed analysis of the AHP model of the ENM and implementation of the model on ENM through descriptive, statistical and quantitative analyses of the responses to the research questionnaires on the factors responsible for the optimal commercialisation of ENMs.

CHAPTER FOUR

DATA ANALYSIS AND MODELLING

4.1 Overview of the chapter

This chapter explores the implementation of the modelling-based approaches. Two rounds of Delphi surveys were conducted at different intervals, with the first administered to obtain some background information from the experts to determine the level of importance of the factors. The respondents, based on their experience in the area of expertise, were requested to rate the importance of the factors for nanotechnology commercialisation for the purpose of developing quantitative models essential for facilitating new technological commercialisation decision-making. These factors were derived from various research articles in literature and the outcomes discussed in Sections 2.5 and 2.6.

The second survey was conducted to carry out pair-wise comparisons of the identified important factors and sub-factors obtained from the first survey. This chapter and the subsequent chapter discussed the results of the surveys. Specifically, this chapter addresses the third research objective outlined in Chapter One, which is to determine the relative importance of the identified factors by investigating via a survey, the knowledge and hence the contributions of academics concerning the impact of nanotechnology and its commercialisation. This is achieved by adopting the concept of the Delphi Method to integrate the diverse experts' opinions towards the importance of the multi-factors of nanotechnology materials.

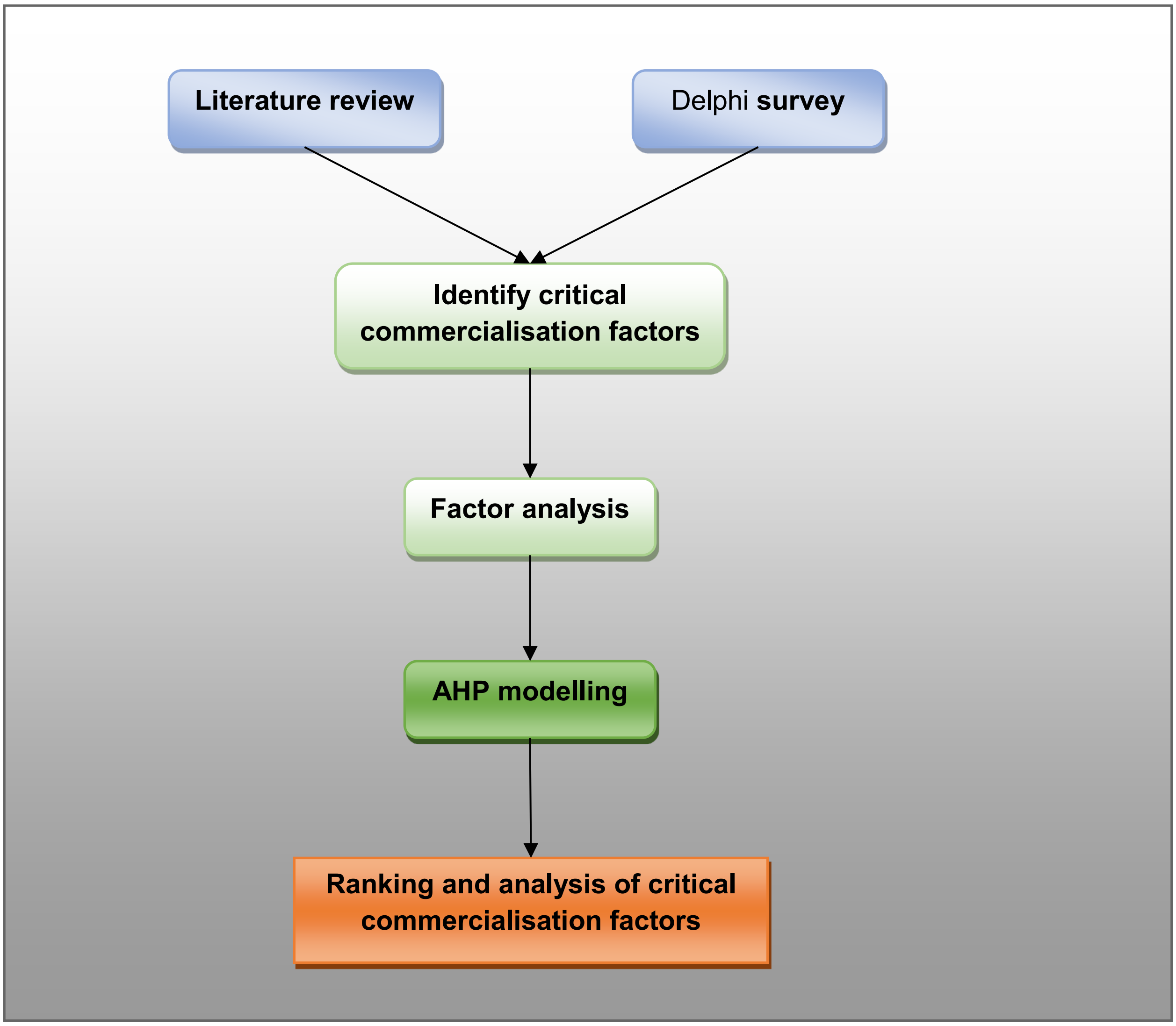


Figure 4.1: The research process

Source: Generated by the researcher

The research process is depicted in Figure 4.1. A review of relevant literature was extensively carried out in Chapter Two of this thesis, while the research processes of the survey were discussed in the third chapter. Section 4.2 of this chapter analysed the commercialisation factors which were identified from the literature and analysed the factors in Section 4.3. This was immediately followed by the AHP modelling of these factors.

4.2 Analysis of survey results

The first survey was designed to conduct relative importance rating of the factors essential for the successful commercialisation of nanotechnology products and concomitantly, complement the current research status of nanotechnology commercialisation. After these critical factors were identified, the outcomes were integrated for the purpose of developing quantitative models essential for facilitating new technological commercialisation decision-making.

4.2.1 Certification, Experience Level and Demographic Information of the Respondents

A response rate of 60% was constituted from the 10 respondents who were requested to complete the online questionnaire made available on http://www.surveymonkey.com/. Observably, this response rate is still in line with the finding of Nashir, Mustapha and Yusoff (2015) for the reliability of a sample size of between 5 and 10 members. The demographic characteristics considered were sex and age. The area of expertise, years of experience and the respondents' highest qualification were also requested to ensure that the respondents were versatile or current with engineered nano-materials and their commercialisation. While one respondent did not respond to the demographic section of the survey, it was observed that 66.67% of the respondents were female and 16.67% were male.

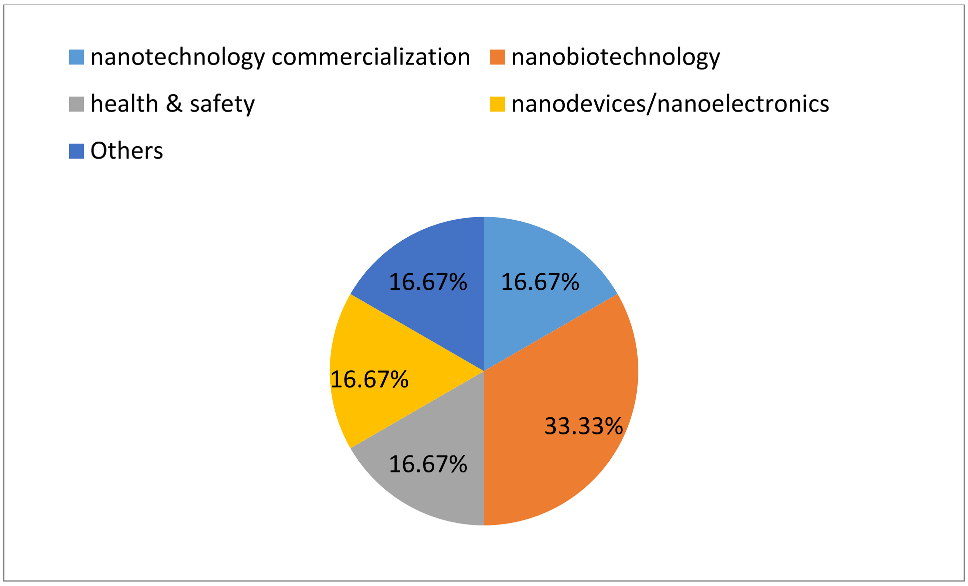


Figure 4.2 Categories of respondents by expertise in nanotechnology

Source: Generated from the study's survey

With a minimum of 1 year and a maximum of 10 years indicating a range of 9 years, the average level of experience of the respondents is 4.17 years. It was also confirmed through the survey that 16.67% of the respondents are experts in nanotechnology commercialisation; 33.33% in nanobiotechnology; 16.67% in health and safety; and 16.67% also deals with nanodevices/nanoelectronics as presented in Figure 4.2, although all the respondents are either not aware (50%) or not sure (50%) that they were conversant with modelling techniques in the commercialisation of ENMs. This confirms attributions to some authors (Davoodi, Farsi and Naseri 2012) that awareness or knowledge of some developmental areas of nanotechnology is still poor. The findings of Masara, Poll and Maaza (2021) can also be deduced that despite several works of literature on nanotechnology, the issue of its commercialisation is still grossly unaddressed.

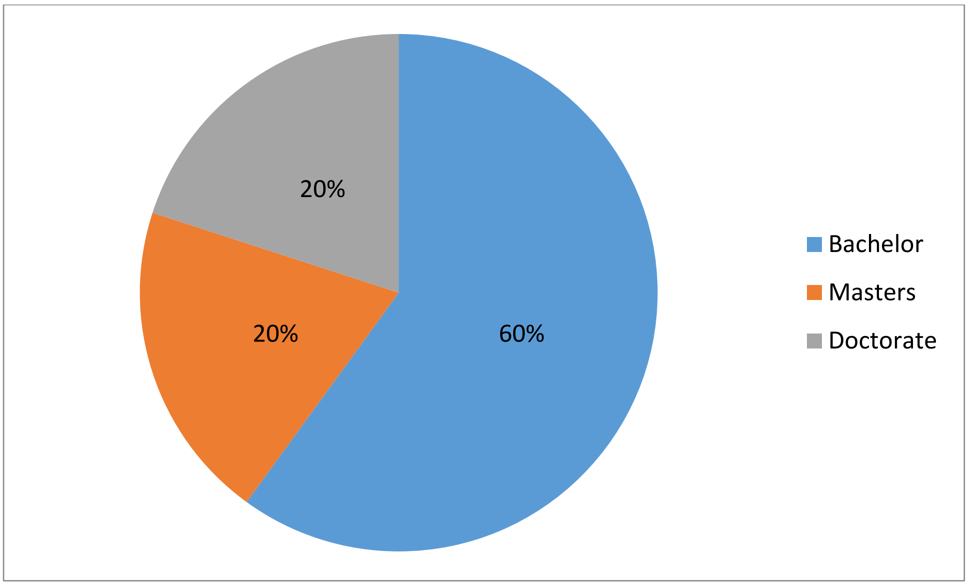


Figure 4.3: Certification categories of respondents

Source: Generated from the study's survey

The highest certification/qualification level of each of the respondents was determined through the questionnaire survey. As summarised in Figure 4.3, twenty percent (20%) of the respondents' highest qualification is a doctorate, with an equivalent percentage having a Master's degree. The remaining 60% of the respondents possessed a Bachelor's degree with a high level of research experience in nanotechnology. This indicates that the respondents are well experienced to supply necessary the information as requested in the survey.

4.2.2 Respondents' perspective of the importance of the factors for nanotechnology commercialisation

Based on the experience of the nanotechnology experts in their respective areas of study, a request was made towards the rating of the importance of the factors for nanotechnology commercialisation listed for the purpose of developing quantitative models essential for facilitating new technological commercialisation decision-making. These factors were derived from various research articles in literature and proposed in the questionnaire. Table 4.1 summarises the responses and the ratings of these factors.

Table 4.1: Respondents' rating of the importance of the factors for nanotechnology commercialisation

Factors	Min	Max	Mean	Std. Deviation	Rate
Technical & Technological feature of the nano product	2	5	3.50	2.121	3
Economic factors	1	2	1.50	0.707	8
Production factors	3	5	4.00	1.414	2
Informative factors	2	4	3.00	1.000	5
Cultural factors	1	3	2.00	1.414	7
Social benefits					9
Regulatory policies	1	5	3.33	2.082	4
Marketing potentiality & forces	2	4	3.00	1.000	5
Organisation's strategic issues & features					9
Health & Safety	3	5	4.33	0.816	1

The results displayed in Table 4.1 indicate that 'Health and Safety' got the highest rating with a mean of 4.33 of the possible 5.00. This factor is immediately followed by the production factors (mean = 4.00). The third, fourth and fifth rated factors are respectively 'Technical and technological feature of the nanotechnology product' (mean = 3.50); 'Regulatory policies' (mean = 3.33); 'Informative factors (mean = 3.00) and 'Marketing potentiality and forces' (mean = 3.00). It can further be deduced from the table that other factors got a low importance rating according to the experts surveyed. While 'Social benefits' and the 'Organisation's strategic issues and features' got a no significance rating, 'Economic factors' (mean = 1.50) and 'Cultural factors' (mean = 2.00) were below an average recommendation. Most notably, the finding of the survey in this section of the study indicates a contradiction to the significance rating attributed to ‘Economic factors’ and ‘Cultural factors’ conducted by te-Kulve and Rip (2013), and Falinski *et al.* (2018), who concluded that ‘Economic factors’ and ‘Informative factors’ are highly significant amongst the factors influencing the commercialisation of nanotechnology. The authors further emphasized the importance of ‘Cultural factors’. This contradiction may be attributed to the fact that the respondents were more scientists and not business managers.

4.2.3 Respondents’ perspective of the importance of the sub-factors for nanotechnology commercialisation

This section is aimed at analysing the diverse experts’ opinions towards the multi-factors of ENMs. The experts’ opinions for technology selection factors were collected by questionnaires and rated significantly. The Delphi Method was used to achieve a consensus amongst the experts on the subject being evaluated. The method serves to draw on a large body of opinion and also meets the requirement for independence in the experts’ judgment. This study therefore, applies the Delphi Method to the selection process of system variables to increase the confidence of the AHP model.

The nanotechnology experts were further requested to rate the sub-factors according to their individual level of importance or significance. The responses were analysed and various observations are listed and discussed in subsequent tables.

Table 4.2: Analysis of 'Technical and Technological features of the nano product'

Sub-factors of Technical & Technological features	Min	Max	Mean	Std. Deviation	Rate
Intersection of nanotechnology with biotechnology	3	5	3.80	0.837	6
Convergence of nanotechnology with information & communication technology (ICT)	3	5	4.20	0.837	3
Scientific changes through high level of technological support & technology management effectiveness	3	5	4.00	0.707	4
Technical abilities of suppliers	3	5	4.00	0.707	4
Local suitability of nanotechnology based on the country's environmental & socio-economic state	4	5	4.60	0.548	1
Technological functionality, trial-ability & reliability	3	5	4.40	0.894	2

Considering the 'Technical and Technological features' of nanotechnology products for commercialisation purpose, at the top of the ratings is 'Local suitability of nanotechnology based on the country's environmental & socio-economic state' (mean = 4.60) and the 'Technological functionality, trial-ability & reliability' (mean = 4.40) as depicted in Table 4.2. 'Scientific changes through high level of technological support and technology management effectiveness' and 'Technical abilities of suppliers' had a similar rating of significance (mean = 4.00). 'Intersection of nanotechnology with biotechnology' received the 'least importance' rating (mean = 3.80). Meanwhile, Roco and Bainbridge (2013) recommended that the futuristic commercialisation and other features of nanotechnology materials will be much impacted, provided there is an intersection through convergence with other existing technological fields like biotechnology, neurotechnology and information and communication technology.

Table 4.3: Analysis of 'Economic factors'

Economic sub-factors	Min.	Max.	Mean	Std. Deviation	Rate
Cost-effectiveness	2	5	4.20	1.304	1
Profit margins	3	5	3.80	1.095	2
Increase in sales turnover	3	5	3.80	1.095	2

Table 4.3 presents the descriptive analysis of the respondents' views on the importance of the sub-factors related to the 'Economic factors' considerable for the commercialisation of ENMs. 'Cost-effectiveness', with a mean of 4.20, had the highest importance rating. 'Profit margins' and 'Increase in sales turnover' are equally close and have high importance rating conforming to the argument of Islam (2014). A weak economic scenario will result in a challenging development in nanotechnology commercialisation, as the findings echo with Tsuzuki (2013) and Aithal and Aithal (2016) that economic factors are important in nanotechnology commercialisation.

Table 4.4: Analysis of 'Production factors'

Production sub-factors	Min	Max	Mean	Std. Deviation	Rate
Production cost issues	3	5	4.40	0.894	1
Labour intensity	3	5	4.20	1.095	2

Issues related to 'Production cost' and 'Labour intensity' are two factors considered for production. Table 4.4 indicates that the 'Production cost' is the more important of the two factors, with a mean of 4.40.

Table 4.5: Analysis of 'Informative factors'

Informative sub-factors	Min	Max	Mean	Std. Deviation	Rate
Publicity through press & media	3	5	4.20	0.837	2
Private-Public Partnership	4	5	4.60	0.548	1

Communication in commercialisation is displayed in Table 4.5 with an average significance of 4.20. More importantly, the respondents recommended private-public partnerships in the implementation of the informative factors for the commercialisation of nano-materials.

Table 4.6: Analysis of 'Cultural factors'

Cultural sub-factors	Min	Max	Mean	Std. Deviation	Rate
Researchers-Investors constructive collaboration	3	5	4.40	0.894	2
Awareness &emphasis of national ministry of technology towards nanotechnology commercialisation	4	5	4.60	0.548	1
Acculturation with respect to commercialisation of nanotechnology	3	5	4.20	0.837	3

Table 4.6 descriptively presents the critical analysis of cultural factors based on the opinions of the experts. 'Awareness and emphasis of national ministry of technology towards nanotechnology commercialisation' is the most rated factor with a mean of 4.60, immediately followed by 'Researchers-investors constructive collaboration' (mean=4.40) and 'Acculturation with respect to commercialisation of nanotechnology' (mean=4.20)

Table 4.7: Analysis of 'Social benefits'

Sub-factors of Social benefits	Min	Max	Mean	Std. Deviation	Rate
Enhancement of social infrastructures / network	3	5	4.20	0.837	1
Employment creation	4	5	4.20	0.447	1
Product branding & brand recognition	4	5	4.20	0.447	1
Cost advantages to customers	3	5	4.20	1.095	1

Table 4.7 shows that there is no difference between the ratings of all the factors. 'Enhancement of social infrastructures/ network' (mean = 4.20); 'Employment creation'; 'Product branding and brand recognition' and 'Cost advantages to customers' are all as rated equally important.

Table 4.8 Analysis of 'Regulatory policies'

Sub-factors of Regulatory policies	Min	Max	Mean	Std. Deviation	Rate
Patent & legal issues	2	5	4.40	1.342	3
Governmental fiscal policies & regulations	4	5	4.80	0.447	1
Grant support & climate control by international community	4	5	4.60	0.548	2

Table 4.8 considers the analysis of 'Regulatory policies' as the need for a special legal framework for the processing and commercialisation of emerging technologies is confirmed with the consideration of 'Governmental fiscal policies and regulations', and is recommended as most important with a mean of 4.80. Although least on log ratings, 'Patent and legal issues' is also highly important, confirming the argument of Handford *et al.* (2015) that these factors innovatively encourage researchers in the creation, processing and commercialisation of new technologies.

Table 4.9: Analysis of 'Marketing potentiality & forces'

Sub-factors of Marketing potentiality & forces	Min	Max	Mean	Std. Deviation	Rate
Price suitability for sales' facilitation	3	5	4.20	0.837	5
Product aesthetic & packaging	3	5	4.40	0.894	2
Product positioning & launch	3	5	4.40	0.894	2
Market potential for end products	3	5	4.40	0.894	2
New market penetration for new & emerging technology	3	5	4.60	0.894	1

Table 4.9 shows the analytical description of the 'Marketing potentiality and forces' for the commercialisation of 'New market penetration that new and emerging technology' has the highest average rating of 4.60. 'Product positioning and launch', 'Market potential for end products' and 'Product aesthetic and packaging' had the subsequent equal average rating of 4.40. 'Price suitability for sales' facilitation' is also an important variable in this factor

rating. Although it could be challenging, it is evident from these ratings, and as argued by Kasthoory (2015), that marketing factors are critically essential in the successful promotion of emerging technologies.

