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RESEARCH PAPER

The "Nanotechnology Innovation Diamond", a model for successful nanoscience research and development

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Abstract Although technology innovation management has been extensively studied, little research has been conducted in nanotechnology-focused innovation management. No model currently exists on nanotechnology innovation management and the related critical success factors. Based on a literature review of nanotechnology characteristics and reported successful nanotechnology research, six essential factors of success were identified. These factors are consumer acceptance of nanotechnology, hybridisation of nanotechnology innovations into existing industries and markets, multidisciplinary project teams, agglomeration and clustering of nanotechnology research projects, research and development (R&D) and commercialisation skills and capabilities, and working within a conducive innovation environment. These six factors were crystallised into the "Nanotechnology Innovation Diamond", a model for successful nanoscience research and development. The proposed model was then validated using confirmatory factor analysis (CFA) from a survey of 167 nanotechnology experts from South Africa. The results indicate that at 95% confidence level, the proposed model satisfied the minimum CFA model fit requirements, and the six proposed critical success factors are significant for successful nanotechnology R&D. The presented model can be used to increase the rate of success of nanotechnology R&D projects, nanotechnology project portfolio selection, and nanotechnology foresight exercises.

Keywords Confirmatory factor analysis · Nanotechnology · Innovation management · Nanotechnology Innovation Diamond · Nanotechnology innovation model · Nanotechnology critical success factors

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Introduction

Nanotechnology is a broad general-purpose technology, with applications in any field imaginable. To ensure limited resources are prudently utilised, countries or businesses cannot invest in nanotech across the board, but they have to select, focus, and concentrate on a few projects (Lee and Song 2007; Connell et al. 2001; Shen et al. 2010). The selected projects must be well managed so that they result in successful nanotechnology research. Although technological innovation strategies have been extensively studied, little research has been conducted on managing innovation in nanotechnology (Meyer 2007; Linton and Walsh 2008). No framework currently exists on successful nanotechnology management. This paper proposes a model that can be used to improve the success rate of nanotechnology innovations and as a tool to aide nanotechnology portfolio management and foresight exercises.

Successful nanotechnology

The construct of successful nanotechnology on one hand centres around taking nanoscience R&D products and services from the lab and commercialising them, and this includes both new products and improvement of existing products. Pathways used for commercialisation include new venture creations, start-ups, spin-offs, and technology licensing (Aithal and Aithal 2016; Maine 2014; Schultz 2011). On the other hand, patents and academic publications are routinely used as indicators for measuring the success of nanotechnology (Marinova and McAleer 2002; Hullman and Meyer 2003; Pouris 2007; Islam and Miyazaki 2010; Karpagam et al. 2011; Tanaka 2013). Thus, successful nanotechnology is thought to result in several R&D outputs that include new products, improved existing products, patents, licenses,academic publications, new ventures, and spin-off companies, among others.

For a firm to produce the above outputs, it requires human capital with capabilities such as scientific-research skills, research publishing, patenting and intellectual property management, licensing, and commercialisation of research. Maine (2014) termed researchers with such skills scientist-entrepreneurs. However, Porter and Stern (2001) argue that in addition to the company's internal R&D and innovation capabilities, the environment in which innovation occurs also has a significant contribution to the success of innovations. As outlined in the sections that follow below, several other factors affecting the success of nanotechnology are found in the literature. This paper discusses these factors and crystallise them into the proposed model, termed the Nanotechnology Innovation Diamond. The article goes on to report on the empirical evaluation of the Nanotechnology Innovation Diamond using confirmatory factor analysis (CFA).

General-purpose technology

Several scholars describe nanotechnology as a general-purpose technology (GPT), which is pervasive and whose applications are found in every economic sector imaginable (Shea et al. 2011; Kreuchauff and Teichert 2014; Bresnahan and Trajtenberg 1995; Shapira and Youtie 2008; Roco et al. 2011; Battard 2012; Cunningham and Werker 2012). Thus, nanotechnology has led to numerous inventions and innovations that are impacting many areas such as information technology, materials, medical diagnostics, catalysis, energy, and environmental applications among others. Salerno et al. (2008) note that when one considers the diverse list of technological applications impacted by nanotechnology, it is reasonable to argue that the "nanotechnology revolution will impact nearly all aspects of human life". This fact is supported by Hullman (2007), who concluded that nanotechnology has the potential to reach economic impact level similar to that of information and communications technology (ICT). Shea et al. (2011) add that from a policy perspective, viewing nanotechnology through the lens of GPT should encourage investment in nanoscience because such investments result in spillovers to all economic sectors due to the pervasive nature of GPTs.

Nanotechnology's pervasiveness has grown to such an extent that it is beginning to move out of technical disciplines to affect humanities, for example management, such that "nanotechnology management research" is starting to appear in peer-reviewed management journals (Shea et al. 2011).

Industry hybridisation

There are several existing industry and market product improvements that can be done using nanoscience. For example, scratch-resistant paints, stain-resistant clothes, smaller electronics, gas sensors, and efficient photovoltaics are all market needs in existing markets and products that can be solved by nanotechnology. Improvements from nanotechnologies can be incorporated into existing products, producing hybrid industries and products such as nanomedicine, nanophotovoltaics, nanofibers, nanoagriculture, nanopolymers, nanosensors, and nanocatalysis, just to name a few (Aithal and Aithal 2016; Avenel et al. 2007). A single nanoscience discovery or invention could result in different applications across several technological sectors (Shea et al. 2011; Salerno et al. 2008). Hence, hybridisation of nanotechnology with the existing industry and socio-economic needs is critical for the success of the nanotech sector.

