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Industry 4.0 implementation strategy for Small Medium Enterprises

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By

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ABSTRACT

An I4.0 implementation strategy is a tool that aids small and medium enterprises to meet the fourth industrial revolution pre-requisites and standards. The main objective of the current research that has been achieved, is that it established an industry 4.0 implementation strategy for SMEs, that is capable of providing enterprises with the most effective road map to overcome the obstacles faced by SMEs during transformation and accomplish the fourth industrial revolution's standards. A roadmap and the implementation strategy will be specifically tailored to the participating enterprise, based on their assessment scores. The implementation strategy requires four consecutive steps including Maturity Assessment, Influence Assessment, Roadmap Construction, and Implementation.

An Industry 4.0 implementation strategy has been devised to increase the accuracy of assessing SME's technological maturity level by providing a weighting factor for relevant implementation dimensions by using an Analytic hierarchy process (AHP). Weight factors were established to identify dimensions that are most influential at small/medium manufacturing enterprises and prioritize their transformation. A total maturity score of the enterprise as a whole valued between 0-100 is determined at the end of the maturity assessment through utilizing radar charts. This research includes a case study that was conducted at SPM Automation Inc. , a local small-sized enterprise, where the proposed four-step implementation strategy was conducted and succeeded to measure the current I4.0 maturity score which was 33%, and create an implementation strategy that targets the most influential dimensions and prioritize their transformation.

DEDICATION

To

my parents & siblings for their continuous support

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CONTENT

Chapter 1: INTRODUCTION

1.1 Research Motivation

The word "revolution" denotes abrupt and radical change. Throughout history, revolutions have occurred when new technologies and novel ways of perceiving the world trigger a profound change in economic systems and social structures. The agrarian revolution, which is considered the mother of all industrial revolutions, initiated the domino effect in the world of production by establishing the transition from foraging to farming, which took place around 10,000 years ago and was made possible by the domestication of animals. The utilization of animals in everyday work improved production, transportation, and communication. The agrarian revolution resulted in industrial revolutions that began in the second half of the 18th century, which remarkably transitioned the industrial processes from muscle power to mechanical power, evolving to where we are today with the fourth industrial revolution that introduced the cyber-physical world. The first industrial revolution took place between 1760 and 1840 which was introduced by the construction of railroads and the introduction of steam engines. Moving to the 20th century the second industrial revolution was triggered by electricity and assembly lines. Later on, in the 1960s the third industrial revolution was triggered by the deployment of the semiconductors, mainframe computing, personal computing, and the internet. Today we are witnessing the approach of the fourth industrial revolution which will introduce cyber-physical systems to the industrial world (Schwab 2016).

Industry 4.0 (the fourth industrial revolution) is recently one of the main interesting topics in the manufacturing industry. The new industrial revolution is transitioning from being just a theoretical view of the future of the industry to the actual implementation phase. Only a handful of industries have indeed adopted this manufacturing feature, while the majority of others are thriving to do so (Schumacher, et al. 2016). Schumacher have discovered that only 1 percent of German companies have reached the level of “expert”, which is level four out of five according to their maturity scale (Schumacher, et al. 2016). None of the companies reached the level “top performer” (level 5). Such results make it very important to create tools and methods to help the enterprises to climb the ladder and achieve the newer industrial revolution’s features and benefits. A very helpful tool to use towards such an objective is constructing an implementation strategy that would help enterprises elevate their readiness level and achieve the fourth industrial revolution’s standards. Other benefits that an implementation strategy can support includes the measuring of enterprise’s readiness or maturity level to provide a better reading on the current status of the enterprise and how far or close they are from achieving I4.0 standards. It would also answer the questions of what is missing? What is the fastest roadmap towards achieving the next maturity level? What are the most important factors?

Various existing maturity models that are concerned with the readiness of industry 4.0, but there is a research gap regarding the implementation strategies of Industry 4.0 concepts for small and medium-sized enterprises (SMEs) (Bär, et al. 2018). Enterprises need to have a plan or a roadmap that provides detailed steps of how enterprises could approach maturity models, and what steps should be considered before and after the assessment.

In this work, a four-step implementation strategy is established to help guide SMEs during their I4.0 transformation process. The strategy includes features such as 1) the introduction of the Analytical Hierarchy Process (AHP) to aid with decision making, and 2) radar chart plotting to provide a visual representation of the maturity status and provide a total maturity score. The implementation strategy with the aid of AHP will help SMEs concentrate on the 16 considered dimensions, listed in Fig 2, with the highest Benefit-cost ratio (BCR). Directing investments to the dimensions with the highest Benefit-cost ratio is essential for SMEs, due to the capital constraints most SMEs face during their transformation (Mittal, et al. 2018).

This research addresses the differences between SMEs and larger enterprises and finds a maturity model that acquires these differences. This is achieved by examining some scholarly publications that focus mainly on industry 4.0 maturity models, which are related in terms of application to this thesis research and creating an adjustable weighing system that provides a weighing scheme to allow enterprises to tailor the maturity models to fit their business needs and capabilities. AHP is a very good candidate for making this possible when implemented in the weighing factor selection process, since it would provide an accurate weighing factor for each dimension of the maturity model, based on the enterprise's preferences, and capabilities since it has proven to be a very effective tool in the field of decision making (Saaty 2001).

1.2 Statement of Engineering Problem

During the transformation process from a regular factory to a smart factory (I4.0), small and medium enterprises face the limited funding barrier. With limited funding, small and medium enterprises find it very difficult to invest capital to transform in all of their enterprise's dimensions at once. Besides, some enterprises yet require more knowledge about I4.0 and how they could achieve its standards, and how far they are standing from achieving it.

1.3 Research Thesis Hypothesis

The research thesis statement of this research could be formulated as the following:

An Industry 4.0 implementation strategy that could provide a roadmap for SMEs to aid their transformation towards becoming a smart factory and overcome their limited funding barriers through prioritizing various dimensions of the enterprise to be transformed over other, could be achieved through utilizing benefit cost ratio, AHP, and an I4.0 maturity model.

1.4 Objective

In this work an I4.0 implementation strategy is proposed that will help SMEs, mostly in the automotive sector, to adopt I4.0 by establishing a roadmap that will aid SMEs throughout their transformation process towards becoming a smart factory. The proposed methodology is a four-step process as displayed in Fig 1.1, which utilizes Benefit-cost ratio, Singapore Smart Industry

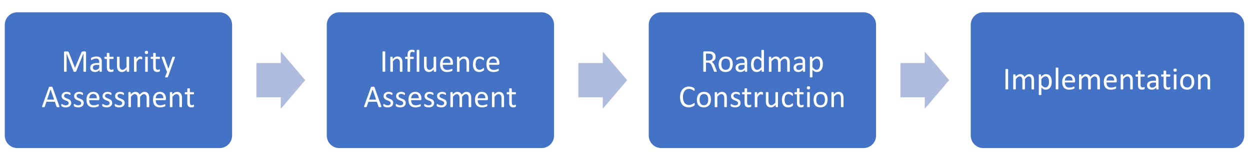

Figure 1.1 *I4.0 Four-step implementation strategy for small medium enterprises*

Readiness Index (SSIRI), and AHP to establish an I4.0 transformation roadmap that will help SMEs overcome the financial barriers that are faced when transformation is considered. This is possible through focusing and directing their funding and efforts towards the most influential elements at their enterprise.

1.5 Research Scope

The scope of this research and the boundary of the work are outlined as follow:

- This research is limited to small-medium enterprises particularly in the automotive field
- Product assembly
- Type of operation: Hybrid automated and manual assembly

1.6 Research Structure

This research is presented in 5 chapters, including the introduction chapter. Chapter 2 summarizes the available research literature on several topics related to this work such as a review over the current maturity models available for both small-medium and multinational enterprises, followed by a review of various applications of AHP in various fields, and finally a review of the current I4.0 implementation strategies available.

Chapter 3 will provide an in-depth detailed explanation of the proposed i4.0 implementation strategy. Chapter 4 displays the case study process, results, and discussion that was conducted on a local medium-sized enterprise (SPM Automation Inc.). Finally, Chapter 5 provides a conclusion, discussion of the novelty of the present research, and suggestions for future work.

Chapter 2: Literature Review

The literature review consists of three sections. Section 1 is a review of the current maturity models available for both small medium enterprises (SMEs) and multinational enterprises (MNEs). Section 2 is a review of various applications of AHP in various fields. Section 3 reviews the current I4.0 implementation strategies and finally, section 4 includes the summary of the literature review.

2.1 Maturity Models for Small Medium and Large Enterprises

A maturity model is a tool that helps people assess the current effectiveness of a person or group. I4.0 maturity models aid with assessing the Industry's maturity or readiness towards obtaining

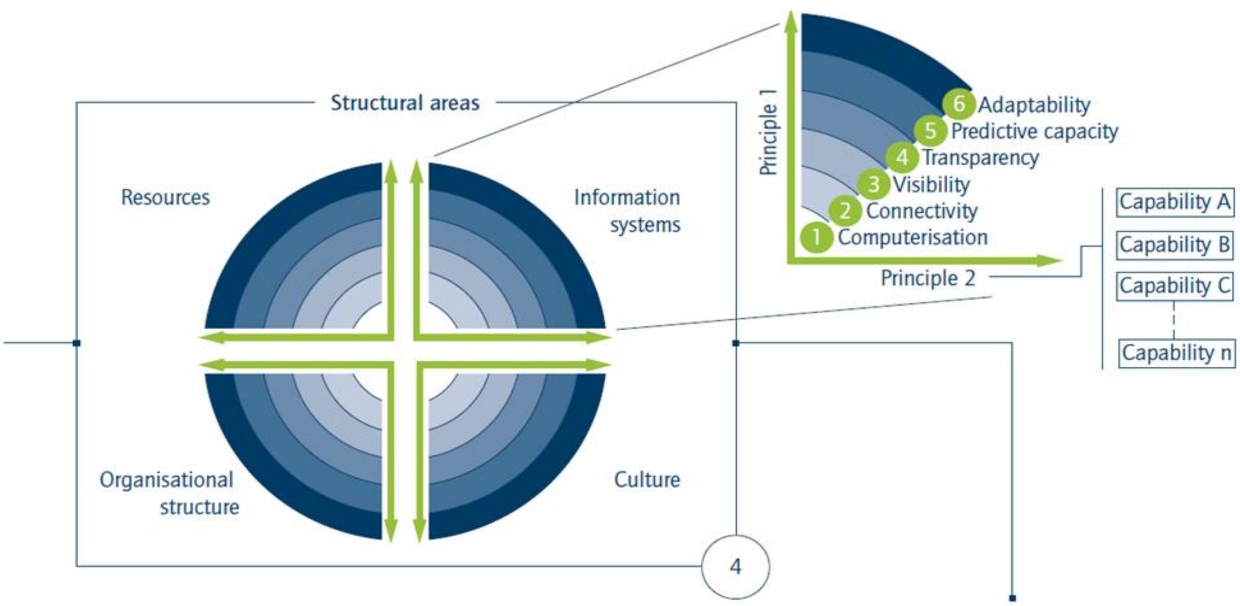

Figure 2.1 *Acatech maturity model (Schuh, et al. 2017)*

the fourth industrial revolution's standards and features. Recent I4.0 maturity models mostly consider Multinational enterprises (MNEs), on the other hand, SMEs do not receive equal attention (Mittal, et al. 2018). Acatech (Schuh, et al. 2017) Fig 2.1 have developed a maturity model that focuses on four main pillars which includes resources, organizational structure, information systems, and culture. Their research consists of 600 questions that determine the level of maturity of each sub-dimension on a scale of 6 maturity levels including computerization, connectivity, visibility, transparency, predictive capacity, and adaptability. Acatech's approach did a great job covering all the major components of I4.0 and presenting a visual representation of the maturity level of each component, but it lacked the ability to provide an aggregated value of a final maturity score, and a weight factor to differentiate between the importance of each pillar.

Schumacher (Schumacher, et al. 2016) introduced a maturity model that consists of 9 sub-dimensions including strategy, leadership, customer, products, operations, culture, people, governance, and technology that assessed each enterprise over 5 maturity levels. The model includes a weighing factor established based on E-mail based distribution of 123 questionnaires to practitioners and researchers which resulted in 23 responses. The practical importance of each maturity item was rated on a Likert-scale (Schumacher, et al. 2016), ranging from "not important" (rating = 1) to "very important" (rating = 4). Schumacher included a weighing factor, but the values represented personal/subjective opinions which may contradict other enterprise's priorities based on their knowledge of their enterprises. Bibby (Bibby and Dehe 2018) Introduced a maturity model that emphasized three main pillars: factory of the future, people and culture, and strategy. It also involved a weight factor where the weight of each pillar is set according to the number of items present in each. The maturity levels ranged from 1 to 4 representing minimal, developed, defined, and excellent respectively. Basing the importance of the pillars on the number of items present in each of them is questionable, since a pillar may have fewer number of items but with great importance. Leyh (Leyh, et al. 2016), developed a maturity model (SIMMI 4.0) that considered four pillars including Vertical Integration, Horizontal Integration, Digital Product Development, and Cross-sectional technology criteria, and five maturity levels including Basic digitization level, cross-departmental digitization, horizontal and vertical digitization, full digitization, and optimized full digitization. The scoring process consists of a set of questions concerning each sub-dimension and a score is determined based on the answers. Each sub-dimension score is the sum of every question score divided by the total number of questions. The total maturity level will be the addition of all sub-dimensions divided by 4. Leyh's approach does not use a weight factor or a graphical representation of the maturity level of each pillar. Lichtblau (Lichtblau, et al. 2015) proposed a maturity model that focuses on seven pillars

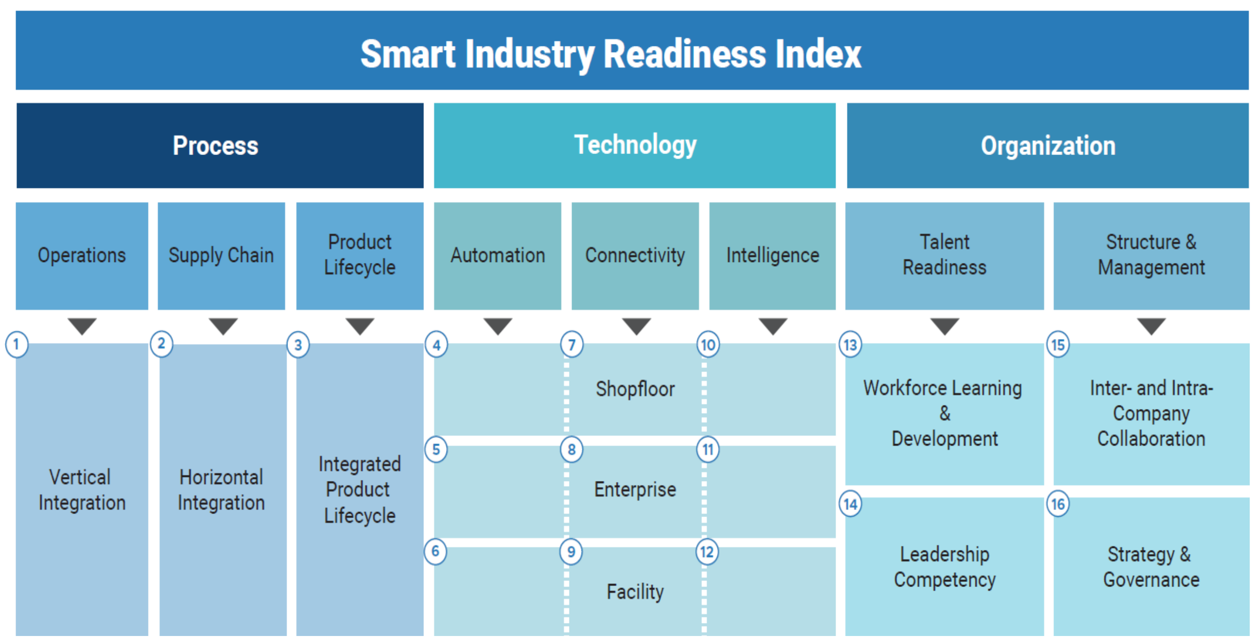

Figure 2.2 *Singapore Smart Industry Readiness index (Board, 2018)*

Including employees, strategy and organization, smart factory, smart operations, smart products, data-driven, and services and six levels of maturity which includes outsider, beginner, intermediate, experienced, expert, and top performer. The scoring process is based on a set of criteria that the enterprise meets. Singapore smart industry readiness Index (SSIRI) (Board 2018) is illustrated in Fig 2.2.

It considers three main pillars (Technology, Process, and Organization) and eight sub-dimensions (operations, supply chain, product Lifecycle, automat, connectivity, intelligence, talent readiness, and structure & management). The SSIRI established six maturity levels ranging from 0-5 representing Undefined, defined, digital, integrated, automated, and intelligent respectively. The scoring is based on a readily available criterion and the enterprise is assessed only based on what criteria it meets. SSIRI is of great interest since It covers all the essential pillars that makeup I4.0 and provides detailed criteria on a scale of 0 to 5 which is very beneficial for assessing SMEs. The S.S.I.R.I smart industry readiness index does not include a weight factor to differentiate the importance and the magnitude of impact of each pillar relative to the other pillars.