Table 4.10: Analysis of 'Organisation's strategic issues and features'

Sub-factors of Organisation's strategic issues and features	Min	Max	Mean	Std. Deviation	Rate
Organisational strategic implications	4	5	4.60	0.548	2
Organisation's business policies	3	5	4.40	0.894	3
Training & development support for technical & marketing staff	4	5	4.40	0.548	3
Personnel resources with generic & specialized nano commercialisation knowledge	4	5	4.80	0.447	1

Table 4.10 discusses the analysis of 'Organisation's strategic issues and features'. According to the distribution, 'Personnel resources with generic and specialised nanotechnology commercialisation knowledge', with a mean of 4.80, are the essential factors. The 'Organisation's business policies and training and development support for technical and marketing staff' had the least rating of 4.40 each for the successful commercialisation of nano-materials.

Table 4.11: Analysis of 'Health and Safety'

Sub-factors of Health and Safety	Min	Max	Mean	Std. Deviation	Rate
Public opinion about toxic issue	4	5	4.80	0.447	2
Safety issue	5	5	5.00	0.000	1

As exhibited in Table 4.11 and similar to other studies (Vance, Kuiken, Vejerano, McGinnis, Hochella, Rejeski and Hull 2015; Johnston, Gonzalez-Rojano, Wilkinson and Xing 2021), Table 4.11 revealed that the experts surveyed are concerned more with health and safety issues in the commercialisation consideration of any ENMs. With a mean of 5.00, 'Safety issues' had a maximum rating and 'Public opinion about toxicity issues' had an average of 4.80. This is in agreement with the recommendation of Capon, Gillespie, Rolfe and Smith (2015).

<u>Toxic/Less Persistent</u> • Iron oxide nanoparticles	<u>Toxic/Persistent</u> • Ag nanotubes • Ni • Co • Zn oxides • Cdse
<u>Less Toxic/Less Persistent</u> • Al nanoparticles • Oxidized fullerenes • Oxidized nanotubes	<u>Less Toxic/Persistent</u> • Fullerenes • Carbon nanotubes

Figure 4.4 Toxicity and persistence classification of engineered nano-materials
Source: Adapted from Olson and Gurian (2012)

Olson and Gurian (2012) advised that before the commercialisation of engineered nano-materials, it is necessary to focus highly on recognizing those ENMs with the potential hazard to the health and safety of consumers. Furthermore, the combination of toxicity and persistence attributes of the engineered nano-materials cause the greatest harm, hence the need to identify the local and global environmental effects of these materials.

Similarly and as observed in the review of dermatological effect of nano-materials by Kaul *et al.* (2018) and Effiong, Uwah, Jumbo and Akpabio (2019), this high rating importance could be attributed to the commercial applications of nano-materials having recently been included in several consumable products, which have given rise to increasing research in nanotoxicology that studies the risks related to applications of ENMs.

4.3 Summary of the chapter

This section has achieved the third objective which was to explore different perceptions of researcher in nanotechnology and present nanotechnology evaluation factors for selected materials to form a general model of technology evaluation through the stakeholders' recommendations. The intent of this research study, as stated earlier, was to carry out an extensive investigation, evaluation and prioritisation of the critical success factors for the commercialisation of ENMs. A literature review and a questionnaire survey through Delphi method were carried out to identify those critical factors essential for the successful commercialisation of nanotechnology products and also to complement the current research status of nanotechnology commercialisation.

Chapter Five (AHP Model Implementation and Discussion) is a follow-up on the data analysis. It discusses the various results and summarises important points based on the results of the previous chapter. The chapter is an analysis of the second survey towards the priority modelling using the Analytical Hierarchy Process.

CHAPTER FIVE

AHP MODEL IMPLEMENTATION AND DISCUSSIONS

5.1 Overview of the chapter

This chapter considers the implementation of the modelling of the simulated scenarios which are based on the ratings obtained through the inputs and opinions of researchers from the CRG who are experts in nanotechnology and nano-materials. Subsequently, pair-wise comparison matrices are constructed, and calculations are made based on the modelling and methodology of the Analytical Hierarchy Process (AHP) described in the previous chapters. Priorities for weights ranking are obtained for calculations with the acceptable consistency ratio (CR<0.10). Cases of inconsistencies were recorded in this study because some of the respondents, more especially those in their Bachelor's programme, indicated that they were not aware of conducting modelling in the commercialisation of nanotechnology and nano-materials. The inconsistencies were eliminated through the application of the Geometric Mean Induced Bias Matrix (GMIBM) available in the Excel AHP template used for the analysis. These induced matrices help in improving the reliability of the data for optimal decision-making.

5.2 Evaluation and prioritisation of critical factors

Based on an extensive review of the literature and the inputs of nanotechnology researchers, the importance ratings of the factors for nanotechnology commercialisation are carried out for the purpose of developing quantitative models essential for facilitating new technological commercialisation decision-making. The factors derived include the following:

- Technical andTechnological features of the nano product (TT)
- Economic factors (EF)
- Production factors (PF)
- Informative factors (IF)
- Cultural factors (CF)
- Social benefits (SB)
- Regulatory policies (RP)

- Marketing potentiality and forces (MF)
- Organisation's strategic issues and features (FS)
- Health and Safety (HS)

5.2.1 Matrix formation for Factors with respect to commercialisation

The ten (10) dimensions of critical factors for the commercialisation of ENMs are analysed for hierarchy. Table 5.1a depicts the pair-wise comparison matrix for the factors identified.

Table 5.1a: Pair-wise comparison matrix (PWCM) of the critical factors

PRIORITISATION OF CRITICAL FACTORS (COMMERCIALISATION)										
	TT	EF	PF	IF	CF	SB	RP	MF	FS	HS
TT	1	1	1	2	1	5	7	5	1	7
EF	1	1	2	2	3	5	7	7	7	7
PF	1	1/2	1	2	3	3	7	7	7	7
IF	1/2	1/2	1/2	1	3	3	7	7	2	7
CF	1	1/3	1/3	1/3	1	3	3	7	2	7
SB	1/5	1/5	1/3	1/3	1/3	1	1	1	1/7	1/2
RP	1/7	1/7	1/7	1/7	1/3	1	1	1	1/7	1/2
MF	1/5	1/7	1/7	1/7	1/7	1	1	1	1/7	1/2
FS	1	1/7	1/7	1/2	1/2	7	7	7	1	1
HS	1/7	1/7	1/7	1/7	1/7	2	2	2	1	1
CR = 0.0870 < 0.1000										

For every cell at the lower-triangular part of the matrix, cell (i,j) is the reciprocal of the cell (j,i). These dimensional weights were provided by the research experts through the survey.

5.2.2 Priority matrix formation for factors

The evaluation of the ten factors results in the priority matrix formation for the factors in Table 5.1b depicts a tabular visualisation of the ranking or prioritisation of the factors. This level of Analytic Hierarchy Process (AHP) modelling is the extraction of the priority matrix for the factors.

Table 5.1b: Priority Matrix for Critical Factors

PRIORITISATION OF CRITICAL FACTORS (COMMERCIALISATION)			
	Weight	Weight (%)	Rank
TT	0.148	14.8%	3rd
EF	0.232	23.2%	1st
PF	0.199	19.9%	2nd
IF	0.134	13.4%	4th
CF	0.101	10.1%	5th
SB	0.029	2.9%	8th
RP	0.021	2.1%	9th
MF	0.020	2.0%	10th
FS	0.083	8.3%	6th
HS	0.033	3.3%	7th
CR = 0.0870 < 0.1000			

Table 5.1b depicts the overall prioritisation scores of the factors for the commercialisation of ENMs, the corresponding priority values of the factors and the ranking order of preference, namely ‘Economic factors’ (EF = 0.232), ‘Production factors’ (PF = 0.199), ‘Technical & Technological features of the nano product’ (TT = 0.148), ‘Informative factors’ (IF = 0.134), ‘Cultural factors’ (CF = 0.101), ‘Organisation’s strategic issues & features’ (FS = 0.083), ‘Health & Safety’ (HS = 0.033), ‘Social benefits’ (SB = 0.029), ‘Regulatory policies’ (RP = 0.021) and ‘Marketing potentiality & forces’ (MF = 0.020).

Based on the analytical results and the priority ordering depicted in Figure 5.2, the most important factor is the ‘Economic factor’ consideration for the commercialisation of ENMs. The least important, according to the experts surveyed, are ‘Social benefits’, ‘Regulatory policies’ and the ‘Marketing potentiality and forces’ of the nano-materials.

5.2.3 Matrix formation for Factors with respect to Quality Control

These ten (10) dimensions of critical factors were further weighed for the quality control of applications of ENMs and analysed for hierarchy. Table 5.2a depicts the pair-wise comparison matrix for the factors identified.

Table 5.2a: Pair-wise comparison matrix (PWCM) of the critical factors

PRIORITISATION OF CRITICAL FACTORS (QUALITY CONTROL)										
	TT	EF	PF	IF	CF	SB	RP	MF	FS	HS
TT	1	5	6	6	5	6	9	9	9	9
EF	1/5	1	2	2	6	6	8	7	7	8
PF	1/6	1/2	1	2	2	2	8	6	6	8
IF	1/6	1/2	1/2	1	2	2	8	6	6	8
CF	1/5	1/6	1/2	1/2	1	2	8	6	8	8
SB	1/6	1/6	1/2	1/2	1/2	1	7	7	8	8
RP	1/9	1/8	1/8	1/8	1/8	1/7	1	1	2	2
MF	1/9	1/7	1/6	1/6	1/6	1/7	1	1	1	2
FS	1/9	1/7	1/6	1/8	1/8	1/8	1/2	1	1	2
HS	1/9	1/8	1/8	1/8	1/8	1/8	1/2	1/2	1/2	1
CR = 0.0960 < 0.1000										

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the research respondents through the survey.

5.2.4 Priority matrix formation for factors

The evaluation of the ten factors results in the priority matrix formation for the factors in Table 5.2b depicts a tabular visualisation of the ranking or prioritization of the factors. This level of Analytic Hierarchy Process (AHP) modelling is the extraction of the priority matrix for the factors.

Table 5.2b: Priority matrix for ranking of critical factors

PRIORITISATION OF CRITICAL FACTORS (QUALITY CONTROL)			
	Weight	Weight (%)	Rank
TT	0.246	24.6%	1st
EF	0.193	19.3%	3rd
PF	0.201	20.1%	2nd
IF	0.163	16.3%	4th
CF	0.058	5.8%	5th
SB	0.052	5.2%	6th
RP	0.032	3.2%	7th
MF	0.023	2.3%	8th
FS	0.019	1.9%	9th
HS	0.015	1.5%	10th
CR = 0.0690 < 0.1000			

Table 5.2b depicts the overall prioritisation scores of the factors when the quality of ENMs applications are considered, the corresponding priority values of the factors and the ranking order of preference. ‘Technical & Technological features of the nano product’ (TT = 0.246), ‘Production factors’ (PF = 0.201), ‘Economic Factors’ (EF = 0.193), ‘Informative factors’ (IF = 0.163), ‘Cultural factors’ (CF = 0.058), ‘Social benefits’ (SB = 0.052), ‘Regulatory policies’ (RP = 0.032), ‘Marketing potentiality & forces’ (MF = 0.023), ‘Organisation’s strategic issues & features’ (FS = 0.019), and ‘Health & Safety’ (HS = 0.015) were the scores respectively.

5.3 Evaluation and prioritisation of sub-factors

The next stage identified for nanotechnology decision-making is the prioritization of the sub-factors in each dimension of the critical factors for the commercialisation of ENMs for effective decision-making.

The AHP framework adopted for the study for the evaluation of nanotechnology commercialisation critical factors, as presented in Figure 3.7, is structured into the following three levels:

Goal:	To prioritise nanotechnology commercialisation critical factors;
Factors:	Ten dimensions of critical factors of nanotechnology commercialisation; and
Sub-factors:	Sub-factors under each dimension of critical factors.

5.3.1 Evaluation of Sub-factors under 'Technical and Technological feature' of the nano-materials

These derived sub-factors include the following:

- Intersection of nanotechnology with biotechnology,
- Convergence of nanotechnology with information and communication technology (ICT),
- Scientific changes through high levels of technological support and technology management effectiveness,
- Technical abilities of suppliers,
- Local suitability of nanotechnology based on the country's environmental and socio-economic state, and
- Technological functionality, trial-ability and reliability.

5.3.1.1 Matrix formation for Sub-factors under 'Technical & Technological features of the nano-materials'

The identified six (6) sub-factors for the commercialisation of applications of engineered nano-materials are analysed for hierarchy. Table 5.3 depicts the pair-wise comparison matrix for the identified factors.

Table 5.3: PWCM of the sub-factors corresponding to Technical & Technological features of the nano-materials

	Intersection	Convergence	Changes	Suppliers	Local	functionability
Intersection of with biotech	1	2	5	5	5	5
Convergence with ICT	1/2	1	2	5	5	5
Scientific changes	1/5	1/2	1	2	5	5
Suppliers abilities	1/5	1/5	1/2	1	2	5
Local suitability	1/5	1/5	1/5	1/2	1	2
functionality, trial-ability & reliability	1/5	1/5	1/5	1/5	1/2	1
CR = 0.0750 < 0.1000						

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.1.2 Priority matrix formation for sub-factors: Technical and Technological features of the nano-materials

The evaluation of the six sub-factors under the technical and technological features of the nano-materials result in the priority matrix formation for the factors in Table 5.4. This table depicts the ranking or prioritisation of the sub-factors.

Table 5.4: Priority matrix for the ranking of critical sub-factors corresponding to Technical & Technological features of the nano product

PRIORITISATION OF SUB-FACTORS corresponding to "Technical & Technological feature of the nano product"			
	Weight	Weight (%)	Rank
Intersection of nanotechnology with biotechnology	0.403	40.3%	1st
Convergence of nanotechnology with ICT	0.260	26.0%	2nd
Scientific changes	0.155	15.5%	3rd
Technical abilities of suppliers	0.092	9.2%	4th
Local suitability of nanotechnolog	0.052	5.2%	5th
Technological functionality, trial-ability & reliability	0.038	3.8%	6th
CR = 0.0750 < 0.1000			

It can be deduced from Table 5.4 that for the overall prioritisation scores of the sub-factors under the technical and technological features of the nano-materials for the commercialisation of ENMs, the priority values of the factors are stated in respective order of preference. ‘Intersection of nanotechnology with biotechnology’ (0.403), ‘Convergence of nanotechnology with information and communication technology’ (0.260), ‘Scientific changes through high level of technological support and technology management effectiveness’ (0.155), ‘Technical abilities of suppliers’ (0.092), ‘Local suitability of nanotechnology based on the country’s environmental and socio-economic state’ (0.052) and ‘Technological functionality, trial-ability and reliability’ (0.038).

Based on the analytical results and the priority ordering, the most important sub-factors with respect to the technical and technological features of the nanotechnology product is the intersection of nanotechnology with biotechnology. The least important, according to the experts surveyed, is the consideration of technological functionality, trial-ability and reliability of the nano-materials.

5.3.2 Evaluation of Sub-factors under Economic factors

These derived Sub-factors include the following:

- Cost-effectiveness
- Profit margins
- Increase in sales turnover

5.3.2.1 Matrix formation for sub-factors under economic factors for the commercialisation of applications of engineered nano-materials

The three (3) related sub-factors identified for the commercialisation of ENMs applications are analysed for hierarchy. Table 5.5 depicts the pair-wise comparison matrix for the identified factors.

Table 5.5: PWCM of the Sub-Criteria under Dimension 2 (Economic factors for the commercialisation of nano-materials)

	Cost	Profit	Turnover
Cost effectiveness	1	5	9
Profit margins	1/5	1	4
Increase in sales turnover	1/9	1/4	1
CR = 0.0740 < 0.1000			
Table 5.5 PWCM of the Sub-Criteria under Dimension 2 (Economic factors)			

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.2.2 Priority matrix formation for sub-factors: Economic factors for the commercialisation of applications of nano-materials

The evaluation of the three sub-factors under the economic factors for the commercialisation of applications of nano-materials results in the priority matrix formation for the factors in Table 5.6 and depicts a graphical visualisation of the ranking or prioritisation of the sub-factors.

Table 5.6 Priority matrix for the ranking of critical sub-factors

PRIORITISATION OF SUB-FACTORS corrensponding to "Economic factors for commercialisation of applications of nanomaterials"			
	Weight	Weight (%)	Rank
Cost effectiveness	0.743	74.3%	1st
Profit margins	0.194	19.4%	2nd
Increase in sales turnover	0.063	6.3%	3rd
CR = 0.0740 < 0.1000			

It can be deduced from Table 5.6 that for the overall prioritisation scores of the sub-factors under the economic factors of nano-materials for the commercialisation of ENMs, the priority values of the factors are stated in respective order of preference: Cost-effectiveness (0.743), profit margins (0.194) and increase in sales (0.063).

Based on the analytical results and the priority ordering, the most important sub-factors with respect to the economic factors for the commercialisation of nano-materials is the cost-effectiveness. The least important, according to the experts surveyed, is the consideration of an increase in sales.

5.3.3 Evaluation of Sub-factors under production factors

These derived sub-factors or factors include the following:

- Production cost issues
- Labour intensity

5.3.3.1 Matrix formation for sub-factors under production factors for the commercialisation of applications of ENMs

The two (2) related sub-factors identified for the commercialisation of applications of ENMs are analysed for hierarchy. Table 5.7 depicts the pair-wise comparison matrix for the identified factors.

Table 5.7: PWCM of the sub-Factors corresponding to "Production factors for the commercialisation of applications of nano-materials"

	Production cost issues	Labour intensity
Production cost issues	1	5
Labour intensity	1/5	1
CR = 0.0010 < 0.1000		

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.3.2 Priority Matrix formation for sub-factors: Production factors for the commercialisation of applications of nano-materials

The evaluation of the three sub-dimensions under the production factors for the commercialisation of applications of nano-materials result in the priority matrix formation for the factors in Table 5.8 and depicts a graphical visualisation of the ranking or prioritisation of the sub-factors.

Table 5.8: Priority matrix for the ranking of critical sub-factors

PRIORITISATION OF SUB-FACTORS corresponding to "Production factors for commercialisation of nano-materials"			
	Weight	Weight (%)	Rank
Production cost issues	0.833	83.3%	1st
Labour intensity	0.167	16.7%	2nd
CR = 0.0010 < 0.1000			

The overall prioritisation scores of the sub-factors under the production factors of the nano-materials for the commercialisation of applications of ENMs shows that the priority values of the factors are stated in respective order of preference: 'Production cost issues' (0.833) and 'Labour intensity' (0.167).

Based on the analytical results and the priority ordering, the more important of the two sub-factors under the 'Economic factors' for the commercialisation of applications of nano-materials is 'Cost-effectiveness'. The least important, according to the experts surveyed, is the consideration of 'Labour intensity'.

5.3.4 Evaluation of sub-factors under informative factors

These derived sub-factors include the following:

- Publicity through the press and media
- Private-Public Partnership

5.3.4.1 Matrix formation for Sub-factors under 'Informative factors' for the commercialisation of applications of ENMs

The two (2) related sub-factors identified for the commercialisation of applications of ENMs are analysed for hierarchy. Table 5.9 depicts the pair-wise comparison matrix for the factors identified.

Table 5.9: PWCM of the sub-criteria corresponding to Informative factors for the commercialisation of applications of nano-materials

	Publicity through press & media	Private-Public Partnership
Publicity through press & media	1	5
Private-Public Partner	1/5	1
CR = 0.0010 < 0.1000		

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.4.2 Priority Matrix formation for sub-factors: 'Informative factors' for the commercialisation of applications of nano-materials

The evaluation of the three sub-dimensions under the production factors for the commercialisation of applications of nano-materials result in the priority matrix formation for the factors in Table 5.10. The table depicts the ranking or prioritisation of the sub-factors.

Table 5.10: Priority matrix for the ranking of critical sub-factors

PRIORITISATION OF SUB-FACTORS corresponding to "Informative factors for commercialisation of nano-materials"			
	Weight	Weight (%)	Rank
Publicity through press & media	0.833	83.3%	1st
Private-Public Partnership	0.167	16.7%	2nd
CR = 0.0010 < 0.1000			

The overall prioritisation scores of the sub-factors under the informative factors of the nano-materials for the commercialisation of applications of ENMs are presented in Table

5.10. The priority values of the factors are stated in respective order of preference: ‘Publicity through press and media’ (0.833) and ‘Private-Public Partnerships’ (0.167).

Based on the analytical results and the priority ordering, the more important of the two sub-factors under the informative factors for the commercialisation of nano-materials is publicity through the ‘Press and media’. The least important, according to the experts surveyed, is the consideration of ‘Private-Public Partnerships’.

