

Development of an Industry 4.0 Competency Maturity Model

Whisper Maisiri, Liezl van Dyk, and Rojanette Coetzee

Abstract—Industry 4.0 (I4.0) transformations in manufacturing industries impact technology, systems, and processes and extend to employees' competency requirements and, consequently, the preparation of graduates who will be ready to practice engineering with professional-level technical know-how and non-technical skills in I4.0. An I4.0 Competency Maturity Model (I4.0CMM) could be used as a tool to assess and guide the development of I4.0 and future skills requirements. This study applied the Delphi technique to evaluate the I4.0CMM's validity and utility, and the improvement thereof, using experts' opinions in two successive rounds. Purposeful sampling was employed to enroll 35 participants. Nineteen experts participated in round one survey, out of which 17 experts participate in round two of the survey. The study used a central tendency statistical tool (the mean) to evaluate expert consensus (mean score $\geq 75\%$) and used means graphs to present the data. The study results demonstrated the sufficiency and relevance of an I4.0CMM to both academic and industry practitioners. The I4.0CMM could provide a comprehensive competency assessment framework that guides the development of graduate attributes that align with the I4.0 competency requirements in the industry.

Index Terms—competency, Delphi technique, graduate attributes, industrial revolutions, Industry 4.0, maturity model

I. INTRODUCTION

Workforce competencies significantly influence the successful adoption of Industry 4.0 (I4.0) in organizations [1]. The evolution of all engineering professions – but particularly the industrial engineering profession – is interwoven with the progression from the initial to the fourth and further industrial revolutions (IR) [2, 3] as depicted by Fig. 1 [3]. Industry 4.0 and its application in the manufacturing industry [4, 5] magnify the role of engineers in driving its successful adoption. Therefore, the engineering education role of “preparing the graduates to practice engineering with competent technical know-how and soft [non-technical] skills at [a] professional level” [6] becomes critical.

Industry 4.0 demands high competency levels and requires broad skills and qualifications [1, 7-9]. The broad skills include professional skills [10], such as effective teamwork [10–13], people skills, such as creativity, empathy, and flexibility [9, 10, 12, 13], and technological skills [10, 11] such as “ability to

work with the Internet of Things, autonomous robots, 3D printing, and other advanced technologies” [11, 12]. In addition, new qualifications will be about enhancing interdisciplinary knowledge and skills [9, 11, 14]. Thus, the alignment of engineering education in producing graduate attributes (GAs) that meet I4.0 competency requirements cannot be avoided [7].

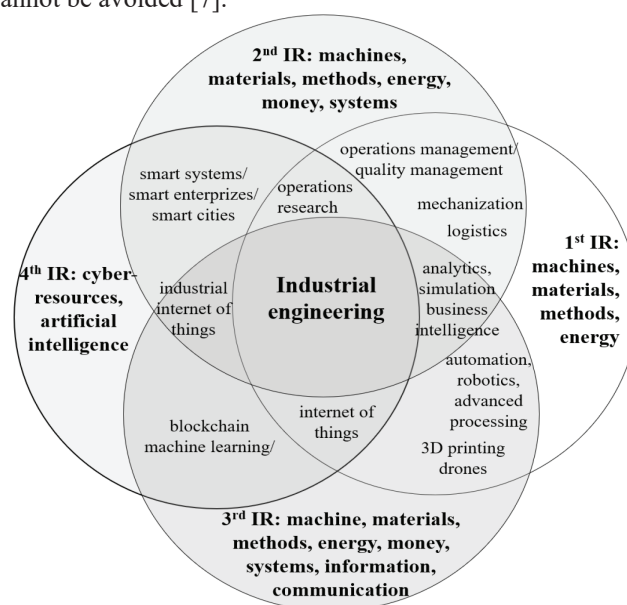


Fig. 1. Relation of Industrial Engineering to the Industrial Revolutions [3]

Literature [15, 16] stresses the significant transformation of the human capital role in I4.0, and thus innovative competency assessment models could assist in the development and assessment of the required competencies. Acerbi *et al.* [17] argued that there was a lack of comprehensive competency assessment models that focus on I4.0, leading Maisiri and van Dyk [18] to assess this gap by conducting a systematic mapping review of existing I4.0 competency models and frameworks in literature. The gap assessment was measured against predefined design requirements guided by literature [19, 20]. The systematic mapping review gap [18] suggested a lack of comprehensive I4.0 competency models and frameworks to assess and align workforce competency requirements in I4.0

W. Maisiri is with the School of Industrial Engineering, Faculty of Engineering, North-West University, Potchefstroom, South Africa (e-mail: 25727265@nwu.ac.za).

L. van Dyk is with the School of Industrial Engineering, Faculty of Engineering, North-West University, Potchefstroom, South Africa (email: Liezl.vandyk@nwu.ac.za).

R. Coetzee is with the School of Industrial Engineering, Faculty of Engineering, North-West University, Potchefstroom, South Africa (email: Rojanette.Coetzee@nwu.ac.za).

and future requirements. This led to the conceptualization and presentation of the I4.0CMM in the 2020 IFEES World Engineering Education Forum – Global Engineering Deans Council (WEEF-GEDC) conference paper [18].

Du Preez and Pintelon [21] stated that “industry and industrial engineering are in a continuous process of improvement...” [21]. The industrial engineering profession matured alongside the industrial revolutions [21, 22] and must be ready for continuous changes in “scientific, economic, social, environmental and technological levels” [2] to maintain its relevance. Sackey and Bester [16] argued that I4.0 could significantly impact the knowledge and skills of industrial engineers. On the other hand, the knowledge and role of industrial engineers regarding “[the] systems engineering approach, information technology, manufacturing technology and integration of system components” [21] position them to be role players in the adoption of I4.0. Therefore, the I4.0CMM capability functions domain presented by Maisiri and an Dyk [18] and discussed in this article aligns with industrial engineering functions. However, there is a possibility of adapting the model to other professions’ functional domains. The study recorded in this article used the Delphi technique to validate the research problem, the usefulness of the model, as well as the improvement thereof, using expert views.

II. STUDY PURPOSE

This study stems from a paper presented by Maisiri and van Dyk [18]. It seeks to prove the validity of the research problem and the sufficiency of the design requirements and verify the compliance of a conceptual I4.0CMM structure against design requirements and the improvement thereof. The study seeks to answer three questions:

- 1) To what extent does the I4.0CMM contribute to assessing and aligning engineering competency requirements in I4.0 and future requirements?
- 2) Which design requirements could direct the development of the I4.0CMM in order to be useful for both industry and academics?
- 3) What are the dimensions required to construct the I4.0CMM?