Multidisciplinarity and convergence

Cross-functional or interdisciplinary teams are viewed as one of the critical success factors for technological innovation (Connell et al. 2001; Torkkeli and Tuominen 2001). Interdisciplinarity in nanoscale research is one major thrust of science policymakers (Schummer 2004), for example, the USA nanotechnology policy (Battard 2012) and the South Africa nanotechnology policy (DST 2005) both advocate for more interdisciplinary collaborations in nanotechnology research.

The fact that nanotechnology is multidisciplinary is undisputed; several authors agree on this point (Karpagam et al. 2011; Roco et al. 2011; Battard 2012; Schummer 2004; Porter and Youtie 2009; Miyazaki and Islam 2007; Gkanas et al. 2013). On the other hand, there is disagreement regarding the extent of interdisciplinarity in nanotechnology. At one end of the spectrum, authors (Karpagam et al. 2011; Tuncel 2015) agree that nanotechnology is an interdisciplinary field that has brought together the cooperation of scientists from different sub-disciplines of science. Some authors are in the middle, where they argue that nanotechnology has an average degree of interdisciplinarity (Hullman and Meyer 2003; Schummer 2004).

Due to its multidisciplinary and interdisciplinary nature, nanotechnology is emerging as the core for the convergence of several disciplines (Meyer 2007; Battard 2012; Salerno et al. 2008; Porter and Youtie 2009; Islam and Miyazaki 2009). Nanotechnology is at the nexus for the convergence of diverse technologies based on the use of nanoscale building blocks (atoms and molecules) and tools of analysis (microscopy, high capacity computers) across various scientific disciplines. This convergence has resulted in the fusion of nanotechnology, biotechnology, information technology, and cognitive sciences, resulting in the field of study referred to with the acronym "NBIC" (Battard 2012; Salerno et al. 2008; Roco and Bainbridge 2003). To succeed in nanotechnology innovation management, R&D managers must ensure they create and plan for multi- and interdisciplinary skills and personnel in their research teams. Secondly, decision-makers can use this as one of the criteria to identify R&D research that possesses the high potential to produce successful innovations in foresight exercises.

Agglomeration in nanotechnology

According to Palmberg et al. (2009), a distinguishing feature of R&D activities is their agglomeration to specific regions rather than being evenly distributed within countries. This view is supported by Porter and Stern (2001) who argue that the physical location of R&D facilities is a significant factor that contributes to successful innovations and that certain areas present a competitive advantage on R&D innovations and commercialisation. The fact that nanotechnology is a general-purpose technology that is multidisciplinary field possibly leads to agglomeration with people working together and sharing resources. Agglomeration in nanotechnology has been observed through nanoclusters in Greece (Gkanas et al. 2013), nanodistricts in the USA (Shapira and Youtie 2008), nanoclusters in Germany (Fiedler and Welpe 2011), and nanoclusters in France Grenoble and the Netherlands (Robinson et al. 2007).

Evidence from literature (Shapira and Youtie 2008; Palmberg et al. 2009; Robinson et al. 2007; Carlino and Kerr 2015) supports the view that technological agglomeration is a critical success factor for nanotechnology innovation. Robinson et al. (Robinson et al. 2007) firmly content that technology clusters are a pre-requisite for success in nanotechnology; they further argue that clusters are a means for entrepreneurs to mobilise resources, build networks, and construct regional centres of excellence in nanotechnology. The following evidence shows the success of nanotechnology districts; firsly, most nanotechnology patents are produced from nanotechnology districts (Shapira and Youtie 2008; Carlino and Kerr 2015), secondly, companies within clusters depend upon the complementary assets of fellow companies within their group to commercialise and license their innovations, and thirdly, firms within a cluster have significantly higher sales than those outside a cluster (Fiedler and Welpe 2011). Thus, agglomeration and clustering of nanotechnology institutions which create research-networks, sharing of research equipment, access to skilled labour, and sharing local-based tacit knowledge serve as catalysts and accelerators of nanotech innovations and commercialisation.

Conducive innovation environment

The framework of academia-industry-government interactions has established itself as a core concept in the discourse of conducive innovation environments. Etzkowitz and Leydesdorff (1997) were the first to formalise a model of university-industry-government relations which they termed the triple helix (TH). Both innovation scholars and policymakers have acknowledged the importance of the triple helix collaborations for innovation (Schultz 2011; Choi et al. 2015; Yoon 2015). The triple helix can manifest in the form of "public-private partnership" (PPP), which are "working arrangements based on a mutual commitment (over and above that implied in any contract) between a public sector organisation with any organisation outside of the public sector" (Bovaird 2004).

There are several examples of successful nanotechnology triple helix PPPs, for instance, the success of innovation in Israeli firms is claimed to be linked to the favourable environment created by strong university-industry linkages and a pool of highly trained scientists and engineers (Porter and Stern 2001). The College of Nanoscale Science and Engineering (CNSE) established by International Business Machines (IBM), New York State, and the University of Albany is another success story; according to (Schultz 2011), CNSE has outperformed other centres in terms of publications and patents. Employment data shows growth in nanorelated industries around CNSE (Schultz 2011). Thus, it can be concluded that the multidisciplinary nature of nanotechnology favours the development of multisector collaborative research centres within the triple helix and PPP model.