5.3.5 Evaluation of sub-factors under cultural factors

These derived Sub-factors include the following:

- Researchers-Investors constructive collaboration;
- Awareness and emphasis of the national ministry of technology towards nanotechnology commercialisation; and
- Acculturation with respect to the commercialisation of nanotechnology

5.3.5.1 Matrix formation for sub-factors under cultural factors for the commercialisation of applications of engineered nano-materials

The three (3) related sub-factors identified for the commercialisation of applications of ENMs are analysed for hierarchy. Table 5.11 depicts the pair-wise comparison matrix for the factors identified.

Table 5.11: PWCM of the Sub-Factors corresponding to Cultural factors for the commercialisation of applications of nano-materials

	Researchers-Investors constructive collaboration	Awareness and emphasis of national ministry of technology	Acculturation with respect to commercialisation of nanotechnology
Investors constructive collaboration	1	4	9
Awareness and emphasis of national ministry of technology	1/4	1	5
Acculturation with respect to commercialisation of nanotechnology	1/9	1/5	1
CR = 0.0740 < 0.1000			

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.5.2 Priority Matrix formation for sub-factors: Cultural factors for the commercialisation of applications of nano-materials

The evaluation of the three sub-dimensions under the production factors for the commercialisation of applications of nano-materials result in the priority matrix formation for the factors in Table 5.12, which depicts a graphical visualisation of the ranking or prioritisation of the sub-factors.

Table 5.12: Priority matrix for the ranking of critical sub-factors

PRIORITISATION OF SUB-FACTORS corresponding to "Cultural factors for commercialisation of applications of nano-materials"			
	Weight	Weight (%)	Rank
Researchers-Investors constructive collaboration	0.709	70.9%	1st
Awareness &emphasis of national ministry of technology	0.231	23.1%	2nd
Acculturation with respect to commercialisation of nanotechnology	0.006	6.0%	3rd
CR = 0.0740 < 0.1000			

Table 5.12 displays the overall prioritisation scores of the sub-factors under the cultural factors of nano-materials for the commercialisation of applications of ENMs. The priority values of the factors are stated in their respective order of preference: 'Researchers-Investors constructive collaboration' (0.709), 'Awareness and emphasis of the national ministry of technology towards nanotechnology commercialisation' (0.231) and 'Acculturation with respect to the commercialisation of nanotechnology' (0.006).

Based on the analytical results and the priority ordering, the most important of the three sub-factors under the cultural factors for the commercialisation of nano-materials is the 'Researchers-Investors constructive collaboration'. The least important, according to the experts surveyed, is 'Acculturation with respect to the commercialisation of nanotechnology'.

5.3.6 Evaluation of sub-factors under social benefits

These derived sub-factors include the following:

- Enhancement of social infrastructure/networks;
- Employment creation;
- Product branding and brand recognition; and
- Cost advantages to customers.

5.3.6.1 Matrix formation for Sub-factors under social benefits for the commercialisation of applications of engineered nano-materials

The three (3) related sub-factors identified for the commercialisation of applications of ENMs are analysed for hierarchy. Table 5.13 depicts the pair-wise comparison matrix for the factors identified.

Table 5.13: PWCM of the Sub-Criteria under the factor "social benefit factors for the commercialisation of applications of nano-materials"

	Enhancement of social infrastructures/network	Employment creation	Product branding & brand recognition	Cost advantages to customers
Enhancement of social infrastructures/network	1	2	5	5
Employment creation	1/2	1	5	5
Product branding & brand recognition	1/5	1/5	1	2
Cost advantages to customers	1/5	1/5	1/2	1
CR = 0.0440 < 0.1000				

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.6.2 Priority matrix formation for sub-factors: Social benefits/factors for the commercialisation of nano-materials

The evaluation of the four sub-dimensions under the Social benefits/factors for the commercialisation of nano-materials result in the priority matrix formation for the factors in Table 5.13 which depicts a graphical visualisation of the ranking or prioritisation of the sub-factors.

Table 5.14: Priority matrix for ranking of critical sub-factors

PRIORITISATION OF SUB-FACTORS UNDER DIMENSION 6: Social benefits/factors for commercialisation of nano-materials			
	Weight	Weight (%)	Rank
Enhancement of social infrastructures/ network	0.488	48.8%	1st
Employment creation	0.345	34.5%	2nd
Product branding & brand recognition	0.098	9.8%	3rd
Cost advantages to customers	0.069	6.9%	4th
CR = 0.0440 < 0.1000			

Table 5.14 displays the overall prioritisation scores of the sub-factors under the social benefits/factors of the nano-materials for the commercialisation of applications of ENMs. The priority values of the factors are stated in respective order of preference: ‘Enhancement of social infrastructure/networks’ (0.488), Employment creation’ (0.345), ‘Product branding and brand recognition’ (0.098) and ‘Cost advantages to customers’ (0.069).

Based on the analytical results and the priority ordering, the most important of the three sub-factors under the social benefits/factors for the commercialisation of nano-materials is the Enhancement of social infrastructure/networks. The least important, according to the surveyed experts, is the cost advantages to customers.

5.3.7 Evaluation of sub-factors under social benefits

These derived sub-factors include the following:

- Patent and legal issues;
- Governmental fiscal policies and regulations; and
- Grant support and climate control by international community.

5.3.7.1 Matrix formation for sub-factors under regulatory policies for the commercialisation of ENMs applications

The three (3) related sub-factors identified for the commercialisation of applications of ENMs are analysed for hierarchy. Table 5.15 depicts the pair-wise comparison matrix for the factors identified.

Table 5.15: PWCM of the sub-factors corresponding to "regulatory policies for the commercialisation of applications of nano-materials"

	Patent & legal issues	Governmental fiscal policies and regulations	Grant support & climate control by international community
Patent & legal issues	1	3	5
Governmental fiscal policies and regulations	1/3	1	3
Grant support & climate control by international community	1/5	1/3	1
CR = 0.0400 < 0.1000			

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.7.2 Priority Matrix formation for sub-factors: Regulatory policies for the commercialisation of nano-materials

The evaluation of the three sub-dimensions under the regulatory policies for the commercialisation of nano-materials result in the priority matrix formation for the factors in Table 5.16 which depicts a graphical visualisation of the ranking or prioritisation of the sub-factors.

Table 5.16: Priority matrix for ranking of critical sub-factors

PRIORITISATION OF SUB-FACTORS UNDER DIMENSION 7: Regulatory policies for commercialisation of nano-materials			
	Weight	Weight (%)	Rank
Patent & legal issues	0.637	63.7%	1st
Governmental fiscal policies & regulations	0.258	25.8%	2nd
Grant support & climate control by international community	0.105	10.5%	3rd
CR = 0.0400 < 0.1000			

Table 5.16 displays the overall prioritisation scores of the sub-factors under the regulatory policies for the commercialisation of applications of ENMs. The priority values of the factors are stated in their respective order of preference: ‘Patent and legal issues’ (0.637), ‘Governmental fiscal policies and regulations’ (0.258) and ‘Grant support and Climate control by the international community’ (0.105).

Sequential to the analytical results obtained and the priority ordering depicted in Figure 5.16, the most important of the three sub-factors under the social benefits/factors for the commercialisation of applications of nano-materials is the ‘Patent and legal issues’. The least important, according to the surveyed experts, is the ‘Grant support and climate control by the international community’.

5.3.8 Evaluation of sub-factors under marketing potentiality and forces

These derived sub-factors include the following:

- Price suitability for sales' facilitation;
- Product aesthetic and packaging;
- Product positioning and launch;
- Market potential for end-products; and
- New market penetration for new and emerging technology.

5.3.8.1 Matrix formation for sub-factors under marketing potentiality and forces for the commercialisation of applications of ENMs

The five (5) related sub-factors identified for the commercialisation of applications engineered nano-materials are analysed for hierarchy. Table 5.16 depicts the pair-wise comparison matrix for the factors identified.

Table 5.17: PWCM of the sub-Factors corresponding to "Marketing potentiality and forces for the commercialisation of applications of nano-materials"

	Price suitability for sales' facilitation	Product aesthetic & packaging	Product positioning & launch	Market potential for end products	New market penetration for new & emerging technology
Price suitability for sales' facilitation	1	2	5	5	5
Product aesthetic & packaging	1/2	1	5	5	5
Product positioning & launch	1/5	1/5	1	2	5
Market potential for end products	1/5	1/5	1/2	1	2
New market penetration for new & emerging technology	1/5	1/5	1/5	1/3	1
CR = 0.0790 < 0.1000					

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the respondents through the survey.

5.3.8.2 Priority matrix formation for sub-factors: Marketing potentiality and forces for the commercialisation of applications of nano-materials

The evaluation of the three sub-dimensions under the marketing potentiality and forces for the commercialisation of applications of nano-materials result in the priority matrix formation for the factors in Table 5.17. The table shows the ranking or prioritization of the sub-factors.

Table 5.18 Priority matrix for ranking of critical sub-factors corresponding to "Marketing potentiality and forces for the commercialisation of applications of nano-materials"

PRIORITISATION OF SUB-FACTORS corresponding to "Marketing potentiality and forces for commercialisation of applications of			
	Weight	Weight (%)	Rank
Price suitability for sales' facilitation	0.492	49.2%	1st
Product aesthetic & packaging	0.328	32.8%	2nd
Product positioning & launch	0.123	12.3%	3rd
Market potential for end products	0.070	7.1%	4th
New market penetration for new & emerging technology	0.049	4.9%	5th
CR = 0.0790 < 0.1000			

Table 5.18 displays the overall prioritisation scores of the sub-factors under the marketing potentiality and forces for the commercialisation of ENMs. The priority values of the factors are stated in their respective order of preference: 'Price suitability for sales' facilitation' (0.429), 'Product aesthetic and packaging' (0.328), 'Product positioning and launch' (0.123), Market potential for end-products (0.071) and 'New market penetration for new and emerging technology' (0.049).

As a sequel to the analytical results obtained and the priority ordering, the most important of the five sub-factors under the marketing potentiality and forces for the commercialisation of applications of nano-materials is the 'Price suitability for sales facilitation', preferably succeeded subsequently by 'Product aesthetic and packaging', 'Product positioning and launch', 'Market potential for end-products' and 'New market penetration for new and emerging technology' based on the views of the experts surveyed.

5.3.9 Evaluation of sub-factors under organisation's strategic issues and features

These derived sub-factors include the following:

- Organisational strategic implications;
- Organisation's business policies;
- Training and development support for technical and marketing staff; and
- Personnel resources with generic and specialised nano commercialisation knowledge.

5.3.9.1 Matrix formation for sub-factors under organisation's strategic issues and features for the commercialisation of applications of engineered nano-materials

The four (4) related sub-factors identified for the commercialisation of applications of ENMs are analysed for hierarchy. Table 5.19 shows the pair-wise comparison matrix for the factors identified.

Table 5.19: PWCM of the sub-Factors corresponding to "Firm's strategic issues & features for the commercialisation of applications of nano-materials"

	Organisational strategic implications	Organization's business policies	Training & development support for technical & marketing staff	Personnel resources with generic & specialised nano commercialisation knowledge
Organisational strategic implications	1	5	9	9
Firm's business policies	1/5	1	3	5
Training & development support for technical & marketing staff	1/9	1/3	1	3
Personnel resources with generic & specialised nano commercialisation knowledge	1/9	1/5	1/3	1
CR = 0.0670 < 0.1000				

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the experts through the survey.

5.3.9.2 Priority Matrix formation for sub-factors: Organisation's strategic issues and features for the commercialisation of applications of nano-materials

The evaluation of the four sub-dimensions under the organisation's strategic issues and features for the commercialisation of applications of nano-materials result in the priority matrix formation for the factors in Table 5.20. The table depicts the ranking or prioritization of the sub-factors.

Table 5.20: Priority Matrix for the Ranking of Critical Sub-Factors corresponding to Firm's strategic issues and features for the commercialisation of applications of nano-materials

PRIORITISATION OF SUB-FACTORS corresponding to "Firm's strategic issues & features for commercialisation of applications of nanomaterials"			
	Weight	Weight (%)	Rank
Organisational strategic implications	0.675	67.5%	1st
Firm's business policies	0.194	19.4%	2nd
Training & development support for technical & marketing staff	0.086	8.6%	3rd
Personnel resources with generic & specialised nano commercialisation knowledge	0.045	4.5%	4th
CR = 0.0670 < 0.1000			

Table 5.20 displays the overall prioritisation scores of the sub-factors under the organisation's strategic issues and features for the commercialisation of applications of ENMs. The priority values of the factors are stated in their respective order of preference: 'Organisational strategic implications' (0.675), 'Organisation's business policies' (0.194), 'Training and development support for technical and marketing' (0.086) and 'Personnel resources with generic and specialised nano commercialisation knowledge' (0.045).

Subsequent to the analytical results obtained and the priority, the most important of the four sub-factors under the 'Organisation's strategic issues and features for the commercialisation of nano-materials' is the 'Organisational strategic implications', preferably succeeded subsequently by 'Organisation's business policies', 'Training and development support for technical and marketing' and 'Personnel resources with generic and specialised nano commercialisation knowledge'.

5.3.10 Evaluation of sub-factors under Health and Safety

These derived sub-factors include the following:

- Public opinion about toxic issues; and
- Safety issues.

5.3.10.1 Matrix formation for sub-factors under health and safety considerations for the commercialisation of applications of ENMs

The two (2) related sub-factors identified for the commercialisation of applications of ENMs are analysed for hierarchy. Table 5.21 shows the pair-wise comparison matrix for the factors identified.

Table 5.21: PWCM of the sub-factors corresponding to Health & safety considerations for the commercialisation of applications of nano-materials

	Public opinion about toxic issue	Safety issue
Public opinion about toxic issue	1	8
Safety issue	1/8	1
CR = 0.0000 < 0.1000		

For every cell at the lower-triangular part of the matrix, cell (i, j) is the reciprocal of the cell (j, i). These dimensional weights were provided by the experts through the survey.

5.3.10.2 Priority matrix formation for sub-factors: Health and Safety considerations for the commercialisation of applications of nano-materials

The evaluation of the four sub-factors under the 'Health and Safety' considerations for the commercialisation of nano-materials' applications result in the priority matrix formation for the factors as presented in Table 5.22. The table shows the ranking or prioritisation of the sub-factors.

Table 5.22: Priority matrix for the ranking of critical sub-factors corresponding to "Health & safety considerations for the commercialisation of applications of nano-materials"

PRIORITISATION OF SUB-FACTORS corresponding to "Health & safety consideration for commercialisation of applications of			
	Weight	Weight (%)	Rank
Public opinion about toxic issue	0.889	88.9%	1st
Safety issue	0.111	11.1%	2nd
CR = 0.0000 < 0.1000			

Table 5.22 displays the overall prioritisation scores of the sub-factors under the 'Health and Safety' consideration for the commercialisation of ENMs. The priority values of the factors are stated in respective order of preference: 'Public opinion about toxic issues' (0.889) and 'Safety issues' (0.111).

As a sequel to the analytical results obtained and the priority ordering, the more important of the two sub-factors under the 'Health and Safety' factors for the commercialisation of nano-materials is the public opinion about toxic issues, preferably succeeded by safety issues.

5.4 Key Critical Factors: Implications for Managers

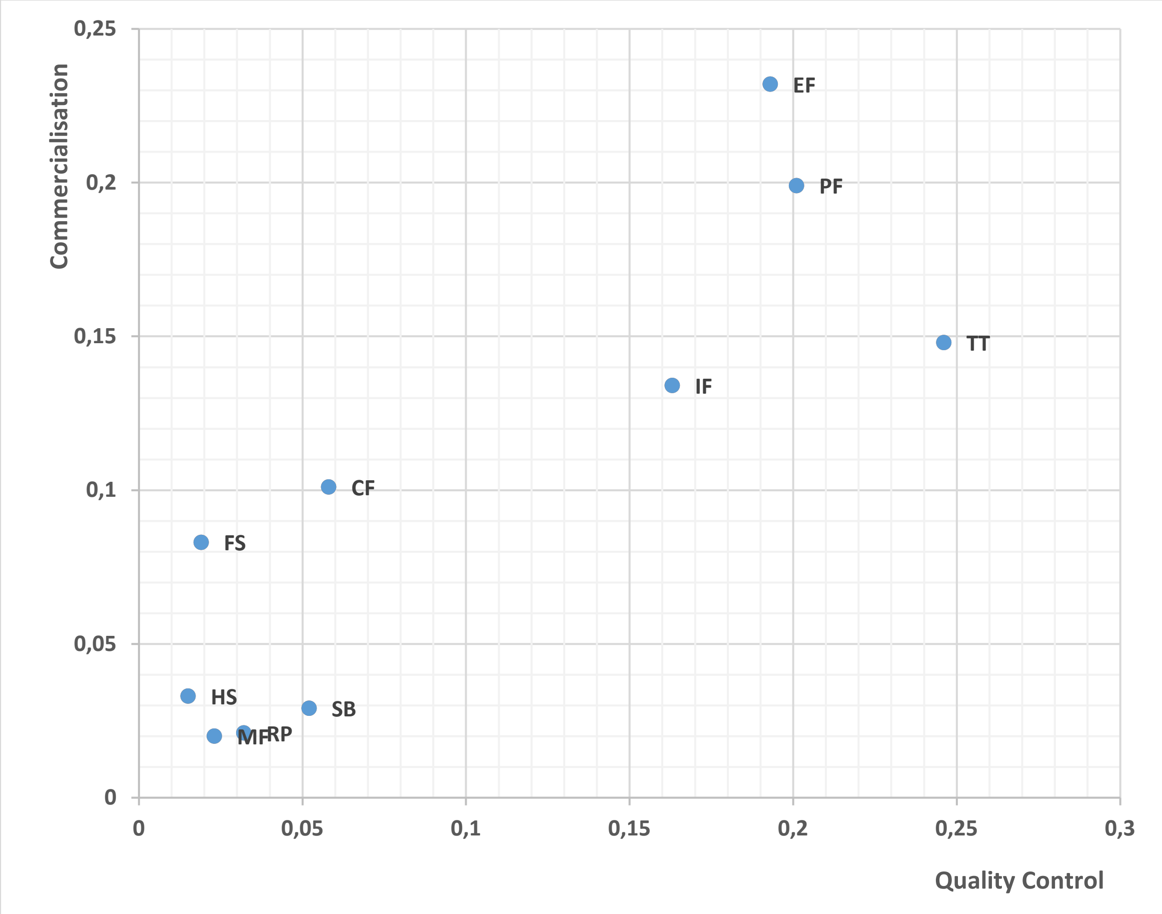
The final priority weights of each of the factor dimensions were evaluated as presented earlier in Section 5.1. Table 5.23 presents a cross section of the overall priority weights for the quality control and commercialisation of applications of ENMs.

Table 5.23: Priority weights for the quality control and commercialisation of applications of ENMs

Critical Factors	Effective Commercialisation weights	Rank	Quality Control weights	Rank
TT	0.246	1	0.148	3
EF	0.193	3	0.232	1
PF	0.201	2	0.199	2
IF	0.163	4	0.134	4
CF	0.058	5	0.101	5
SB	0.052	6	0.029	8
RP	0.032	7	0.021	9
MF	0.023	8	0.020	10
FS	0.019	9	0.083	6
HS	0.015	10	0.033	7

The key critical factors for quality control and commercialisation were identified by plotting a two-dimensional graphical model of the corresponding priority weights with respect to quality control and the commercialisation of the ENMs applications.

Graph 5.1: Determinants of Key Critical Factors for Quality Control and Commercialisation



The critical factors dimensions mapped into the upper right-hand quadrant, as depicted in Graph 5.1, are clearly the key critical factors. These are 'Economic factors', 'Production factors'; 'Technical and Technological features of the nano product' and the 'Informative factors'. The model suggests that all other critical factors, namely 'Cultural factors', 'Organisation's strategic issues and features, 'Health and Safety'; 'Social benefits', 'Regulatory policies' and 'Marketing potentiality and forces' scored low values against both measures. Therefore, 'Economic factors', 'Production factors'; 'Technical and Technological features of the nano product' and the 'Informative factors' are the key critical factors for managerial decisions towards quality control and the effective commercialisation of applications of ENMs.

Hence, the major determinants to be considered in this study in the building of a hierarchical modelling framework for the quality control and the effective commercialisation of applications of ENMs are the economic factors, production factors; technical and technological features of the nano product and the informative factors.