III. THE DEVELOPMENT OF AN INDUSTRY 4.0 COMPETENCY MATURITY MODEL (I4.0CMM)

A capability maturity model (CMM) is a framework with five maturity levels (initial, repeatable, defined, managed, and optimizing) used to assist organizations in adopting best practices in a targeted domain [23-25]. Best practices develop from ad hoc, chaotic processes to become mature, disciplined processes [25]. Maturity models can serve a descriptive purpose if applied for assessing the "as-is" capability by comparing the entity's capabilities under investigation against given criteria [19, 20, 26]. On the other hand, maturity models can serve a prescriptive purpose if used to show how to find a desirable maturity level and stipulate guidelines to achieve a better state [19, 20, 26].

The People Capability Maturity Model (PCMM) is a maturity model that targets human capital management processes [23,

24]. PCMM was developed to assist organizations in enhancing their human capital capabilities. Application of the PCMM enables organizations to mature their “capability for attracting, developing and retaining the talent” [24] needed.

The disruptive nature of I4.0 on competency requirements [15, 16] requires continuous alignment of human capital competencies to meet current requirements. Thus, Maisiri and van Dyk [18] initiated the development of an I4.0CMM, which adopts the principles of maturity models and PCMM. The I4.0CMM could contribute to managing human capital competencies from a graduate-level to a professional level, which is a crucial ingredient for organizations’ success [27].

The development of an I4.0CMM started with the generation of design requirements. The design requirements were to direct the development of a model which serves both descriptive and prescriptive purposes [19, 20, 26]. The framework of maturity model design principles of Pöppelbuß and Röglinger [19], as applied by van Dyk [20], guided the initial set of the design requirements [18]. These design requirements were refined and validated in this study (see Section VI of this article) using expert opinions and input.

Consequently, these design requirements guided the conceptualization of the I4.0CMM preliminary structure. The I4.0CMM, as presented by Maisiri and van Dyk [18], comprises three domains: a competency domain, a capability functions domain, and a maturity levels domain. Furthermore, Maisiri and van Dyk [18] illustrated the model using data management and human-machine interaction capability functions [18]. The next stage in the development of the model was to seek expert views to verify the rigor of the I4.0CMM preliminary structure and further refinement thereof.

IV. I4.0CMM SIGNIFICANCE TO THE ENGINEERING EDUCATION

According to the International Engineering Alliance [28], the “fundamental purpose of engineering education is to build a knowledge base and attributes to enable the graduate to continue learning and to proceed to formative development that will develop the competencies required for independent practice.” After entering the workplace, the engineering graduate develops professional competencies leading to professional registration [28].

The I4.0 era requires cross-functional competencies that combine technological advancements and manufacturing knowledge [9, 14, 29]. These competency requirements are created faster than the development of engineering qualifications, therefore widening the misalignment between industry professional competency requirements and engineering education [30]. The I4.0CMM could assist engineering education and workplace human resource development providers in aligning GAs and professional competencies.

In addition, the assessment of GAs, a complex task, can be simplified by using competency models [31]. Competency models provide a framework that facilitates self-evaluation by students and educators in the attainment of GAs. The I4.0CMM could aid students and employees to self-evaluate and self-

regulate the achievement of I4.0 skills and future requirements compared to past revolution requirements.

V. METHODOLOGY

The current study utilized the Delphi technique to validate the I4.0CMM design requirements and verify the sufficiency of the I4.0CMM structure using expert consensus. The Delphi technique is a continuous iteration process of gathering data from experts until reaching an acceptable consensus level [32]. It suited this study as it has many applications, including validating studies that involve the development of various instruments and models that require expert knowledge and input [33, 34].

Four principles guide the Delphi technique: participants anonymity, an iterative process, controlled feedback, and quantitative data analysis and interpretation, as discussed by Hsu and Sandford [32] and Skulmoski *et al.* [35]. Correctly employing the Delphi method contributes to reaching justifiable, valid, and credible input from experts. Thus, to ensure the credibility and validity of this study, the study was conducted and reported in line with the guidelines of “Conducting and Reporting Delphi Studies” [36, 37].

A. Sampling and participant enrolment

Purposeful sampling, a sampling technique appropriated for establishing an expert panel [37] and commonly used in the Delphi technique [35, 38, 39], was employed to enroll 35 potential experts who meet the following inclusion criteria [35]:

- A minimum of five years known and demonstrated experience in the industrial engineering environment;
- A demonstrated understanding of I4.0 competency requirements;
- The capacity and willingness to participate; and
- Effective communication skills.

Potential participants who meet inclusion criteria were initially identified via LinkedIn profiles. Furthermore, the authors’ LinkedIn profiles included an open invitation to participate in the Delphi study. The identified potential participants received a formal invitation via e-mail specifying the study’s purpose and explaining the study process. The questionnaire included a compulsory prerequisite check section to ensure only eligible participants completed the survey.

To minimize bias and maintain the validity of the study, potential participants were excluded from the study if:

- there was an existing power relationship with the researchers; and/or
- the potential participants could benefit directly from the study.

B. Data collection

Data were collected between April and May 2021, with a gap of three weeks between each round: two weeks for data collection, and one week for the data analysis. Questionnaires were administered via a Google form questionnaire link sent to the participants in an e-mail and in a message via LinkedIn.

In this study, expert opinions were collected in two consecutive rounds using a questionnaire survey with a five-point Likert scale [37, 40]. In addition, the questionnaire

included a single open-ended question at the end of every section to solicit expert comments and recommendations.

Guided by previous studies [37, 40, 41], one author developed the introduction to the study, the questionnaire survey, and participation instructions. These were piloted among the other two authors before sending them to the participants [37].

The participants rated compulsory statements (Appendix – Table V) in round one to validate the research problem and the I4.0CMM design requirements presented in the conference paper by Maisiri and van Dyk [18]. Furthermore, the participants verified the adherence of the I4.0CMM structure [18] to the design requirements. Finally, participants had the opportunity to comment and offer improvement suggestions regarding the design requirements and the I4.0CMM structure.

The outcome of the first-round data analysis was used to develop the second-round questionnaire. The round-two questionnaires omitted round-one statements that achieved expert consensus. The second-round questionnaire statements were designed to rate the refinements and improvements on areas of non-consensus in round-one [36] and additional aspects according to expert comments and suggestions [42]. The first-round data analysis results, aggregated suggestions, and recommendations accompanied the second-round questionnaire that was sent to the participants.