R&D capabilities

Successful nanotechnology thrives on scientist-entrepreneurs (Maine 2014) that is human capital with capabilities in scientific research, research publishing, patenting and intellectual property management, licensing, and commercialisation of research. Thus, there is a need for appropriate education and training systems to build these skills and capabilities. The proper education and training system can be provided through a conducive innovation environment established by the academia-industry-government interactions, as discussed in the triple helix model (Schultz 2011; Etzkowitz and Leydesdorff 1997; Choi et al. 2015; Yoon 2015; Bovaird 2004). Within the triple helix universities, working with industry and government will know the right type of education, skills, and training required by industry and government priority areas. In turn, industry and government will support the education system by providing appropriate symbiotic support to academia through arrangements such as internships, graduate support, and joint research programmes.

Consumer needs and preferences

Ivanova (2014) suggested a modification of the triple helix to incorporate the role of consumers in the innovation system, contending that the growth of biotechnology and nanotechnology contributes to a reconfiguration of the triple helix system, such that the triple helix is immersed in the space formed by consumers or the public. This framework presents an attractive innovation environment model for nanotechnology, where the preferences of consumers often determine the success and uptake of innovations. The consumer perceptions are also influenced by government and lobby organisations such as environmentalists and consumer bodies since they shape policies and labelling preferences of nanotechnology products (Yue et al. 2015; Giles et al. 2015; Berube et al. 2011). An excellent example of government and lobby group influence on nanotechnology and biotechnology products uptake is the rejection of genetically modified (GM) foods (Paarlberg 2014). Thus, the primary factors driving the nanotechnology products market are consumer needs and government requirements, and these have to be integrated into the design of nanotechnology products (Khosravi and Sadeghi 2014). However, there is also the view that consumers who purchase nano-enabled products are not aware that they are buying nanotechnology products (Berube et al. 2011; Casolani et al. 2015).

Nanotechnology Innovation Diamond

From the above literature review, it can be concluded that six interrelated critical success factors influence the success of nanotechnology innovations. At the very core of success are consumer needs, preferences, and acceptance of nanotechnology products. The consumer needs are continually shaping and determining the nano-enabled products' market. Market needs must then be addressed through hybridisation of nanotechnologies into existing industries and socio-economic needs. Examples of hybridisation are nanomedicine, nanoelectronics, nanocosmetics, and nanoengineering, among others.

The multidisciplinary nature of nanotechnology and the need to hybridise with other fields will favour scientist working together in interdisciplinary research teams, thereby effectively establishing research teams and clusters. Hence, to save costs and time in developing their competencies, nanotechnology firms will build nanotech R&D innovation and commercialisation capabilities more quickly through locating in a nanotechnology cluster. Within the cluster, firms benefit from knowledge spillovers between firms, industry association, sharing tacit knowledge, local availability of specialised infrastructure, e.g., nanofabrication centres, and services localised skilled labour. The final factor is aligning nanotech research with government strategy through adopting the triple helix model, for example, forging public-private partnerships to leverage resources, support, and complementary skills. The proposed nanotechnology innovation model was tested through the confirmatory factor analysis using nanotechnology experts from South Africa.

Methodology

In this research, the Nanotechnology Innovation Diamond was proposed, expert and survey research was used to collect data for CFA analysis of the proposed model. A cross-sectional survey of nanotechnology experts in South Africa was conducted.

Measurement tool

The survey instrument was designed through the identification of possible constructs and variables from literature. The questions used to measure each variable are shown in Table 1. A survey questionnaire was developed, it consists of six variables for successful nanotechnology construct, and all other constructs consisted of four variables. Each variable was rated on a 5-point Likert-type scale (1 Strongly Disagree, 2 Disagree, 3 Undecided, 4 Agree, 5 Strongly Agree).

A pilot survey was conducted to improve validity and reliability. The pilot survey and consultation was done using six nanotechnology experts, one expert from the Centre for Scientific and Industrial Research (CSIR) Nanotechnology Centre, one from iThembaLABS, two from the University of Pretoria, one from the University of Venda, and one from the Nelson Mandela University. The research instrument was adjusted using feedback from the pilot survey.

Study population and sampling frame

The survey population is composed of scientists working in nanotechnology-related fields in South Africa. The sampling frame was built through compiling databases of nanotechnology researchers obtained from the South African Institute of Physics (SAIP), the Nanotechnology Centre at the Council for Scientific and Industrial Research (CSIR), and publicly available data from the internet on various nanotechnology research programmes across the country.

The sampling frame constructed was composed of 632 experts distributed in 245 organisations. The economic sectors involved were stratified into 37. These sectors varied from universities, agriculture and veterinary, biotechnology, pharmaceuticals, medicine, cosmetics, materials, electronics aviation, engineering, and mining, among others.