5.5 Discussions of findings

Nanotechnology commercialisation is new, especially amongst developing countries, and has been regarded as an approach of high purpose assisting organisations in gaining a competitive advantage over one another (Kumar, Luthra, Haleem, Mangla and Garg, 2015). To this end, this section discusses the findings of this study towards the determining of the most prioritised factors which will assist organisations to commercialise applications of ENMs to gain a marketing edge considering the factors priorities.

This research has been able to identify and evaluate several critical factors for the effective commercialisation of nanotechnology and ENMs through a review of recent and current literature and opinions or suggestions of nanotechnology experts through the Delphi Method. Thirty-four (34) critical factors grouped into ten (10) dimensions were identified and evaluated for importance and subsequently for priority scaling. The Analytical Hierarchy Process (AHP) technique was further used in this study in the evaluation of these critical factors for effective nanotechnology commercialisation decision-making.

5.5.1 AHP priority model of the main factors

The AHP priority model of the main factors in Figure 5.1 indicates that amongst the ten (10) dimensions of the critical factors for effective nanotechnology commercialisation, ‘Economic factors’ was found to be the most important. ‘Economic factors’ was followed closely in descending order by ‘Production factors’; ‘Technical and Technological feature of the nano product’; ‘Informative factors’; ‘Cultural factors’ and ‘Organisation’s strategic issues and features’. At the tail end of the priority or importance rating are ‘Health and Safety’, ‘Social benefits’ and ‘Regulatory policies’.

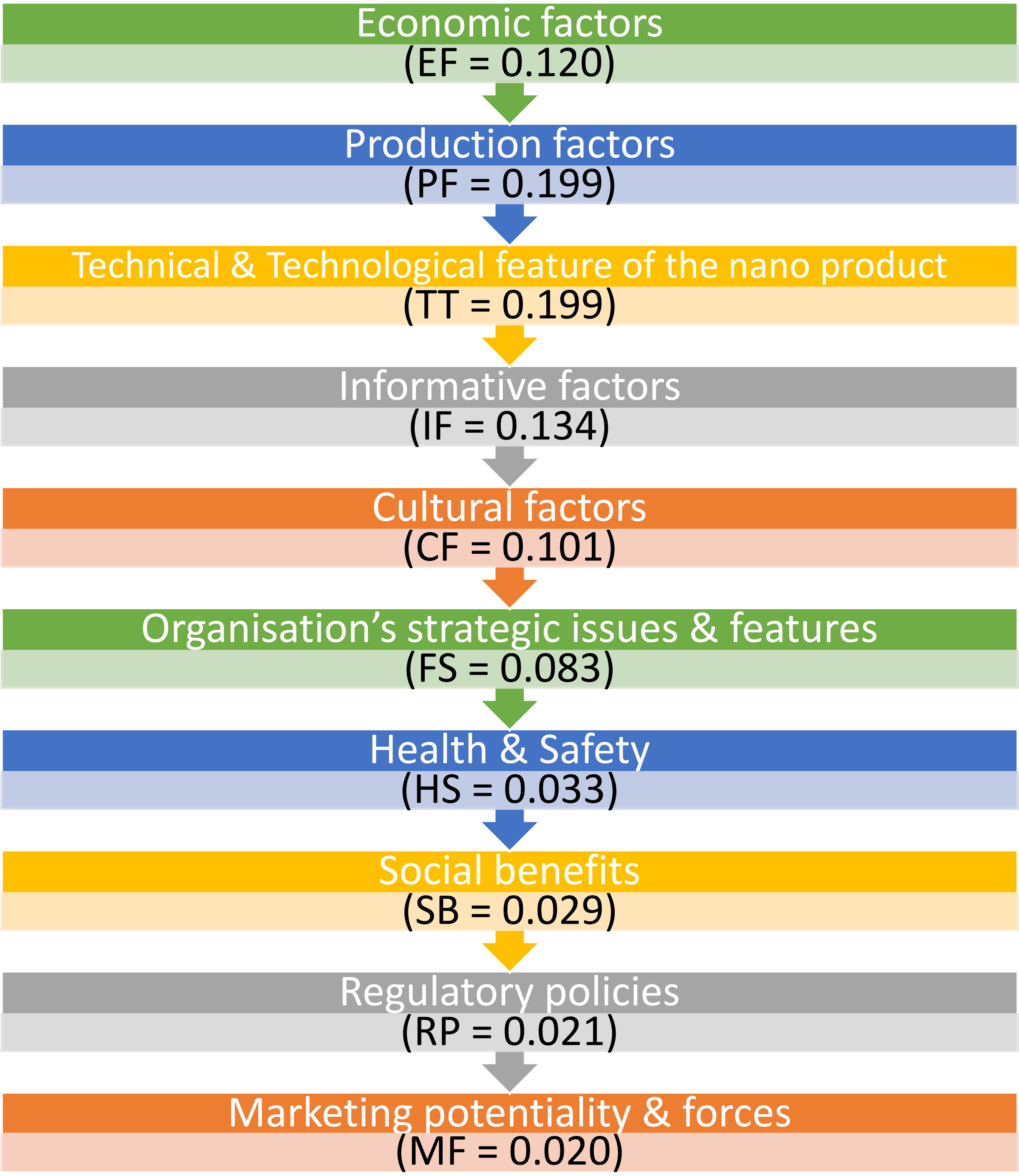


Figure 5.1: AHP priority order of the 10 factors

Source: Developed by the Researcher

'Marketing potentiality and forces' was found to be the least important of these factors for the commercialisation of nanotechnology. These lead to the development of the Hierarchical Model or Managerial Strategic Action Plan as presented in Section 5.5.2, which represents the development of the model as outlined in Objective 2.

5.5.2 Hierarchical Model for Quality Control and Commercialisation of ENMs

The hierarchical model hereby developed is a managerial, strategic action plan for the Quality Control and Commercialisation of ENMs. The developed process is presented in Figure 5.2 and suggested for optimum decision-making in the commercialisation of products of ENMs. Its greatest strength is the systematic and hierarchical algorithm as it is also strategically designed towards the improvement of commercialisation and quality control in the field of nanotechnology. Designed to bring quantitative analysis capacity into the resource planning process, the model has the ability to lower the subjectivity of Managers who have to decide between product alternatives.

However, the potential weakness is that the factors considered were generated from literature and academic experts' contributions. The preferential judgment of leaders in the nanotechnology industry may be an essential input as the experience and/or intuition of the industrial leader could be viewed in choice-making.

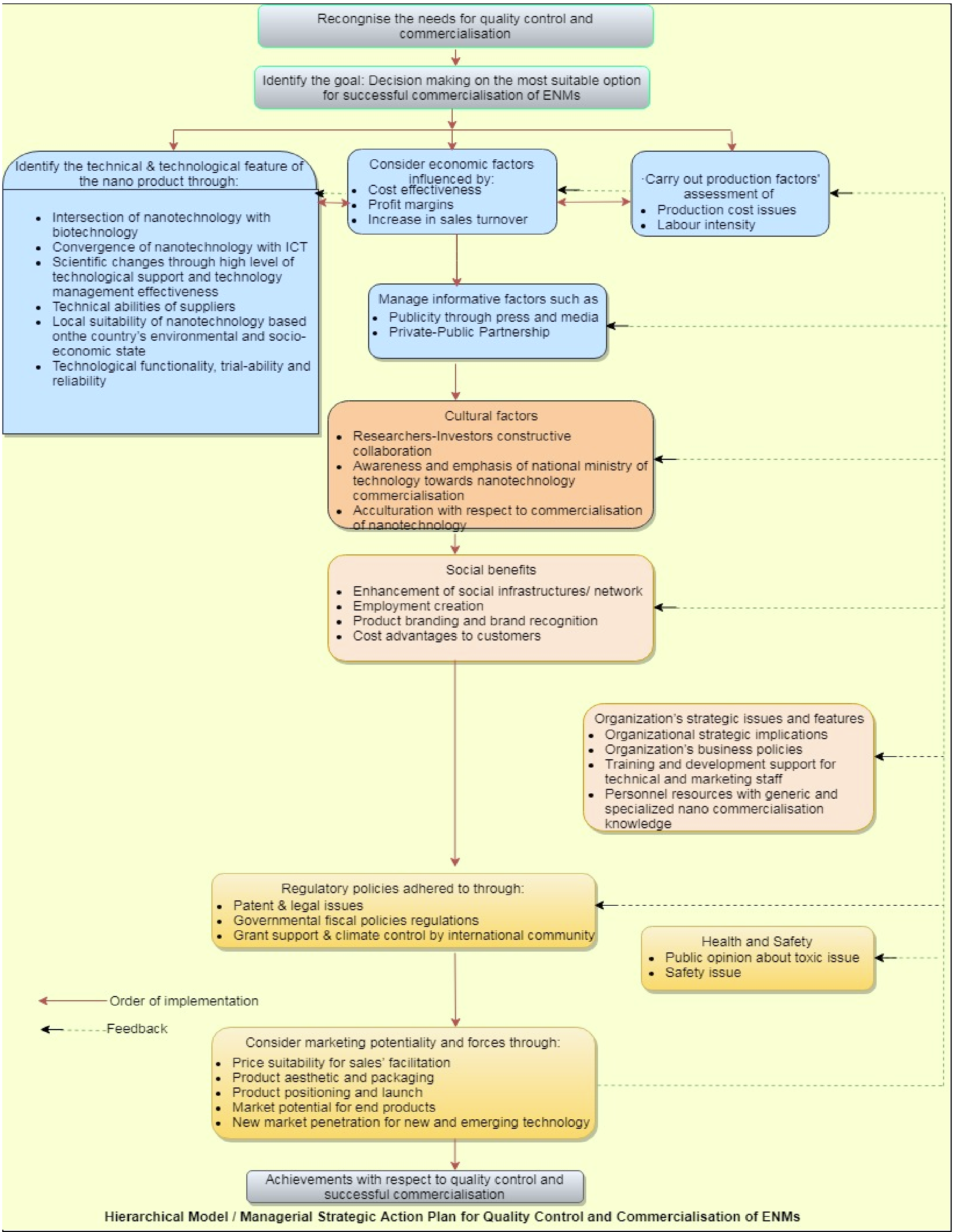


Figure 5.2: Hierarchical Model / Managerial Strategic Action Plan for the Quality Control and Commercialisation of ENMs
Source: Developed by the Researcher

The sub-factors were further analysed for hierarchy under each factor, and the subsequent findings were made. The AHP priority model is as illustrated in Figure 5.3. In the evaluation of factors under dimension 1 ‘Technical and technological features of the nanotechnology product’, the most important is the intersection of nanotechnology with biotechnology, followed by ‘Convergence of nanotechnology with information and communication technology’, ‘Scientific changes through high level of technological support and technology management effectiveness’, ‘Technical abilities of suppliers’, ‘Local suitability of nanotechnology based on the country’s environmental and socio-economic state’. The least important, according to the survey, is the consideration of the ‘Technological functionality, Trial-ability and Reliability’ of the nano-materials.

The ‘Economic factors’ were considered for the commercialisation of applications of ENMs. ‘Cost-effectiveness’ is the most important of the factors, followed by ‘Profit margins’. ‘Increase in sales’ is the least important of the critical factors.

Production factors consist of sub-factors: ‘Cost effectiveness’ and ‘Labour intensity’. Of these two factors, the former was found to be more important.

Furthermore, the more important of the two sub-factors under the ‘Informative factors’ for the commercialisation of applications of nano-materials is the ‘Publicity through press and media’. The least important, according to the experts surveyed, is the consideration of ‘Private-Public Partnership’.

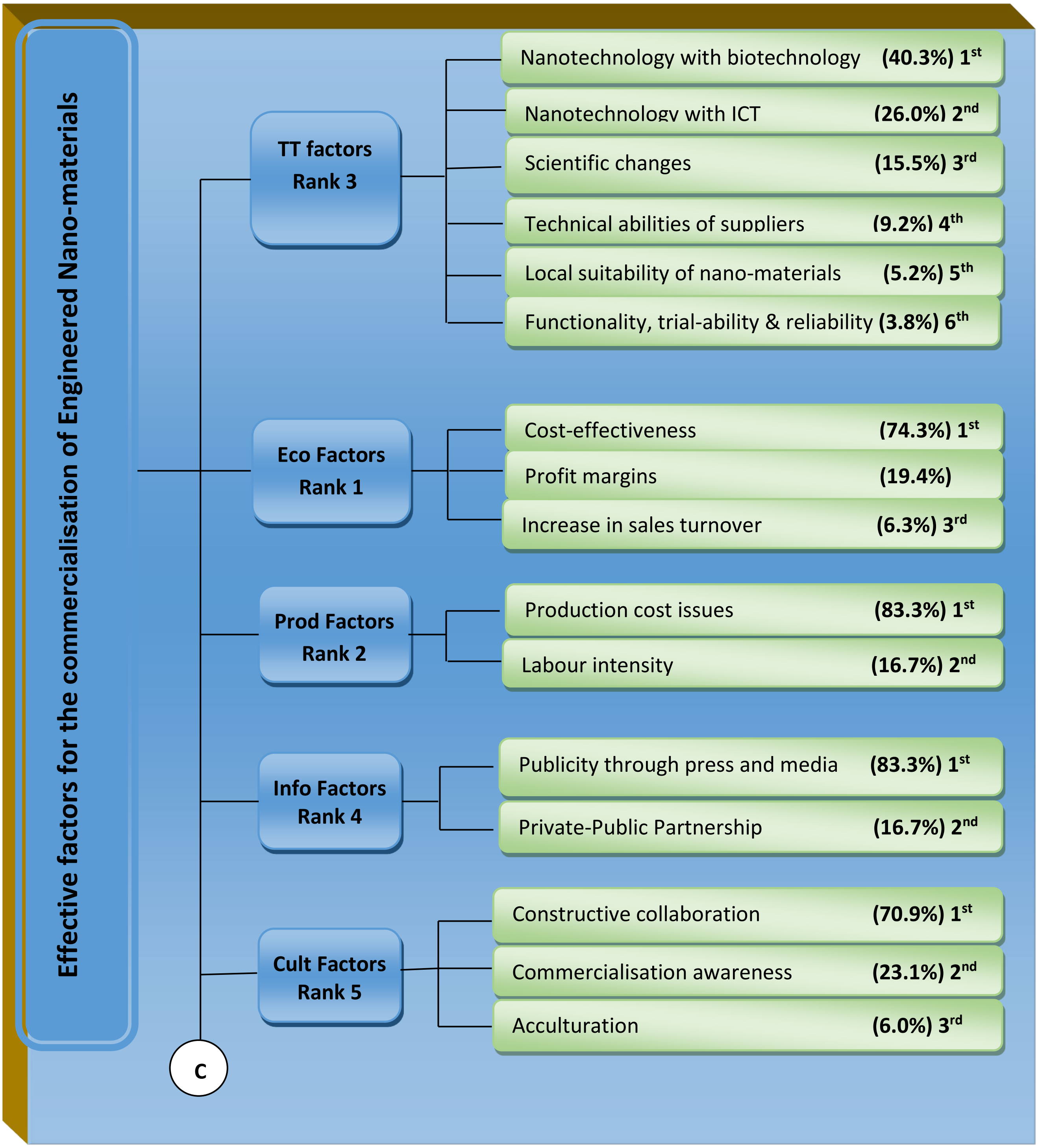


Figure 5.3: AHP Priority Model of the critical factors and sub-factors

Source: Developed by the Researcher

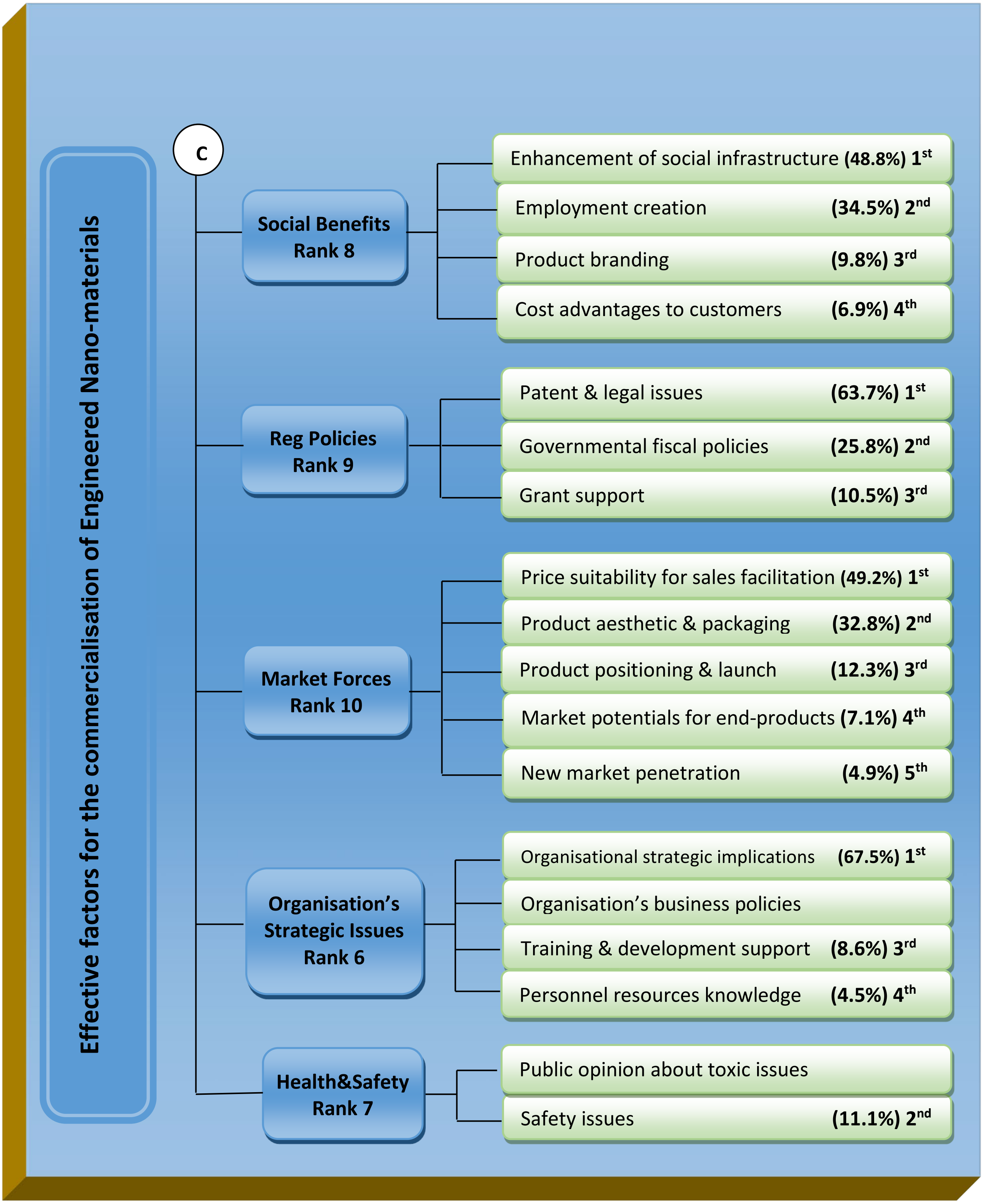


Figure 5.3 (continued): AHP Priority Model of the critical factors and sub-factors

Source: Developed by the Researcher

Similarly, three factors were listed under the cultural factors: ‘Researchers-Investors constructive collaboration’, ‘Awareness and emphasis of national ministry of technology towards nanotechnology commercialisation’ and ‘Acculturation with respect to commercialisation of nanotechnology’. The most important of the three sub-factors under the ‘Cultural factors’ for the commercialisation of nano-materials is the ‘Researchers-Investors constructive collaboration’ while the least important is ‘Acculturation with respect to the commercialisation of nanotechnology’.

‘Enhancement of social infrastructures/network’, ‘Employment creation’, ‘Product branding and brand recognition’ and ‘Cost advantages to customers’ are the critical factors under the ‘Social benefits/factors’. The former is the most important, and the latter is the least important of the sub-factors.

‘Social benefits’ is made up of three Sub-factors: ‘Patent and legal issues’; ‘Governmental fiscal policies and regulations’ and ‘Grant support and climate control by the international community’. ‘Patent and legal issues’ was found to be the most important, and ‘Grant support and climate control by the international community’ the least important.

‘Marketing potentiality and forces’ was listed with five sub-factors: ‘Price suitability for sales facilitation’, ‘Product aesthetic and packaging’ ‘Product positioning and launch’, Market potential for end-products’ and ‘New market penetration for new and emerging technology’. Found to be the most important of the five sub-factors is the ‘Price suitability for sales facilitation’, preferably succeeded subsequently by ‘Product aesthetic and packaging’, ‘Product positioning and launch’, ‘Market potential for end-products’ and ‘New market penetration for new and emerging technology’.