C. Data analysis

The study utilized descriptive analysis [37, 43] to evaluate expert consensus and agreement on various aspects assessed on a five-point Likert scale (1 - strongly disagree, 2 - disagree, 3 - do not know, 4 - agree, 5 - strongly agree). Though the definition of consensus could be subject to interpretation in a Delphi process [32], this study considered an average rating of 3.75 (75% on a five-point Likert scale) as the consensus for any particular question [32, 37, 40, 42, 44]. The study used a central tendency statistical tool (the mean) [34] and presented the data using means graphs [32, 43].

D. Ethical consideration

The study was conducted according to the guidelines of and approved by the North-West University Engineering Research Ethics Committee (NWU-ENGREC) – ethics clearance number NWU-00284-19-A1.

VI. RESULTS ANALYSIS

Nineteen experts participated in the round-one survey, out of which 17 experts participated in the round-two survey. Fig. 2 shows the distribution of round-one and round-two participants according to their years of experience in the industrial engineering environment.

The study results are presented as follows: Section A – round-one results analysis, Section B – refinements and improvements made to the design requirements and I4.0CMM structure, and Section C – round-two results.

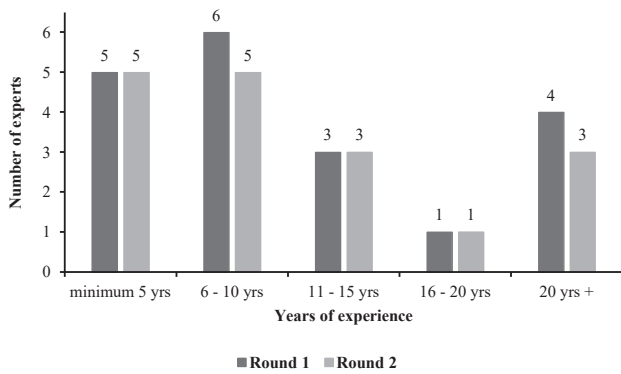


Fig. 2. Participants' Distribution by Years of Experience

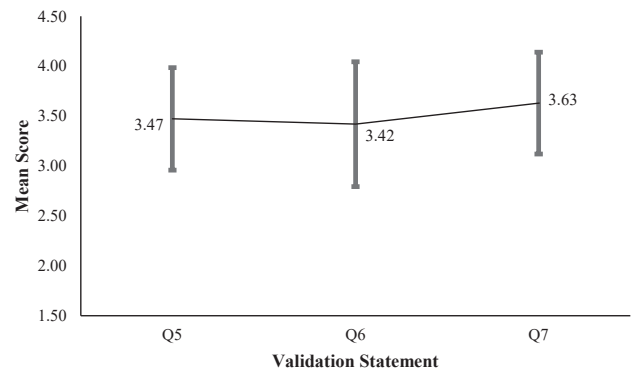


Fig. 4. Design requirements validation means graph.

A. First-round results

Fig. 3 presents the responses of experts to first-round research problem validation statements (Q1 to Q4 in Table V) in the form of a means graph. There was expert consensus (all means >3.75) for each research problem validation statement. Therefore, the research problem was considered valid. Consequently, the second-round questionnaire excluded research problem validation statements

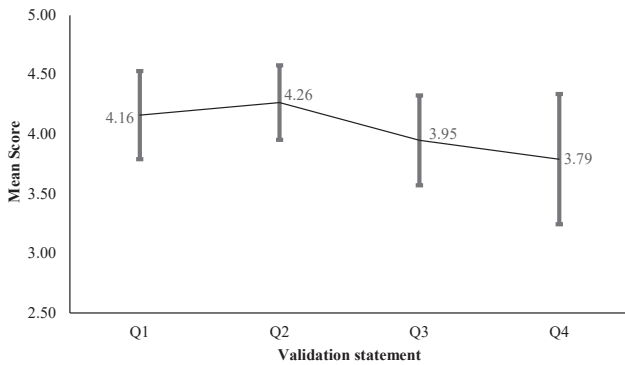


Fig. 3. Problem validation means graph (CI: 95%).

Fig. 4 shows the means graph of the responses of experts to the first-round design requirements validating statements (Q5 to Q7 in Table V). Expert consensus was not achieved (all means < 3.75) for any design requirements validation statement. Therefore, the design requirements presented by Maisiri and van Dyk [18] were not sufficient to direct the development of an I4.0CMM. As a result, the design requirements required improvements and re-testing for validity in the second-round survey.

Fig. 5 presents the means graph of the responses of experts to the I4.0CMM structure verification statements (Q8 to Q12 in Table V). Experts did not reach a consensus (all means < 3.75) on the sufficiency of the I4.0CMM structure as presented by Maisiri and van Dyk [18]. Consequently, the I4.0CMM required improvements and re-testing for compliance with the improved design requirements

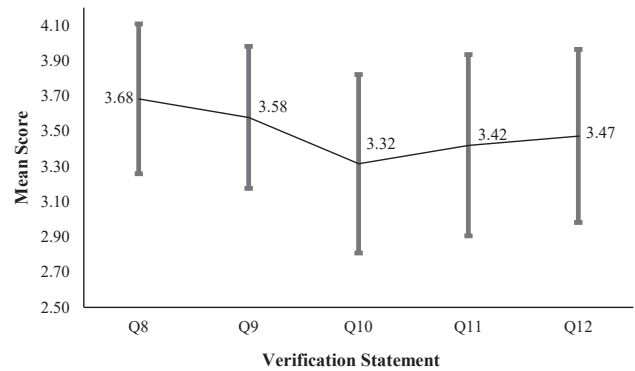


Fig. 5. I4.0CMM structure verification against design requirements

B. Design requirements and I4.0CMM structure improvements

Round-one results showed a lack of expert consensus on the sufficiency of the design requirements and compliance of a conceptual I4.0CMM structure as assessed against design requirements. Improvements were based on the feedback and suggestions from round-one's expert inputs to open-ended questions.

Table VI (see Appendix) presents the improved design requirements compared to the initial design requirements [18] rated in round-one.

In response to the open-ended questions, the experts pointed to the need for a self-assessment function in the I4.0CMM. Thus, Table VI includes an additional design requirement, "DR6: The I4.0CMM must have a self-assessment function against which users can gauge their level of competency."

Refinement of design requirement DR2 captured the whole meaning of competency: knowledge, skills, attitudes, values, and self-concepts. Design requirements rated in round-one only included knowledge and skills.