Sample size

A sample of 239 units was determined as the right sample using the (Krejcie and Morgan 1970) equation at 95% confidence level. The second aspect considered was what works of literature say on the number of responses required for CFA and Structural Equation Modelling (SEM). Literature (Zainudin 2012) suggest that a model such as the proposed Nanotechnology Innovation Diamond with seven latent constructs where each construct has a minimum of four variables requires 150 responses for SEM. The survey sample size was adjusted after experiencing a low response rate during the pilot survey. Expecting a 50% response rate, the sample size was adjusted to 478.

Sampling and data collection

Stratified random sampling was used to ensure the uniform representation of all economic sectors

Table 1 Nanotechnology critical success factors and their related measurable variables

Construct	Variables affecting the construct (questionnaire item)	References
Successful nanotechnology R&D results in innovation and commercialisation outputs	5(a) Successful nanotechnology R&D results in the development of new products and services 5(b) Successful nanotechnology R&D results in the improvement of existing products and services 5(c) Successful nanotechnology R&D results in the production of patents and/or trade secrets 5(d) Successful nanotechnology R&D leads to new technology licensing opportunities 5(e) Successful nanotechnology R&D leads to commercialisation of research results 5(f) Successful nanotechnology R&D leads to the formation of new companies and/or spin-off companies	(Aithal and Aithal 2016; Maine 2014; Schultz 2011),
Government policy creating conducive innovation environment (TH and PPP) is critical for nanotech success	6(a) The primary factor driving successful nanotechnology innovations is a conducive innovation environment created by government policies 6(b) Most successful R&D innovations in nanotechnology are those aligned with government priorities 6(c) Strategic partnerships between government, industry, academia, and research institutions are important for successful nanotechnology innovation 6(d) Government-supported research infrastructure and skills development are critical for successful nanotechnology innovations	(Schultz 2011; Porter and Stern 2001; Etzkowitz and Leydesdorff 1997; Yoon 2015; Bovaird 2004; Ivanova 2014)
Consumer needs and preferences are critical for nanotechnology products success	7(a) In order for nanotech innovations to be successful, they must be accepted by the final consumer 7(b) Market perceptions of nanotechnology products by the public is a key success factor for nanotech innovations, especially those with applications in medicine, environment, cosmetics, and food 7(c) Successful nanotechnology research must incorporate consumer and market needs early in the research 7(d) Most consumers of nanotechnology products are not aware that they are using nanotechnology-based products	(Ivanova 2014; Yue et al. 2015; Giles et al. 2015; Berube et al. 2011; Paarlberg 2014; Khosravi and Sadeghi 2014; Casolani et al. 2015),
Agglomeration and clustering of nano R&D facilities and companies are critical for nanotech success	8(a) The physical location of nanotechnology R&D facilities is a significant factor that contributes to innovation success; some locations present a competitive advantage in facilitating successful nanotech innovations 8(b) There is a higher success rate for nanotechnology research conducted within nanotech research centres, science parks, and clusters 8(c) Working within a nanocluster enables sharing tacit knowledge, specialised infrastructure, and resources. Hence it increases the success rate of nanotechnology innovations.	(Porter and Stern 2001; Shapira and Youtie 2008; Gkanas et al. 2013; Palmberg et al. 2009; Fiedler and Welpe 2011; Robinson et al. 2007; Carlino and Kerr 2015),

Table 1 (continued)

Construct	Variables affecting the construct (questionnaire item)	References
	8(d) Nanotechnology clusters and nanotech centres of excellence provide a conducive environment for entrepreneurs and nanotech start-up companies.	
R&D, innovation, and commercialisation capabilities are critical nanotech success	9(a) Successful nanotechnology innovations emanate from R&D teams with high skills in scientific research, e.g., teams that have a high number of publications and a high number of citations 9(b) Successful nanotech innovations emanate from R&D teams that possess innovation management and commercialisation skills 9(c) Successful nanotech innovations emanate from teams with intellectual property management skills such as the ability to patent and license innovations 9(d) Successful nanotech innovations emanate from R&D teams that have technological entrepreneurship skills	(Maine 2014; Porter and Stern 2001),
Nano R&D hybridisation to existing industries and socio-economic needs is critical for nanotech success	10(a) Successful nanotechnology innovations must be aligned to existing industry sectors, for example, nanoenergy, nanobiotechnology, nanoelectronics, nanoagriculture, and nanomedicine 10(b) Industry and academia collaboration are essential for successful nanotechnology innovations 10(d) Successful nanotechnology innovations must be aligned to socio-economic needs, e.g., energy security, clean water, and medical needs 10(e) Strategic R&D partnerships between industry and national research facilities are important for successful nanotechnology research	(Aithal and Aithal 2016; Kreuchauff and Teichert 2014) (Salerno et al. 2008; Hullman 2007; Avenel et al. 2007),
Multi- and interdisciplinary teams are critical for nanotech success	11(a) Nanotechnology is a multidisciplinary field 11(b) Successful nanotechnology innovations are produced by interdisciplinary teams 11(c) Nanotechnology cannot be viewed as a stand-alone discipline but combines several cross-cutting scientific skills 11(d) Due to its multidisciplinarity and interdisciplinarity nature, nanotechnology is emerging as the core for the convergence of several disciplines	(Connell et al. 2001; Hullman and Meyer 2003; Islam and Miyazaki 2010; Karpagam et al. 2011; Roco et al. 2011; Battard 2012; Salerno et al. 2008; Schummer 2004; Porter and Youtie 2009; Gkanas et al. 2013)

identified in the sampling frame. Stratification and proportional representation were necessary because nanotechnology is a general-purpose technology. Proportional random samples were drawn from each economic sector. Ethical clearance was obtained from the University of South Africa Graduate School of Business Leadership. Data was collected through electronic internet-based questionnaires. The questionnaire links were sent via email to the survey sample.