Furthermore, the most important of the four sub-factors under ‘Organisation’s strategic issues and features’ for the commercialisation of nano-materials is the ‘Organisational strategic implications’, followed by ‘Organisation’s business policies’, ‘Training and development support for technical and marketing’, while ‘Personnel resources with generic and specialized nano commercialisation knowledge’ is the least important.
The more important of the two sub-factors under the ‘Health and Safety’ factor for the commercialisation of nano-materials is the public opinion about toxic issues, preferably succeeded by safety issues.

Meanwhile, if these results and model are to have any worthy applicative impact, it becomes essential to conduct an exploration of the model validation. This is necessary for the optimum commercialisation and quality control of nanotechnology-enabled products.

5.6 Summary of the Chapter

This chapter has considered the prioritisation of the critical success factors for the commercialisation of ENMs through the adoption of the AHP as a follow-up on the data analysis. The next chapter of this thesis is dedicated to this objective as it adopts the Data Envelopment Analysis (DEA) to carry out extensive programming of the commercialisation framework validation.

CHAPTER SIX

VALIDATION OF THE COMMERCIALISATION FRAMEWORK

6.1 Overview of the chapter

This chapter represents a milestone in the progression of this research work as it outlines the validation of the commercialisation framework developed in the course of this study for the successful commercialisation and quality control of nanotechnology products. The objective is to reveal the true input-output relations of the commercialisation framework of the critical success factors identified in Chapter Two and the prioritisation modelling constructed in Chapter Five. As an innovative application in Operations Research, Data Envelopment Analysis (DEA) is adopted in this chapter to carry out extensive programming of the commercialisation framework validation as obtained through the AHP priority ranking. According to Ravaba (2013), DEA is the most suitable method applicable in validating an AHP priority framework. The DEA has been applied in evaluating effectiveness in systems such as industries, healthcare works, organisations, countries and supply chains (Ghahremanloo *et al*. 2020). The literature review in Chapter Two and the questionnaire survey in Chapter Three were adopted to identify those critical factors essential for the successful commercialisation of nanotechnology-enabled products. The Analytical Hierarchy Process (AHP) was adopted for the determination of the weights of the identified criteria and to subsequently obtain the hierarchical structure or mode. This chapter serves as a support for the basis of drawing up conclusions towards the validation of the framework developed for the purpose of managerial efficiency in the commercialisation of products designed from enabled-nanotechnology materials.

The framework for this research, as depicted in Figure 6.1 and in preceding chapters, used a hybrid approach of the Analytical Hierarchy Process and the Data Envelopment Analysis (AHP/DEA). In dealing with complex problems, AHP is accepted to be a flexible and robust multi-criteria decision-making (MCDM) technique, while DEA has been accepted to be one of the most popular tools in management and commercialisation analysis (Arunyanart and Pruekthaisong, 2018). The duo of AHP and DEA are complex decision-making techniques (Kavurmaci and Üstün 2016).

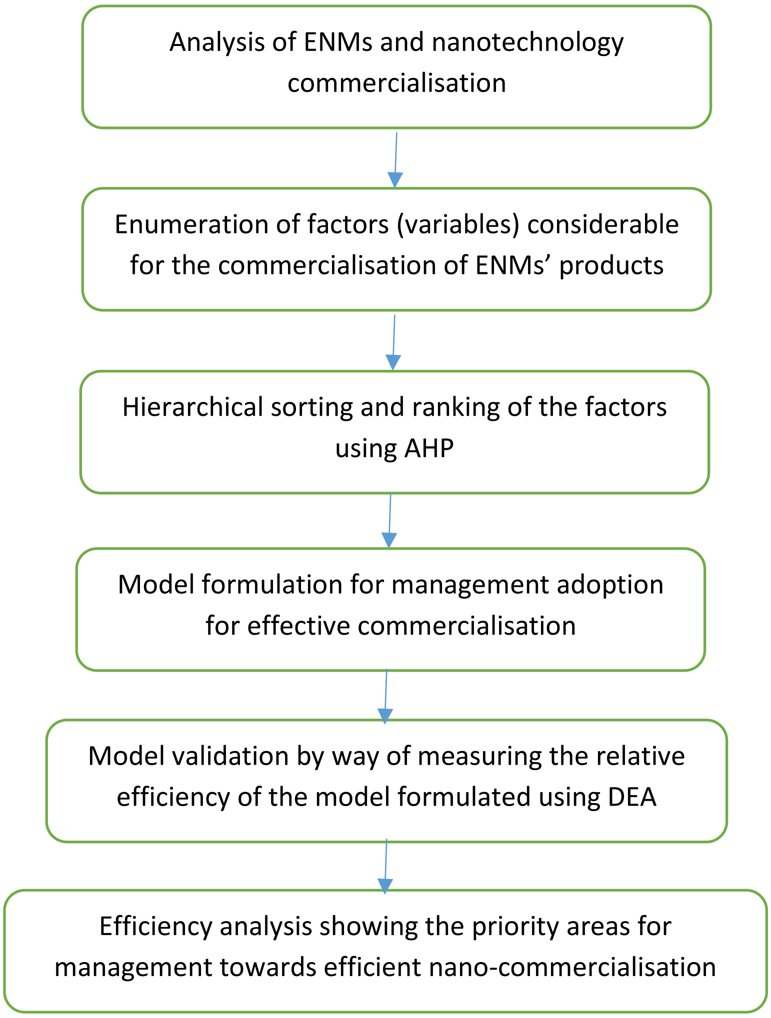


Figure 6.1: Flowchart of the research process

Furthermore, the chapter investigates the validity of the commercialisation framework developed in the preceding chapter by adopting the Data Envelopment Analysis. This technique is discussed and proposed with the aid of linear programming. As a follow-up, a hypothesis was proposed for the validation of the framework. This hypothesis was subsequently tested using the rank correlation for its acceptance or rejection.

6.2 Hypothesis/Objective

The following hypothesis has been proposed for the validation of the model developed in this study:

Null Hypothesis (H_0): There is no significant difference between the priority rankings obtained through the Analytical Hierarchy Process (AHP) and Data Envelopment Analysis (DEA).

Alternative Hypothesis (H_1): There is a significant difference between the priority rankings obtained through the Analytical Hierarchy Process (AHP) and Data Envelopment Analysis (DEA).

The acceptance or rejection of the hypothesis will validate the hierarchical model for the successful commercialisation of products from ENMs. The acceptance or rejection of the hypothesis is statistically determined in Section 6.4.

6.3 Linear Programming Model Formulation and Solution

The most optimal priority weights of the decision criteria are easily generated by adopting the models (2), (5) and (6) for linear programming solution as presented in section 2.10. Considering a perfectly consistent pairwise comparison matrix, Wang, Luo and Xu (2013); Sun, Wu and Guo (2013) and Moeini, Karimi and Khorram (2015) proved that both models (2) and (5) could produce valid weights, while Hosseinian, *et al* (2012) and Li *et al.* (2020) argued that model (6) would produce the most favourable weights.

Considering the ten (10) dimensions of critical factors for the commercialisation of ENMs presented in Table 5.1a depicting the pair-wise comparison matrix for the factors identified, the following linear programming model was formulated:

$$Maximize\ Z$$

$$
subject\ to \begin{cases}
w_1 - Z \geq 0 \\
w_2 - Z \geq 0 \\
w_3 - Z \geq 0 \\
w_4 - Z \geq 0 \\
w_5 - Z \geq 0 \\
w_6 - Z \geq 0 \\
w_7 - Z \geq 0 \\
w_8 - Z \geq 0 \\
w_9 - Z \geq 0 \\
w_{10} - Z \geq 0 \\
v_1 + 5v_2 + 6v_3 + 6v_4 + 5v_5 + 6v_6 + 9v_7 + 9v_8 + 9v_9 + 9v_{10} - w_1 = 0 \\
(\frac{1}{5})v_1 + v_2 + 2v_3 + 2v_4 + 6v_5 + 6v_6 + 8v_7 + 7v_8 + 7v_9 + 8v_{10} - w_2 = 0 \\
(\frac{1}{6})v_1 + (\frac{1}{2})v_2 + v_3 + 2v_4 + 2v_5 + 2v_6 + 8v_7 + 6v_8 + 6v_9 + 8v_{10} - w_3 = 0 \\
\left(\frac{1}{6}\right)v_1 + \left(\frac{1}{2}\right)v_2 + \left(\frac{1}{2}\right)v_3 + v_4 + 2v_5 + 2v_6 + 8v_7 + 6v_8 + 6v_9 + 8v_{10} - w_4 = 0 \\
\left(\frac{1}{5}\right)v_1 + \left(\frac{1}{6}\right)v_2 + \left(\frac{1}{2}\right)v_3 + \left(\frac{1}{2}\right)v_4 + v_5 + 2v_6 + 8v_7 + 6v_8 + 8v_9 + 8v_{10} - w_5 = 0 \\
\left(\frac{1}{6}\right)v_1 + \left(\frac{1}{6}\right)v_2 + \left(\frac{1}{2}\right)v_3 + (\frac{1}{2})v_4 + (\frac{1}{2})v_5 + v_6 + 7v_7 + 7v_8 + 8v_9 + 8v_{10} - w_6 = 0 \\
\left(\frac{1}{9}\right)v_1 + \left(\frac{1}{8}\right)v_2 + \left(\frac{1}{8}\right)v_3 + (\frac{1}{8})v_4 + (\frac{1}{8})v_5 + (\frac{1}{7})v_6 + v_7 + v_8 + 2v_9 + 2v_{10} - w_7 = 0 \\
\left(\frac{1}{9}\right)v_1 + \left(\frac{1}{7}\right)v_2 + \left(\frac{1}{6}\right)v_3 + \left(\frac{1}{6}\right)v_4 + \left(\frac{1}{6}\right)v_5 + \left(\frac{1}{7}\right)v_6 + v_7 + v_8 + v_9 + 2v_{10} - w_8 = 0 \\
\left(\frac{1}{9}\right)v_1 + \left(\frac{1}{7}\right)v_2 + \left(\frac{1}{6}\right)v_3 + \left(\frac{1}{8}\right)v_4 + \left(\frac{1}{8}\right)v_5 + \left(\frac{1}{8}\right)v_6 + \left(\frac{1}{2}\right)v_7 + v_8 + v_9 + 2v_{10} - w_9 = 0 \\
\left(\frac{1}{9}\right)v_1 + \left(\frac{1}{8}\right)v_2 + \left(\frac{1}{8}\right)v_3 + \left(\frac{1}{8}\right)v_4 + \left(\frac{1}{8}\right)v_5 + \left(\frac{1}{8}\right)v_6 + \left(\frac{1}{2}\right)v_7 + \left(\frac{1}{2}\right)v_8 + \left(\frac{1}{2}\right)v_9 + v_{10} - w_{10} = 0
\end{cases}
$$

$$
\begin{cases}
w_1 + w_2 + w_3 + w_4 + w_5 + w_6 + w_7 + w_8 + w_9 + w_{10} = 1 \\
v_1 - (\frac{1}{16.69})w_1 \geq 0 \\
v_2 - \left(\frac{1}{16.69}\right)w_2 \geq 0 \\
v_3 - \left(\frac{1}{16.69}\right)w_3 \geq 0 \\
v_4 - \left(\frac{1}{16.69}\right)w_4 \geq 0 \\
v_5 - \left(\frac{1}{16.69}\right)w_5 \geq 0 \\
v_6 - \left(\frac{1}{16.69}\right)w_6 \geq 0 \\
v_7 - (\frac{1}{16.69})w_7 \geq 0 \\
v_8 - (\frac{1}{16.69})w_8 \geq 0 \\
v_9 - \left(\frac{1}{16.69}\right)w_9 \geq 0 \\
v_{10} - \left(\frac{1}{16.69}\right)w_{10} \geq 0 \\
v_1 - \left(\frac{1}{10}\right)w_1 \leq 0 \\
v_2 - \left(\frac{1}{10}\right)w_2 \leq 0 \\
v_3 - \left(\frac{1}{10}\right)w_3 \leq 0 \\
v_4 - \left(\frac{1}{10}\right)w_4 \leq 0 \\
v_5 - \left(\frac{1}{10}\right)w_5 \leq 0 \\
v_6 - \left(\frac{1}{10}\right)w_6 \leq 0 \\
v_7 - \left(\frac{1}{10}\right)w_7 \leq 0 \\
v_8 - \left(\frac{1}{10}\right)w_8 \leq 0 \\
v_9 - \left(\frac{1}{10}\right)w_9 \leq 0 \\
v_{10} - \left(\frac{1}{10}\right)w_{10} \leq 0 \\
v_i \; and \; w_i \geq 0 \; for \; every \; i = 1,2,\ldots,10
\end{cases}
$$

Where the following is defined:

i	**DMUi or criteria**
1	Technical & Technological feature of the nano product **(TT)**
2	Economic factors **(EF)**
3	Production factors **(PF)**
4	Informative factors **(IF)**
5	Cultural factors **(CF)**
6	Social benefits **(SB)**
7	Regulatory policies **(RP)**
8	Marketing potentiality & forces **(MF)**
9	Organisation's strategic issues & features **(FS)**
10	Health & Safety **(HS)**

The DEA value of each DMU (critical factor) is calculated by using the software LINDO 6.1 through the application of the basic CCR principle of the DEA method. The computer output of the LP solution is attached in Appendix 5.

Table 6.1: The β calculation for the matrix in Table 5.1b

Row	r_i	$\sum_{j=1}^{n} a_{ij}r_j$	$\frac{1}{r_i}\sum_{j=1}^{n} a_{ij}r_j$	Column	c_i	$\sum_{j=1}^{n} a_{ij}c_j$	$\frac{1}{c_i}\sum_{j=1}^{n} a_{ij}c_j$
1	65	1279.852	19.69	1	$\frac{7}{3}$	2186.112	32.465
2	$\frac{236}{5}$	761.627	16.14	2	$\frac{63}{8}$	1782.136	226.474
3	$\frac{107}{3}$	420.159	11.78	3	11	1527.73	137.840
4	$\frac{205}{6}$	368.159	10.78	4	$\frac{88}{7}$	1509.605	119.969
5	$\frac{275}{8}$	313.817	9.13	5	17	1580.729	92.957
6	$\frac{197}{6}$	260.776	7.94	6	$\frac{39}{2}$	1546.092	79.142
7	$\frac{27}{4}$	60.635	8.98	7	51	313.623	6.149
8	$\frac{53}{9}$	60.482	10.26	8	$\frac{89}{2}$	266.960	5.999
9	$\frac{16}{3}$	55.087	10.32	9	$\frac{97}{2}$	240.401	4.957
10	$\frac{13}{4}$	42.482	13.13	10	56	136.775	2.442

From Table 6.1,

$$\max_i \left(\frac{1}{r_i}\sum_{j=1}^{n} a_{ij}r_j\right) = 19.69$$

$$\max_i \left(\frac{1}{c_i}\sum_{j=1}^{n} a_{ij}c_j\right) = 932.465$$

so that $\beta = min\left\{\max_i \left(\frac{1}{r_i}\sum_{j=1}^{n} a_{ij}r_j\right),\ \max_i \left(\frac{1}{c_i}\sum_{j=1}^{n} a_{ij}c_j\right)\right\}$ = 19.69

The LINDO solution to the derived linear programming model yields an optimal solution after 34 iterations. The resulting weights of the comparison matrix obtained from the DEA-LP model, are as stated in Table 6.2.

Table 6.2: Weights and Ranking of the Criteria

DMU_i (Criteria)	TT	EF	PF	IF	CF
w_i **of** DMU_i	0.3689	0.1736	0.1150	0.0993	0.0886
Ranking	1	2	3	4	5
DMU_i (Criteria)	**SB**	**RP**	**MF**	**FS**	**HS**
w_i **of** DMU_i	0.0805	0.0207	0.0203	0.0186	0.0145
Ranking	6	7	8	9	10

The validation computed through LINDO optimization software and the objective function presents the efficiency of the hierarchical model. The comparison of the results of both the AHP and DEA techniques are presented in Table 6.3.

Table 6.3 Comparative Results of the AHP and DEA techniques

Criteria (Critical Factors)	AHP Hierarchical Model Results	Ranking	DEA Results (Efficiency & Validation)	Ranking
TT	0.246	1	0.3689	1
EF	0.193	3	0.1736	2
PF	0.201	2	0.1150	3
IF	0.163	4	0.0993	4
CF	0.058	5	0.0886	5
SB	0.052	6	0.0805	6
RP	0.032	7	0.0207	7
MF	0.023	8	0.0203	8
FS	0.019	9	0.0186	9
HS	0.015	10	0.0145	10

The comparison of the DEA and AHP approaches for the same priority matrix from Table 6.3 and the results obtained from both techniques are closely similar for the ranking of the critical factors. This confirms that the DEA method is most suitable for the validation of the AHP model. In the succeeding section, the correlation of the ranks is computed to assess how well the relationship between the two variables (approaches) can be statistically described.

6.4 Test of Hypothesis

This section seeks to determine the acceptability or otherwise of the hypothesis proposed in Section 6.2. The Spearman correlation coefficient is adopted in carrying out this test. Denoted by ρ (rho), it is popularly referred to as the 'Pearson correlation coefficient measuring two ranked variables'. Hence, it is termed a Rank correlation coefficient applied as a non-parametric statistical tool for measuring the linear dependence between two continuous variables (Howard, 2015). For distinct ranks as observed in Tables 6.3 and 6.4, the formula for this Product Moment Correlation is expressed as:

$$\rho = 1 - \frac{6\sum d^2}{n(n^2 - 1)} \qquad (7)$$

Where d is the deviation of ranks assigned to each pair of the variables and

n is the number of observations

Table 6.4 Rank Correlation Coefficient between the AHP and DEA techniques

Criteria (Critical Factors)	AHP Hierarchical Model Results	AHP Rank	DEA Results (Efficiency & Validation)	DEA Rank	d	d^2
TT	0.246	1	0.3689	1	0	0
EF	0.193	3	0.1736	2	1	1
PF	0.201	2	0.1150	3	-1	1
IF	0.163	4	0.0993	4	0	0
CF	0.058	5	0.0886	5	0	0
SB	0.052	6	0.0805	6	0	0
RP	0.032	7	0.0207	7	0	0
MF	0.023	8	0.0203	8	0	0
FS	0.019	9	0.0186	9	0	0
HS	0.015	10	0.0145	10	0	0

From Table 6.4, $\sum d^2 = 2$ and $n = 10$, substituting these values into (7), the following evaluations are obtained:

$$\rho = 1 - \frac{6\sum 2^2}{10(10^2 - 1)}$$

$$\rho = 1 - 012$$

$$\rho = 0.988$$

The computed rank correlation coefficient $\rho = 0.988$ shows very strong linear dependence between the two continuous variables representing the results obtained from the AHP and DEA techniques. This confirms the rejection of the proposed null hypothesis, and thereby accepts the alternative hypothesis that there is no significant difference between the priority rankings obtained through AHP and DEA. This validates the hierarchical model for the successful commercialisation of products from ENMs.

6.5 Discussions

This chapter considered the application of the Data Envelopment Analysis (DEA) in the validation of the Analytical Hierarchy Process (AHP) results and model as obtained in Chapter 5 of this thesis. The outputs of this chapter have been considerably able to validate the commercialisation framework obtained through the AHP priority ranking. Results of this chapter have also confirmed the statement credited to Ravaba (2013) that DEA is the most reliable tool for AHP validation.

The linear programming (LP) model of the DEA was formulated from the priority matrix constructed earlier. This LP has ten (10) decision variables representing the weights of the critical factors and forty-one (41) structural constraints with twenty (20) non-negativity constraints. LINDO optimization software was employed in solving for the decision variables of the LP problem

Cooperatively, the succeeding chapter draws upon various discussions that can be used to develop a structure that could guide the development of operational business modelling for the commercialisation of nanotechnology, especially that of applications of ENMs. Being the concluding chapter of the study, Chapter Seven covers the final section of the research. It also considered the managerial and commercial applicability and makes recommendations for future research.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Overview of the chapter

This study set out to conduct an extensive investigation, evaluation and prioritisation of the critical success factors for the commercialisation of ENMs. A literature review and questionnaire survey were conducted to identify those critical factors essential for the successful commercialisation of nanotechnology products and complement the current research status of nanotechnology commercialisation as highlighted in Figure 7.1. The study the comprised data from an initial survey (Delphi study) and implementations of models [Analytical Hierarchy Process (AHP)]. The adoption of AHP is for the achievement of optimal decision-making by management in technological industries and the improvement of organisational competitiveness in the application of ENMs (e-Silva and Hurts 2014; Shen, Muduli and Barve, 2015). This chapter is purposefully designed to draw conclusions and recommendations based on findings in Chapter Four to Chapter Six.