Design requirement DR6 [18], now DR7 in Table VI, limited the use of the model to manufacturing professionals, which experts raised concerns over. Therefore, the usefulness of the model was generalized to practicing professionals. The term "distinct maturity levels domain" in design requirement DR8, now DR9 in Table VI, was changed to "progressive maturity levels domain." The change revealed the essence of progression from the first IR to the fourth IR and for future requirements. Consequently, design requirement DR10, now DR11 in Table VI, was changed from "The competency statements must clearly differentiate between maturity levels" to "The

competency statements must differentiate competency requirements progression through the different industrial revolutions.”

Round-one question Q10’s (“The competencies dimensions are sufficient and relevant”) mean analysis result (mean = 3.32) showed notable divergence from expert consensus on the matter. This result suggests that the I4.0CMM structure presented by Maisiri and van Dyk [18] and rated in round-one had a noticeable deficiency in the competency domain. Participant 17 commented, “Competencies is where the real lack comes into the model. I would propose the Propensity Towards Success model that asks five critical questions: I Head, I Am, I Know, I Can, I Fit. You have worked with the I Know

(Knowledge) and I Can (Skill)...”. Participant 15 added, “The competence domain needs a bit of work in my mind; the skills maturity (can be renamed knowledge maturity) can perhaps be studied here so that things start out as skills and develop to competencies?”

The current I4.0CMM model in Fig. 6 presents incremental improvements on the model structure when compared with the initial I4.0CMM structure presented in the conference paper by Maisiri and van Dyk [18]. The improvements guided by literature [23, 24, 27, 45-49] and expert inputs include an improved capability functions domain and competency level domain.

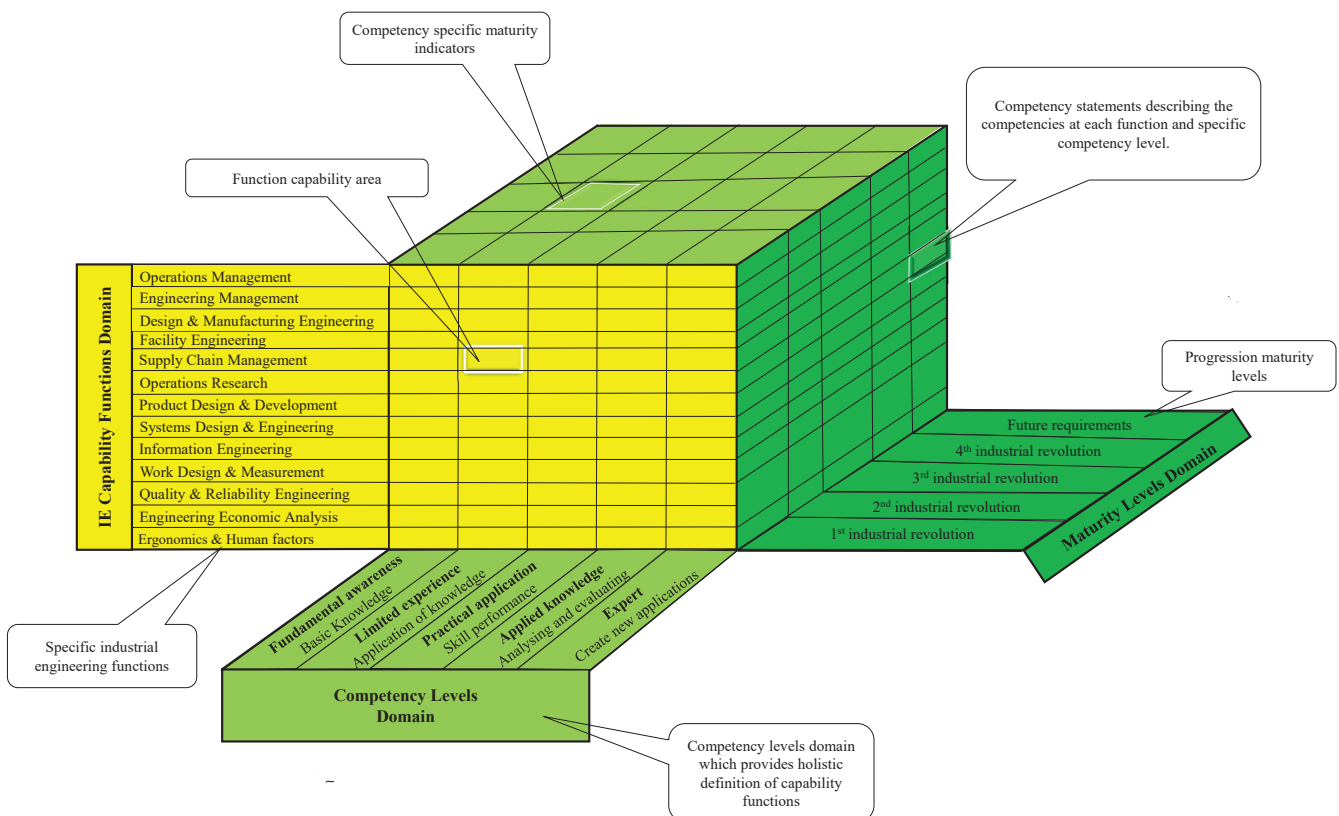


Fig. 6. I4.0CMM structure verification against design requirements

The capability functions domain was demonstrated using industrial engineering functions and was refined to give a better representation of the industrial engineering profession.

The maturity level domain shows the progression maturity of each capability function through the IRs. The illustration in Fig. 1 relates to the intercepts between the IR maturity level and the capability functions domain presented in Fig. 6.

The competency domain changed to competency level domain. The I4.0CMM assumes five competency levels [23, 24, 27, 48]: fundamental awareness, limited experience, practical application, applied knowledge, and expert levels. The competency levels assess an individual’s ability to demonstrate a competency [48] in a specific function and progression maturity level. The competency level domain descriptors are adapted from Bloom’s taxonomy’s six dimensions for the intended outcome of learning [49].

The Fundamental level concerns individual learning [48] and corresponds to Bloom’s taxonomy’s ‘remembering and understanding’ dimensions [49]. At this level, an individual has a conceptual comprehension of techniques and concepts.

The Limited experience level is a novice level where an individual has limited experience through the practical application of knowledge and experience attained through the learning process [48] and corresponds to the ‘apply’ dimension in Bloom’s taxonomy [49]. Limited experience can come from on-the-job training.

The Practical level is an intermediate level at which an individual can perform a skill without or with minimal supervision [48]. This level also corresponds to the ‘apply’ level in Bloom’s taxonomy [49]. However, the application is aimed at practical and real-life problem-solving. At this level, the individual focuses on enhancing their skills.