Even though it is not sufficient, in the means of attention and number of researches that SMEs demand, SMEs have their share with maturity models developed in their favor.

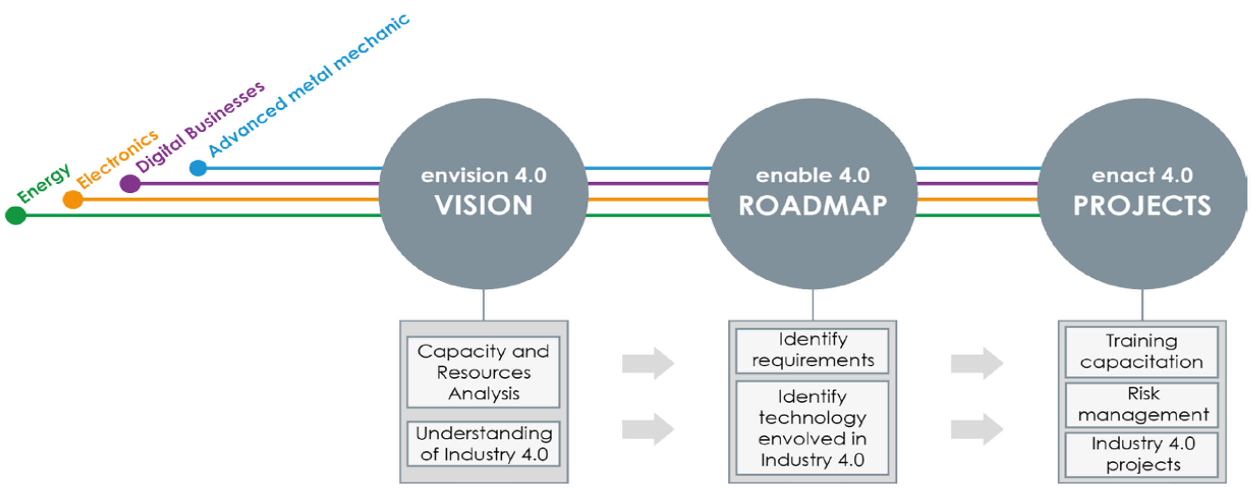

Figure 2.3 *Ganzaraon's three staged approach (Ganzarain and Errasti, 2016)*

Hamidi’s (Hamidi, et al. 2018) maturity model consists of six dimensions Including Employment, Data-driven services, smart product, smart operations, smart factory, strategy and organization. The survey questionnaires are designed based on quantitative data collection and were adopted from previous research based on the IMPULS maturity model (Lichtblau, et al. 2015). Ganzarain and Errasti (Ganzarain and Errasti 2016) Proposed a process model as a guiding framework for Industry 4.0 through three main stages (Fig 2.3): diversification vision, strategy and action building.

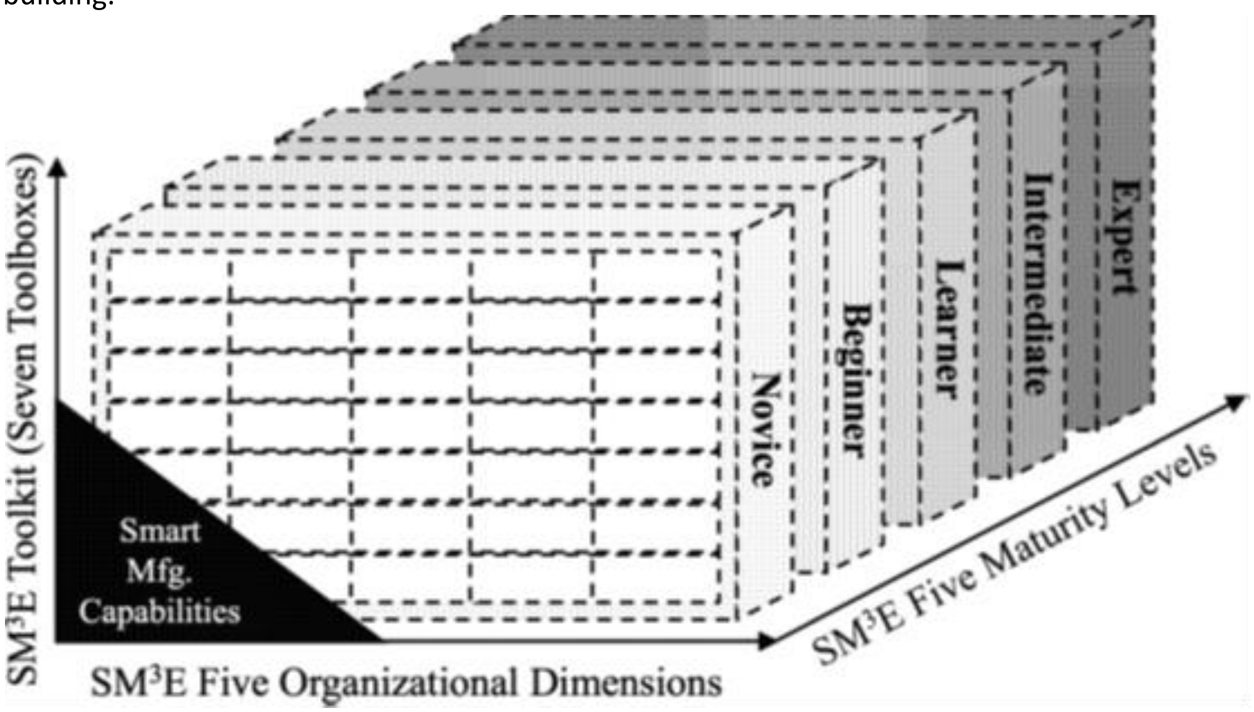

Figure 2.4 *Small medium Enterprises 3D (SM^3E) three-dimensional figure for maturity assessment over toolkit, organization and five maturity levels dimensions (Mittal, et al. 2018)*

SM3E (Mittal, et al. 2018) has approached SMEs by concentrating on five pillars which they proposed to be ‘‘essential for SMEs’’. The pillars included are finance, people, strategy, process, and product. Each of these pillars is measured on a 5 leveled scale from 1 to 5 representing novice, beginner, learner, intermediate, and expert respectively. SM3E has introduced a three-dimensional (Fig 2.4) with three-axis which includes toolboxes, organizational dimension and maturity levels. SM3E has introduced a very basic level to Include the majority of SMEs that lag behind in many fields compared to large enterprises, such fields include technology, connectivity, and organizational complexity. SM3E still misses a numerical value of maturity and a weight factor, which affects the accuracy of the assessment. Chonsawat (Chonsawat and Sopadang 2019) has created an I4.0 assessment method that included 5 Dimension, which to his standards the main important dimensions are manufacturing and operations, people capability, technology driven process, digital support and the Least important is Business and Organization Strategy and included 43 Sub-Dimension. His approach also included a graphical representation and a weight factor. Chonsawat's approach introduces a scale ranging from 0 to 5, a scale with smaller increments such as 0-100, would display a better accuracy in the assessment results. In addition, it is only limited to assessing and not providing information on how SMEs can progress and transform to the next maturity level or provide criteria for each sub-dimension.

Table 2.1 *Literature review summary*

Source	Year	Main Pillars	Use of Weights or Aggregated values	SME and/or MNE oriented
Schuh, Anderl et al.	2017	Acatech Technology Organization Culture	None	MNE
Schumacher	2016	Strategy leadership customer products operations culture people governance Technology	Both	MNE
Bibby and Dehe	2018	factory of the future peopleand culture strategy	Weight Factor	MNE
Leyh, Bley et al.	2016	SIMMI 4.0 Vertical Integration Horizontal Integration Digital Product Development Cross-sectional technology	None	MNE
(Lichtblau, Stich et al.	2015	Employees Strategy and organization Smart factory Smart operations Smart products Data-driven Services	None	MNE
Board	2018	SSIRI Technology Process Organization	None	SME and MNE
Hamidi, Aziz et al.	2018	Employment Data driven services smart product smart operations smart factory strategy organization	None	MNE
Ganzarain and Errasti	2016	Diversification vision Strategy Action building	None	MNE
Mittal, Romero et al.	2018	SM3E Finance People Strategy Process Product	None	SME
Chonsawat	2019	Manufacturing and Operations People Capability Technology Driven Process Digital Support Business and Organization	Weight Factor	MNE

2.2 Decision Support Tool

The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It is used to support decision making when multiple criteria are involved. The AHP methodology is a flexible tool that can be applied to any hierarchy of performance measures (Rangone 1996). According to (Chou and Liang 2001), most of the multiple criteria decision-making (MCDM) approaches consist of two steps: (1) Aggregation of the judgments with respect to all goals and decision-making alternatives; and (2) Ranking of the decision alternatives according to the aggregated judgements (scores). (Vreeker, et al. 2002) Suggests that the basic rules for solving multi-level hierarchical problems involve essentially four steps: (1) specification of choice problem; (2) information analysis; (3) choosing the appropriate method; and (4) evaluation of alternatives.

The success of the AHP in research in several areas supports its use to solve decision-making problems, for example in (Vreeker, et al. 2002), (Lirn, et al. 2004), (Chang and Yeh 2001), (Chang and Yeh 2001), (Tzeng 1994) and (Frankel 1992). Lirn used the AHP to study job attractiveness in the airline industry in Taiwan. (Yedla and Shrestha 2003) utilized the AHP to select environmentally friendly transport systems in India. (Chou and Liang 2001) used the AHP to create a model capable of evaluating the performance of shipping companies. (Lirn, et al. 2004) applied AHP methodology to reveal preferences regarding transshipment port selection. As argued by (Forgionne, et al. 2002) the AHP methodology as a decision support system mechanism can easily accommodate model modifications and simulations through sensitivity analysis, since the main objective of four-step implementation methodology established in this work is to make decisions of which dimensions to prioritize out of the sixteen, it needs a decision-making tool to support this process. Chapter 4 will include a detailed explanation of the AHP mathematical process and all the details on how it works through treating data collected during the case study process.

2.3 Difference Between Large and Small Manufacturing Enterprises Maturity Models and Adoption

According to the European Commission (EC,2018), SMEs may be defined as the enterprises which employ less than 250 employees and have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million. When small-medium enterprises are compared to multinational enterprises, at the first glance they seem to be with no significant impact on the fourth industrial revolution, but SMEs are the driving force of many manufacturing economies (Schumacher, et al. 2016). As the backbone of the manufacturing industry, SME's impact on the Fourth Industrial Revolution is significant (Schiersch 2013). SMEs often face different challenges and barriers than larger enterprises when it comes to i4.0 transformation (Wuest, et al. 2014), (Wadhwa 2012). Schröder (Schröder, 2016) emphasized that the biggest challenges that small and medium-sized enterprises have to meet in this context are the development of an appropriate strategy, a cost–benefit analysis of the relevant technologies and lack of data security and uniform standards.

The current literature considers and debates numerous opportunities and challenges faced by SMEs. Wuest (Wuest, et al. 2014) highlighted the influence of information management in manufacturing SMEs. On the other hand, Dyerson (Dyerson, et al. 2016) performed an empirical analysis of 117 small manufacturing firms in the UK and clustered them based on their degree of IT readiness. In 2003 Kennedy and Hyland (Kennedy and Hyland 2003) gathered analyzed data from 632 SMEs and met the conclusion that SMEs are to be distant when the deployment of Advanced Manufacturing Technologies (AMTs) is considered. Terziovski (Terziovski 2010) studied 600 Australian manufacturing SMEs and discovered that SMEs suffer from a shortage of innovation culture and strategy to succeed. Kumar (Kumar, et al. 2014) compared the numerous quality management practices in the United Kingdom and Australian manufacturing SMEs and discovered that leadership, fact-based decision-making, networking with government bodies and academic institutions, as well as an ISO 9000 certification are critical success factors for SMEs. In 2017 Müller and Voigt (Müller and Voigt 2017) conducted interviews with CEOs, managers, and manufacturing consultants to discover the influence of knowledge management in Indian manufacturing SMEs.

In Mittal's work (Mittal, et al. 2018) it was concluded that global awareness on manufacturing, regular interaction between the employees, attending workshops or conferences abroad, as well as industry-academia interaction, are critical activities that promote knowledge creation. Müller and Voigt (Müller and Voigt 2017) proposed the design interaction strategies for the introduction of Industry 4.0 in German SMEs and interviewed 68 specialists including 41 CEOs in firms dealing in mechanical and plant engineering, electrical engineering and automotive suppliers, and determined that standardization, personnel resources, financial resources, and a belief on digitization are distinctive constraints for SMEs.

In 2018 Mittal (Mittal, et al. 2018) has reviewed the previous literature and constructed (Table 2.2) which depicts particular SME features, stresses on the differences between the standpoints of small and multinational enterprises.

Table 2.2 *Comparison of SME and MNE features (Mittal, et al. 2018)*

Comparison of SME and MNE based on defining features

#	Features	SMEs	MNEs
1	Financial Resources	Low	High
2	Use of Advanced Manufacturing Technologies (AMTs)	Low	(Very) High
3	Software Umbrella (incl. Data Analytics)	Low (Often Tailored Solutions)	High (With More Standardized Solutions)
4	Research & Development	Low	High
5	Nature of Product Specialization	High	Low
6	Standards consideration	Low	High
7	Organization culture/ Leadership flexibility	Low	High
8	Company Strategy	Dictated by Instinct Of Leader (Owner)	Market Research & Accurate Analyses
9	Decision Making	Restricted to Leader/ Few Knowledge Carriers	Board of Advisors & (Int./Ext.) Consultants
10	Organizational Structure	Less Complex And Informal	Complex And Formal
11	Human Resources Engagement	Multiple Domains	Specialized Domains
12	Exposure to Human Resource Development	High in The Industry/ Low Outside The Industry	Low Within Industry/ High Outside the Industry
13	Knowledge and Experience Industry	Focused In A Specific Area	Spread Around Different Areas
14	Alliances with Universities/ Research Institutions	Low	High
15	Important Activities	Outsourced	Internal to The Organization
16	Dependence on Collaborative Network	High	Low
17	Customer/Supplier Relations	High (Strong)	Low (Not So Strong)

Mittal also grouped the various similar SME requirements into eight clusters (finance, technical resource availability, product specialization, standards, organizational culture, employee participation, alliances and collaboration). All the following subsections (a-g) are influenced by research works by (Mittal, et al. 2018) (Schiersch, 2013) (Wuest, et al. 2014) (Wadhwa, 2012) (Dyerson, et al. 2016) (Kennedy 2003) (Müller 2017).

2.3.1 Finance

SMEs face capital constraints compared to MNEs such as lack of collaterals, the informational asymmetries between small businesses and investors, etc. which is due to the fact that SMEs are often owned by and individual and various risk factors are involved with the small-scale businesses.

2.3.2 Technology

Due to the financial constraints, SMEs find it more challenging to upgrade and adopt Advanced Manufacturing Technologies (AMTs) in addition they do not have the technical resources readily available. These facts cause a further impact by being the reason behind SMEs low performance towards research and development. SMEs in comparison with MNEs show a lack of IT integration, limiting the software and the technology used to preserve the SME record to only be tailored towards resolving a specific issue faced by SMEs.

2.3.3 Specialized products

Due to the lack of funding and technical resources mentioned in section 3a, and 3b SMEs have an overload of work and responsibilities which leads to highly specialized products that encourage SMEs to stand out compared to their competitors.

2.3.4 Standards

MNEs tend to strictly obey standards such as ISO, but on the other hand, SMEs that do the same are very rare. This is due to the lack of essential resources required to prepare and achieve certification; therefore, SMEs have to be motivated to adopt industrial standards.

2.3.5 Organizational culture

Organizational behavior is a critical aspect of an enterprise. When SMEs are compared with MNEs in organizational culture domain SMEs display a lower level of complexity and stand out to be informal. In addition, SMEs organizational structure is often not flexible enough to experiment and consider implementation initiatives for cutting-edge technologies which leads SMEs to be not able to invest comparably in market research and analysis. Consequently, on many occasions, SME’s decisions are not as informed and are mostly based on a ‘gut feeling’. Gut feeling is considered to be accompanied with high levels of uncertainty, compared with the MNEs approach which is based on market research and accurate analyses that are discussed by a board of consultants.

2.3.6 Employee participation

Employees in SMEs and MNEs receive different exposures and opportunities in their working field. While MNEs get the opportunity to be more specialized and thus considered experts, SME’s employees are refrained from that subject due to various responsibilities that lay on their shoulders, making it less likely to develop high levels of expertise in a particular field. SMEs employees often lack the opportunity to attend workshops, supervised industrial training, and mentors resulting in a lack of employee participation.

2.3.7 Alliances and collaboration

The collaboration strategies are considered essential for the success of an enterprise. However, SMEs show a low level of alliance with research institutes and universities, depending on learning from their personal experience due to their shortage of access to shared knowledge. SMEs often focus their knowledge on specific domains, while MNEs expand their knowledge in various areas, causing SMEs to outsource various important activities. Adding the fact that SMEs have fewer products to manage, resulting in weaker collaborative networks.