Table 2 Individual latent constructs reliability measures

Latent construct	Cronbach's alpha	Composite reliability
Successful nanotechnology	0.847	0.848
Conducive innovation environment	0.733	0.753
Consumer perceptions of nanotechnology	0.759	0.733
Agglomeration and clustering	0.746	0.720
R&D, innovation, and commercialisation capabilities	0.786	0.754
Nano hybridisation	0.701	0.749
Multi- and interdisciplinary	0.762	0.676

Reliability

Reliability was evaluated using Cronbach's alpha and composite reliability (CR). The minimum acceptable values of reliability for these two measures are 0.7 for Cronbach's alpha and CR > 0.6. Reliability of the measurement tool was evaluated for the individual latent constructs as well as the combined model using Cronbach's alpha. Table 2 below shows that both Cronbach's alpha and CR were satisfied for the individual latent constructs.

The entire 30 variable measurement scale has a Cronbach's alpha value of 0.95, which demonstrates a high internal consistency and reliability of the measurement instrument.

Results and discussion

A total of 171 responses were received, showing a 36% response rate. Four responses were removed due to missing information for the questions required for CFA; hence, 167 responses were used for the analysis.

Respondents' demographic information

The demographic statistics of the respondents was evaluated according to their job descriptions, economic sectors in which they work, and the stage of the nanotechnology value chain at which they are involved. These results are reported in Figs. 1, 2, and 3.

Figure 1 shows the job descriptions of the survey respondents. The majority of respondents (71%) work as researchers and acdemics, and engineers constitute only 4% of responses. Figure 2 shows that the majority of the respondents who are academics and researchs describe their economic sector as material science, energy, and university. Only 3% indicate that they work in industry, thus suggesting a low involvment of South African industry in nanotechnology.

The transformation of nanotechnology inventions from ideation to commercialisation occurs in three main