The applied knowledge level is when an individual can perform a specific functional task by applying knowledge. The level corresponds to the ‘analyzing and evaluating’ dimension in Bloom’s taxonomy [49]. On this level an individual can consistently apply knowledge and implement improvements related to functional tasks [48]. Moreover, the individual has gained experience to coach others in performing similar tasks.

The expert level corresponds to the ‘create’ dimension in Bloom’s taxonomy [49], where an individual can create a new application in functional area competencies.

C. Round-two results

In round-two, the experts rated the improved design requirements in Table VI and the improved I4.0CMM in Fig. 6. The participants rated the importance of each design requirement in Table VI in developing the I4.0CMM. The mean scores rating results (Table I) show expert consensus (all means > 3.75) on the importance of all the design requirements

TABLE I:
INDIVIDUAL DESIGN REQUIREMENTS EXPERTS’ VALIDATION MEAN SCORES

| Design requirement | Mean score |
|--------------------|------------|
| DR1 | 4.71 |
| DR2 | 4.71 |
| DR3 | 4.47 |
| DR4 | 4.29 |
| DR5 | 4.35 |
| DR6 | 4.32 |
| DR7 | 4.47 |
| DR8 | 4.06 |
| DR9 | 4.24 |
| DR10 | 4.65 |
| DR11 | 4.47 |

Table II compares round-one Q5 to Q7 mean scores on design requirements validating statements against second-round mean scores. Experts reached a consensus (all means > 3.75) on each design requirements validation statement in round-two. Therefore, the improved design requirements in Table VI are sufficient to direct the development of the I4.0CMM, consequently answering study question 2 presented in Section II.

TABLE II:
DESIGN REQUIREMENTS VALIDATION: ROUND-ONE VERSUS ROUND-TWO

| Question | Mean scores | |
|----------|-------------|--------------|
| | First round | Second round |
| Q5 | 3.47 | 3.76 |
| Q6 | 3.42 | 4.12 |
| Q7 | 3.63 | 4.12 |

Table III compares round-one Q8 to Q12 mean scores on the I4.0CMM structure verification statements against round-two mean scores. Experts reached a consensus (all means > 3.75) on the sufficiency of the improved I4.0CMM structure presented in Fig. 6. Thus, the dimensions in the three domains of Fig. 6. can direct the development of an I4.0CMM and this addresses study question 3 presented in Section II.

TABLE III:
I4.0CMM STRUCTURE VERIFICATION AGAINST DESIGN REQUIREMENTS:
ROUND-ONE VERSUS ROUND-TWO

| Question | Mean scores | |
|----------|-------------|--------------|
| | First round | Second round |
| Q8 | 3.68 | 3.94 |
| Q9 | 3.58 | 4.12 |
| Q10 | 3.32 | 4.29 |
| Q11 | 3.42 | 4.18 |
| Q12 | 3.47 | 4.24 |

VII. UNITS

The current study focused on validating the need for the I4.0CMM, proving the sufficiency of the design requirements, and verifying the compliance of the I4.0CMM structure against the design requirements, using expert opinions. Table IV maps the research questions presented in Section II against the research instrument. In this study, expert consensus was achieved in the second round of the Delphi technique, similar to other studies that used the same technique [37, 38].

Experts agreed that there are challenges around the I4.0 skills requirements and development, consistent with findings in other studies [50-52]. Furthermore, there was consensus on the need for an I4.0CMM to assess and align human capital competency requirements in I4.0 and for future requirements. In support of the need for I4.0CMM, Participant 2 commented that “A CMM tool can help identify the gap between where we want to go and where we are now. I4.0 maturity assessment tools can help with how we can get there.” Participant 14 highlighted that “I4.0 skills requirements in the engineering profession need to be clearly defined for use in the South African manufacturing industry”.

The development of I4.0CMM adopted PCMM principles, different from other I4.0 competency models presented in the literature [13, 15, 53, 54]. Thus, in response to study question 1 presented in Section II, the I4.0CMM could significantly contribute to assessing and aligning engineering competency requirements in I4.0 and future requirements.

It could be expected that expert consensus would start to form in the second round of the Delphi technique [37, 38]. In this study's first round, experts did not reach consensus on the sufficiency of the design requirements and the structure of the I4.0CMM presented by Maisiri and van Dyk [18]. However, a consensus on the design requirements (Table VI) was reached in the second round after refining the areas of disagreement using expert views from the first round. Thus, the design requirements are sufficient to direct the development of an I4.0CMM, answering study question 2. The I4.0CMM dimensions presented in Fig 6. were verified against the design requirements, thus addressing study question 3.

The contribution by Kamaruzaman *et al.* [54] shows the importance of developing frameworks and models to enhance competencies development of engineering graduates. Furthermore, competency models significantly contribute to the development and assessment of GAs [31]. Thus, the I4.0CMM presented in this study could potentially assist engineering education and workplace human resource development providers in aligning GAs and professional competencies.

VIII. CONCLUSION

This study extended the work presented by Maisiri and van Dyk [18] by seeking the views of experts to prove the validity of the research problem, prove the design requirements' sufficiency, and verify the I4.0CMM structure against design requirements. Experts reached a consensus that I4.0 skills development and availability are a challenge that can be solved through developing an I4.0 competency assessment model.

The study presented an I4.0CMM comprising three domains: capability functions, competency level and maturity domain. Though the competency level domain and maturity level domain are generic to any engineering field, the current study used industrial engineering to demonstrate the capability function domain. For the model to be usable in different engineering domains, we recommend that the capability functions domain be adapted to suit the dimensions for a specific engineering domain. Future work could include collaborating with other engineering domain experts to illustrate the use of the model in other engineering function domains.

The I4.0CMM adapted Blooms' taxonomy in the competency level domain to enhance the function of self-assessment to demonstrate a competency on a specific capability function and progression maturity level. Thus, increasing the relevance of the model to students and graduates' self-evaluation and professional development mapping.

Though expert consensus was reached for the aspects addressed in this study, some limitations of the study should be mentioned. First, the small number of participants (19), although similar to other studies [37, 40], could be regarded as insufficient to generalize the results of the study. However, the study employed purposeful sampling to ensure the enrolling of only experts who met the inclusion criteria.

Second, the current study did not include the model capability statements and illustration of how the model functions. Thus, the recommended next step in this work is to generate the capability statements for the specific capability functions. Then, testing the model in the real working environment could follow.