2.4 Summary of literature and Research Gaps

The literature review conducted has considered the most recent ten I4.0 maturity models and four implementation strategies. Recent maturity models display a lack of consideration to compare the importance of each dimension compared to the other. Enterprises are part of the economy, and since profit is an essential aspect of any economy, maturity models must display importance or priority of each dimension compared to the other based on the benefit-cost ratio, aiding in managing investments, and funding, that are directed towards the transformation process. Recent I4.0 maturity models display lack of attention towards SMEs as seen in table 2.2. The main objective of this research is to create an implementation strategy that will obtain all the criteria mentioned in table 2.2 and fill the gap. Filling the gap would require an implementation strategy that is capable of providing an aggregated value of the maturity score, a weight factor to display the magnitude of influence of each dimension, and capable of considering both SMEs and MNEs. Singapore smart industry readiness index has been chosen since it provides a detailed 6-level criteria (0-5) using which enterprises can assess their I4.0 maturity with high accuracy, and it includes level 0 which is a very basic level of maturity that many SMEs can relate to. Singapore smart industry readiness index has also been proven to be successful since it has been implemented in more than 300 enterprises. Such characteristics made the Singapore smart industry readiness index the best candidate to be considered in this research.

Chapter 3 will further explain in detail the Singapore smart industry readiness index mentioned in the literature review since it will be the assessment tool to be used in the four-step implementation strategy.

Chapter 3: Readiness Assessment Model

3.1 Four-Step Implementation Strategy

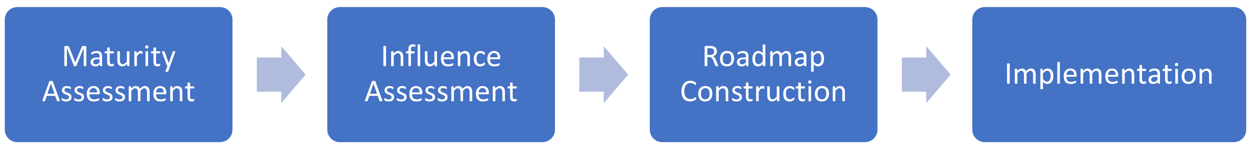

Figure 3.1 *I4.0 Four-step implementation strategy for SMEs*

3.1.1 Maturity assessment

Maturity assessment is the first and most important step in the implementation strategy. During maturity assessment, the enterprise's current I4.0 maturity level is measured. This process includes the application of the Singapore smart industry readiness index. After dissecting the differences between SMEs and MNEs requirements, it was possible to pick a maturity model that would be utilized in the implementation strategy. Singapore Smart Industry Readiness Index (SSIR) (Board, 2018), has been chosen to be the maturity model that will be used through the maturity assessment process. The (SSIR) has been chosen to be the best fit candidate since it provides room to accept SMEs basic requirements by including maturity level zero, which is a very basic stage of maturity. Such consideration will allow the majority of SMEs with basic maturity levels to participate in the assessment and eventually the implementation process as well. In addition (SSIR) has readily available criteria for each maturity level which allows it to be numerical quantitative score based, which means it is capable of adopting a weight factor.

During the application, every dimension of the 16 dimensions listed in the Singapore index will be measured and assessed, to measure its maturity level. The assessment process will be conducted by comparing each maturity level's criteria to the criteria existing at the enterprise. There are six levels ranging from 1-5. After all dimensions are assessed, a radar chart will be constructed based on the results obtained. The radar chart will provide a visual of the assessment results to easily compare all the 16 dimensions at once. Radar charts will provide a total maturity score by calculating the shaded mature area of the graph and dividing it by the total area.

3.1.2 Influence assessment

The influence assessment's main objective is to establish the influence of each of the 16 dimensions on the enterprise. The influence of each dimension is measured based on the return on investment each dimension will bring back, after its transformation. This is calculated by obtaining the benefit-cost ratio of each dimension. Next, the benefit-cost ratios of all the dimensions will be plugged in the analytic hierarchy process (AHP). AHP will compare each of the benefit-cost ratios of each dimension with the other dimensions resulting with a weight value for each dimension. The weight value will represent the importance of each dimension and this will determine its priority to be transformed over the other.

$$Benifit\ Cost\ Ratio = \frac{estimated\ benefits}{estimated\ cost}$$

3.1.3 Road map construction

A road map, in general meaning, is a plan intended to achieve a particular goal while a strategy is considered a plan of action or policy designed to achieve a major or overall aim. In this research, road map expression is with respect to the dimensions that will be prioritized for transformation before others, creating a plan to which dimension to prioritize first, second, third and so on. The prioritizing process has a protocol Table 4.30. Firstly, dimensions with the highest weight factor will be chosen to be transformed first. If two dimensions have equal weight factors, the one with the lower maturity level will be prioritized. At the end of this step, a roadmap will be established with a bundle of most influential dimensions, and their order of transformation.

3.1.4 Implementation

Implementation is the fourth and last step, at this stage, the criteria of the listed dimensions in the roadmap will be listed. The implementation process includes 3 steps (Fig 3.2). The first step in the implementation process is to Fig out the next maturity level to be met and the criteria of that maturity level. Second step is to plan, during planning the implementation of the chosen dimension, the enterprise will assess the feasibility, integration, and training for their employees, to make it easier to adapt to the changes the enterprise will go through. At the end of this stage, the enterprise will have options for business plans for how they would achieve the next maturity level. The third step is to pilot the best business plan.

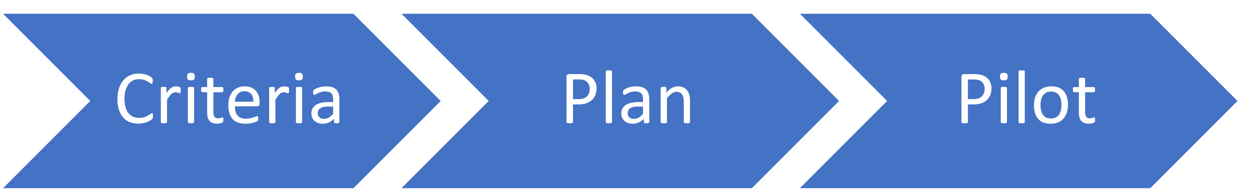

Figure 3.2 *Steps of implementation stage*

3.2 IDEF0

As displayed in Fig 3.3 the IDEF0 of the four-step implementation strategy consists of two main processes, the first is the I4.0 maturity assessment. In this process, the input is the company data that will be provided after the maturity assessment is over. Since the assessment process is conducted through the deployment of both the Singapore smart readiness index and Chonswat's maturity model they are both considered mechanisms. The radar chart is the third mechanism since it will aid in providing a total maturity score. The availability of data and its accuracy are limiting factors of the assessment process since they are not always available due to the team's knowledge and availability, which is the second limiting factor. The output achieved from this process will be the current maturity score and the benefit-cost ratio of each dimension.

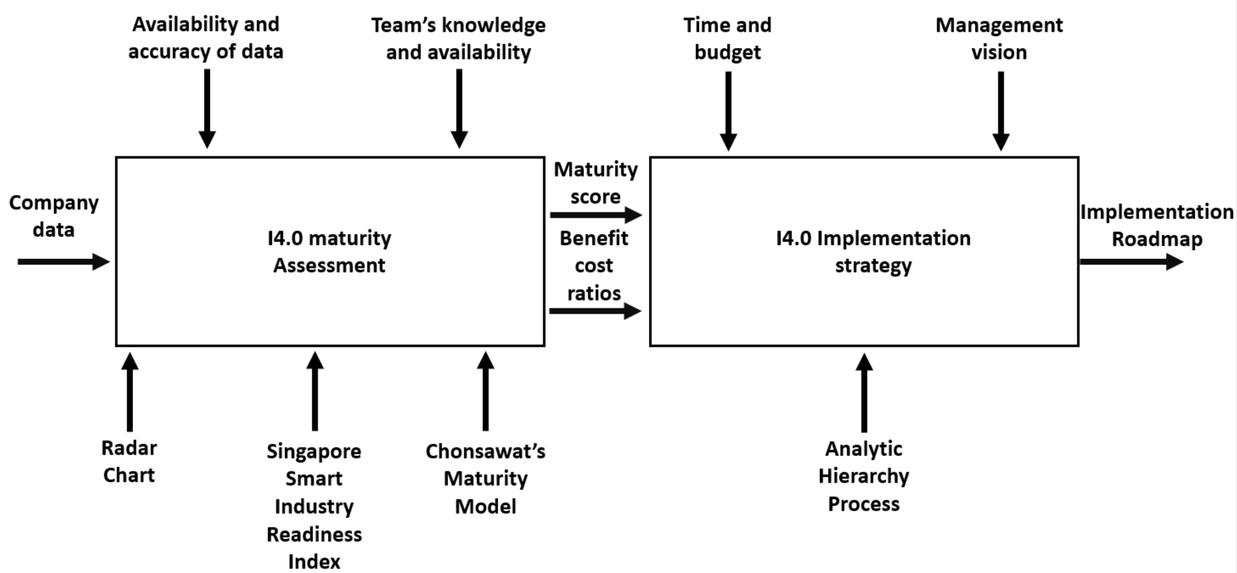

Figure 3.3 *IDEF0 of the four step i4.0 implementation strategy*

The second process is the implementation strategy, during this process, the maturity score and the benefit-cost ratios achieved in the previous process will be the input from which AHP will create a weight factor for each dimension and aid in the selection process of the most influential dimensions. In the second process time and budget and the limiting factors as well as management vision. since if time and budget will limit the accuracy of the roadmap construction and if the management vision to how much they are ready to transform is short it will limit the roadmap to shorter goals. The output of this process will be an i4.0 implementation roadmap.

3.3 Singapore Smart Industry Readiness Index

Singapore Smart Industry Readiness Index (SSIRI), is an I4.0 readiness assessing model that has been created in partnership with global testing, inspection, certification, and training company TÜV SÜD and validated by an advisory panel of industry and academic experts (Board,2018). The Index is comprised of three layers. The topmost layer is made up of the 3 fundamental building blocks of Industry 4.0: Process, Technology, and Organization. Underpinning these 3 building blocks are 8 pillars of focus. The 8 pillars then map onto 16 dimensions of assessment, which companies can use to evaluate their facilities (Board, 2018).

3.3.1 Singapore smart industry readiness index structure

The assessment model (SSIRI) consists of 3 building blocks, 8 pillars 16 dimensions (Fig 3.4). First is process building block which includes vertical integration, supply chain, and product lifecycle pillars and under these pillars lies vertical integration, horizontal integration, and integrated product lifecycle respectively. Second is technology building block, which includes automation, connectivity, and intelligence pillars in each shop floor, enterprise and facility level, summing up to 3 dimensions of each totaling 9 dimensions under technology building block. The third building block is the Organization, it includes 4 dimensions and 2 pillars. The pillars under Organization building block include talent readiness in both workforce learning and leadership, and structure dimensions and second pillar are management which includes both inter, and intra collaborations and strategy dimension and governance dimension.

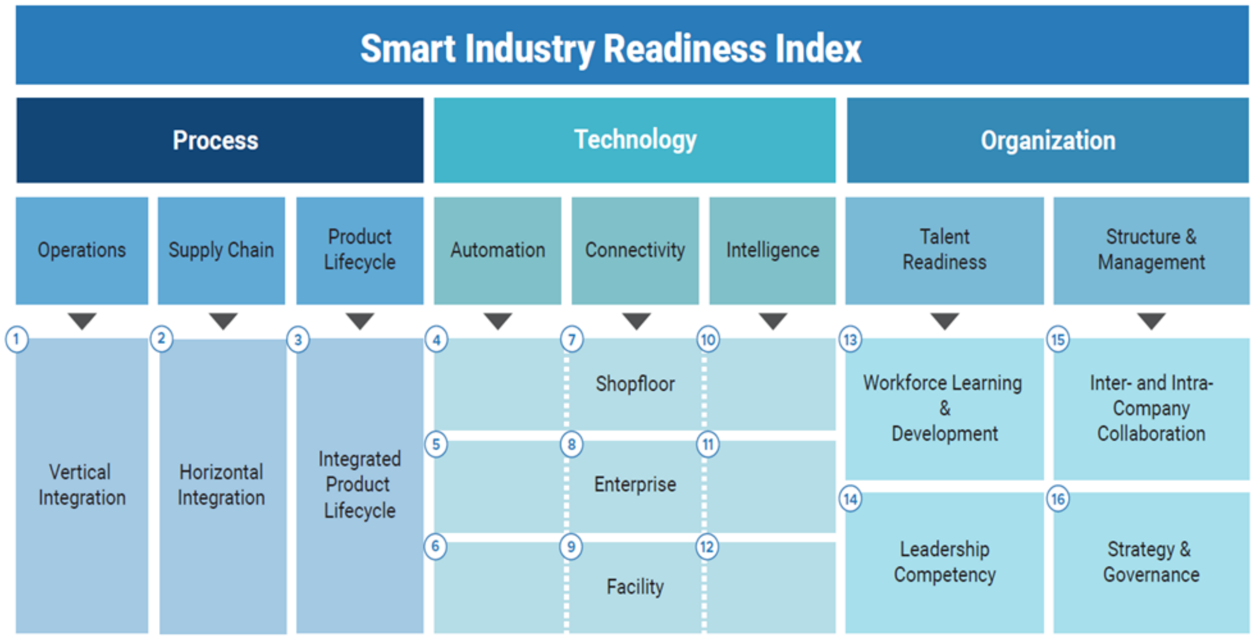

Figure 3.4 *Singapore Smart Readiness Index Maturity Model (Board, 2018)*

3.3.2 Singapore smart industry readiness index criteria

Each of the 16 dimensions listed in Fig 3.3 has a unique list of criteria to aid the assessment process. For each dimension there are 6 maturity levels and 6 criteria (one for each maturity level). According to how much of the criteria the enterprise can meet, will eventually determine the maturity level of the enterprise in that particular dimension. Fig 3.5 displays the criteria for technology building block, automation pillar, shop floor dimension.

Technology Building Block | Automation Pillar | Shop Floor Automation Dimension			
Shop Floor Automation is the application of technology to monitor, control and execute the production and delivery of products and services, within the location where the production and management of goods is carried out.			
Band		Definition	Description
0	None	Repetitive production[5] and support processes[6] are not automated.	Production processes are executed by humans.
1	Basic	Repetitive production processes are partially automated, with significant human intervention. Repetitive support processes are not automated.	Production processes are executed by humans with the assistance of equipment, machinery and computer-based systems.
2	Advanced	Repetitive production processes are automated, with minimal human intervention. Repetitive support processes are not automated.	Production processes are predominantly executed by equipment, machinery and computer-based systems. Human intervention is required to initiate and conclude each process.
3	Full	Repetitive production processes are fully automated, with no human intervention. Repetitive support processes are partially automated, with limited human intervention.	Production processes are fully automated through the use of equipment, machinery and computer-based systems. Human intervention is required for unplanned events.
4	Flexible	Automated production processes are reconfigurable through plug-and-play automation. Repetitive support processes are partially automated, with limited human intervention.	Equipment, machinery and computer-based systems can be modified, reconfigured, and re-tasked quickly and easily when needed. Limited human intervention is required for unplanned events.
5	Converged	Flexible production and support processes are converged with enterprise and facility automation platforms to form highly autonomous networks.	Equipment, machinery and computer-based systems are flexible and formally integrated with enterprise and facility systems, to allow for dynamic, cross-domain interactions.

Figure 3.5 *Technology pillar automation dimension criteria in Singapore Model (Board, 2018)*

3.4 Radar Chart

The radar chart is plotted at the end of the assessment to provide a visual representation of the maturity level for all dimensions. A visual representation will make it easier to spot the weak points or where the enterprise has the lowest maturity level and what dimensions need attention. Radar charts make it easier to compare the maturity levels of all dimensions at a glance. Last but not least by calculating the area of maturity plot and dividing the value by the total area of the plot chart we are capable to calculate the total maturity scores the enterprise is currently standing at. The final maturity score is calculated as follows:

$$\boldsymbol{Total\ maturity\ score} = \frac{\boldsymbol{Total\ shaded\ area}}{\boldsymbol{Total\ area}} x100$$

$$\boldsymbol{Total\ shaded\ area} = \frac{\mathbf{1}}{\mathbf{2}}\left[[(\boldsymbol{C_1\ X\ C_{16}}) + \sum_{\boldsymbol{i=1}}^{\boldsymbol{i=15}}(\boldsymbol{C_i\ X\ C_{i+1}})]\right]\mathbf{sin}\left(\frac{\mathbf{360}}{\mathbf{16}}\right)$$

$$\boldsymbol{Total\ area} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \frac{\mathbf{5^2} \times \boldsymbol{sin}\frac{\mathbf{360}}{\boldsymbol{n}}}{\mathbf{2}}$$

Where C_i is the maturity score of the dimension, while n is the number of dimensions considered.

The discussed assessment model and radar chart will be further explained in chapter 4, as they will be implemented and used to display assessment results from data collected during a case study conducted on SPM Automation Inc. facility.

3.5 Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology (Rangone 1996). Since the implementation strategy involves decision making, then it requires a decision-making tool. AHP has proven to provide the best decisions when multiple criteria are listed, from multiple categories, by providing a bundle of best options to be considered under each category (Chou and Liang 2001). Such results are achieved by comparing the cost and benefit of each choice with all the other listed choices. In this research, our choices are the dimensions of the enterprise, and AHP will aid in selecting the most influential dimensions to prioritize for transformation. Chapter 4 will demonstrate the mathematical details AHP performs to generate its final results.