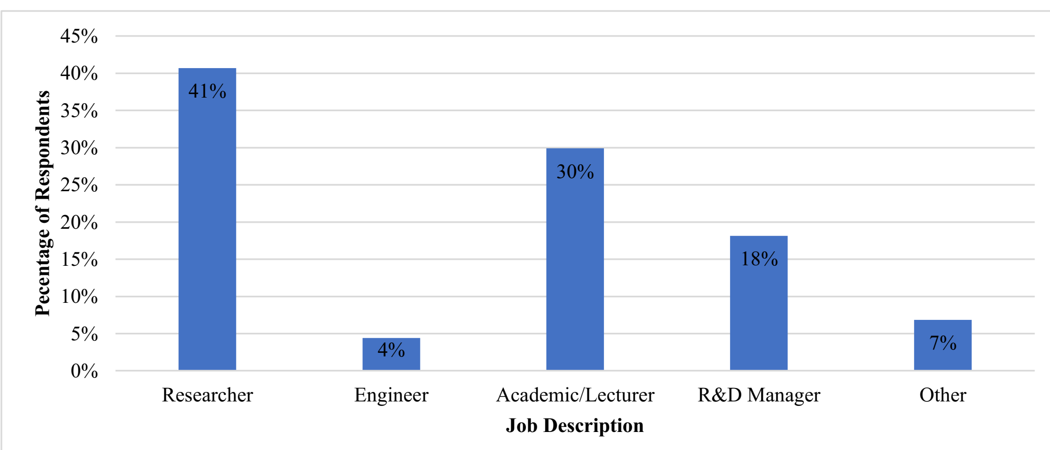

Fig. 1 Respondents job description

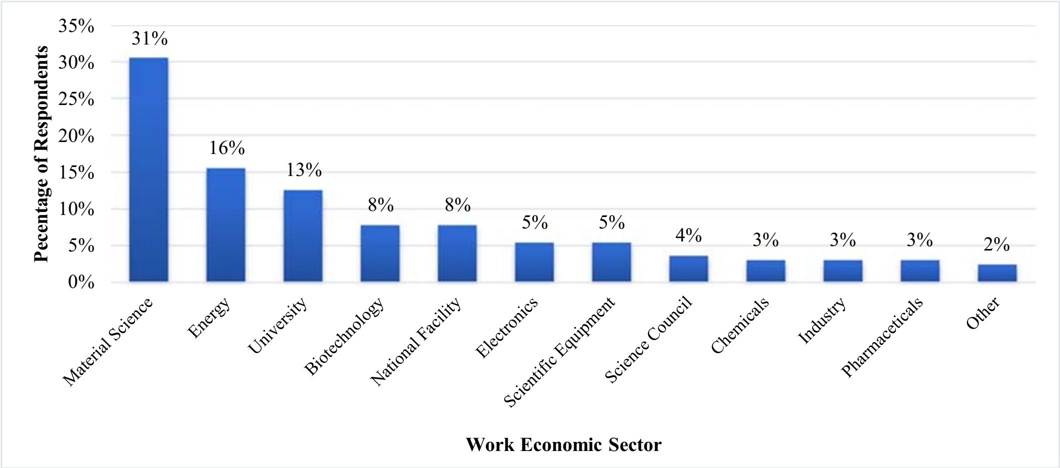

Fig. 2 Economic sector in which respondents are employed

steps known as the nanotechnology value chain (Gkanas et al. 2013; Shapira et al. 2011; Wang and Guan 2012). The initial upstream stage of this value chain produces nanomaterials, which are the raw materials for nanotechnology; examples of nanomaterials are carbon nanotubes, quantum dots, and thin films. The second part of the value chain is where nano-intermediate products are produced. These are products that use nanoscale characteristics for innovative applications; examples include nanocoatings, nanocomposites, electronic components, and various types of sensors. Nano-enabled products are downstream in the third segment of the value chain. It is mostly large corporations that develop and produces nano-enabled products using the nano-intermediates. Nano-enabled products include consumer products such as electronic gadgets and medical equipment clothing. A key component holding together the nanotechnology value chain is the nanotools that are used at all three stages of the nanotechnology value chain to manipulate and assemble the nanomaterials.

Figure 3 shows the stage of the nanotechnology value chain at which the respondents work. The majority of respondents, 47%, work in the initial stage of the value chain (nanomaterials). The second and third stages which are nano-intermidiaries and nano-enabled products have only 17% and 16% respectively; this result confirms findings reported in Figs. 1 and 2 which indicate that the majority of nanotechnology experts in South Africa are academics in material science, and there is a low number of engineers and low industry involvement. Hence, from a foresight and technology management perspective, there is a need for more

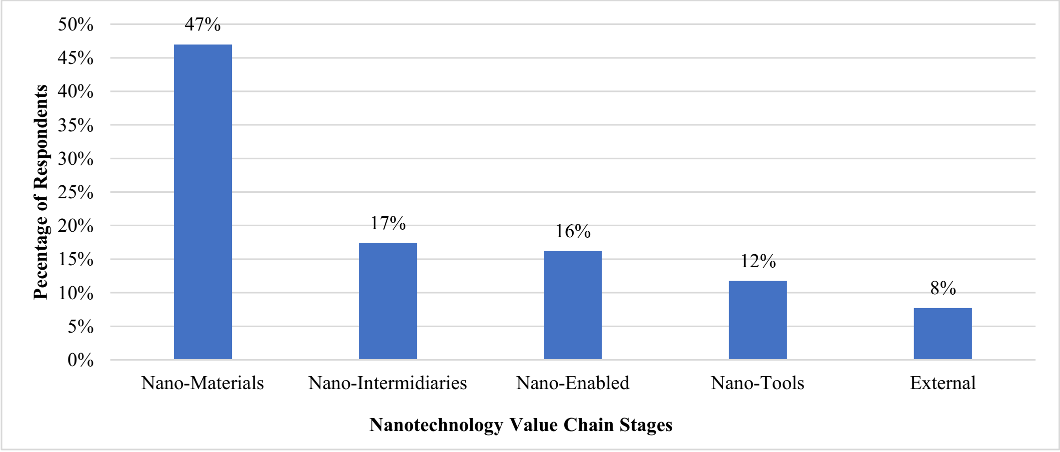

Fig. 3 Stage of the nanotechnology value chain at which respondents work

nanotechnology experts to concentrate in the development of nano-intermidiates and nano-enabled products so that South Africa can position itself to produce more nanotechnology products.

An analysis of publications and patents in nanotechnology was done to confirm if most of the South African nanotechnology experts are working in nanomaterials and not in the more innovative stages of the nanotechnology value chain. The publication search query developed by (Porter et al. 2008) and further refined by (Arora et al. 2013) was modified and used to search the Web of Science (WoS) Core Collection for nanotechnology publications from South Africa between 2000 and 2019. The results indicate that South Africa produced 11,624 publications on WoS as compared to only 43 patents on the European Patents Office (EPO) database. This simple comparison confirms that it is mostly academics and researchers working in nanotechnology material science research as opposed to inventors and engineers who patent more.

Confirmatory factor analysis of the nanotechnology innovation model

AMOS Graphic was used to optimise and evaluate the validity of the proposed nanotechnology innovation model, the Nanotechnology Innovation Diamond. The model is composed of six factors that contribute to the latent construct of successful nanotechnology. Figure 4 shows the optimised standardised model of the Nanotechnology Innovation Diamond and how the six critical success factors interact with each other.

CFA model fit analysis

AMOS Graphic version 26 was used to evaluate the validity of the proposed model using confirmatory factor analysis (CFA) model fit indices. There is an extensive collection of CFA fit indices which causes two problems: firstly, there is no agreement on which fit indices to use, and secondly, the cut-off values for accepting model fit are also a subject of significant debate (Matsunaga 2010; Marsh et al. 2004; Fan et al. 1999; Hu and Bentler 1999). The CFA model fit indices are classified into absolute fit indices, incremental fit indices, and parsimony fit indices. Hooper et al. (2008) present a guideline of reporting indices, in which they advise to always include the Chi-square statistic, its degrees of freedom, the root mean square error of approximation (RMSEA), the standardised root mean square residual (SRMR), the comparative fit index (CFI), and one parsimony fit index, the normed fit index (NFI) or Tucker-Lewis index (TLI). Hu and Bentler (1999)) propose a two-index reporting approach with three options reporting either TLI and SRMR or RMSEA and SRMR or CFI and SRMR.