This maturity model can be used by engineering education and workplace human resources development providers as a benchmark framework for aligning GAs, and required professional competencies, and for identifying improvement points required to match curriculum provisions to the current and future industry requirements resulting from the fourth – and further – industrial revolutions. Furthermore, it can aid students and graduates in self-evaluating and self-regulating their achievement of I4.0 skills requirements and planning their professional development

APPENDIX

TABLE IV:
STUDY QUESTIONS MAP

| Study question | Related survey questions | Answers provided in this study |
|---|--------------------------|--|
| To what extent does the I4.0CMM contribute to | Questions Q1 to Q4 | The validation of the I4.0 skills challenge and the need for the |

| | | |
|--|--------------------------------|---|
| assessing and aligning engineering competency requirements in I4.0 and future requirements? | in Table V | I4.0 competency assessment model show that the I4.0CMM could significantly contribute to the assessing and aligning of engineering competency requirements. |
| Which design requirements could direct the development of the I4.0CMM in order to be useful for both industry and academics? | Questions Q5 to Q7 in Table V | A list of design requirements (Table V) proven for validity through a Delphi study. |
| What are the dimensions required to construct the I4.0CMM? | Questions Q8 to Q12 in Table V | Dimensions for the three domains, capability functions, competency level and maturity domain (Fig. 6), were established and validated through a Delphi study. |

TABLE V:
QUESTIONNAIRE SURVEY SECTIONS

| Sections | Validation statements |
|--------------------------------|---|
| Problem validation | Q1 There is a misalignment between Industry 4.0 skills requirement in industry and skills development in the education system. |
| | Q2 Industry 4.0 skills definition in the manufacturing industry is not clear. |
| | Q3 There is a lack of I4.0 competency assessment models to assess and align workforce competency requirements in Industry 4.0 and future requirements. |
| | Q4 There is a need for an I4.0CMM to assess and guide I4.0 competency requirements and development. |
| Design requirements validation | Q5 The design requirements are specific and easy to interpret. |
| | Q6 The design requirements are sufficient to direct the development of an I4.0 competency model useful for both industry and academics. |
| | Q7 The design requirements are sufficient to direct the development of an I4.0CMM that assesses and guides I4.0 competency requirements and development. |
| I4.0CMM structure verification | Q8 The conceptual model structure is simple. |
| | Q9 The conceptual model dimensions are sufficient and relevant. |
| | Q10 The competencies dimensions are sufficient and relevant. |
| | Q11 The functional capability areas are an accurate representation of the industrial engineering practice functional areas. |
| | Q12 The maturity level dimensions are sufficient and relevant. |

TABLE VI:
I4.0CMM DESIGN REQUIREMENTS

| Categories | Design requirements (DR) |
|--------------------|---|
| Application domain | DR1: The I4.0CMM must outline engineering profession competency requirements for the manufacturing industry and must be adaptable to other industries. |
| Purpose of use | DR2: The I4.0CMM must provide a set of knowledge, skills, attitudes, values, and self-concepts required to perform specific capability functions. |
| | DR3: The I4.0CMM must support and guide engineering professionals' practice and continuous professional development. |
| | DR4: The I4.0CMM must provide competency reference standards for engineering education and quality assessment of engineering professionals along the career continuum. |
| | DR5: The I4.0CMM must be helpful to assess employees' competencies measured against the |

| | |
|---------------------------------------|--|
| | industrial revolutions and future requirements. DR6: The I4.0CMM must have a self-assessment function against which users can gauge their level of competency. |
| Target group | DR7: The I4.0CMM must be easily understood and be useful for researchers, academics, practicing professionals, and human resources practitioners. |
| Class of entities under investigation | DR8: The I4.0CMM must have a function to identify future competency requirements beyond I4.0 applications and technologies. |
| Maturity and dimensions of maturity | DR9: The I4.0CMM must include a competency levels domain, a capability functions domain, and a progressive maturity levels domain. DR10: The I4.0CMM competency statements must be clearly defined and easy to interpret. |
| Maturity levels and maturation paths | DR11: The competency statements must differentiate competency requirements progression through the different industrial revolutions. |