Chapter 4: Application of I4.0 Four-step Implementation Strategy

This chapter will demonstrate the application of the four-step 1.40 implementation strategy, using real industry case study.

4.1 Illustrative Case study

For the purpose of testing and further explaining the proposed implementation strategy, the following hypothetical case study is conducted using XYZ which is an SME in the automotive sector.

4.1.1 Maturity assessment

Table 4.1 displays the hypothetical data concerning the results of the I4.0 maturity assessment process conducted on XYZ.

Table 4.1 *I4.0 Maturity Assessment results*

Dimension	Maturity level
Operation (Vertical Integration)	1
Supply Chain (Horizontal Integration)	2
Product Lifecycle (Integrated Product Lifecycle)	1
Automation	Shopfloor-2 Enterprise-2 Facility-2
Connectivity	Shopfloor-2 Enterprise-2 Facility-2

Intelligence	Shopfloor-1 Enterprise-2 Facility-1
Talent Readiness	Workforce learning and development- 2 Leadership competency- 3
Structure and management	Inter and intra company collaboration- 3 Strategy and governance- 3

Constructing a radar chart from the maturity assessment results displayed in table 4.1, it was possible to conclude that the total maturity score at XYZ is 14.83 %

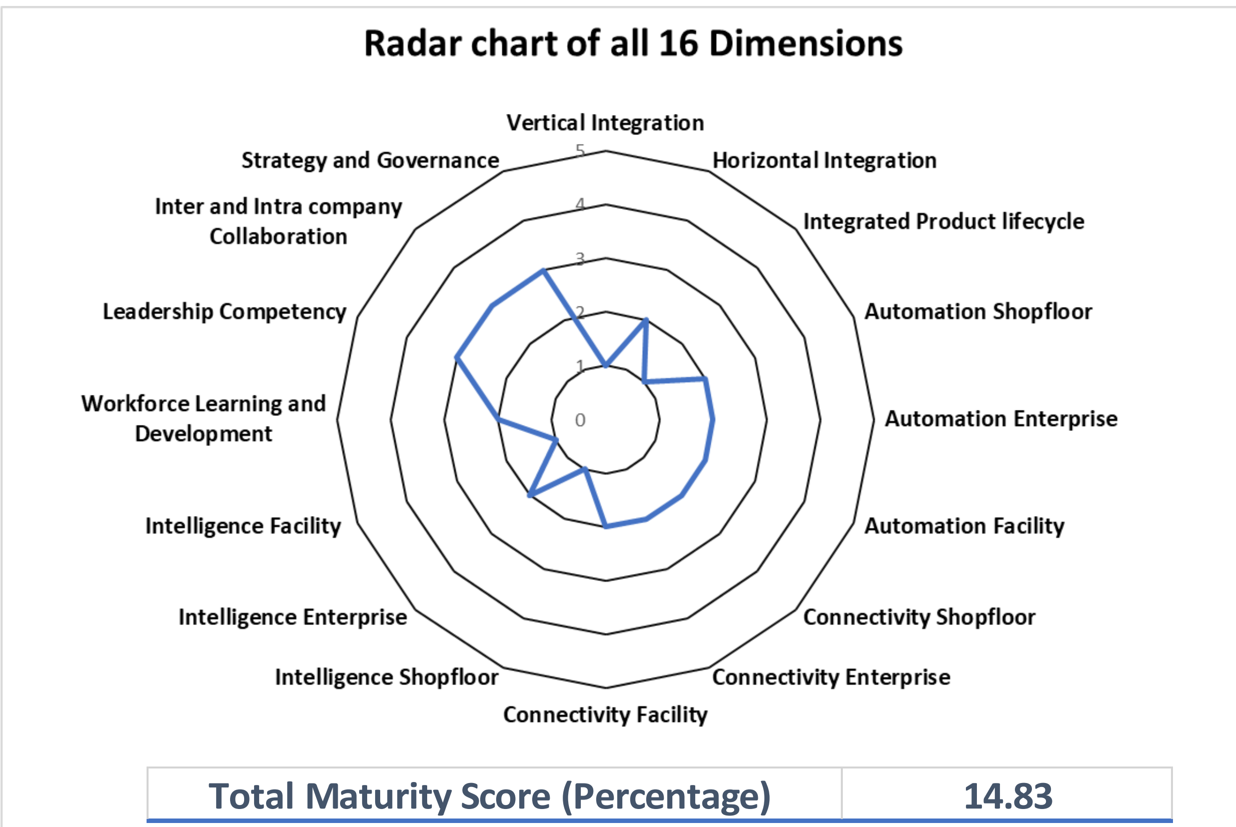

Figure 4.1 Radar chart of all 16 dimensions at XYZ facility

4.1.2 Influence assessment

Next, the benefit cost ratio will be concluded for each dimension of the S.S.I.R.I. This process will help determine the influence of each department on the enterprise as a whole. After multiple meetings with officials from various departments of the assembly plant of XYZ, it was possible to gather the following data Table 4.2. The following data is the Benefit cost ratio of each of the dimensions mentioned in Singapore smart industry readiness index.

Table 4.2 *Benefit cost ratio of each dimension*

Dimension	Benefit cost ratio
Vertical Integration	6.5
Horizontal Integration	7.1
Integrated Product Lifecycle	5.2
Automation Shop floor	7.2
Automation Enterprise	6.6
Automation Facility	6.1
Connectivity Shop floor	8.2
Connectivity Enterprise	6.3
Connectivity Facility	6
Intelligence Shop floor	7.4
Intelligence Enterprise	6.3
Intelligence Facility	5.8
Workforce Learning & Development	4.9

Leadership Competency	5.8
Inter- and Intra- Company Collaboration	6.3
Strategy & Governance	6.8

A comparative calculation of the collected data will be conducted to convert the data to a form that is compatible with AHP. The following is an example of comparative calculation of two dimensions that share the same category in Singapore smart industry readiness index:

As seen in figure 4.2, operation, supply chain, and product lifecycle are under the process category.

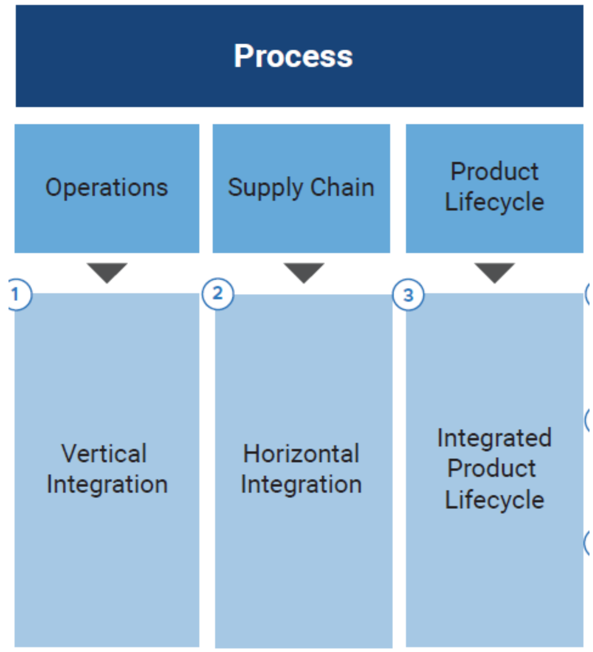

Figure 4.2 *Process category of S.S.I.R.I (Board, 2018)*

Comparative calculation:

Vertical integration to horizontal integration $= \frac{B.C\ of\ V.Integ}{B.C\ of\ H.Integ} = \frac{6.5}{7.1} = 0.91$

Vertical integration to Integrated product lifecycle $= \frac{B.C\ of\ V.Integ}{B.C\ of\ Product\ lifecycle} = \frac{6.5}{5.2} = 1.25$

Horizontal integration to product lifecycle $= \frac{B.C\ of\ H.Integ}{B.C\ of\ Product\ lifecycl} = \frac{7.1}{5.2} = 1.36$

Plugging in the calculated values in AHP calculator Fig 4.3, a weigh value for each dimension is generated.

2nd sub Dimension	Operation	Supply chain	Product lifecycle
Operation	1.00	0.91	1.25
Supply chain	1.10	1.00	1.36
Product lifecycle	0.80	0.74	1.00
Total	2.90	2.65	3.61

2nd sub Dimension	Operation	Supply chain	Product lifecycle	weight(%)
Operation	0.35	0.35	0.35	35.00
Supply chain	0.38	0.38	0.38	37.79
Product lifecycle	0.28	0.28	0.28	27.66

Figure 4.3 *AHP calculations results*

Table 4.3 *AHP weight results for all 16 dimensions*

Process pillar	weight value (%)
Operation	35
Supply chain	38
Product lifecycle	28
Automation pillar	weight value (%)
shop floor	36
enterprise	33
facility	31
Connectivity pillar	weight value (%)
shop floor	40
enterprise	31
facility	29
Intelligence pillar	weight value (%)
shop floor	32
enterprise	38
facility	30
Organization pillar	weight value (%)
Work force learning	46
Leadership competency	54
Inter- and Intra-company collaboration	48
Strategy &Governance	52

4.1.3 Road map construction

At this stage, priorities to which dimension to be selected will be based on the prioritizing protocol displayed in Table 4.4.

Table 4.4 *Prioritizing protocol*

Scenarios	***Prioritizing action***
Different weights	Highest weight value
Identical weights different maturity level	Lowest maturity leveled dimension is prioritized
Identical weights and maturity levels	Free selection of either

Looking at the results from AHP and linking each weight factor with its corresponding dimension, it is very clear that supply chain, connectivity-shop floor, and leadership competency are the most influential dimensions within the process, technology, and organization pillars respectively. Hence, they will be prioritized for transformation and the transformation plan will be as shown in Fig 4.4.

Figure 4.4 *transformation road map for all three building blocks at XYZ facility*

4.1.4 Implementation

At this stage, all the readily available criteria that belong to each of the selected dimensions will be considered and implement transformation. A roadmap that holds a bundle of most influential dimensions accompanied by their respective criteria Fig 4.5 will be supplied to XYZ, which will be a very useful tool to help achieve the next maturity level in each dimension.

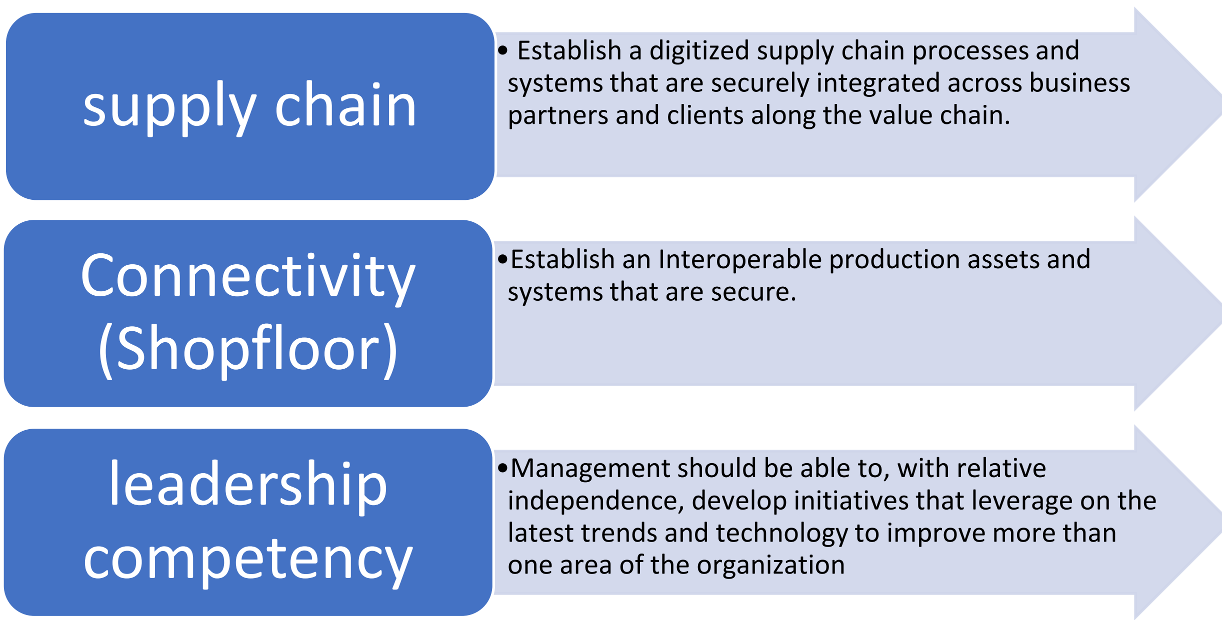

Figure 4.5 *Implementation strategy*

4.1.5 Conclusion

After the maturity level and influence magnitude of each dimension at XYZ has been assessed, an implementation strategy was constructed, and it states that for XYZ to improve their total maturity score which at the moment is standing at 14.83%. They should firstly establish a digitized supply chain processes and systems that are securely integrated. Second, they need to Establish an Interoperable production assets and systems that are secure. Third, is to develop management that is able to, with relative independence, develop initiatives. Doing so, they would have transformed the most influential dimensions at their facility. The implementation strategy that has been concluded at the end of the illustrative example, is specifically customized for XYZ. In Chapter 4.2 the same four step implementation strategy is be used but the result and recommended roadmap are totally different which demonstrates the sensitivity of the developed assessment process and its impact on the finals results.

4.2 Case Study at **SPM Automation Inc.**

A case study is arranged with S.P.M Automation in Windsor, Ontario. SPM Automation Inc. is an SME that provides automatic solutions for various challenging plastics joining, finishing, and assembly applications. SPM Automation Inc. currently hires 50 employees, 11 of which mechanical engineers, 8 programmers, and the rest are certified maintenance and CNC operators. SPM Automation Inc.'s clients are usually automotive parts suppliers, such as Magna, FlexNGate, Inteva, AP Plasma, and others. SPM Automation Inc. design and build various types of welding machines that manufacture various automotive parts such as taillights, spoilers, gas tanks, and other interior component. During the case study, the four-step implementation strategy was conducted which will execute a transformation roadmap tailored to SPM Automation Inc.'s work environment and priorities.

4.2.1 Assessment

The assessment process began with a visit to SPM Automation Inc.'s facilities. The cite visit had three main objectives on the list, first which is to obtain a visual of the work process that the enterprise practices, the machines and tools used, and the organizational structure. Second, was to meet and interact with officials who could provide feedback based on their experience and knowledge of the enterprise. Third was to collect data concerning how influential is every dimension of the maturity model to the industry. The work process and the organizational structure is as following: The client (usually an automotive supplier) provides the institute with detailed description of the part they would like to manufacture, these descriptions(drawing and parameters) are then passed on to engineering who move forward with designing the machines that are capable of manufacturing the part and choosing the materials of each of the machine's components. The designs and raw materials are supplied to the shop floor where operators will begin the manufacturing process. The manufacturing processes consists of CNC machining, welding, controls design, software programming, assembly, and machine testing.