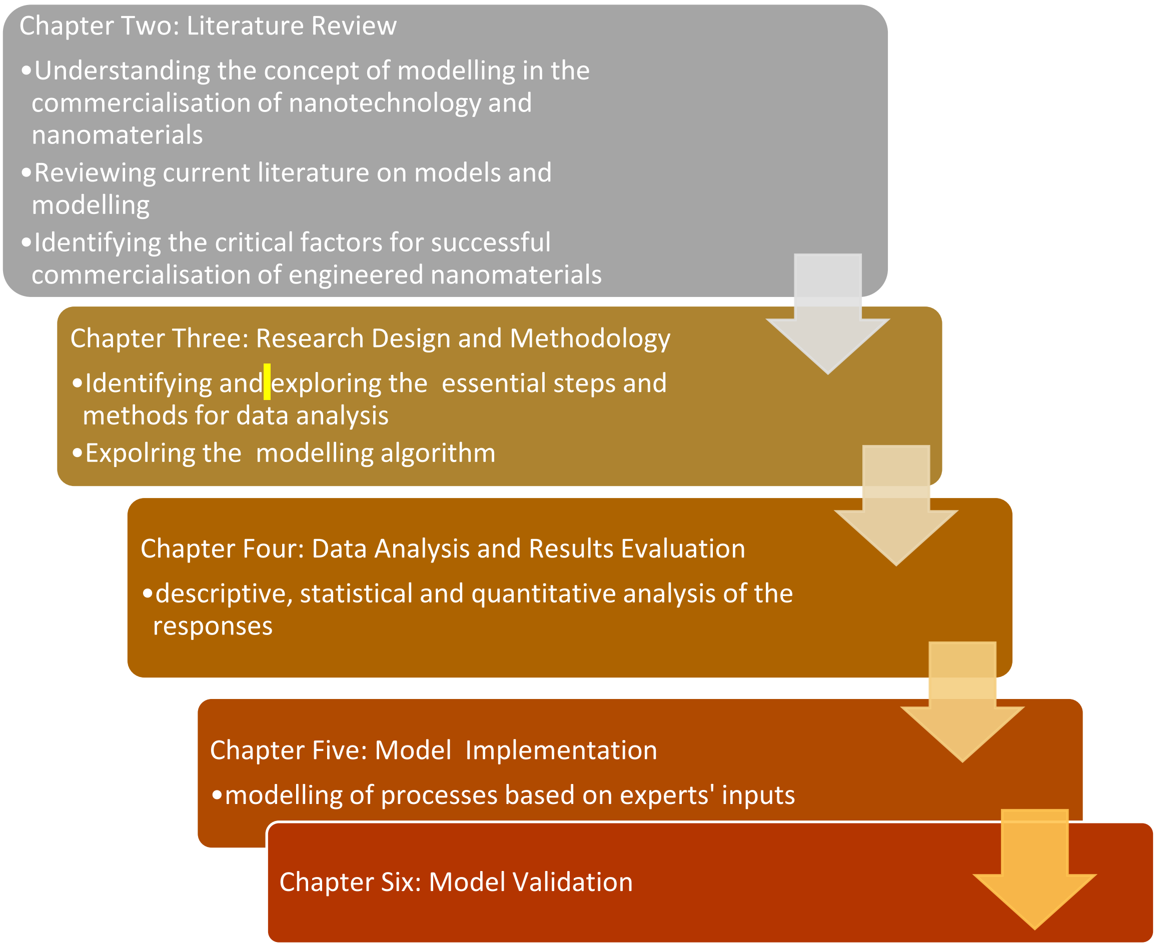


Figure 7.1: Framework for the entire study

Furthermore, this chapter is also designed to develop a background structure that will make available directions for the development of operational business modelling for the commercialisation of nanotechnology, especially that of engineered nano-materials using Operations Research techniques. The chapter concludes by highlighting some salient points for directions for future research in this new area of modelling nanotechnology commercialisation.

7.2 Conclusions

In an attempt to get a better understanding of the management and commercialisation of ENMs, this study was able to critically and analytically explore the empirical application of Operational Research techniques [(Analytical Hierarchy Process (AHP) and Data

Envelopment Analysis (DEA)] in the development of nanotechnology. This study has been able to address the various objectives highlighted in Chapter One.

Objective 1: To identify the critical factors and sub-factors necessary for effective the commercialisation of engineered nanotechnology materials. This has been achieved through the use of existing and current literature. The knowledge of nanotechnology researchers concerning the important factors of nanotechnology and its commercialisation were investigated by adopting the concept of the Delphi Method.

The study successfully identified ten critical evaluation factors. Each of these factors were further classified into various sub-factors, as depicted in Table 7.1.

Table 7.1: Identified Critical Factors for the Commercialisation of ENMs Application

Factor 1: Technical and Technological features of the nano product
▪ Intersection of nanotechnology with biotechnology ▪ Convergence of nanotechnology with information and communication technology (ICT) ▪ Scientific changes through a high level of technological support and technology management effectiveness ▪ Technical abilities of suppliers ▪ Local suitability of nanotechnology based on the country's environmental and socio-economic state ▪ Technological functionality, trial-ability and reliability
Factor 2: Economic factors
▪ Cost effectiveness ▪ Profit margins ▪ Increase in sales turnover
Factor 3: Production factors
▪ Production cost issues ▪ Labour intensity

Factor 4:	**Informative factors**
	▪ Publicity through the press and media ▪ Private-Public Partnership
Factor 5:	**Cultural factors**
	▪ Researchers-Investors constructive collaboration ▪ Awareness and emphasis of the national ministry of technology towards nanotechnology commercialisation ▪ Acculturation with respect to the commercialisation of nanotechnology
Factor 6:	**Social benefits**
	▪ Enhancement of social infrastructure/networks ▪ Employment creation ▪ Product branding and brand recognition ▪ Cost advantages to customers
Factor 7:	**Regulatory policies**
	▪ Patent & legal issues ▪ Governmental fiscal policies regulations ▪ Grant support & climate control by the international community
Factor 8:	**Marketing potentiality and forces**
	▪ Price suitability for sales facilitation ▪ Product aesthetic and packaging ▪ Product positioning and launch ▪ Market potential for end-products ▪ New market penetration for new and emerging technology
Factor 9:	**Organisation's strategic issues and features**
	▪ Organisational strategic implications ▪ Organisation's business policies ▪ Training and development support for technical and marketing staff

	▪ Personnel resources with generic and specialized nano commercialisation knowledge
Factor 10:	**Health and Safety**
	▪ Public opinion about toxic issues ▪ Safety issues

The study achieved this objective by highlighting the salient and critical factors that could be considered in management decision-making of the commercialisation of applications on emerging technology.

Objective 2: To develop a framework for modelling the commercialisation of nanotechnology materials in general and carbon nanotubes in particular. The study has been able to introduce the applications of modelling-based approaches to the commercialisation of engineered nano-materials. The Delphi technique and Analytical Hierarchy Process (AHP) were proposed. The Data Envelopment Analysis (DEA) was successfully used to confirm the results of the AHP by determining the efficiencies of the critical factors, thereby validating the priority model.

This research had been able to conduct an exploratory study on these modelling-based approaches. The applications of these techniques have also been introduced into the commercialisation of applications of engineered nano-materials. The Delphi Method was adopted to gather and authenticate data on the opinions of nanotechnology experts concerning the impact of nanotechnology and nano-materials and the commercialisation of their applications. The Analytical Hierarchy Process (AHP) was adopted to integrate the the opinions of nanotechnology researchers for the prioritisation of factors essential for the commercialisation of applications of nanotechnology materials.

The identified critical factors were prioritised for optimal nanotechnology commercialisation in the perspective of Operations Research and thereby a conceptualised framework was constructed for the effective and efficient commercialisation of engineered nano-materials. The framework was represented as a Hierarchical Model / Managerial Strategic Action Plan for the Quality Control and Commercialisation of ENMs in Figure 5.2.

This research adopted the Analytical Hierarchy Process (AHP) technique in prioritising identified critical factors for the optimum commercialisation of nanotechnology and nano-materials. The successful commercialisation of nanotechnology and engineered nano-materials is without doubt known to face prodigious challenges and hurdles, including the attainment of the ultimate goal of investors in nanotechnology and nano-materials which are to identify and prioritise the critical factors for successful commercialisation. This study used the AHP in achieving the ultimate goal of investors in nanotechnology and nano-materials through the identification and prioritisation of the critical factors for successful commercialisation. This was executed by fragmenting data into detailed performance factors and sub-factors, further distributed into hierarchical structures. The AHP – an Operational Research analytical technique - is appropriately used to solve real-world complex decision-making problems.

Objective 3: To determine if there is a significant difference between the priority rankings obtained through the Analytical Hierarchy Process (AHP) and Data Envelopment Analysis (DEA). A hypothesis was proposed for the validation of the priority model, which was subsequently tested using the rank correlation for its acceptance or rejection.

The computed rank correlation coefficient $\rho = 0.988$ shows very strong linear dependence between the two continuous variables representing the results obtained from the AHP and DEA techniques, validating the hierarchical model for the successful commercialisation of products from ENMs.

Expectedly, it is a common phenomenon for every study to leave opportunities for improvement. This study is no exemption. Although in this study an empirical attempt was made to prioritise the critical factors for the effective commercialisation of nanotechnology and ENMs, the following limitations have been observed:

- The Analytical Hierarchy Process (AHP) technique is subject to the opinions, and suggestions of experts and experts' opinions may be preconceived.
- The factors were assumed to be independent and regarded many times as limitations of the Analytical Hierarchy Process (AHP) and other Multi-factors Decision-Making methodologies (Kumar, Luthra and Haleem 2015).

- The Analytical Hierarchy Process pair-wise comparison matrices were populated through questionnaires sent to experts in the field of nanotechnology through an online survey website (www.surveymonkey.com).

In these views, the following research suggestions are proposed:

- In future research, there may be a need for the introduction of triangular fuzzy numbers into the Delphi Method and AHP techniques. It is known that uncertainties and ambiguities characterised the experts' judgments. These observed bottle-necks related with this bias could be eliminated by means of fuzzy numbers. The combination of the Fuzzy Theory and the traditional Delphi Method is the Fuzzy Delphi Method (FDM) (Saffie and Rasmani 2016). According to Devadoss, Sudha and Ajay (2014), the Fuzzy Delphi Method was christened by Murray, Pipino and Gigch (1985) in an attempt to resolve some linguistic ambiguity in the opinions and judgments of the experts interviewed and to empirically provide a model towards technology selection (Habibi, Jahantigh and Sarafrazi 2015). The FDM is a variant of the traditional DM (Lawnik and Banasik 2020) and has the potential of being used in gathering variables from the opinions of experts which are relevant and useful for the aim of integrating these variables in the process of decision-making (Detcharat, Pongpun and Tarathorn 2013). In cases of real life decision making environments, fuzzy logic, according to Devadoss, Sudha and Ajay (2014), is an essential tool in tackling decision making problems which are multi-factored and often characterised with fuzzy data that are imprecise and intrinsically vague. The adoption of the analytical methods in future studies will attempt to eliminate all nature of inexactness that may be encountered in experts' responses in the process of collecting data.

  The FDM is a kind with the goal of achieving a forecast without influence. It is a collective decision-making method (Chen and Wang 2013) comprising multiple rounds of surveys administered to seek the opinions of experts. Lin (2013); Tahriri, Mousavi, Haghighi and Dawal (2014); Kharat *et al.* (2019) confirmed that the application of the FDM to group decisions can solve the fuzziness of the common understanding of expert opinions. According to Suzianti, Mualim and Danisworo (2021), this analytical tool is characterised by the four unique properties, which are statistical, anonymity, feedback and convergence. Ishikawa, Saffie and Rasmani (2016) confirmed that the method is effective and economical in the process of integrating the opinions of decision-makers with technology evaluation factors. Based on these properties, the FDM could be applied to future studies on the process of the selection of a system, thereby increasing the model's development and application confidence.

The concept of Fuzzy Analytic Hierarchy Process (FAHP) was identified and adopted by Lan and Sheng (2014). The FAHP was used by the authors to analyse the relative weight and ranking of the critical factors that are identified to influence the consumers' purchase, which was earlier constructed from the critical review of the literature and by the Delphi technique. The study conducted is targeted at compensating for the insufficiency encountered in the previous study, which had been minimally researched by a negligible number of savants in a study that could be used as a reference for governmental policies for marketing strategy. The step-by-step procedure of FAHP was given in this study by Vinogradova-Zinkevič, Podvezko and Zavadskas (2021). This algorithm was also reported from the works of Drissi, Oumsis and Aboutajdine (2017) and Fan *et al.* (2020). Furthermore, the geometric mean is applied in integrating the opinions of the experts for the purpose of generating consistently concise and precise factor judgment in the process of constructing the fuzzy positive reciprocal matrix (Prascevic and Prascevic 2017) and the λ_{max} method is applicable in calculating the fuzzy weights (Ishizaka 2014).

- This study has been able to identify the factors that could enhance the successful commercialisation of engineered nano-materials through a literature review and experts' recommendations. The AHP was also attempted to carry out priority importance of these factors and this attempt was validated through the use of the DEA. It is recommended that future studies can consider the empirical analysis of the causal relationships amongst these sets of critical factors and their effects on organisational performance.

- Expert Choice software could be adopted subsequently against the Excel program. Expert Choice is known to be beneficial to AHP as the software is supporting and user-friendly and has contributed enormously to several breakthroughs in Analytical Hierarchy Process (Mangla, Kumar and Barua (2015).

- The study population could be heterogeneously well-defined to include a significant proportion of experts in nanotechnology operating in the market or industry. These are known to give a more consistent analysis, thereby reducing opinion biases of the experts (Lawnik and Banasik, 2020). Bursten *et al.* (2016) alluded that there is a need for synergy between the scientific experts and the members of the investment community in order to lead nano-based inventions to a successful market position.

- There exists some other Multi-factor Decision-Making methodologies which can also be adopted in modelling the commercialisation of nanotechnology and ENMs. These methods include TOPSIS and Analytic Network Process (ANP), amongst others. Despite its limitation, the Analytic Network Process (ANP) eliminates the limitation of factors independence in AHP and other Multi-factors Decision Making techniques, with the introduction of feedbacks to adjust weights (Huang and Wey 2019).

It is therefore expected that there should be a significant increase of Operational Research applications, especially Analytical Hierarchy Process and the Data Envelopment Analysis, in the modelling of effectiveness in the commercialisation of nanotechnology and engineered nano-materials. It is also expected that the various findings in this study would be used by policy-makers and scholars and serve as input for the national and international Science and Technology platform development.

7.3 Recommendations

Importantly, this study has been able to show that empirical analysis and modelling have much to offer in the practical development, optimisation and commercialisation of nanotechnology and engineered materials.

Based on the study exigency for the application of Operational Research modelling techniques to applications in emerging technology like nanotechnology, this research has been able to seek and study the factors necessary for the successful commercialisation of engineered nano-materials. It is envisaged that this will increase the Operational Research knowledge as regards nanotechnology commercialisation.

In addition, the results of this research have been able to provide scientific knowledge that will help researchers, technology investors and managers in the commercialisation process of engineered nano-materials. This study is a good test of the business modelling of nanotechnology commercialisation as it has been able to exhibit the benefits and challenges. In response to the challenges, this study has successfully met its objectives. Firstly, using existing and current literature, the study introduced the applications of the Analytical Hierarchy Process (AHP) for quantitative and business modelling for optimal nanotechnology commercialisation.

Another contribution is that the study has been able to investigate, via a survey, the knowledge and opinions of academics concerning the impact of nanotechnology and its commercialisation by adopting the concepts of the Delphi Method to integrate the diverse experts' opinions towards the multi-factors of nanotechnology materials.

The third important contribution is that the study was able to present nanotechnology evaluation factors for engineered nano-materials. This has helped in forming a general model of technology evaluation through a literature survey and experts' recommendations.

Furthermore, the vital contribution of this research is the prioritisation of ten (10) identified critical factors, which are illustrated in Figure 7.2 with their priority factors. These factors were further classified into sub-factors for optimal nanotechnology commercialisation in the perspective of Operations Research. The priority rating of the sub-factors is presented in Figures 7.3a-j.

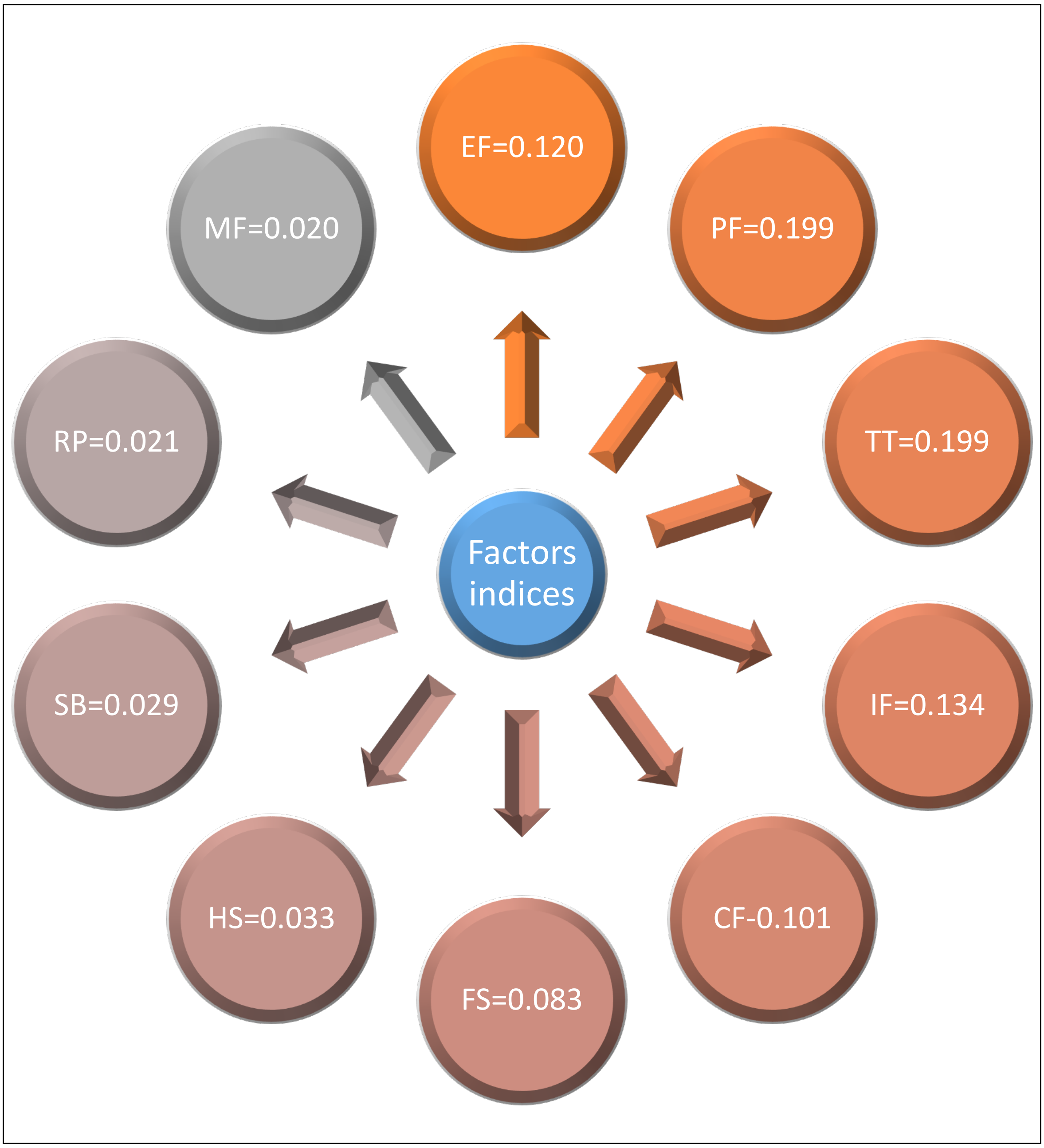


Figure 7.2: Factors indices for priority ranking of the 10 critical factors

This study uniquely identified ten (10) factors and thirty-four (34) critical sub-factors related to nanotechnology commercialisation. These factors and sub-factors of nanotechnology commercialisation will enable an improvement in the implementation of nanotechnology commercialisation within an organisation.