REFERENCES

- [1] A. Benešová, and J. Tupa, "Requirements for education and qualification of people in Industry 4.0," *Procedia Manuf.*, vol. 11, pp. 2195-2202, Jun, 2017. Accessed on: March, 20, 2020, DOI: 10.1016/j.promfg.2017.07.366, [Online].
- [2] J. H. Mendoza-Chacó, J. F. Ramírez-Bolaños, H. S. Floréz-Obceno, and J. D. Díaz-Castro, "Developing and evolution of industrial engineering and its paper in education," *Ingeniería y competitividad*, vol. 18, no. 2, pp. 89-100, Mar. 2017.
- [3] L. van Dyk, "The Fourth Industrial [R]evolution: An (in)agural lecturer by an Industrial Engineer," Jun. 6, 2019, North-West University.
- [4] C. J. Bartodziej, "The concept Industry 4.0," in *The Concept Industry 4.0: An Empirical Analysis of Technologies and Applications in Production Logistics*, Berlin, Germany: Springer, 2016, ch. 3, pp. 27-50.
- [5] Plattform Industrie 4.0. (2019). What is Industrie 4.0. [Online]. Available: <https://www.plattform-i40.de/PI40/Navigation/EN/Industrie40/WhatIsIndustrie40/what-is-industrie40.html>
- [6] IGI Global. (2020). What is Engineering Education. [Online]. Available: <https://www.igi-global.com/dictionary/engineering-education/33646>
- [7] A. Benešová, M. Hirman, F. Steiner, and J. Tupa. Requirements for Education 4.0 and study programs within Industry 4.0. Presented at the 2019 International Conference on Industrial Engineering and Operations Management. [Online]. Available: <http://ieomsociety.org/pilsen2019/papers/358.pdf>
- [8] M. Maria, F. Shahbodin, and N. C. Pee, "Malaysian higher education system towards industry 4.0: Current trends overview," in *AIP Conference Proceedings*, 2018. [Online]. DOI: 10.1063/1.5055483.
- [9] M. Gabrieland E. Pessl, "Industry 4.0 and sustainability impacts: Critical discussion of sustainability aspects with a special focus on future of work and ecological consequences," *Annals of the Faculty of Engineering Hunedoara*, vol. 14, no. 2, pp. 131-136, 2016.
- [10] Chowdhury, T. M. and H. Murzi, "The evolution of teamwork in the engineering workplace from the First Industrial Revolution to Industry 4.0: A literature review," in *2020 ASEE Virtual Annual Conference Content Access*, Maryland, pp. 1-16.
- [11] W. Maisiri, H. Darwish, and L. van Dyk, "An investigation of Industry 4.0 skills requirements," *S. Afr. J. Ind. Eng.*, vol. 30, no. 3, pp. 90-105, Nov, 2019.
- [12] T. C. Piñol, S. A. Porta, M. R. Arévalo, and J. Minguella-Canela, "Study of the training needs of industrial companies in the Barcelona Area and proposal of Training Courses and Methodologies to enhance further competitiveness," *Procedia Manuf.*, vol. 13, pp. 1426-1431, 2017.
- [13] M. Graczyk-Kucharska, M. Szafrański, M. Goliński, and M. Spychała, "Model of competency management in the network of production enterprises in Industry 4.0: Assumptions," in *Advances in Manufacturing*, A. Hamrol, O. Ciszak, S. Legutko, and M. Jurczyk, Eds. New York: Springer, 2018, ch. 19, pp. 195-204.
- [14] P. Caratozzolo, and A. Álvarez, "A new transdisciplinary approach to foster soft skills in engineering: Using critical reading micro-workshops," in *2018 World Engineering Education Forum-Global Engineering Deans Council (WEEF-GEDC)*, Albuquerque, NM, USA, pp. 1-6, DOI: 10.1109/WEEF-GEDC.2018.8629775
- [15] L. Prifti, M. Knigge, H. Kienegger, and H. Krcmar, "A competency model for 'Industrie 4.0' employees," presented at the *13th International Conference on Wirtschaftsinformatik*, St. Gallen, Switzerland, Feb. 12-15, 2017.
- [16] S. M. Sackey, and A. Bester, "Industrial engineering curriculum in Industry 4.0 in a South African context," *S. Afr. J. Ind. Eng.*, vol. 27, no. 4, pp. 101-114, Dec, 2016.
- [17] F. Acerbi, S. Assiani, and M. Taisch, "A methodology to assess the skills for an Industry 4.0 factory," in *Advances in Production Management Systems: Towards Smart Production Management Systems*, New York, USA: Springer, 2019, ch. 2, pp. 520-527.
- [18] W. Maisiri, and L. van Dyk, "Industry 4.0 Competence Maturity Model design requirements: A systematic mapping review," in 2020 IFEEES World Engineering Education Forum-Global Engineering Deans Council (WEEF-GEDC), Cape Town, pp. 124-130, DOI: 10.1109/WEEF-GEDC49885.2020.9293654
- [19] J. Pöppelbuß, and M. Röglinger. (2011, June), What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management. Presented at the 2011 European Conference on Information Systems (ECIS).
- [20] L. van Dyk, "The development of a telemedicine service maturity model," Ph.D. dissertation, Department of Industrial Engineering, Stellenbosch University, Stellenbosch, 2013. [Online]. Available: https://scholar.sun.ac.za/bitstream/handle/10019.1/85787/vandyk_development_2013.pdf?sequence=1&isAllowed=y
- [21] N. du Preez, and L. Pintelon, "The industrial engineer: Caught between two revolutions?," *Production Planning & Control*, vol. 8, no. 5, pp. 418-430, Nov. 2010.
- [22] V. Ravi, "Introduction to Industrial Engineering," in *Industrial Engineering and Management*, New Delhi, India: PHI Learning, 2015, pp. 3-5.
- [23] B. Curtis, W. E. Hefley, and S. Miller, *Overview of the people capability maturity model*, Pittsburgh: Carnegie-Mellon University, 1995. [ebook]. Available: https://resources.sei.cmu.edu/asset_files/MaturityModule/1995_008_001_16349.pdf [Accessed May 23, 2019].
- [24] B. Curtis, W. Hefley, and S. Miller, *People capability maturity model (P-CMM) version 2.0*, 2nd ed. Pittsburgh: Carnegie-Mellon University, 2009. [ebook]. Available: https://resources.sei.cmu.edu/asset_files/TechnicalReport/2009_005_001_15095.pdf [Accessed May 23, 2019].
- [25] A. Gillies and J. Howard, "Managing change in process and people: Combining a maturity model with a competency-based approach," *TQM & Business Excellence*, vol. 14, no. 7, pp. 779-787, Sep. 2003.
- [26] J. Becker, R. Knackstedt, and J. Pöppelbuß, "Developing maturity models for IT management," *Bus. Inf. Syst. Eng.*, vol. 1, no. 3, pp. 213-222, Mar. 2009.
- [27] H. El-Baz, and I. A. Zulkernan, "Employee competency maturity model and its application in global software outsourcing," *Int. J. Comput. Appl.*, vol. 40, no. 3, pp. 170-180, 2011.
- [28] International Engineering Alliance. (2013). *Graduate attributes and professional competencies*. [Online]. Available from: <https://www.ieagreements.org/assets/Uploads/Documents/Policy/Graduate-Attributes-and-Professional-Competencies.pdf>
- [29] S. C. Onar, A. Ustundag, Ç. Kadaifci, and B. Oztaysi., "The changing role of engineering education in Industry 4.0 era," in *Industry 4.0: Managing the Digital Transformation*, New York, USA:Springer, 2018, ch. 8, pp. 137-151.
- [30] J. Walther, and D. Radcliffe, "The competence dilemma in engineering education: Moving beyond simple graduate attribute mapping," *AJEE*, vol. 13, no. 1, pp. 41-51, Nov, 2007. Accessed on: April 25, 2021, DOI: 10.1080/22054952.2007.11464000, [Online].
- [31] D. Ipperciel, D. and S. ElAtia, "Assessing graduate attributes: Building a criteria-based competency model," *IJHE*, vol. 3, no. 3, Jun. 2014.
- [32] C. C. Hsu, and B. A. Sandford, "The Delphi technique: Making sense of consensus," *PARE*, vol. 12, no. 10, pp. 1-10, Aug, 2007. Accessed on: February, 17, 2021, DOI: 10.7275/pdz9-th90, [Online].
- [33] L. M. S. de Linhares, P. M. G. Kawakame, D. H. Tsuha, A. S. de Souza, and A. R. Barbieri, "Construction and validation of an instrument for the assessment of care provided to people with suicidal behavior," *Revista de Saude Publica*, vol. 53, Sep. 2019.
- [34] J. Barroso-Osuna, J. J. Gutiérrez-Castillo, M. d. C. Llorente-Cejudo, and R. Valencia Ortiz, "Difficulties in the incorporation of augmented reality in university education: Visions from the experts," *NAER Journal*, vol. 8, no. 2, pp. 126-141, 2019.