Finally, the product is tested and assembled at the client's shop floor. The CNC machining varies from fully automated such as EROWA (by EROWA®)

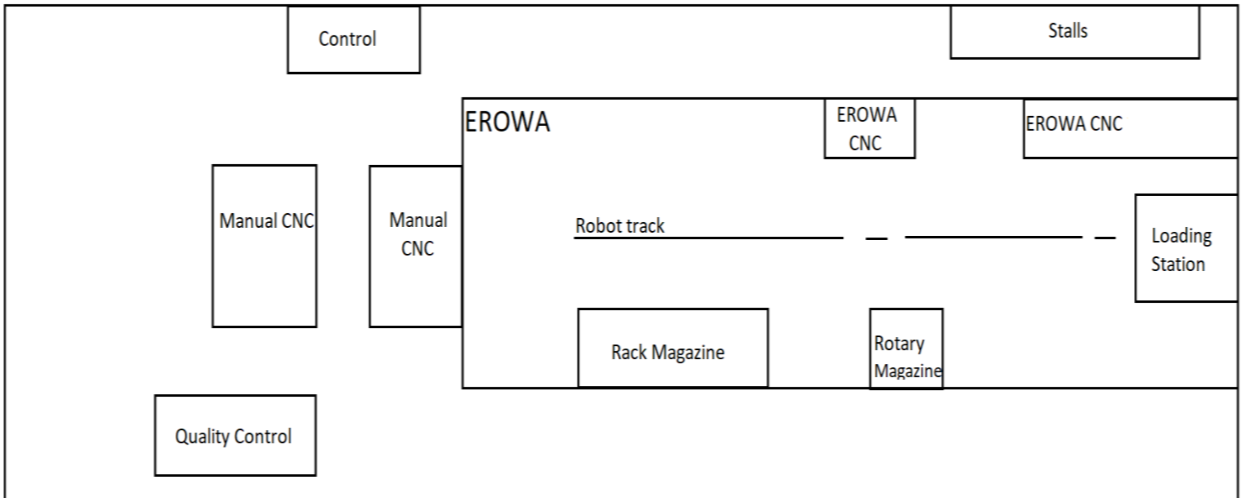

Figure 4.6 *SPM Automation Inc. Facility Floor Plan and the EROWA automated manufacturing system.*

Figure 4.7 *EROWA ® from outside*

Figure 4.8 *EROWA® from inside*

Figure 4.9 *EROWA® Rack magazine*

Figure 4.10 *EROWA® Round fixtures*

Figure 4.11 *SPM Automation Inc. operator loading EROWA® rotary magazine*

Figure 4.12 *SPM Automation Inc. operator operating a manual CNC machine*

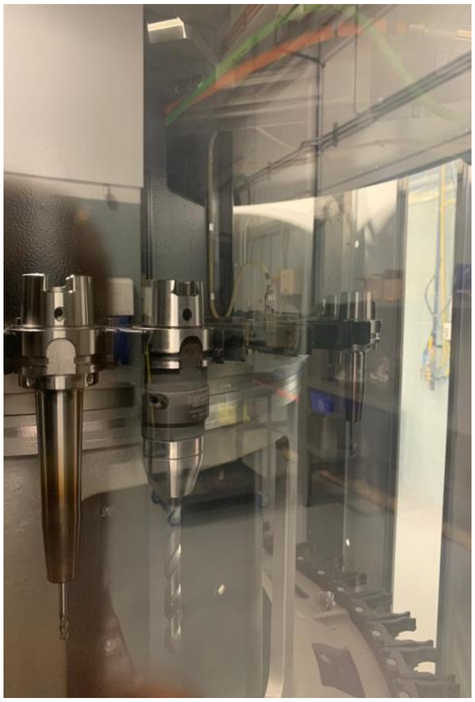

Figure 4.14 *one of EROWA CNC machines*

Figure 4.13 *EROWA tools magazine*

As shown in Fig 4.6 A huge area of the shop-floor is occupied by EROWA since it is a multi-cellular CNC machine. It Includes a Rack magazine Fig 4.9 which loads the rectangular fixtures displayed in Fig 4.10 and a rotary magazine Fig 4.11 which loads the spherical fixtures displayed in Fig 4.10. It as well includes two CNC stations and a loading station. Figs 4.7 and 4.8 display a visual of the actual size of EROWA on the shop-floor. EROWA is operated as follows: The operator loads the rack with the raw material fixed on a rectangular fixture (if the part is larger in size), or the magazine fixed on a spherical fixture (if the parts are smaller in size). Within EROWA a robot moving on a track fetches the fixtures and places them in the appropriate CNC machine station. When the CNC machine is done with all required manufacturing processes, the robot fetches the part and places it back on the rack, throughout the process no human being intervention is required. Away from EROWA other processes such as welding, and assembly processes are conducted 100 percent manually. During the manufacturing process, there is no live feed of the manufacturing process, management is separated from shop floor, for one department to contact the other it is still conducted the old fashion way which is by either physically being present, through phone or email. SPM Automation Inc. shows no live feedback existing between their facility and its suppliers or clients. SPM Automation Inc. give attention to workforce learning and development since their operators are always required to attend training to keep them updated with the operational and repair procedures of the most recent machines existing in their facilities. SPM Automation Inc. has proven to be connected to academic institutes such as the University of Windsor since they provide visits for students to their facilities and share their knowledge and experiences with students through providing guest speakers and allow their facilities to participate in case studies concerning recent researches. All these facts have made its shape on the maturity model and illustrated the current maturity level the enterprise has achieved. With the enterprise's initial maturity level assessed (Results in Table 4.21) through comparing the facility's criteria to the criteria available at each level for each dimension in the SSRI, it was possible to construct a radar chart (Fig 4.15) to display the maturity level of each dimension.

The following is the results of the assessment process that took place at SPM Automation Inc., for each dimension and according to the maturity level SPM Automation Inc. scored, the row of that specific maturity level is cropped from Singapore Smart Industry Readiness Index criteria page and displayed (all levels of all the dimensions and their criteria are available in Appendix (A) in the tables below. Each table displays three columns band, definition, and description. The band row displays the maturity level which could range between 1-5 and the level name. The definition column explains the maturity level's requirements and main features. The description column further explains the definition column and elaborates on the situation that and industry must be functioning under to score a certain maturity level. Under each table the feedback from SPM Automation Inc.'s assessment that explains why SPM Automation Inc.'s facility has scored the displayed maturity level.

1. Vertical integration assessment

Table 4.5 *Maturity level criteria (Board, 2018) (Table A.1)*

Band		Definition	Description
2	Digital	Defined vertical processes are completed by humans with the support of digital tools.	Resource planning and technical production processes are managed and executed in silos, by Operations Technology (OT) and Information Technology (IT) systems.

Operations technology and information technology are not yet formally linked but instead, each is conducted and operates separately. The vertical processes at SPM Automation Inc. such as raw material, supplier, inbound logistics, manufacturing, outbound logistics are yet conducted by humans with the support of digital tools such as computer servers instead of paper.

2. Horizontal integration assessment

Table 4.6 Maturity level criteria (Board, 2018) (Table A.2)

Band		Definition	Description
3	Integrated	Digitized supply chain processes and systems are securely integrated across business partners and clients along the value chain.	IT systems managing enterprise processes are formally linked; however the exchange of data and information across different functions is predominantly managed by humans.

At SPM Automation Inc. it is noticeable that the information across different functions such as Management, supervision, execution, strategic management, tactical management, and operational management are totally managed by humans and the IT systems are far from being linked from one end to the other. The supply chain process at SPM Automation Inc. is defined and executed digitally.

3. Integrated product lifecycle assessment

Table 4.7 *Maturity level criteria (Board, 2018) (Table A.3)*

Band		Definition	Description
2	Digital	Defined product lifecycle processes are completed by humans, with the support of digital tools.	Processes along the product lifecycle are managed and executed in silos, by digital tools.

The processes at SPM Automation Inc. whether it is vertical, horizontal, or product lifecycle such as design and development, engineering, production, customer use, service and disposal are conducted mainly by humans but with the aid of digital tools. SPM Automation Inc. is still not at the point where human interaction can be eliminated. Some human interaction has been eliminated over the years and replaced by computers and processes, however, due to the nature of our business, we do not believe that human interaction can ever be completely eliminated.

4. Automation shopfloor assessment

Table 4.8 *Maturity level criteria (Board, 2018) (Table A.4)*

Band		Definition	Description
3	Full	Repetitive production processes are fully automated, with no human intervention. Repetitive support processes are partially automated, with limited human intervention.	Production processes are fully automated through the use of equipment, machinery and computer-based systems. Human intervention is required for unplanned events.

With the sophisticated CNC machine EROWA on the shop floor, repetitive production processes at SPM Automation Inc. such as moving materials to CNC machines, machining process, and bringing it back to the racks is fully automated with no human intervention. However, some repetitive operations such as raw material loading, and CAD supply are still human dependent. SPM Automation Inc. is working on developing a system and process to automate the CAD design supply, which will leave only one human dependent operation.

5. Automation enterprise assessment

Table 4.9 *Maturity level criteria (Board, 2018) (Table A.5)*

Band		Definition	Description
2	Advanced	Enterprise processes are automated, with minimal human intervention.	Enterprise processes are predominantly executed by computer-based systems. Human intervention is required to initiate and conclude each process.

At SPM Automation Inc. processes at the enterprise layer are yet in need of human intervention but are not fully dependent on it. Computer based systems are in place and execute various processes. However, at the end of the day, humans are needed to initiate or conclude certain processes and unplanned events.

6. Automation facility assessment

Table 4.10 *Maturity level criteria (Board, 2018) (Table A.6)*

Band		Definition	Description
2	Advanced	Facility processes are automated, with minimal human intervention.	Facility processes are predominantly executed by equipment, machinery and computer-based systems. Human intervention is required to initiate and conclude each process.

Just like the enterprise processes, processes at the facility layer are not yet fully automated and still require minimal human intervention. Even though facility processes are executed with computer support, human intervention is required to initiate and conclude certain processes.

7. Connectivity shop floor assessment

Table 4.11 *Maturity level criteria (Board, 2018) (Table A.7)*

Band		Definition	Description
3	**Interoperable And Secure**	Interoperable production assets and systems are secure.	There is a vigilant and resilient security framework to protect the network of interoperable equipment, machinery, and computer-based systems from undesired access and/or disruption.

Production assets on the shop-floor such as equipment, machines, and systems that reside within the shop-floor are not connected but instead are interoperable. Systems on the shop floor interfaces can communicate with other products that are present at the moment or might be included in the future. As an example, the EROWA system can adapt to a new type or shape of fixtures that might be introduced in the future and be able to identify the part it is working on to perform the manufacturing process that it requires.

8. Connectivity enterprise assessment

Table 4.12 *Maturity level criteria (Board, 2018) (Table A.8)*

Band		Definition	Description
3	**Interoperable And Secure**	Interoperable Enterprise IT systems are secure.	There is a vigilant and resilient security framework to protect the network of interoperable computer-based systems from undesired access and/or disruption.

The systems at SPM Automation Inc. are computer-based, they are capable of exchanging information without any restrictions and in addition to being well secured. Real-time communication is yet not existing.

9. Connectivity facility assessment

Table 4.13 *Maturity level criteria (Board, 2018) (Table A.9)*

Band		Definition	Description
3	Interoperable And Secure	Interoperable facility assets and systems are secure.	There is a vigilant and resilient security framework to protect the network of interoperable equipment, machinery, and computer-based systems from undesired access and/or disruption.

Just like connectivity at the enterprise layer at SPM Automation Inc., equipment, machines, and systems that reside within the enterprise level are computer-based. They are capable of exchanging information without any restrictions, in addition to being well secured. Real-time communication is yet on existing.

10. Intelligence shop floor assessment

Table 4.14 *Maturity level criteria (Board, 2018) (Table A.10)*

Band		Definition	Description
3	Diagnostic	Computerized OT & IT systems are able to identify deviations and diagnose potential causes.	Equipment, machinery and computer-based systems are able to notify operators of deviations, and provide information on the possible causes.

At the shop floor level at SPM Automation Inc., equipment such as EROWA®, are equipped with advanced technology that is capable of identifying and reporting errors, which is why SPM Automation Inc. scored a diagnostic maturity level in this dimension.

11. Intelligence enterprise assessment

Table 4.15 *Maturity level criteria (Board, 2018) (Table A.11)*

Band		Definition	Description
3	Diagnostic	Enterprise IT systems are able to identify deviations and diagnose potential causes.	Enterprise computer-based systems are able to notify relevant personnel of deviations, and provide information on the possible causes.

Intelligence at enterprise layer of SPM Automation Inc.'s facility is at the lower bands, basic intelligence is derived by processing large quantities of data and detecting any deviations from predefined parameters.

12. Intelligence facility assessment

Table 4.16 *Maturity level criteria (Board, 2018) (Table A.12)*

Band		Definition	Description
3	Diagnostic	Computerized OT & IT systems are able to identify deviations and diagnose potential causes.	Equipment, machinery and computer-based systems are able to notify relevant personnel of deviations, and provide information on possible causes.

At SPM Automation Inc., equipment such as information technology (IT) and Operational Technology (OT) systems at the facility layer that holds the greater load of the manufacturing process is capable of identifying problems or issues that may arise during manufacturing. This equipment is capable of informing the operator of the issue, as well as providing a solution to the issue.

13. Workforce learning and development assessment

Table 4.17 *Maturity level criteria (Board, 2018) (Table A.13)*

Band		Definition	Description
3	Integrated	Continuous L&D programmes are formally aligned with the organization's business needs and human resources (HR) functions.	There is a continuous L&D curriculum that is integrated with organizational objectives, talent attraction, and career development pathways.

Employees at SPM Automation Inc. are constantly being updated with the knowledge and skills required to adapt to the changes in the industry. This is achieved by providing the employees the opportunity to attend local and international seminars, tradeshows, conferences, etc. Traditional engineering capabilities are augmented with new digital skills, such as data analytics, systems integration, and software development.

14. Leadership competency assessment

Table 4.18 *Maturity level criteria (Board, 2018) (Table A.14)*

Band		Definition	Description
4	Independent	Management is able to, with relative independence, develop initiatives that leverage on the latest trends and technology to improve more than one area of the organization.	Management is able to apply the latest concepts to enable improvements across multiple areas.

The management team is capable to apply the most relevant concepts to enable improvements across multiple areas. The management team uses their education and experience to make these decisions. A flatter organizational structure is implemented creating a decentralized decision-making environment.

15. Inter and Intra company collaboration assessment

Table 4.19 *Maturity level criteria (Board, 2018) (Table A.15)*

Band		Definition	Description
3	Coordinating	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams have the mandate to alter or adjust certain obligations and responsibilities, to reduce the barriers for cooperation on joint tasks and projects.

Teams are encouraged to make any appropriate adjustments that will facilitate cooperation on discrete tasks and projects. Teams have the authority to influence certain obligations and responsibilities to reduce the barriers for cooperation on joint tasks and projects.

16. Strategy and governance assessment

Table 4.20 *Maturity level criteria (Board, 2018) (Table A.16)*

Band		Definition	Description
4	Scaling	Transformation initiative towards a Factory/Plant-of-the-Future is expanded to include more than one functional area.	The long-term strategy and governance model to establish a Factory/Plant-of-the-Future is scaled up to include other secondary areas.

SPM Automation Inc. had implemented the latest technology pushing towards the I4.0 integration, by implementing a fully automated CNC machining center and developing the connectivity and intelligence of systems in the facility. SPM Automation Inc. has developed and recently implementing its strategy, and a robust governance model.

Table 4.21 *SPM Automation Inc. Assessment results for each dimension's maturity level*

Dimension	**Maturity level**
Operation (Vertical Integration)	2
Supply Chain (Horizontal Integration)	3
Product Lifecycle (Integrated Product Lifecycle)	2
Automation	Shopfloor-3 Enterprise-2 Facility-2
Connectivity	Shopfloor-3 Enterprise-3 Facility-3
Intelligence	Shopfloor-3 Enterprise-3 Facility-3
Talent Readiness	Workforce learning and development- 3 Leadership competency- 4
Structure and management	Inter and intra company collaboration- 4 Strategy and governance- 4

Calculating maturity score:

$$\boldsymbol{Total\ shaded\ area} = \frac{1}{2}\left[[(C_1\,X\,C_{16}) + \sum_{i=1}^{i=15}(C_i\,X\,C_{i+1})]\right]\sin\left(\frac{360}{16}\right)$$

$$= \frac{1}{2}[[2X4) + 124]\sin\left(\frac{360}{16}\right) = 25.21$$

$$\boldsymbol{Total\ area} = \sum_{i=1}^{n}\frac{5^2 \times sin\frac{360}{n}}{2}$$

$$= \sum_{i=1}^{16}\frac{5^2 \times sin\frac{360}{16}}{2} = 76.4$$

$$\boldsymbol{Total\ maturity\ score} = \frac{Total\ shaded\ area}{Total\ area}x100$$

$$= \frac{25.21}{76.4}x100 = 33\%$$

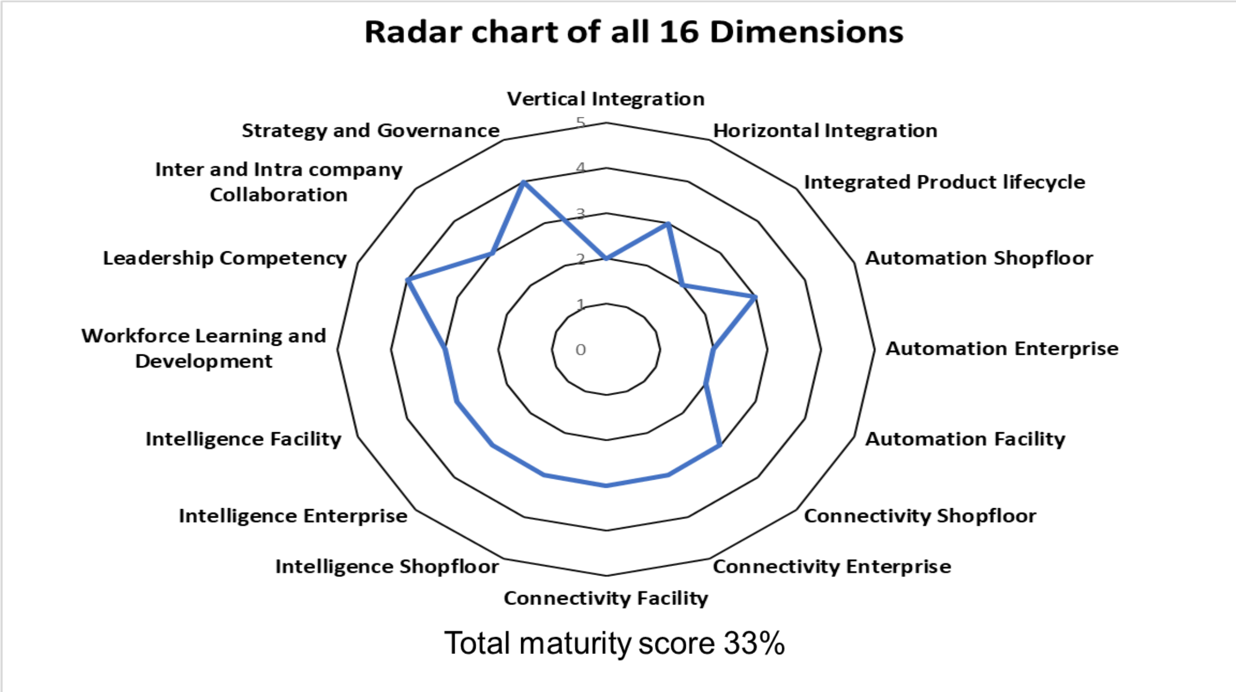

Figure 4.15 *Radar chart constructed based on the assessment results of all 16 dimensions at SPM Automation Inc.*