The cut-off values for the various indices start at low of greater than or equal to 0.90 for CFI, TLI, or RNI, and RMSEA less than 0.08 (Matsunaga 2010). The upper limits for cut off are RMSEA less than 0.07, SRMR less than 0.08, and CFI, TLI, or RNI greater than or equal to 0.95 (Hu and Bentler 1999; Hooper et al. 2008). The higher values given in literature were taken as cut-off values for the model fit in this study. Table 3 reports the fit analysis of the proposed model. The results indicate that the optimised proposed nanotechnology innovation model shown in Fig. 4 satisfied the set minimum CFA model fit requirements.

After fitting the model, the next step was to evaluate if all the six proposed success factors significantly contributed in the proposed model using hypothesis testing.

- The null hypothesis stated that *the six critical success factors proposed by the Nanotechnology Innovation Diamond are not significant for successful nanotechnology research and development.*
- The alternate hypothesis state that *the six critical success factors identified by the Nanotechnology Innovation Diamond are significant for successful nanotechnology research and development*.

The relationship between the six factors shown in Fig. 4 was analysed and the results reported in Table 4 presents the standardised regression estimates (S.E), the critical ratio (C.R), and the p value (p) between the critical success factors as proposed in the Nanotechnology Innovation Diamond. The factors' relationship level of significance was evaluated based on the critical ratio (CR) of the regression estimate, such that $CR > 2.58$ indicates a 99% level of significance in the relationship (Byrne 2013).

The analysis results in Table 4 indicates that all factors have a highly significant contribution in the model shown in Fig. 4 with a $^{***}p < 0.001$ which indicates a highly significant p value at relationship. Thus, the null hypothesis is rejected, and the alternate hypothesis is accepted; that is, all the six identified critical success factors are significant for the innovation model.