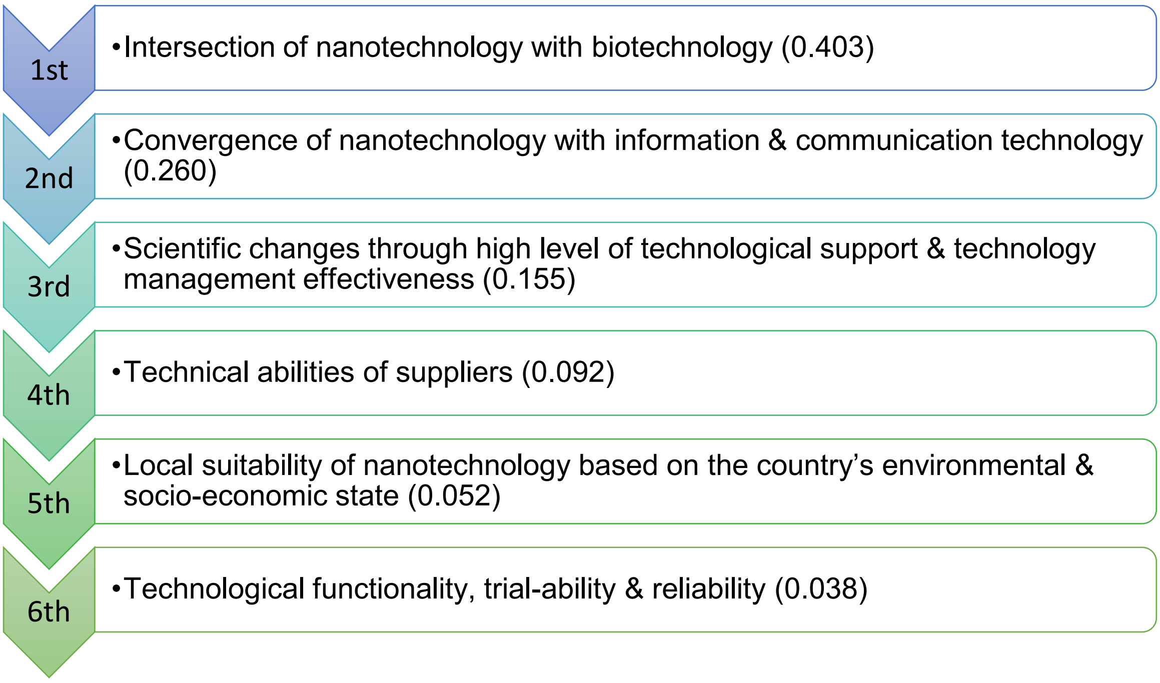


Figure 7.3a: Priority order of sub-factors related to the technical and technological features of the nanotechnology product

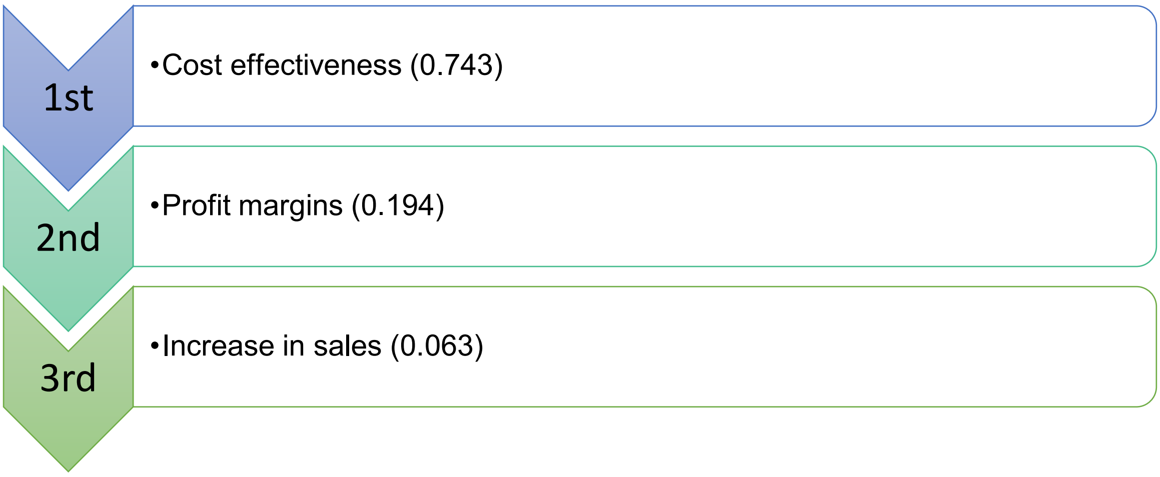


Figure 7.3b: Priority order of sub-factors related to the economic factors for the commercialisation of applications of nano-materials

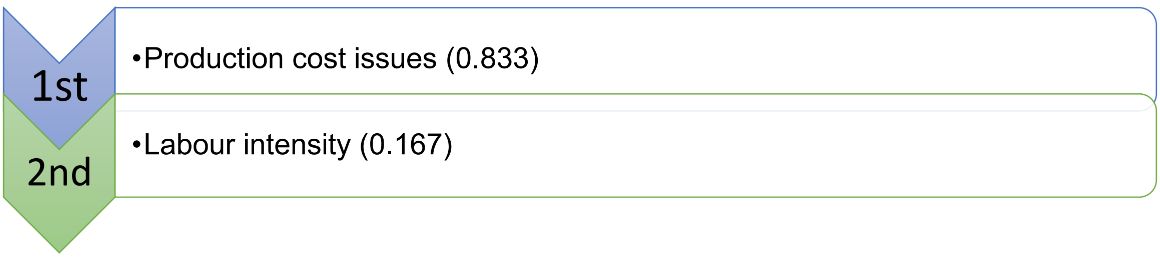


Figure 7.3c: Priority order of sub-factors related to the production factors

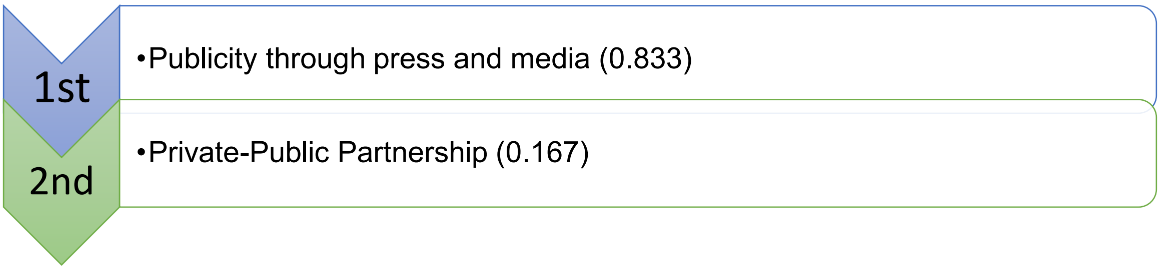


Figure 7.3d: Priority order of sub-factors related to the informative factors

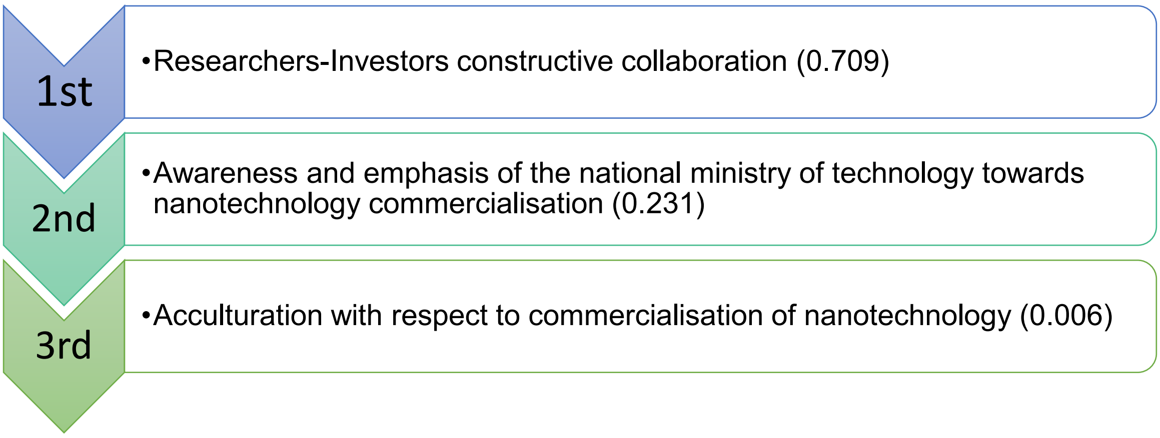


Figure 7.3e: Priority order of sub-factors related to the cultural factors

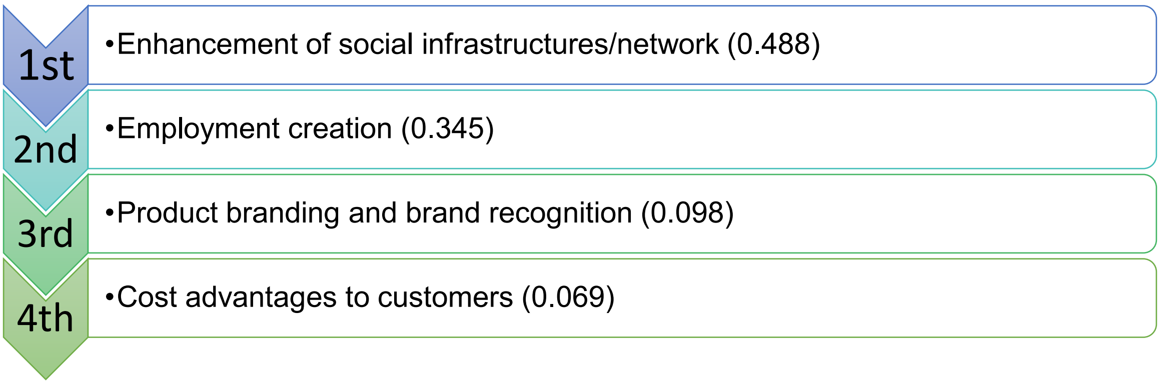


Figure 7.3f: Priority order of sub-factors related to the social benefits/factors

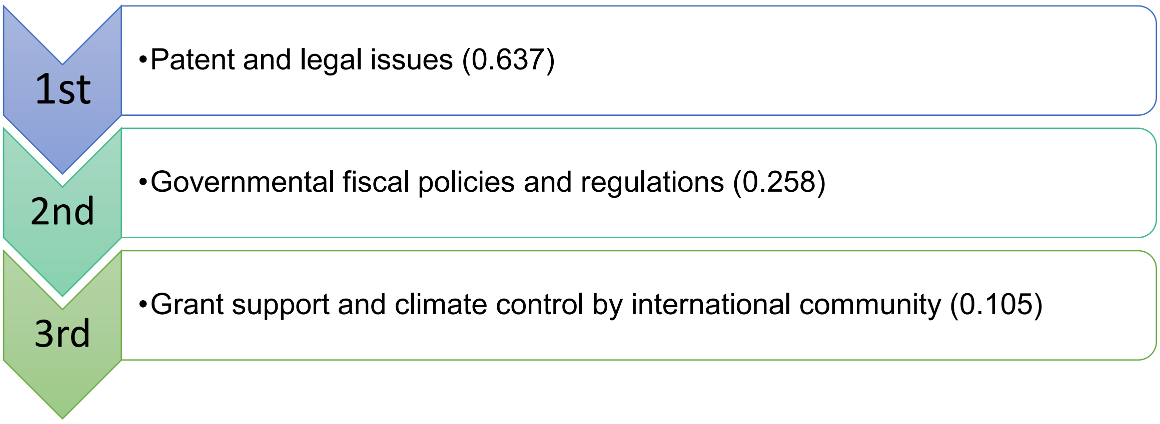


Figure 7.3g: Priority order of sub-factors related to the regulatory policies for the commercialisation of applications of nano-materials

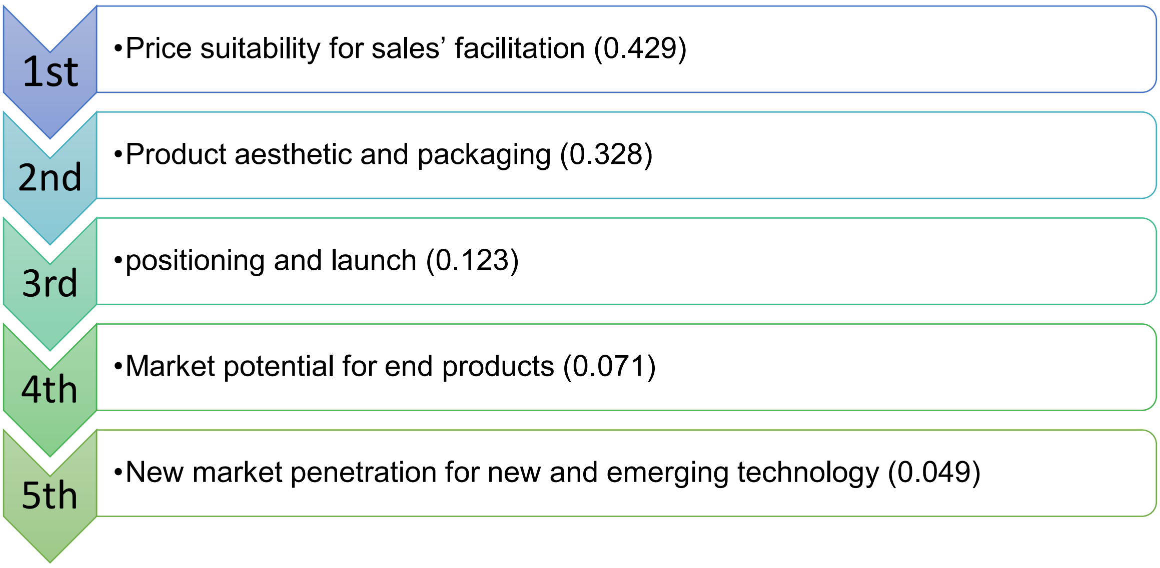


Figure 7.3h: Priority order of sub-factors related to the marketing potentiality and forces for the commercialisation of nano-materials' applications

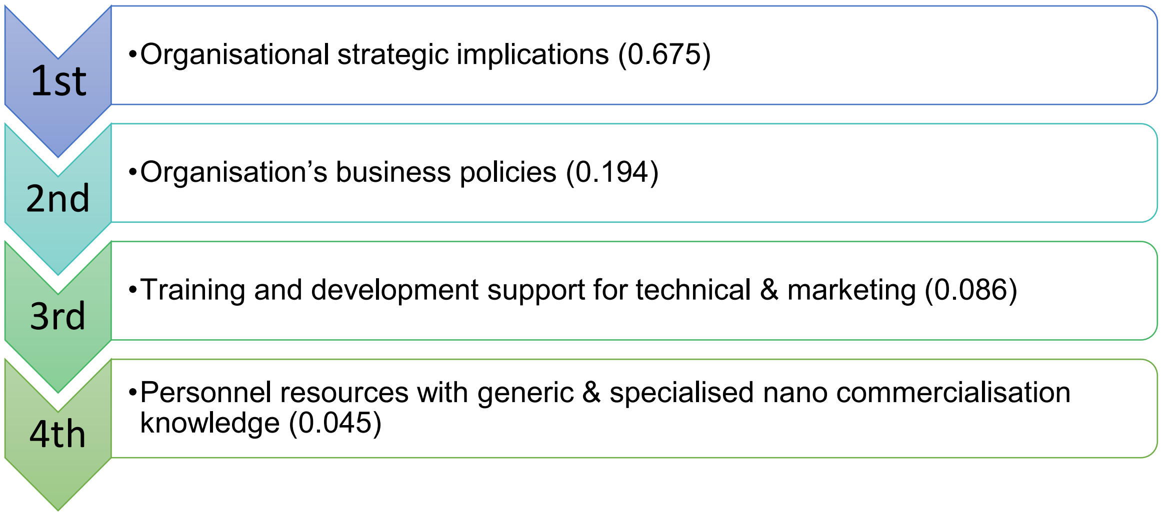


Figure 7.3i: Priority order of sub-factors related to the organisation's strategic issues and features

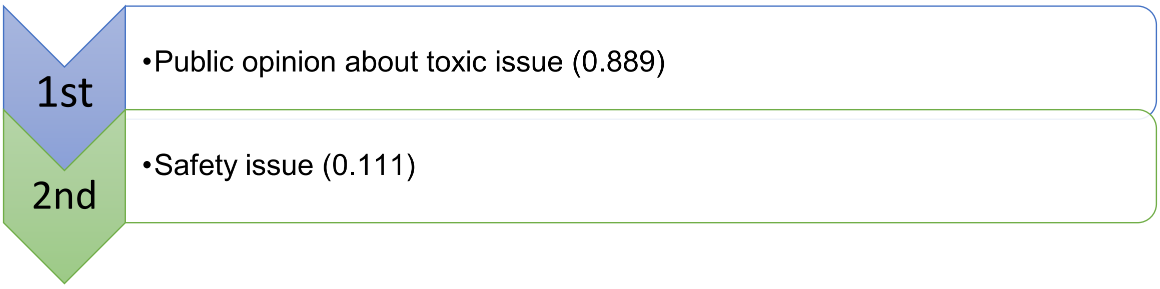


Figure 7.3j: Priority order of sub-factors related to the 'Health and Safety' factor for the commercialisation of applications of nano-materials.

Mostly importantly, this research has been able to construct a conceptualised analytical model for the effective and efficient commercialisation of engineered nano-materials. Finally, the methodology adopted in this study could serve as a roadmaps for the researcher or other researchers into various other nanofields specifically, nanomedicine, nanoelectronics and nanoenergy, amongst others.

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APPENDIX 1

DELPHI PILOT SURVEY RESEARCH QUESTIONNAIRE

INVITATION FOR INTERVIEW PARTICIPATION

(MODELLING OF COMMERCIALISATION OF NANOTECHNOLOGY ENGINEERED MATERIALS)

Dear Sir/Madam

I am a doctoral candidate in the Department of Operations & Quality Management of the Durban University of Technology (DUT). My research is aimed at developing a quantitative model for the consideration and evaluation of the critical success factors for the commercialisation of nanotechnology engineering materials.

Commercialisation of Nanotechnology has increasingly been emerging as a recent and relevant point of discussion and research among businesses, industries, nongovernmental organisations, governments and of course academics in last few years across the world as well as in South Africa. A critical knowledge of commercialisation of emerging technology has also been identified as a very useful approach to gain competitive leverage especially in a competitive business environment.

Being an expert in nanotechnology, your relevant and valuable expertise and experience (business or technology) in this field of study is highly desirous and cherished as you are invited to participate in this survey.

The questionnaire is divided into 4 sections. Attached as Appendix 2. This will not take more than 12 minutes of your time.

The survey is designed to seek your expert opinions as there is no expected correct or incorrect answer for each question.

Confidentiality will be strictly adhered to.

For any queries, kindly contact me on olahezekiah@yahoo.co.uk or 21452297@dut4life.ac.za or my Principal Supervisor, Dr Shalini Singh on singhs@dut.ac.za.

Your contributions towards this study are highly appreciated.

Yours sincerely,

Hezekiah Oladimeji
Doctoral candidate
Department of Operations & Quality Management
Durban University of Technology (DUT)
Durban, South Africa

APPENDIX 2

Interview Question

BUSINESS MODELLING FOR QUALITY CONTROL & COMMERCIALISATION OF NANO-ENGINEERED MATERIALS

Background: From time to time, new technologies with the potential to change the configuration of the entire global economy arise. Nanotechnology seems to be one of the technologies with such potential. Scientists have made some progress at building devices, including computer components, at nanoscales. Faster progress has occurred in the incorporation of nano-materials in other products, such as stain-resistant coatings for clothes and invisible sunscreens.

Awareness of managers of Nanotechnology organisations about the necessity and importance of a Business model in surviving and developing commercialisation of this technology is vital. Meanwhile, the commercialisation of nanotechnology depends on several factors. Modelling of these important factors is essential for any nanotechnology device to 'hit' the market.

This research aims to explore available nanotechnology quantitative models and modelling of factors essential for success of commercialisation of nanotechnology products from an empirical viewpoint and to solve practical problems through basic mathematical models.

Objective: The basic aim of this questionnaire is to identify the critical factors essential for successful commercialisation of nanotechnology products, concomitantly, complement the current research status of nanotechnology commercialisation. As soon as these critical factors are identified, the outcomes will be integrated for the purpose of developing quantitative models essential for facilitating new technological commercialisation decision making.

Privacy: All responses will be kept highly confidential and purposely for this research only.

Survey Time Frame: Please feel free to complete the questionnaire within a time frame of 9-12 minutes.