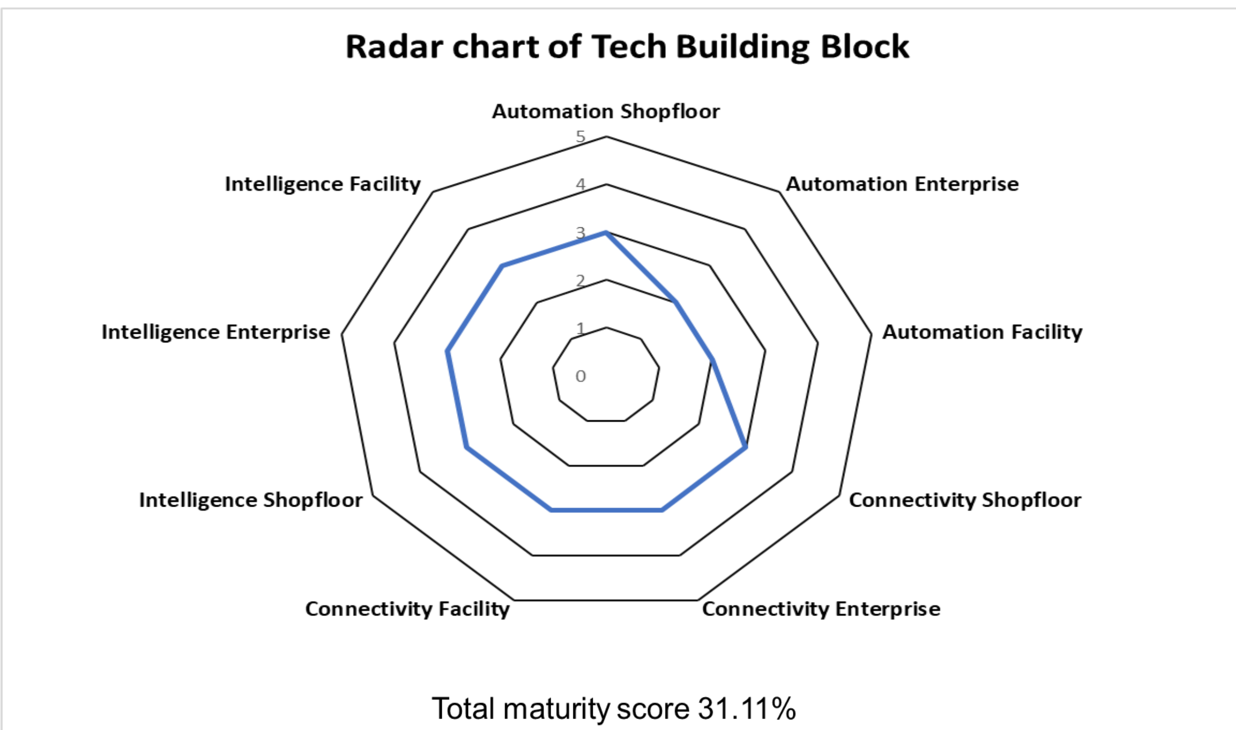

Figure 4.16 *Radar chart constructed based on the assessment results of technology building block dimensions at SPM Automation Inc.*

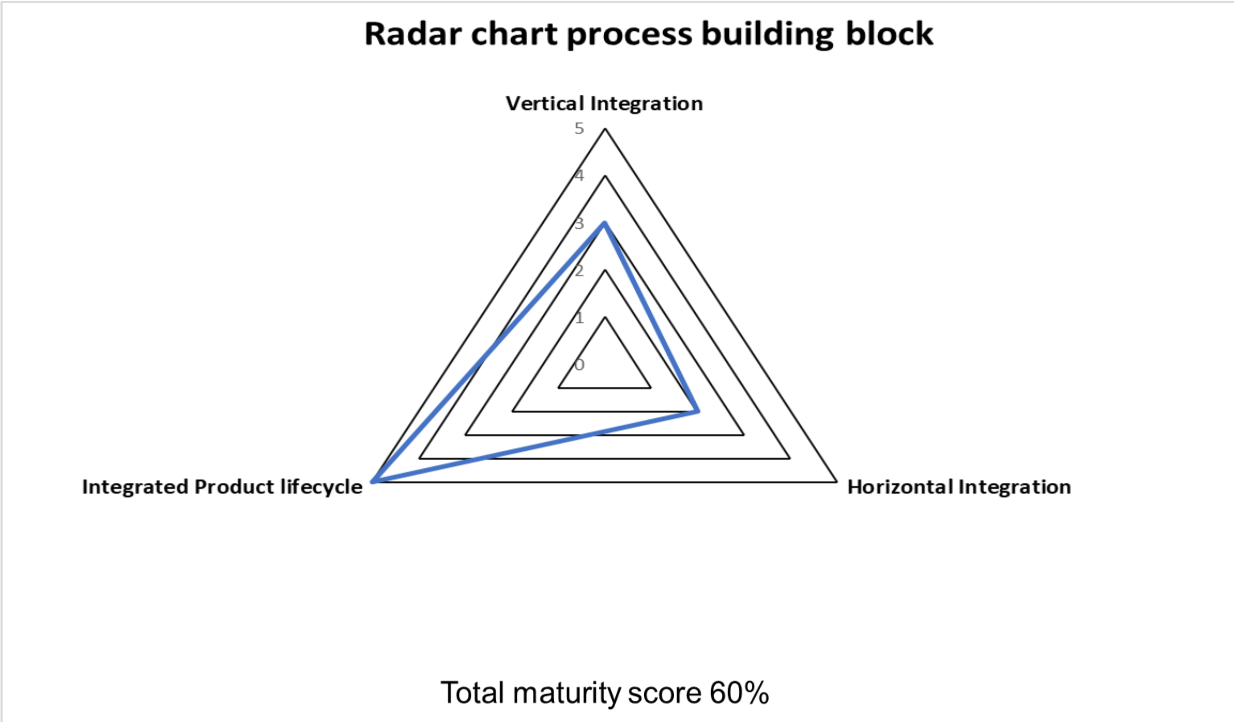

Figure 4.17 *Radar chart constructed based on the assessment results of Processes building block dimensions at SPM Automation Inc.*

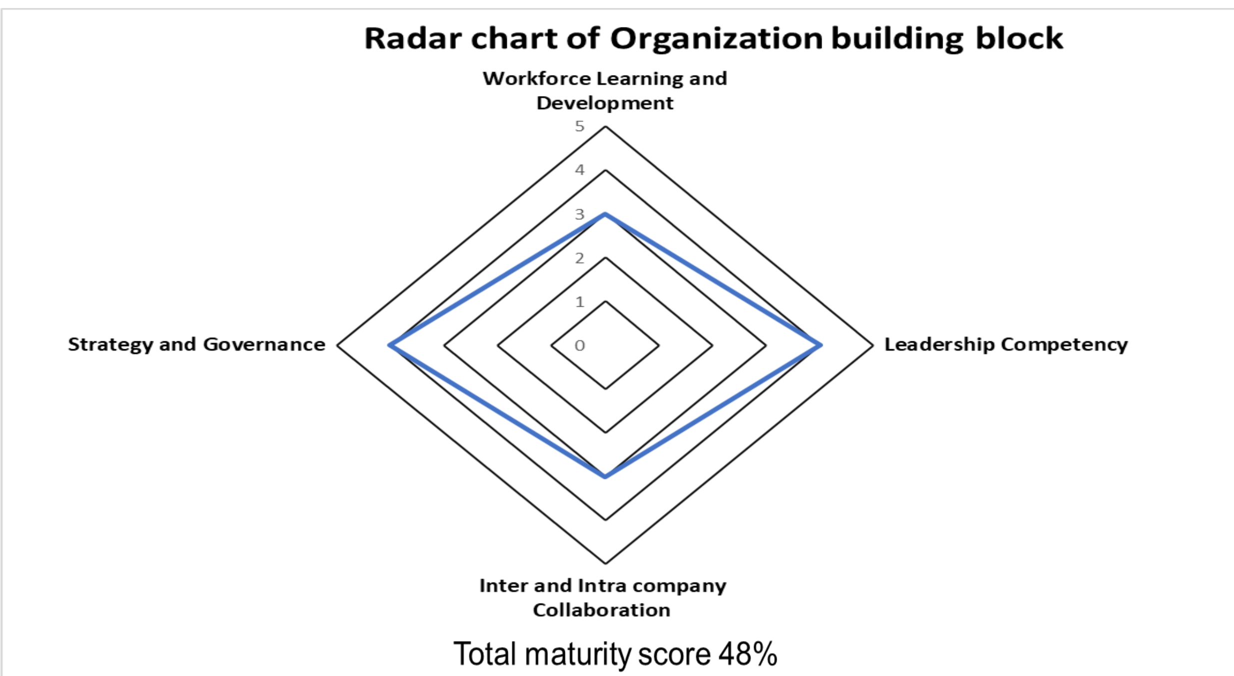

Figure 4.18 *Radar chart assessment results of organization building block dimensions at SPM Automation Inc.*

4.2.2 Dimension's influence assessment

The site visit made it possible to work with various types of employees (engineers, management, and operators) during the assessment process, who kept us in company during the whole process and answered all our questions to understand the work process, history of the enterprise and it's plans. During a week, we had all the feedback we aimed for, the team at SPM Automation Inc. provided us with all the information needed to complete the assessment process. With the importance of each dimension based on how influential every dimension to the enterprise is, and the term influential meaning the cost-benefit ratio each beholds (Table 4.22), we were ready to move forward to the next step and treat the collected data. First, to make it possible to input the collected data into AHP, a comparison between all dimensions was calculated. A sample of the comparison calculation is displayed in Table 4.23 (The numbers are colored red to keep track of the plugging in positions and calculations).

Table 4.22 *Dimension's influence at SPM Automation Inc.*

Dimension	**Dimension's influence on scale of 1-10** (1 Non influential, 5 influential, 10 very influential)
Operation (Vertical Integration)	9
Supply Chain (Horizontal Integration)	5
Product Lifecycle (Integrated Product Lifecycle)	7
Automation	Shopfloor-7 Enterprise-9 Facility-5
Connectivity	Shopfloor-7 Enterprise-7 Facility-9
Intelligence	Shopfloor-8 Enterprise-7 Facility-7
Talent Readiness	Workforce learning and development- 9 Leadership competency- 9
Structure and management	Inter and intra company collaboration- 8 Strategy and governance- 8

Table 4.23 *sample calculation*

Dimension comparison	**calculation and Results**
Operation to supply chain	(9/5) = **1.8**
Operation to product life cycle	(9/7) = **1.28**
Supply chain to product lifecycle	(5/7) = **0.71**

Table 4.24 *AHP Calculations part 1*

2nd sub Dimension	Operation	Supply chain	Product lifecycle
Operation	1.00	1.80	1.29
Supply chain	0.56	1.00	0.71
Product lifecycle	0.78	1.41	1.00
Total	2.33	4.21	3.00

Table 4.25 *AHP Calculations part 2*

2nd sub Dimension	Operation	Supply chain	Product lifecycle	
Operation	1.00	1.80	1.29	
Supply chain	0.56	1.00	0.71	
Product lifecycle	0.78	1.41	1.00	
Total	2.33	4.21	3.00	
2nd sub Dimension	Operation	Supply chain	Product lifecycle	weight(%)
Operation	0.43	0.43	0.43	42.84
Supply chain	0.24	0.24	0.24	23.76
Product lifecycle	0.33	0.33	0.33	33.40

At this stage, the collected data will be plugged in AHP (Table 4.24) ready constructed excel sheet, which will convert the collected data to weight factors. The process that takes place in the AHP calculator is as follows: First, the collected data is plugged into a matrix to calculate the reciprocal of each comparison value (Table 4.24), this way all dimensions are compared to each other. Next, each compared value is divided by the total of each column (Table 4.25, Green/Yellow = Red). Finally, the values of each row in the new matrix are added and divided by 3 to calculate the average, and the average value is then multiplied by 100 to achieve a percentage value (Table 4.27, [Total of values in Green/3] x 100 = Red). The results from AHP are displayed in (Table 4.28).

Table 4.26 *AHP Calculations part 3*

2nd sub Dimension	Operation	Supply chain	Product lifecycle	weight(%)
Operation	0.43	0.43	0.43	42.84
Supply change	0.24	0.24	0.24	23.76
Product lifecycle	0.33	0.33	0.33	33.40
Total				

Table 4.27 *AHP results based on SPM data*

Operation	**43**
Supply chain	**24**
Product lifecycle	**33**

Table 4.28 *AHP final results*

	Total weight (%)			
Process	31			
Operation	13			
Supply Chain	7			
Product lifecycle	10			
Technology	38	Total weight (%)	Total weight (%)	Total weight (%)
		Shopfloor	Enterprise	Facility
Automation	12	**33**	**43**	**24**
Connectivity	13	30	30	39
Intelligence	13	36	32	32
Organization	31	Total weight (%)	Total weight (%)	
		Workforce and learning	Leadership competency	
Talent Readiness	16	50	50	
		Company colaboration	Strategy and governance	
Structure & Management	14	50	50	

4.2.3 Road map construction

At this stage priorities to which dimension to be selected will be based on the prioritizing protocol displayed in (Table 4.29).

Table 4.29 *prioritizing protocol*

Scenarios	Prioritizing action
Different weights	Highest weight value
Identical weights different maturity level	Lowest maturity leveled dimension is prioritized
Identical weights and maturity levels	Free selection of either

Looking at the results from AHP and linking each weight factor with its corresponding dimension, it is very clear that operations, connectivity, and intelligence (since they are equal), and talent readiness are the most influential dimensions within the process, technology, and organization pillars respectively. Analyzing even further it is noticed from the radar (Fig 4.15) chart that the enterprise is weakest (level of maturity-wise) at operation or vertical integration dimension and according to the AHP results it is ranked from the top four most influential to the enterprise, which makes it a priority for transformation. In the technology pillar, connectivity and intelligence share equal maturity level and weight factor, which allows for free selection of either to be prioritized (if one of them had a lower maturity level it would have been prioritized). Road map construction is customizable, and it could consider as many dimensions as the enterprise is capable of transforming. For instance, as shown in Fig 4.19 a simple road map that aims for only the three highest dimensions from all three pillars, On the other hand, if SPM Automation Inc.

would wish to concentrate their transformation on one building block at a time then a roadmap for each building block can be formed for only one pillar just like displayed (Fig 4.20).

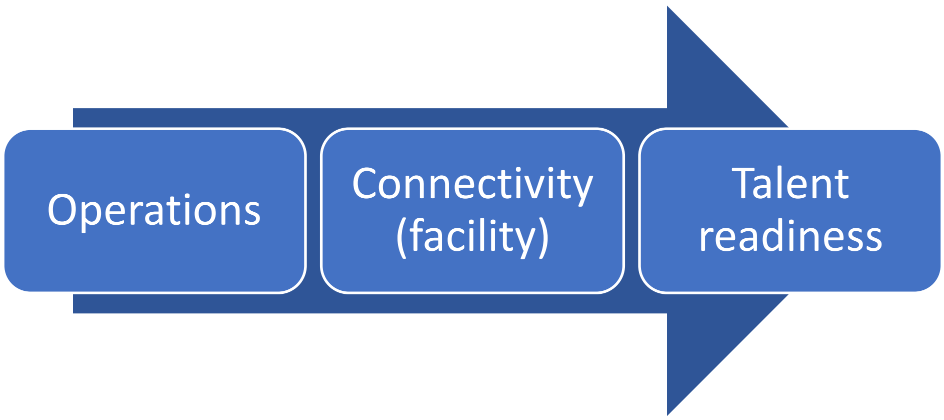

Figure 4.19 *Transformation Roadmap for all three building blocks*

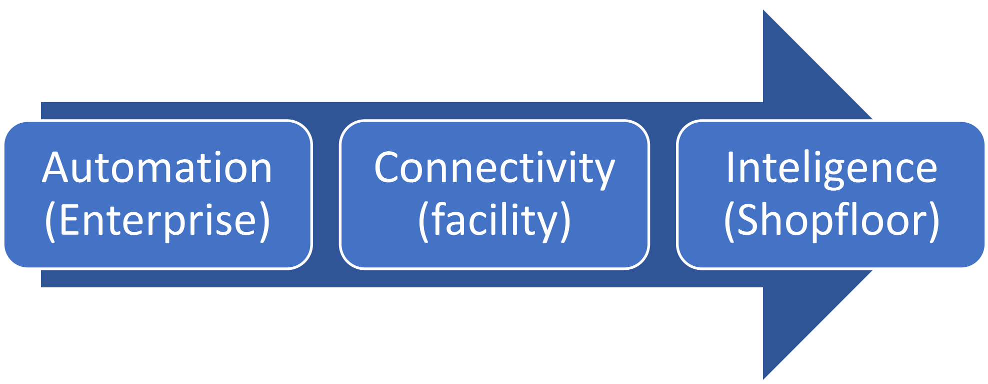

Figure 4.20 *Transformation Roadmap only for technology building block*

4.2.4 Implementation

At this stage, all the readily available criteria that belong to each of the selected dimensions will be considered and implement transformation. A roadmap that holds a bundle of most influential dimensions accompanied by their respective criteria (Fig 4.21 and 4.22) will be supplied to SPM

Automation Inc., which will be a very useful tool to help achieve the next maturity level in each dimension.