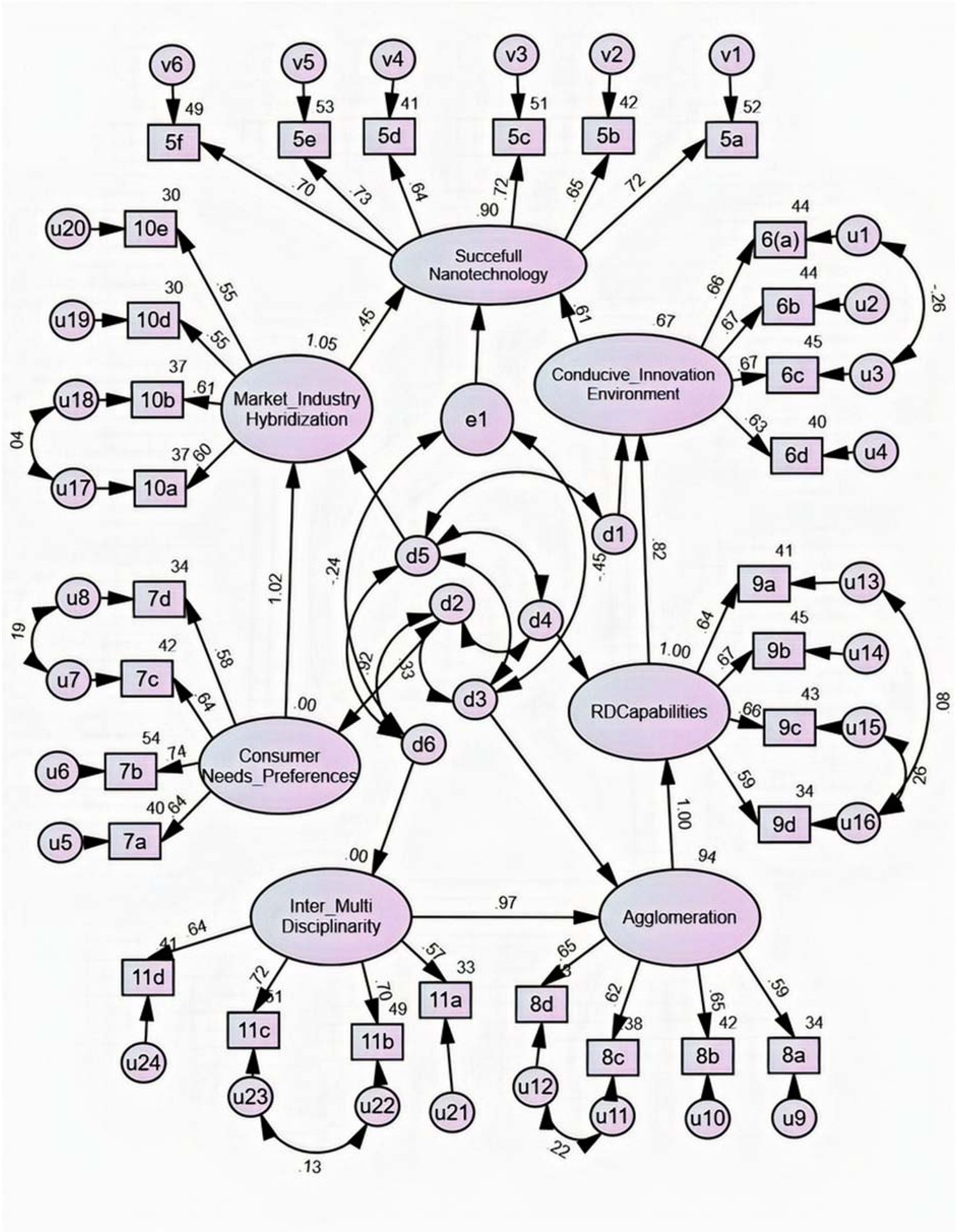

Fig. 4 Nanotechnology Innovation Diamond AMOS optimised model diagram

Table 3 Model fit indices for Nanotechnology Innovation Diamond model

Model	Chi-square (χ^2)	Degrees of freedom (DF)	χ^2/DF (<3.0)	RMSEA (<0.08)	SRMR (<0.09)	TLI (>0.95)	CFI (>0.95)	Comment
Initial non--optimised model 1	522.963	398	1.314	0.043	0.064	0.937	0.942	1. All criteria achieved except TLI/CFI >0.95 2. Acceptable with loosed fit criteria TLI/CFI>0.90 (Marsh et al. 2004; Fan et al. 1999)
Final optimised model 2	464.068	383	1.212	0.036	0.059	0.957	0.962	1. Model fit achieved with set criteria 2. Model fit achieved with two-index criteria (Hu and Bentler 1999)

Conclusions

The demographic information of the nanotechnology experts in South Africa indicates that the majority work as academics and researchers and their primary focus is on material science, primarily working in the nanomaterials stage of the value chain. Thus, there is a need to strengthen the nano-intermediaries and nano-enabled stages on the value chain in South Africa.

CFA has confirmed that all the six critical success factors proposed in the Nanotechnology Innovation Diamond are significant for successful nanotechnology. The model shows that the consumer needs lead to hybridisation of nanotechnologies into existing industries and socio-economic needs such as nanomedicine, nanoelectronics, nanocosmetics, nanoengineering, and nanoagriculture. The inter- and multidisciplinary teams working together in nanotechnology and the need to hybridise with other industries favour agglomeration and clustering of nanotechnology research institutions. The agglomeration of institutions will develop nanotechnology R&D and commercialisation capabilities. In a cluster, R&D capabilities are enhanced because companies benefit from knowledge spillovers between firms, industry association, sharing tacit knowledge, local availability of specialised infrastructure, and localised skilled labour. The final factor is working in a conducive innovation environment such as the triple helix, for example, forging public-private partnerships to leverage resources, support, and complementary skills.

The model can be used for innovation management in nanotechnology. For example, to improve the success rate of nanotechnology innovations R&D managers have to work with multidisciplinary teams and locate in a cluster to enhance their R&D capabilities. They also need to understand that nanotechnology is a general-purpose technology such that if they have one discovery or invention, that same invention can have various applications across several technological sectors; that is, they have to investigate how to hybridise their nanotechnology inventions with existing industries and socio-economic needs.

The model can also be used as a tool in nanotechnology foresight exercises and project portfolio management. For example, to identify a project with a high likelihood of success, the project must have a multidisciplinary team, and the project must be addressing a

Table 4 Regression weights between success factors in the nanotechnology innovation model

Nanotechnology innovation diamond success factors			SE	CR	*p*	Result
Multi- and interdisciplinarity	➔	Agglomeration	0.162	5.861	***	Significant
Agglomeration	➔	R&D capabilities	0.176	6.669	***	Significant
Consumer needs	➔	Market hybridisation	0.141	6.773	***	Significant
R&D capabilities	➔	Conducive innovation environment	0.124	6.617	***	Significant
Conducive innovation environment	➔	Successful nanotechnology	0.162	3.900	***	Significant
Market hybridisation	➔	Successful nanotechnology	0.156	3.422	***	Significant

market/consumer need and working on hybridising the innovation with existing industries. The research team must ideally be located in a cluster and working in public-private partnerships.

In conclusion, this study has reported on a nanotechnology innovation management and foresight model, the Nanotechnology Innovation Diamond. This model can be used to increase successful innovations in nanotechnology, and alternatively, as a foresight tool in identifying strategic nanotechnology research areas that have a high likelihood of success.

Limitations and recommendations

Although there is a consensus that CFA requires large samples sizes, there is no agreed rule of the thumb on the minimum sample size and reported minimum sample sizes vary from 100 to 200 (Zainudin 2012; Marsh et al. 2004; Fan et al. 1999; Hooper et al. 2008; Byrne 2013; Hair et al. 2010; Karakaya-Ozyer and Aksu-Dunya 2018). This research used a minimum sample size suggested by Hair et al. (2010) which uses the number of constructs and variables in a model. The "Nanotechnology Innovation Diamond model" has seven constructs, and each construct has a minimum of four variables. Hair et al. (2010) recommend that a model with seven or fewer constructs and individual constructs have more than three items requires a minimum sample of 150.

This study was carried out using responses from 167 experts satisfying the minimum criteria of 150 selected for the research. However, all experts interviewed are based in South Africa and most work in academia and research (71%) and nanomaterials (47%). Hence, there is a need to test the model with a sample from other countries outside South Africa. For example, the model in the BRICS countries (Brazil, India, Russia, China) must be evaluated and a bigger ratio working in other diverse nanotechnology areas outside academia and nanomaterials must be targeted. Also, a bigger minimum sample of 200 experts can be used in future research.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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