SECTION I: RESPONDENT'S TECHNICAL EXPERTISE

1. What is your area of expertise or specialisation in nanotechnology?

   Nanomedicine ☐

   Nanobiotechnology ☐

   Nanoprocessing ☐

   Health & Safety ☐

   Nanoenergy ☐

   Nano R&D ☐

   Nanodevice/Nanoelectronics ☐

   Nanocommercialisation ☐

   Nanoentrepreneurship ☐

   OTHERS: (Please state) …………………

2. What is your experience (in years) in nanotechnology?

   1-5…… 5-10…… 10-15….. Above 15……

3. Are you aware of any modelling technique in commercialisation of nanotechnology engineered materials?

   Yes………. No……… Not sure…………..

4. If your answer in 3 above is Yes, please state the model(s)

   ………………………………….

   ………………………………….

   ………………………………….

   ………………………………….

5. Which of the model (s), in your own opinion, is/are relevant for successful commercialisation of nanotechnology? …………………………………………

   …………………………………………………………………………………….

   …………………………………………………………………………………….

SECTION II: RATING OF CRITICAL FACTORS/FACTORS FOR NANOTECHNOLOGY COMMERCIALISATION

Instruction: Based on your experience in this area of expertise, kindly rate the significance of the factors for nanotechnology commercialisation as listed for the purpose of developing quantitative models essential for facilitating new technological commercialisation decision making. These factors have been derived from various research articles in literature.

Please, simply tick level of importance:

	Factors	Level of importance (Low)1 2 3 4 5 (High)
1	Technical & Technological feature of the nano product	
2	Economic factors	
3	Production factors	
4	Informative factors	
5	Cultural factors	
6	Social benefits	
7	Regulatory policies	
8	Marketing potentiality & forces	
9	Organisation's strategic issues & features	
10	Health & Safety	

This list of factors might not be exhaustive, kindly suggest other factor(s) which, in your candid opinion, can influence successful commercialisation of emerging technologies such as nanotechnology:

……………………………………………………………

……………………………………………………………

……………………………………………………………

SECTION III: RATING OF SUB-FACTORS FOR NANOTECHNOLOGY COMMERCIALISATION

Instruction: Based on your experience in this area of expertise, kindly rate the significance of the sub-factors for nanotechnology commercialisation as listed for the purpose of developing quantitative models essential for facilitating new technological commercialisation decision making in nanotechnology. These sub-factors have been derived from various reviews and articles in literature.

Please, simply tick level of importance:

	Sub-factors	Level of importance (Low)1 2 3 4 5 (High)
1a	Intersection of nanotechnology with biotechnology	
1b	Convergence of nanotechnology with information & communication technology (ICT)	
1c	Scientific changes through high level of technological support & technology management effectiveness	
1d	Technical abilities of suppliers	
1e	Local suitability of nanotechnology based on the country's environmental & socio-economic state.	
1f	Technological functionality, trial-ability & reliability	
2a	Cost effectiveness	
2b	Profit margins	
2c	Increase in sales turnover	
3a	Production cost issues	
3b	Labour intensity	
4a	Publicity through press & media	
4b	Private-Public Partnership	
5a	Researchers-Investors constructive collaboration	
5b	Awareness &emphasis of national ministry of technology towards nanotechnology commercialisation	
5c	Acculturation with respect to commercialisation of nanotechnology	
6a	Enhancement of social infrastructures/network	
6b	Employment creation	
6c	Product branding & brand recognition	
6d	Cost advantages to customers	
7a	Patent & legal issues	
7b	Governmental fiscal policies & regulations	
7c	Grant support & climate control by international community	
8a	Price suitability for sales' facilitation	
8b	Product aesthetic & packaging	

8c	Product positioning & launch	
8d	Market potential for end products	
8e	New market penetration for new & emerging technology	
9a	Organisational strategic implications	
9b	Organisation's business policies	
9c	Training & development support for technical & marketing staff	
9d	Personnel resources with generic & specialized nano commercialisation knowledge	
10a	Public opinion about toxic issue	
10b	Safety issue	

SECTION IV: PERSONAL CHARACTERISTICS OF RESPONDENTS

SEX: Male ☐ Female ☐

AGE: Below 25 ☐ 25-35 ☐ 35-45 ☐ 45-55 55 & Above

Degree qualification: BSc ☐ MSc ☐ PhD ☐ Others ☐

Kindly state any other comments or recommendations about this project either relating to the statements above or otherwise: ………………………………………………….

…………………………………………………………………………………………

…………………………………………………………………………………………..

Thank you so much!!

APPENDIX 3 (RESEARCH QUESTIONNAIRE)

INVITATION FOR ANALYTICAL HIERARCHICAL PROCESS (AHP) QUESTIONNAIRE PARTICIPATION

Dear Sir/Madam

The intent of this research study is to carry out an extensive investigation and evaluation of critical success factors for commercialisation of nanotechnology engineered materials. Previous surveys (Literature and Questionnaire Survey) were designed to identify those critical factors essential for successful commercialisation of nanotechnology products, concomitantly, complements the current research status of nanotechnology commercialisation.

Essentially, your input to this survey, as a result of your experience and expertise in nanotechnology, is highly important.

Privacy: All responses will be kept highly confidential and purposely for this research only.

Survey Time Frame: Please feel free to complete the questionnaire within a time frame of 9-12 minutes.

Your contributions towards this study are highly appreciated.

Yours sincerely,

Hezekiah Oladimeji

Doctoral candidate
Department of Operations & Quality Management
Durban University of Technology (DUT)
Durban, South Africa

APPENDIX 4 (QUESTIONNAIRE)

DUT DURBAN UNIVERSITY OF TECHNOLOGY

(MODELLING OF COMMERCIALISATION OF ENGINEERED NANO-MATERIALS)

General Instruction: This questionnaire consists of a number of questions sets for the purpose of pair-wise comparison. A rating scale is giving for each set as stated thus:

Linguistic Scale for Importance	Scale
Absolutely More Important	9
Very Strong More Important	8
Strong More Important	7
Weakly More Important	6
Equal Important	5
Weakly Low Important	4
Strong Low Important	3
Very Strong Low Important	2
Absolutely Low Important	1

Kindly compare the importance of the factor on the left against (vs) the factor on the right and cross mark 'X' for the desired option under the importance level column.

Section 1: Relative importance of critical factors for successful nanotechnology commercialisation

The ten critical factors and their respective abbreviation are:

	Factors	Abbreviation
1	Technical & Technological feature of the nano product	TechFeature
2	Economic factors	EcoFactor
3	Production factors	ProdFactor
4	Informative factors	InfoFactor
5	Cultural factors	CultFactor
6	Social benefits	SocBenefit
7	Regulatory policies	RegPolicy
8	Marketing potentiality & forces	MarketForce
9	Organisation's strategic issues & features	OrganisationStrategy
10	Health & Safety	HealthSafety

Pair-wise comparison (FACTORS)	1	2	3	4	5	6	7	8	9
TechFeature VS EcoFactor									
TechFeature VS ProdFactor									
TechFeature VS InfoFactor									
TechFeature VS CultFactor									
TechFeature VS SocBenefit									
TechFeature VS RegPolicy									

TechFeature VS MarketForce									
TechFeature VS OrganisationStrategy									
TechFeature VS HealthSafety									
EcoFactor VS ProdFactor									
EcoFactor VS InfoFactor									
EcoFactor VS CultFactor									
EcoFactor VS SocBenefit									
EcoFactor VS RegPolicy									
EcoFactor VS MarketForce									
EcoFactor VS OrganisationStrategy									
EcoFactor VS HealthSafety									
ProdFactor VS InfoFactor									
ProdFactor VS CultFactor									
ProdFactor VS SocBenefit									
ProdFactor VS RegPolicy									
ProdFactor VS MarketForce									
ProdFactor VS OrganisationStrategy									
ProdFactor VS HealthSafety									
InfoFactor VS CultFactor									
InfoFactor VS SocBenefit									
InfoFactor VS RegPolicy									
InfoFactor VS MarketForce									
InfoFactor VS OrganisationStrategy									
InfoFactor VS HealthSafety									
CultFactor VS SocBenefit									
CultFactor VS RegPolicy									
CultFactor VS MarketForce									
CultFactor VS OrganisationStrategy									
CultFactor VS HealthSafety									
SocBenefit VS RegPolicy									
SocBenefit VS MarketForce									
SocBenefit VS OrganisationStrategy									
SocBenefit VS HealthSafety									
RegPolicy VS MarketForce									
RegPolicy VS OrganisationStrategy									
RegPolicy VS HealthSafety									
MarketForce VS OrganisationStrategy									
MarketForce VS HealthSafety									
OrganisationStrategy VS HealthSafety									

Section 2: Relative importance of sub-factors for successful nanotechnology commercialisation

Sub-section 2-1: This sub-section compares the sub-factors related to **Technical & Technological feature of the nano product**

Q1: How important is *intersection of nanotechnology with biotechnology* when compared with *convergence of nanotechnology with information & communication technology (ICT)*

Q2: How important is *intersection of nanotechnology with biotechnology* when compared with *scientific changes through high level of technological support & technology management effectiveness*

Q3: How important is *intersection of nanotechnology with biotechnology* when compared with *technical abilities of suppliers*

Q4: How important is *intersection of nanotechnology with biotechnology* when compared with *local suitability of nanotechnology based on the country's environmental & socio-economic state.*

Q5: How important is *intersection of nanotechnology with biotechnology* when compared with *technological functionality, trial-ability & reliability*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q1									
Q2									
Q3									
Q4									
Q5									

Q6: How important is *convergence of nanotechnology with information & communication technology (ICT)* when compared with *scientific changes through high level of technological support & technology management effectiveness*

Q7: How important is *convergence of nanotechnology with information & communication technology (ICT)* when compared with *technical abilities of suppliers*

Q8: How important is *convergence of nanotechnology with information & communication technology (ICT)* when compared with *local suitability of nanotechnology based on the country's environmental & socio-economic state.*

Q9: How important is *convergence of nanotechnology with information & communication technology (ICT)* when compared with *technological functionality, trial-ability & reliability*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q6									
Q7									
Q8									
Q9									

Q10: How important is *scientific changes through high level of technological support & technology management effectiveness* when compared with *technical abilities of suppliers*

Q11: How important is *scientific changes through high level of technological support & technology management effectiveness* when compared with *local suitability of nanotechnology based on the country's environmental & socio-economic state*

Q12: How important is *scientific changes through high level of technological support & technology management effectiveness* when compared with t*echnological functionality, trial-ability & reliability*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q10									
Q11									
Q12									

Q13: How important is *technical abilities of suppliers* when compared with *local suitability of nanotechnology based on the country's environmental & socio-economic state*

Q14: How important is *technical abilities of suppliers* when compared with t*echnological functionality, trial-ability & reliability*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q13									
Q14									

Q15: How important is *local suitability of nanotechnology based on the country's environmental & socio-economic state* when compared with t*echnological functionality, trial-ability & reliability*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q15									

Sub-section 2-2: This sub-section compares the sub-factors related to **Economic factors**

Q16: How important is *cost effectiveness* when compared with *profit margins*

Q17: How important is *cost effectiveness* when compared with *increase in sales turnover*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q16									
Q17									

Q18: How important is *profit margins* when compared with *increase in sales turnover*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q18									

Sub-section 2-3: This sub-section compares the sub-factors related to **Production factors**

Q19: How important is *Production cost issues* when compared with *labour intensity*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q19									

Sub-section 2-4: This sub-section compares the sub-factors related to **Informative factors**

Q20: How important is *publicity through press & media* when compared with *Private-Public Partnership*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q20									

Sub-section 2-5: This sub-section compares the sub-factors related to **Cultural factors**

Q21: How important is *researchers-Investors constructive collaboration* when compared with *awareness &emphasis of national ministry of technology towards nanotechnology commercialisation*

Q22: How important is *researchers-Investors constructive collaboration* when compared with *acculturation with respect to commercialisation of nanotechnology*

Q23: How important is *awareness &emphasis of national ministry of technology towards nanotechnology commercialisation* when compared with *acculturation with respect to commercialisation of nanotechnology*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q21									
Q22									

Q23: How important is *awareness &emphasis of national ministry of technology towards nanotechnology commercialisation* when compared with *acculturation with respect to commercialisation of nanotechnology*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q23									

Sub-section 2-6: This sub-section compares the sub-factors related to **Social Benefits**

Q24: How important is *enhancement of social infrastructures/network* when compared with *employment creation*

Q25: How important is *enhancement of social infrastructures/network* when compared with *Product branding & brand recognition*

Q26: How important is *enhancement of social infrastructures/network* when compared with *cost advantages to customers*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q24									
Q25									
Q26									

Q27: How important is *employment creation* when compared with *product branding & brand recognition*

Q28: How important is *employment creation* when compared with *cost advantages to customers*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q27									
Q28									

Q29: How important is *product branding & brand recognition* when compared with *cost advantages to customers*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q29									

Sub-section 2-7: This sub-section compares the sub-factors related to **Regulatory policies**

Q30: How important is *patent & legal issues* when compared with *governmental fiscal policies & regulations*

Q31: How important is *patent & legal issues* when compared with *grant support & climate control by international community*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q30									
Q31									

Q32: How important is *governmental fiscal policies & regulations* when compared with *grant support & climate control by international community*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q32									

Sub-section 2-8: This sub-section compares the sub-factors related to **Marketing potentiality & forces**

Q33: How important is *price suitability for sales' facilitation & regulations* when compared with *product aesthetic & packaging*

Q34: How important is *price suitability for sales' facilitation & regulations* when compared with *product positioning & launch*

Q35: How important is *price suitability for sales' facilitation & regulations* when compared with *market potential for end products*

Q36: How important is *price suitability for sales' facilitation & regulations* when compared with *new market penetration for new & emerging technology*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q33									
Q34									
Q35									
Q36									

Q37: How important is *product aesthetic & packaging* when compared with *product positioning & launch*

Q38: How important is *product aesthetic & packaging* when compared with *market potential for end products*

Q39: How important is *product aesthetic & packaging* when compared with *new market penetration for new & emerging technology*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q37									
Q38									
Q39									

Q40: How important is *product positioning & launch* when compared with *market potential for end products*

Q41: How important is *product positioning & launch* when compared with *new market penetration for new & emerging technology*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q40									
Q41									

Q42: How important is *market potential for end products* when compared with *new market penetration for new & emerging technology*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q42									

Sub-section 2-9: This sub-section compares the sub-factors related to **Organisation's strategic issues & features**

Q43: How important is *organisational strategic implications* when compared with *organisation's business policies*

Q44: How important is *organisational strategic implications* when compared with *training & development support for technical & marketing staff*

Q45: How important is *organisational strategic implications* when compared with *personnel resources with generic & specialized nano commercialisation knowledge*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q43									
Q44									
Q45									

Q46: How important is *organisation's business policies* when compared with *training & development support for technical & marketing staff*

Q47: How important is *organisation's business policies* when compared with *personnel resources with generic & specialized nano commercialisation knowledge*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q46									
Q47									

Q48: How important is *training & development support for technical & marketing staff* when compared with *personnel resources with generic & specialized nano commercialisation knowledge*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q48									

Sub-section 2-10: This sub-section compares the sub-factors related to **Health & Safety**

Q49: How important is *public opinion about toxic issue* when compared with *safety issue*

Pair-wise comparison	1	2	3	4	5	6	7	8	9
Q49									

Time spent is really appreciated.

All information will be kept confidential and strictly for academic research purposes only.

For completing this questionnaire, we say 'THANK YOU'

End!!!

APPENDIX 5 (LINDO –OUTPUT- SOLUTION OF LP MODEL)

LP OPTIMUM FOUND AT STEP 34

OBJECTIVE FUNCTION VALUE

1) 0.1445676E-01

VARIABLE	VALUE	REDUCED COST
Z	0.014457	0.000000
W1	**0.368921**	0.000000
W2	**0.173596**	0.000000
W3	**0.114992**	0.000000
W4	**0.099311**	0.000000
W5	**0.088565**	0.000000
W6	**0.080515**	0.000000
W7	**0.020729**	0.000000
W8	**0.020276**	0.000000
W9	**0.018638**	0.000000
W10	**0.014457**	0.000000
V1	0.036892	0.000000
V2	0.017360	0.000000
V3	0.011499	0.000000
V4	0.009931	0.000000
V5	0.004951	0.000000
V6	0.004501	0.000000
V7	0.001873	0.000000
V8	0.002028	0.000000
V9	0.001864	0.000000
V10	0.001446	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.354464	0.000000
3)	0.159139	0.000000
4)	0.100535	0.000000
5)	0.084854	0.000000
6)	0.074108	0.000000
7)	0.066058	0.000000
8)	0.006272	0.000000
9)	0.005819	0.000000
10)	0.004182	0.000000
11)	0.000000	-1.000000
12)	0.000000	0.004910
13)	0.000000	0.006686
14)	0.000000	0.009379
15)	0.000000	0.010801
16)	0.000000	0.014647
17)	0.000000	0.015813
18)	0.000000	0.014457

19)	0.000000	0.007495
20)	0.000000	0.013452
21)	0.000000	-1.031315
22)	0.000000	0.014457
23)	0.016269	0.000000
24)	0.007656	0.000000
25)	0.005071	0.000000
26)	0.004380	0.000000
27)	0.000000	-0.003400
28)	0.000000	-0.024258
29)	0.000714	0.000000
30)	0.000894	0.000000
31)	0.000822	0.000000
32)	0.000638	0.000000
33)	0.000000	0.095469
34)	0.000000	0.077711
35)	0.000000	0.050776
36)	0.000000	0.036557
37)	0.003906	0.000000
38)	0.003551	0.000000
39)	0.000200	0.000000
40)	0.000000	0.069614
41)	0.000000	0.010051
42)	0.000000	0.457715

NO. ITERATIONS= 34

RANGES IN WHICH THE BASIS IS UNCHANGED:

	OBJ COEFFICIENT RANGES		
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
Z	1.000000	INFINITY	1.000000
W1	0.000000	0.001592	0.011155
W2	0.000000	0.001251	INFINITY
W3	0.000000	0.006085	0.004801
W4	0.000000	0.007046	0.005560
W5	0.000000	0.030280	0.002155
W6	0.000000	0.039124	0.002027
W7	0.000000	0.652144	0.009071
W8	0.000000	1.455801	0.029681
W9	0.000000	INFINITY	0.018881
W10	0.000000	INFINITY	1.000000
V1	0.000000	0.015915	0.092095
V2	0.000000	0.012512	0.081997
V3	0.000000	0.060854	0.048014
V4	0.000000	0.070462	0.039944
V5	0.000000	0.003729	0.249424
V6	0.000000	0.026281	0.036255

V7	0.000000	0.010327	0.012109
V8	0.000000	14.558015	0.068607
V9	0.000000	INFINITY	0.009543
V10	0.000000	INFINITY	0.437682

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	0.000000	0.354464	INFINITY
3	0.000000	0.159139	INFINITY
4	0.000000	0.100535	INFINITY
5	0.000000	0.084854	INFINITY
6	0.000000	0.074108	INFINITY
7	0.000000	0.066058	INFINITY
8	0.000000	0.006272	INFINITY
9	0.000000	0.005819	INFINITY
10	0.000000	0.004182	INFINITY
11	0.000000	0.014457	0.004182
12	0.000000	0.029186	0.097245
13	0.000000	0.015676	0.052927
14	0.000000	0.011724	0.039579
15	0.000000	0.010375	0.034947
16	0.000000	0.013657	0.044824
17	0.000000	0.012868	0.042300
18	0.000000	0.002004	0.012615
19	0.000000	0.002133	0.007623
20	0.000000	0.001848	0.006852
21	0.000000	0.001387	0.004713
22	1.000000	INFINITY	1.000000
23	0.000000	0.016269	INFINITY
24	0.000000	0.007656	INFINITY
25	0.000000	0.005071	INFINITY
26	0.000000	0.004380	INFINITY
27	0.000000	0.002623	0.000753
28	0.000000	0.002469	0.000710
29	0.000000	0.000714	INFINITY
30	0.000000	0.000894	INFINITY
31	0.000000	0.000822	INFINITY
32	0.000000	0.000638	INFINITY
33	0.000000	0.010772	0.002836
34	0.000000	0.005589	0.001543
35	0.000000	0.004121	0.001159
36	0.000000	0.003621	0.001027
37	0.000000	INFINITY	0.003906
38	0.000000	INFINITY	0.003551
39	0.000000	INFINITY	0.000200
40	0.000000	0.000768	0.000213
41	0.000000	0.000690	0.000184
42	0.000000	0.000512	0.000139