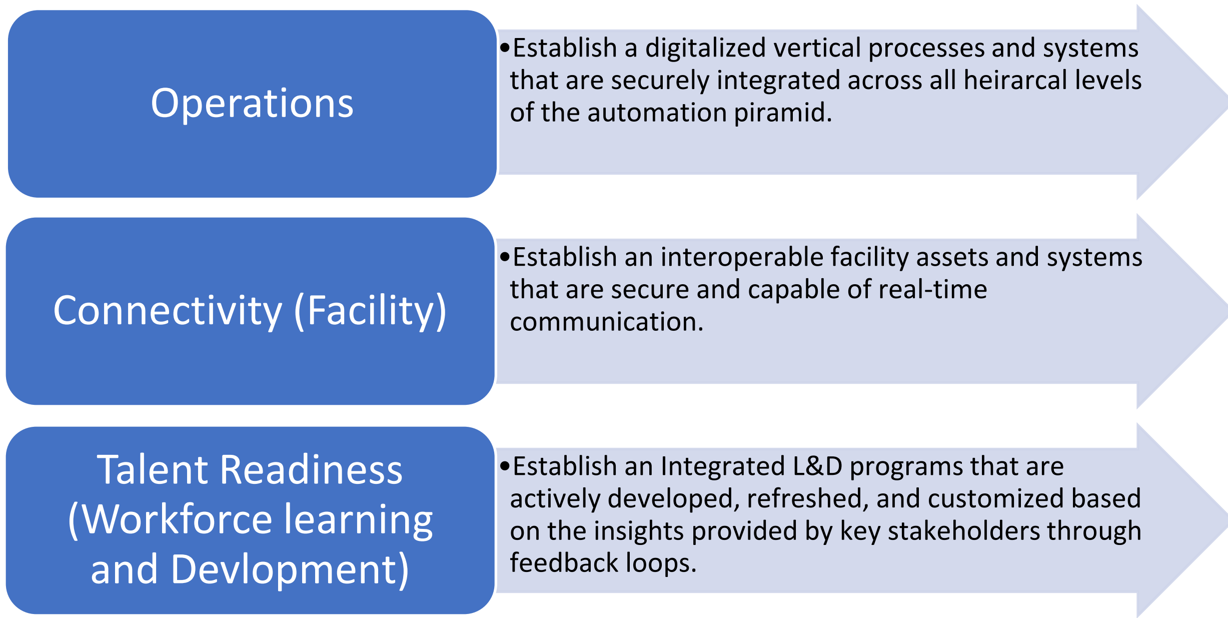

Figure 4.20 *implementation strategy*

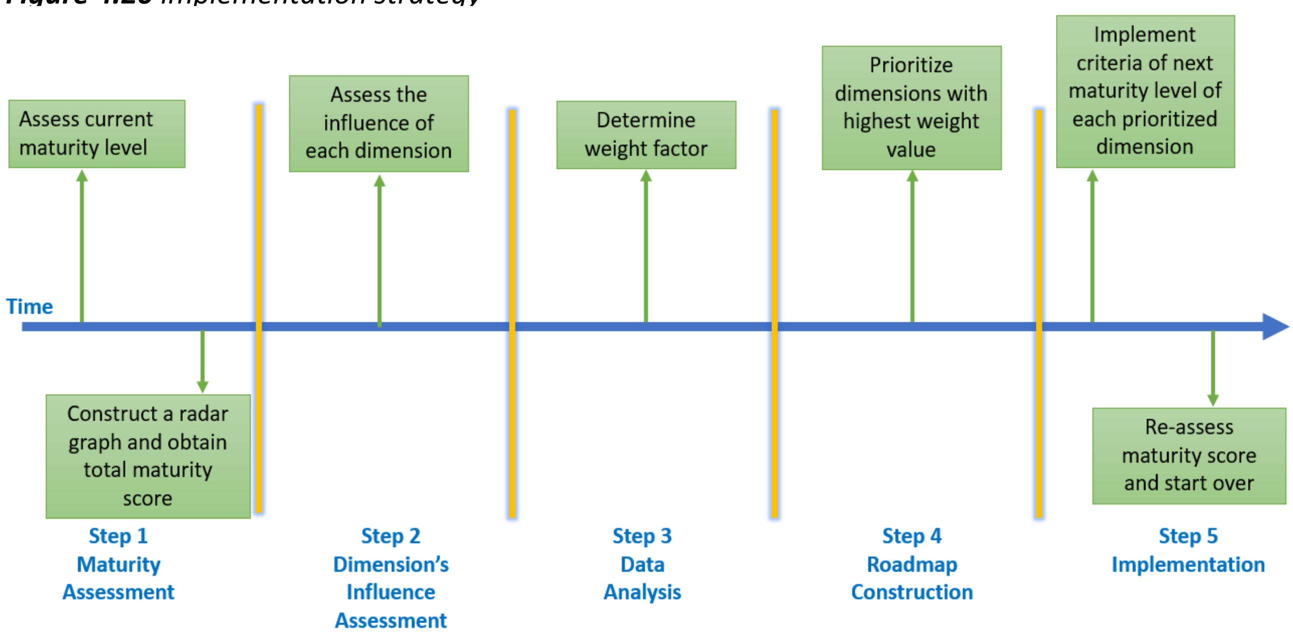

Figure 4.22 *Implementing Industry 4.0 timeline at SPM Automation Inc.*

Fig 4.17 displays the timeline and sequence of tasks that need to be conducted according to the implementation strategy established in this research.

4.3 Considering Chonswat’s Maturity Model

Together with The Singapore Smart industry readiness index Chonswat’s (Chonsawat, 2019) maturity model was considered during the assessment process. Chonswat’s maturity model was considered since it is considered one of the most recent maturity models that are SMEs oriented in the literature. Also, Chonswat’s model possessed key features such as radar chart display and an equation that delivers a weight factor for each dimension. Chonswat’s model was declared insufficient to be used since it lacked a detailed criterion for each dimension which is an essential feature in assessing the process and developing a transformation roadmap. With no criteria available, it is tougher to assess an enterprise with high accuracy since there is no information provided for the enterprise to compare itself with to acknowledge its current maturity level. Readily available criteria are also important for enterprises to acknowledge what features they need to possess to upgrade to the next maturity level. The second reason why SSIRI was considered instead of Chonswat’s maturity model is that it possesses a larger maturity scale which consists of 6 maturity levels which is an asset to the assessment’s accuracy. Last but not least SSIRI is very popular in the industry as it has been implemented in more than 300 industries across the globe. Table 4.31 summarizes the key differences between both maturity models.

Table 4.30 Comparison of SSIRI and Chonswat's maturity models

Maturity model	Criteria	Number of maturity levels	Weight factors	Popularity within the industry
SSIRI	✓	6		Implemented in 300+ industries
Chonsawat maturity model		5	✓	No records of implementation

4.4 Case Study Summary

The case study conducted on SPM Automation Inc. has proven that the proposed implementation strategy is functional, and capable of providing actual results on both maturity scores, and a plan for implementing I4.0. SPM Automation Inc. has scored a total maturity score of 33% on it is initial assessment. For SPM Automation Inc. to increase their score and become closer to establish industry 4.0 capabilities, SPM Automation Inc. needs to firstly transform their operations (vertical integration) by establishing a digitalized vertical processes and systems that are securely integrated across all hierarchical levels of the automation pyramid by establishing a real time feedback of their supply chain, that is capable of providing updates on all the steps taken to get the product from its original state to the customer. This includes SPM's suppliers progress, SPM's manufacturing progress, and customer's feedback. Second, they need to transform connectivity at the facility level by establishing an interoperable facility assets and systems that are secure and capable of real-time communication. This would be achieved through establishing a network that provides management and every manufacturing sector (programmers, operators, welders, CNC operators, and assembly operators) at SPM Automation Inc. a real-time feedback of the status of any project undertaken by SPM Automation Inc. This network will provide the identity of the project, the manufacturing process it is going under, and estimated time to be released to the next manufacturing process. Third they need to transform their talent readiness (workforce learning and development) by establishing an Integrated learning and development programs that are actively developed, refreshed, and customized based on the insights provided by key stakeholders through feedback loops. This is achieved through having SPM's employees participate in workshops which provides training that would help employees become more familiar with the forthcoming technologies, work processes, and the future of manufacturing as a whole. Once the three listed dimensions are transformed successfully, SPM Automation Inc. can reassess their total maturity score and re-transform the second prioritized group of dimensions.

Chapter 5 will provide a conclusion of the result this research has achieved and more about the future of this work.

Chapter 5: Conclusions

5.1 Conclusions

In this research, it has been proven that by utilizing I4.0 maturity models, graphing methods, and decision-support methodologies, it is possible to establish an implementation strategy concerning the fourth industrial revolution, that is capable of aiding SMEs to apply phased implementation of necessary improvements to overcome the financial barrier that is faced during the transformation process. The four-step implementation strategy developed in this research has proven to be capable of assessing the current maturity level of an SME over sixteen different dimensions and providing a total maturity score that reflects on them all, and generating an implementation strategy that prioritizes the most influential dimensions of the facility for transformation, following the Pareto effect. Applying the implementation strategy over two case studies, and comparing their results in Fig 4.5 and Fig 4.20, it has also been proven that the transformation plan, and implementation strategy resulting from the four step methodology established in this research, is completely tailored to the enterprise that is being considered. The final results are completely based on the assessment process scores, in other words it is based on the enterprise's status from maturity and work process point of view.

SMEs form the backbone of almost every nation's economy, and they deserve the right amount of attention from research and development to provide solutions for the various obstacles they face to maintain a healthy economy. With the new technologies arising every day SMEs need to keep up with the rapid change to stay competitive and survive. The fourth industrial revolution is one of the most important topics in the manufacturing industry, and it is seen as the future of manufacturing. This research provides an industry 4.0 implementation strategy for SMEs that are willing to go through the transformation process. The proposed implementation strategy provides a solution to the most common barrier SMEs face during their transformation, which is the lack of an appropriate strategy to overcome their financial barrier. The Four-step strategy helps overcome this obstacle by directing all financials and effort to the dimensions that are most influential to the enterprise. The return on investment will help the SMEs to further transform to finally achieve industry 4.0 standards. The main benefit this research comes with is that it provided a tool that helps SMEs transform and establish I4.0 standards by providing an implementation strategy that overcomes the financial obstacles faced by SMEs.

5.2 Recommended Future Work

The limitation of this research is that it evaluated the I4.0 assessment process using only two maturity models, future research could include more maturity models. Another room for improvement concerning this subject would be an implementation strategy that would consider the relationship and dependency between the proposed dimensions since a transformation in one dimension could be depending on or influencing the transformation of another (such as automation and connectivity).

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Appendix A: Criteria of each of the 16 dimensions

Table A.1 Criteria for vertical integration (Board, 2018)

Process Building Block | Operations Pillar | Vertical Integration Dimension			
Vertical Integration is the integration of processes and systems across all hierarchical levels of the automation pyramid within a facility to establish a connected, end-to-end data thread.			
Band		**Definition**	**Description**
0	**Undefined**	Vertical processes are not explicitly defined.	Resource planning and technical production processes are managed and executed in silos, based on informal or ad-hoc methods.
1	**Defined**	Vertical processes are defined and executed by humans, with the support of analogue tools.[1]	Resource planning and technical production processes are managed and executed in silos, based on a set of formally defined instructions.
2	**Digital**	Defined vertical processes are completed by humans with the support of digital tools.	Resource planning and technical production processes are managed and executed in silos, by Operations Technology (OT) and Information Technology (IT) systems.
3	**Integrated**	Digitized vertical processes and systems are securely integrated across all hierarchical levels of the automation pyramid.[2]	OT and IT systems managing resource planning and technical production processes are formally linked; however the exchange of data and information across different functions is predominantly managed by humans.
4	**Automated**	Integrated vertical processes and systems are automated, with limited human intervention.	OT and IT systems managing the resource planning and technical production processes are formally linked, with the exchange of data and information across different functions predominantly executed by equipment, machinery and computer-based systems.
5	**Intelligent**	Automated vertical processes and systems are actively analysing and reacting to data.	OT and IT systems are integrated from end to end, with processes being optimized through insights generated from analysis of data.

Table A.2 Criteria for Horizontal integration (Board, 2018)

Process Building Block | Supply Chain Pillar | Horizontal Integration Dimension			
Horizontal Integration is the integration of enterprise processes across the organization and with stakeholders along the value chain.			
Band		Definition	Description
0	Undefined	Supply chain processes[3] are not explicitly defined.	Enterprise processes are managed and executed in silos, based on informal or ad-hoc methods.
1	Defined	Supply chain processes are defined and executed by humans, with the support of analogue tools.	Enterprise processes are managed and executed in silos, based on a set of formally defined instructions.
2	Digital	Defined supply chain processes are completed by humans with the support of digital tools.	Enterprise processes are managed and executed in silos by IT systems.
3	Integrated	Digitized supply chain processes and systems are securely integrated across business partners and clients along the value chain.	IT systems managing enterprise processes are formally linked; however the exchange of data and information across different functions is predominantly managed by humans.
4	Automated	Integrated supply-chain processes and systems are automated, with limited human intervention.	IT systems managing enterprise processes are formally linked, with the exchange of data and information across different functions being predominantly executed by computer-based systems.
5	Intelligent	Automated supply chain processes and systems are actively analysing and reacting to data.	IT systems are integrated from end to end, with processes being optimized through insights generated from analysis of data.

Table A.3 Criteria for Product Lifecycle Dimension (Board, 2018)

Process Building Block | Product Lifecycle Pillar | Integrated Product Lifecycle Dimension			
Integrated Product Cycle is the integration of people, processes and systems along the entire product lifecycle, encompassing the stages of design and development, engineering, production, customer use, service, and disposal.			
Band		**Definition**	**Description**
0	**Undefined**	Product lifecycle[4] processes are not explicitly defined.	Processes along the product lifecycle are managed and executed in silos, based on informal or ad-hoc methods.
1	**Defined**	Product lifecycle processes are defined and executed by humans, with the support of analogue tools.	Processes along the product lifecycle are managed and executed in silos, based on a set of formally defined instructions.
2	**Digital**	Defined product lifecycle processes are completed by humans, with the support of digital tools.	Processes along the product lifecycle are managed and executed in silos, by digital tools.
3	**Integrated**	Digitized product lifecycle processes and systems are securely integrated across all stages of the product lifecycle.	Digital tools and systems that manage the product lifecycle are formally linked with each other; however, the exchange of information along the product lifecycle is predominantly managed by humans.
4	**Automated**	Integrated product lifecycle processes are automated, with limited human intervention.	Digital tools and systems that manage the product lifecycle are formally linked with each other, and the exchange of information along the product lifecycle is predominantly executed by computer-based systems.
5	**Intelligent**	Automated product lifecycle processes are actively analysing and reacting to data.	Digital tools and systems deployed for the management of the product lifecycle are integrated from end to end, with the processes being optimized through insights generated from analysis of data.

Table A.4 Criteria for Automation Shop floor (Board, 2018)

Technology Building Block | Automation Pillar | Shop Floor Automation Dimension			
Shop Floor Automation is the application of technology to monitor, control and execute the production and delivery of products and services, within the location where the production and management of goods is carried out.			
Band		**Definition**	**Description**
0	**None**	Repetitive production[5] and support processes[6] are not automated.	Production processes are executed by humans.
1	**Basic**	Repetitive production processes are partially automated, with significant human intervention. Repetitive support processes are not automated.	Production processes are executed by humans with the assistance of equipment, machinery and computer-based systems.
2	**Advanced**	Repetitive production processes are automated, with minimal human intervention. Repetitive support processes are not automated.	Production processes are predominantly executed by equipment, machinery and computer-based systems. Human intervention is required to initiate and conclude each process.
3	**Full**	Repetitive production processes are fully automated, with no human intervention. Repetitive support processes are partially automated, with limited human intervention.	Production processes are fully automated through the use of equipment, machinery and computer-based systems. Human intervention is required for unplanned events.
4	**Flexible**	Automated production processes are reconfigurable through plug-and-play automation. Repetitive support processes are partially automated, with limited human intervention.	Equipment, machinery and computer-based systems can be modified, reconfigured, and re-tasked quickly and easily when needed. Limited human intervention is required for unplanned events.
5	**Converged**	Flexible production and support processes are converged with enterprise and facility automation platforms to form highly autonomous networks.	Equipment, machinery and computer-based systems are flexible and formally integrated with enterprise and facility systems, to allow for dynamic, cross-domain interactions.