- [35] G. J. Skulmoski, F. T. Hartman, and J. Krahn, "The Delphi method for graduate research," *JITE:Research*, vol. 6, no. 1, pp. 1-21, 2007.
- [36] S. Jünger, S. A. Payne, J. Brine, L. Radbruch and S. G. Brearley, "Guidance on conducting and reporting Delphi studies (CREDES) in palliative care: Recommendations based on a methodological systematic review," *Palliative medicine*, vol. 31, no. 8, pp. 684-706, 2017.
- [37] A. T. Wildeboer, H. A. Stallinga, and P. F. Roodbol, "Validation of the International Classification of Functioning, Disability and Health (ICF) core set for Diabetes Mellitus from nurses' perspective using the Delphi method," *Disability and Rehabilitation*, 2020. Accessed on: March 20, 2021, DOI: 10.1080/09638288.2020.1763485, [Online].
- [38] E. Tchouaket Nguemeleu *et al.*, "Development and validation of a time and motion guide to assess the costs of prevention and control interventions for nosocomial infections: A Delphi method among experts," *PloS one*, vol. 15, no. 11, pp. e0242212, 2020.
- [39] Z. Rastegari, M. H. Yarmohammadian, F. Mohammadi and S. Kohan, "A comprehensive home-care program for health promotion of mothers with preeclampsia: Protocol for a mixed method study," *Reproductive Health*, vol. 16, no. 1, pp. 1-6, 2019.
- [40] N. Nordina, B. M. D. Md Deros, D. A. Wahab and M. N. Ab. Rahman, "Validation of lean manufacturing implementation framework using Delphi technique," *Jurnal Teknologi*, vol. 59, no. 2, 2012.
- [41] R. Coetzee, "Development of the Respect for People model for lean implementation in the South African context," Ph.D. dissertation, School of Industrial Engineering, North-West University, Potchefstroom, 2019. [Online]. Available: <https://repository.nwu.ac.za/handle/10394/34154>
- [42] S. Caino, P. Domínguez, V. Aguerre, V. Castellano, E. A. Gilardon, J. C. Cernadas, and M. D. Vanesa Castellano, "Instrument to assess research projects that apply for a fellowship by the Sociedad Argentina de Pediatría: Validation using the Delphi method," *Arch Argent Pediatr.*, vol. 117, no. 4, pp. e333-e339, Feb. 2019.
- [43] W. Maisiri, and L. van Dyk, "Industry 4.0 readiness assessment for South African industries," *S. Afr. J. Ind. Eng.*, vol. 30, no. 3, pp. 134-148, Nov. 2019.
- [44] L. F. C. da Cunha, C. L. Baixinho, and M. A. Henriques, "Preventing falls in hospitalized elderly: Design and validation of a team intervention," *Revista da Escola de Enfermagem*, vol. 53, pp. e3479, Jul. 2019.
- [45] C. Woodruffe, "What is meant by a competency?," *Leadership & Organization Development Journal*, vol. 14, no. 1, pp. 29-36, 1993.
- [46] T. Hoffmann, "The meanings of competency," *Journal of European Industrial Training*, vol. 26, no. 6, pp. 275-285, Mar. 1999.
- [47] R. Palan, "Introduction," in *Competency Management*, Kaula Lumpar, Malaysia: Specialist Management Resources, 2003, pp. 5-25.
- [48] National Institute of Health. (2020). *Competencies proficiency scale*. [Online]. Available: <https://hr.nih.gov/working-nih/competencies/competencies-proficiency-scale>.
- [49] D. R. Krathwohl, "A revision of Bloom's taxonomy: An overview," *Theory into Practice*, vol. 41, no. 4, pp. 212-218, 2002.
- [50] D. Horváth, and R. Z. Szabó, "Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?," *Technol. Forecast. Soc. Chang*, vol. 146, pp. 119-132, 2019.
- [51] A. Raj, G. Dwivedi, A. Sharma, A. B. Lopes de Sousa Jabbour, and S. Rajak, "Barriers to the adoption of Industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective," *Int. J. Prod. Econ.*, vol. 224, pp. 1-17, 2019.
- [52] A. B. L. de Sousa Jabbour, C. J. C. Jabbour, M. F. Godinho, and D. Roubaud, "Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations," *Ann. Oper. Res.*, vol. 210, no. 1-2, pp. 273-286, 2018.
- [53] A. Jerman, A. Bertoncelj, G. Dominici, M. Pejić Bach, and A. Trnavčević, "Conceptual key competency model for smart factories in production processes," *Organizacija*, vol. 53, no. 1, pp. 68-79, 2020.
- [54] F. M. Kamaruzaman, R. Hamid, A. A. Mutalib, and M. S. Rasul, "Conceptual framework for the development of 4IR skills for engineering graduates," *Glob. J. Eng. Educ.*, vol. 21, no. 1, pp. 54-61, 2019



Whisper Maisiri received MEng in Mechanical Engineering from the North-West University, Potchefstroom, South Africa, and a BEng (Honours) in Industrial and Manufacturing Engineering from the National University of Science and Technology, Bulawayo Zimbabwe. He is pursuing a Doctor of Philosophy degree in Industrial Engineering at North-West

University, South Africa.

From 2017 to 2019, he was a Lecturer with Walter Sisulu University, Butterworth, South Africa. He is currently a Lecturer in the School of Industrial Engineering at North-West University, Potchefstroom, South Africa. His research interest is on technology, innovation, and society, currently focusing on sustainable adoption of the Fourth Industrial Revolution and Industry 4.0.



Liezl van Dyk was awarded a PhD in Industrial Engineering by Stellenbosch University (2013), an MSc in Manufacturing Systems Engineering by the University of Warwick (2000) and a Bachelors of Engineering degree from University of Pretoria (1996).

She is the Executive Dean of the North-West University Faculty of Engineering and is rated by the National Research Foundation of South Africa as an established researcher focusing on ICT-supported service systems.

Prof van Dyk was awarded a lifelong honorary fellowship in 2020 by the South African Institute for Industrial Engineering



Rojanette Coetzee was awarded a Doctoral degree in Industrial Engineering, a Masters degree in Engineering Management and a Bachelors of Mechanical Engineering by the Northwest University, Potchefstroom, South Africa.

She is currently a Senior Lecturer at the School of Industrial Engineering and a Research Director of the Faculty of Engineering at the North-West University. Her research focus is on lean manufacturing and human factors engineering.