Table A.5 Criteria for Enterprise Automation Dimension (Board, 2018)

Technology Building Block | Automation Pillar | Enterprise Automation Dimension			
Enterprise Automation is the application of technology to monitor, control and execute processes, within the location where the administrative work is carried out. These processes include, but are not limited to, sales and marketing, demand planning, procurement, and human resource management and planning.			
Band		Definition	Description
0	None	Enterprise processes are not automated.	Enterprise processes are executed by humans.
1	Basic	Enterprise processes are partially automated, with significant human intervention.	Enterprise processes are executed by humans with the assistance of computer-based systems.
2	Advanced	Enterprise processes are automated, with minimal human intervention.	Enterprise processes are predominantly executed by computer-based systems. Human intervention is required to initiate and conclude each process.
3	Full	Enterprise processes are fully automated, with no human intervention.	Enterprise processes are fully automated through the use of computer-based systems. Human intervention is required for unplanned events.
4	Flexible	Automated enterprise processes are adaptable.	Computer-based systems can be modified, reconfigured, and re-tasked quickly and easily when needed. Limited human intervention is required for unplanned events.
5	Converged	Flexible enterprise processes are converged with shop floor and facility automation platforms to form highly autonomous networks.	Computer-based systems are flexible and formally integrated with those of shop floor and facility systems to allow for dynamic, cross-domain interactions.

Table A.6 Criteria for Facility Automation Dimension (Board, 2018)

Technology Building Block | Automation Pillar | Facility Automation Dimension			
Facility Automation is the application of technology to monitor, control and execute processes within the physical building and/or premises where the production area is located. These processes include but are not limited to the management of HVAC, chiller, security, and lighting systems.			
Band		**Definition**	**Description**
0	**None**	Facility processes are not automated.	Facility processes are executed by humans.
1	**Basic**	Facility processes are partially automated, with significant human intervention.	Facility processes are executed by humans, with the assistance of equipment, machinery and computer-based systems.
2	**Advanced**	Facility processes are automated, with minimal human intervention.	Facility processes are predominantly executed by equipment, machinery and computer-based systems. Human intervention is required to initiate and conclude each process.
3	**Full**	Facility processes are fully automated, with no human intervention.	Facility processes are fully automated through the utilization of equipment, machinery and computer-based systems. Human intervention is required for unplanned events.
4	**Flexible**	Automated facility processes are adaptable.	Equipment, machinery and computer-based systems can be modified, reconfigured, and re-tasked quickly and easily when needed. Limited human intervention is required for unplanned events.
5	**Converged**	Flexible facility processes are converged with shop floor and enterprise automation platforms to form highly autonomous networks.	Equipment, machinery and computer-based systems are flexible and formally integrated with those of shop floor and enterprise systems to allow for dynamic, cross-domain interactions.

Table A.7 Criteria for shop floor connectivity Dimension (Board, 2018)

Technology Building Block | Connectivity Pillar | Shop Floor Connectivity Dimension			
Shop floor connectivity is the interconnection of equipment, machines and computer-based systems, to enable communication and seamless data exchange, within the location where the production and management of goods is carried out.			
Band		**Definition**	**Description**
0	**None**	Production assets and systems are not connected.	Equipment, machinery and computer-based systems are not able to interact or exchange information.
1	**Connected**	Production assets and systems are connected via multiple communication technologies & protocols.	There are formal network links that will enable equipment, machinery and computer-based systems to interact or exchange information.
2	**Interoperable**	Connected production assets and systems are interoperable across multiple communication technologies & protocols.	Equipment, machinery and computer-based systems are able to interact and exchange information without significant restrictions.
3	**Interoperable And Secure**	Interoperable production assets and systems are secure.	There is a vigilant and resilient security framework to protect the network of interoperable equipment, machinery, and computer-based systems from undesired access and/or disruption.
4	**Real-Time**	Interoperable production assets and systems are secure and capable of real-time communication.	Interoperable and secure network links across different equipment, machinery and computer-based systems are able to interact or exchange information as the information is generated without delay.
5	**Scalable**	Interoperable production assets and systems are secure, capable of real-time communication, and scalable.	Existing networks can be configured quickly and easily to accommodate any modifications made to the existing composition of equipment, machinery and computer-based systems.

Table A. 8 Criteria for shop Enterprise Connectivity Dimension (Board, 2018)

Technology Building Block | Connectivity Pillar | Enterprise Connectivity Dimension			
Enterprise connectivity is the interconnection of equipment, machines and computer-based systems, to enable communication and seamless data exchange, within the location where the administrative work is carried out.			
Band		**Definition**	**Description**
0	**None**	Enterprise IT systems are not connected.	Computer-based systems are not able to interact or exchange information.
1	**Connected**	Enterprise IT systems are connected via multiple communication technologies & protocols.	There are formal network links that will enable computer-based systems to interact or exchange information.
2	**Interoperable**	Enterprise IT systems are interoperable across multiple communication technologies & protocols.	Computer-based systems are able to interact and exchange information without significant restriction.
3	**Interoperable And Secure**	Interoperable Enterprise IT systems are secure.	There is a vigilant and resilient security framework to protect the network of interoperable computer-based systems from undesired access and/or disruption.
4	**Real-Time**	Interoperable Enterprise IT systems are secure and capable of real-time communication.	Interoperable and secure network links across the different computer-based systems are able to interact or exchange information as the information is generated without delay.
5	**Scalable**	Interoperable Enterprise IT systems are secure, capable of real-time communication, and scalable.	Existing networks can be configured quickly and easily to accommodate any modifications made to the existing composition of computer-based systems.

Table A.9 Criteria for facility connectivity Dimension (Board, 2018)

Technology Building Block | Connectivity Pillar | Facility Connectivity Dimension			
Facility connectivity is the interconnection of equipment, machines and computer-based systems, to enable communication and seamless data exchange, within the physical building and/or land plot where the production area is located.			
Band		**Definition**	**Description**
0	**None**	Facility assets and systems are not connected.	Equipment, machinery and systems are not able to interact or exchange information.
1	**Connected**	Facility assets and systems are connected via multiple communication technologies & protocols.	There are formal network links that will enable equipment, machinery and computer-based systems to interact or exchange information.
2	**Interoperable**	Facility assets and systems are interoperable across multiple communication technologies & protocols.	Equipment, machinery and computer-based systems are able to interact and exchange information without significant restrictions.
3	**Interoperable And Secure**	Interoperable facility assets and systems are secure.	There is a vigilant and resilient security framework to protect the network of interoperable equipment, machinery, and computer-based systems from undesired access and/or disruption.
4	**Real-Time**	Interoperable facility assets and systems are secure and capable of real-time communication.	Interoperable and secure network links across different equipment, machinery and computer-based systems are able to interact or exchange information as the information is generated with delay.
5	**Scalable**	Interoperable facility assets and systems are secure, capable of real-time communication, and scalable.	Existing networks can be configured quickly and easily to accommodate any modifications made to the existing composition of equipment, machinery and computer-based systems.

Table A.10 Criteria for shop floor intelligence Dimension (Board, 2018)

Technology Building Block | Intelligence Pillar | Shop Floor Intelligence Dimension			
Shop Floor Intelligence is the processing & analysis of data to optimize existing processes and create new applications, products, and services, within the location where the production and management of goods is carried out.			
Band		**Definition**	**Description**
0	**None**	OT & IT systems are not in use.	No electronic or digital devices are used.
1	**Computerized**	OT & IT systems execute pre-programmed tasks and processes.	Equipment, machinery and computer-based systems are able to perform tasks based on pre-programmed logic.
2	**Visible**	Computerized OT & IT systems are able to identify deviations.	Equipment, machinery and computer-based systems are able to notify operators of deviations from predefined parameters.
3	**Diagnostic**	Computerized OT & IT systems are able to identify deviations and diagnose potential causes.	Equipment, machinery and computer-based systems are able to notify operators of deviations, and provide information on the possible causes.
4	**Predictive**	Computerized OT & IT systems are able to diagnose problems and predict future states of assets and systems.	Equipment, machinery and computer-based systems are able to predict and notify operators of potential deviations, and provide information on the possible causes.
5	**Adaptive**	Computerized OT & IT systems are able to diagnose problems, predict future states and autonomously execute decisions to adapt to changes.	Equipment, machinery and computer-based systems are able to predict and diagnose potential deviations, and independently execute decisions to optimize performance and resource efficiency.

Table A.11 Criteria for Enterprise Intelligence Dimension (Board, 2018)

Technology Building Block | Intelligence Pillar | Enterprise Intelligence Dimension			
Enterprise Intelligence is the processing & analysis of data to optimize existing administrative processes and create new applications, products and services.			
Band		Definition	Description
0	None	Enterprise systems are not in use.	No electronic or digital devices are used.
1	Computerized	Enterprise IT systems execute pre-programmed tasks and processes.	Enterprise computer-based systems perform tasks based on pre-programmed logic.
2	Visible	Enterprise IT systems are able to identify deviations.	Enterprise computer-based systems are able to notify relevant personnel of deviations from predefined parameters.
3	Diagnostic	Enterprise IT systems are able to identify deviations and diagnose potential causes.	Enterprise computer-based systems are able to notify relevant personnel of deviations, and provide information on the possible causes.
4	Predictive	Enterprise IT systems are able to diagnose problems and predict future states of assets and systems.	Enterprise computer-based systems are able to predict and notify relevant personnel of potential deviations, and provide information on the possible causes.
5	Adaptive	Enterprise IT systems are able to diagnose problems, predict future states, and autonomously execute decisions to adapt to changes.	Enterprise computer-based systems are able to predict and diagnose potential deviations, and independently execute decisions to optimize performance and resource efficiency.

Table A.12 Criteria for shop Facility Intelligence Dimension (Board, 2018)

Technology Building Block | Intelligence Pillar | Facility Intelligence Dimension			
Facility Intelligence is the processing & analysis of data to optimize existing processes and create new applications, products and services, within the physical building and premises where the production area is located at.			
Band		Definition	Description
0	None	OT & IT systems are not in use.	No electronic or digital devices are used.
1	Computerized	OT & IT systems execute pre-programmed tasks and processes.	Equipment, machinery and computer-based systems perform tasks based on pre-programmed logic.
2	Visible	Computerized OT & IT systems are able to identify deviations.	Equipment, machinery and computer-based systems are able to notify relevant personnel of deviations from predefined parameters.
3	Diagnostic	Computerized OT & IT systems are able to identify deviations and diagnose potential causes.	Equipment, machinery and computer-based systems are able to notify relevant personnel of deviations, and provide information on possible causes.
4	Predictive	Computerized OT & IT systems are able to diagnose problems and predict future states of assets and systems.	Equipment, machinery and computer-based systems are able to predict and notify relevant personnel of potential deviations, and provide information on the possible causes.
5	Adaptive	Computerized OT & IT systems are able to diagnose problems, predict future states, and autonomously execute decisions to adapt to changes.	Equipment, machinery and computer-based systems are able to predict and diagnose potential deviations, and independently execute decisions to optimize performance and resource efficiency.

Table A.13 Criteria for Workforce learning and development Dimension (Board, 2018)

Organization Building Block | Talent Readiness Pillar | Workforce Learning & Development Dimension			
Workforce Learning & Development ("L&D") is a system of processes and programmes that aims to develop the workforce's capabilities, skills and competencies to achieve organizational excellence.			
Band		**Definition**	**Description**
0	**Informal**	Informal mentorship and apprenticeship is the predominant mode of workforce L&D.	There is no formal L&D curriculum to on-board and train the workforce.
1	**Structured**	Formally designed training curricula for skills acquisition is the predominant mode of workforce L&D.	There is a formal L&D curriculum with clear commencement and conclusion points. The scope of L&D is limited to skills acquisition.
2	**Continuous**	Structured L&D programmes are designed to run on an ongoing basis, to enable the ongoing enhancement and/or expansion of employees' skillsets.	There is a structured L&D curriculum that adopts an approach of continuous learning, to enable the constant learning, re-learning, and improvement of new and existing skills.
3	**Integrated**	Continuous L&D programmes are formally aligned with the organization's business needs and human resources (HR) functions.	There is a continuous L&D curriculum that is integrated with organizational objectives, talent attraction, and career development pathways.
4	**Adaptive**	Integrated L&D programmes are actively developed, refreshed and customized based on insights provided by key stakeholders through feedback loops.	Formal feedback channels are in place to allow integrated L&D programmes to be jointly curated and updated by employees, HR, and business teams.
5	**Forward-looking**	Active efforts are made to identify and incorporate innovative L&D practices and training for future skillsets into the adaptive L&D programmes.	There are proactive steps to incorporate requirements for future skillsets and novel L&D methodologies into existing L&D programmes.

Table A.14 Criteria for Leadership Competency Dimension (Board, 2018)

Organization Building Block | Talent Readiness Pillar | Leadership Competency Dimension			
Leadership competency refers to the readiness of the management core to leverage the latest trends and technologies for the continued relevance and competitiveness of the organization.			
Band		**Definition**	**Description**
0	**Unfamiliar**	Management is unfamiliar with the most recent trends and technologies.	Management is unacquainted with the latest concepts that can enable the next phase of advancement.
1	**Limited Understanding**	Management has some awareness, through ad-hoc channels, of the most recent trends and technologies.	Management is partially familiar with the latest concepts that can enable the next phase of advancement.
2	**Informed**	Management is well-informed, through formal channels and avenues, of the most recent trends and technologies.	Management is fully familiar with the latest concepts that can enable the next phase of advancement.
3	**Semi-dependent**	Management is reliant on external partners to develop initiatives that leverage on the most recent trends and technologies to improve at least one area of the organization.	With external assistance, management is able to apply the latest concepts to enable improvements in at least one area.
4	**Independent**	Management is able to, with relative independence, develop initiatives that leverage on the latest trends and technology to improve more than one area of the organization.	Management is able to apply the latest concepts to enable improvements across multiple areas.
5	**Adaptive**	Management is able to independently adapt its organizational transformation framework to changing trends and technologies.	Management is able to augment its improvement initiatives as the latest concepts change or evolve over time.

Table A.15 Criteria for Inter and Intra Company Collaboration Dimension (Board, 2018)

Organization Building Block | Structure & Management Pillar | Inter- and Intra- Company Collaboration Dimension			
Inter- and intra- company collaboration is the process of working together, through cross-functional teams and with external partners, to achieve a shared vision and purpose.			
Band		**Definition**	**Description**
0	**Informal**	Communication and information sharing across teams happens on an informal basis.	Teams generally work in silos. Communication and collaborations happen on a casual, ad hoc basis.
1	**Communicating**	Formal channels are established for communication and information sharing across teams.	Teams are provided with formal avenues to exchange information.
2	**Cooperating**	Formal channels are established to allow teams to work together on discrete/one-off tasks and projects.	Teams are provided with formal avenues to interact and work on discrete tasks and projects together.
3	**Coordinating**	Teams are empowered by the organization to make adjustments that will facilitate cooperation on discrete tasks and projects.	Teams have the mandate to alter or adjust certain obligations and responsibilities, to reduce the barriers for cooperation on joint tasks and projects.
4	**Collaborating**	Teams are empowered by the organization to share resources on both discrete and longer-term tasks and projects.	Teams have the mandate to commit resources to both discrete and longer-term tasks and projects. Risk, responsibility and rewards are partially shared.
5	**Integrated**	Formal channels are established to enable dynamically-forming teams to work on cross-functional projects with shared goals, resources and KPIs.	Teams can be formed with flexibility and agility to address problem statements as they arise. Risk, responsibility and rewards are predominantly shared.

Table A.16 Criteria for strategy and governance Dimension (Board, 2018)

Organization Building Block | Structure & Management Pillar | Strategy & Governance Dimension			
Strategy and governance is the design and execution of a plan of action to achieve a set of long-term goals. It includes identifying priorities, formulating a roadmap, and developing a system of rules, practices and processes to translate a vision into business value.			
Band		**Definition**	**Description**
0	**None**	Transformation towards a Factory/Plant-of-the-Future is not present in any part of the organization strategy.	Intentions to establish a Factory/Plant-of-the-Future are not identified as a strategic focus in the company's current or future plans.
1	**Formalization**	Transformation towards a Factory/Plant-of-the-Future has been formally identified as a business strategy at the corporate or business level.	Intentions to establish a Factory/Plant-of-the-Future have been identified as a strategic focus in the company's current or future plans.
2	**Development**	Transformation initiative towards a Factory/Plant-of-the-Future is being developed or has been developed by a dedicated team.	A long-term strategy and governance model to establish a Factory/Plant-of-the-Future is being developed or has been developed.
3	**Implementation**	Transformation Initiative towards a Factory/Plant-of-the-Future has been formally implemented in least one functional area.	The long-term strategy and governance model to establish a Factory/Plant-of-the-Future has been put into action.
4	**Scaling**	Transformation initiative towards a Factory/Plant-of-the-Future is expanded to include more than one functional area.	The long-term strategy and governance model to establish a Factory/Plant-of-the-Future is scaled up to include other secondary areas.
5	**Adaptive**	Transformation initiative towards a Factory/Plant-of-the-Future is refreshed and updated dynamically.	The long-term strategy and governance model to establish a Factory/Plant-of-the-Future is constantly reviewed and dynamically refreshed to account for the latest advancements in technology, business philosophy, and practices.

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