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The Development of a Framework for the Implementation of Industry 4.0 for Manufacturing in a Developing Country: A Case Study of Saudi Arabia

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Abstract

Objective of the Research: The purpose of this research is to investigate Industry 4.0 implementation barriers in Small and Medium-Sized enterprises within the manufacturing sector in developing countries. One of the objectives driving this research is the exploration of associations between Industry 4.0 enablers and lean manufacturing. Further, the research aims to construct a framework guiding stakeholders in implementing Industry 4.0 by overcoming common barriers cited by experts in the field.

Research Problems: The main problem driving this research is the dearth of information on Industry 4.0 implementation in developing countries. Simultaneously, little research has been conducted to identify the barriers of industry 4.0 in SMEs within manufacturing realms in emerging economies. Inadequate research investigated the associations between lean manufacturing and industry 4.0 implementation.

Methodology: This is a mixed methods research study. On the qualitative side, focus groups are used to collect open-ended responses to questions related to barriers facing the adoption of Industry 4.0. Quantitatively, Interpretive Structural Modelling is used to construct the framework driving stakeholders' decisions to adopt and implement industry 4.0. Further, survey research is used to validate experts' opinions on the utility of the ISM based model. In sum, three distinct data collection techniques were used: (a) focus groups, (b) descriptive data for interpretive structural modeling, and (c) survey responses. Based on the quantitative and qualitative methods of data collection, a series of data analysis strategies were followed.

Key Findings: The current study reported strong associations linking Industry 4.0 enablers and lean manufacturing outcomes. On the one hand, the use of Industrial Internet of Things (IIoT) improved customers' connectivity and engagement in each stage of the sustainable manufacturing

process. Thereby, improving customer satisfaction, a key element in measuring lean manufacturing. Additionally, the deployment of cyber security as well as cloud computing technology facilitates the transfer and storage of information minimizing the wasteful utilization of physical and technical infrastructure, and manifestation of lean manufacturing practices. By the same token, the increasing use of simulation and analytics technology minimizes the reliance on manning thereby reducing further waste, the purpose of lean manufacturing.

Implications of the Research: Results of the ISM model were validated by using a questionnaire showing the reliability and validity of the ISM constructed model that has been adopted as the accepted framework guiding Industry 4.0 implementation. The proposed framework in this study departs from existing models in significant ways. First, it does not prescribe sequential steps since Industry 4.0 implementation is a complex process requiring simultaneous work from various divisions across the organization. Second, the framework is scalable and flexible, allowing it to fit many applications regardless of the size or nature of the industry. Third, the model originated from contexts in developing countries, making it appropriate for implementation in markets like Saudi Arabia.

Conclusion of the Research: This research concluded that the implementation of Industry 4.0 is neither straightforward nor linear. Experts voiced concern regarding the technical and management infrastructures facing developing countries' manufacturing sectors. The research suggested that the adoption of Industry 4.0 is a multi-step simultaneous process involving more than a single practice overcoming several barriers at the same time.

Keywords: *Industry 4.0; Lean Manufacturing; Small and Medium-Sized Enterprises; Developing Countries; Saudi Arabia; Interpretive Structural Modeling; Focus Groups; Expert Opinions.*

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Dedication

I dedicate this work to my parents, my beloved wife, and my children.

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Publications

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Acronyms

Industry 4.0	Fourth Industrial Revolution
LM	Lean Manufacturing
IoT	Internet of Things
IIoT	Industrial Internet of Things
KSA	Kingdom of Saudi Arabia
AI	Artificial Intelligence
ML	Machine Learning
AM	Additive Manufacturing
AR	Augmented Reality
VR	Virtual Reality
JIT	Just in time
TPM	Total Productive Maintenance
SMED	Single-Minute Exchange of Die
CS	Cybersecurity
BD	Big Data
DA	Data Analytics
BA	Bottleneck Analysis
Kanban	Pull System
5S	Sort, Straighten, Shine, Standardize, and Sustain
DE	Digital Enterprise
IR	Industrial Revolution
CI	Continuous Improvement

CT	Cycle Time
DFM	Design for Maintenance
ERM	Enterprise Risk Management
SME	Small and Medium-Sized Enterprise
ETO	Engineer to Order
ISO	International Standards Organization
IX	Industrial Transformation
M2M	Machine to Machine
MTO	Made to Order
OTD	On Time Delivery
PDM	Product Lifestyle Management
R&D	Research and Development
ROI	Return on Investment
SCM	Supply Chain Management
SOP	Standard Operational Procedure
TCoQ	Total Cost of Quality
VSM	Value Stream Mapping
WMS	Warehouse Management System

Chapter One

Introduction

The purpose of the current study is to investigate the implementation of Industry 4.0 in SMEs within the manufacturing sector. The significance of this topic lies in the colossal financial and workforce efficiencies accrued by manufacturers that have already adopted I.4.0 technologies. Further, the significance of this research extends to the practical knowledge of factors preventing many interested stakeholders from adopting Industry 4.0. Talking to experts directly allows researchers to learn why many individuals around developing countries are hesitant to apply the new smart technologies.

1.1 Historical Background

Throughout human history, production has featured as an indispensable characteristic of ordinary life. Early man produced basic tools helping him to hunt and provide both himself and his social unit with food. With evolving human development, production has taken several significant shifts. One of the main trends is a movement from production for ones' own use to production for commercial purposes. For thousands of years, merchants have set up simple workshops, hired assistants to manufacture goods for sale, and nomadic traders such as the Arabs traveled thousands of miles to sell their garments among the Romans and Persians. In Arabia, small shops filled with cloth, basic weaving tools, and sheer manpower also manufactured elaborate gowns using highly specialized manufacturing processes. With the development of states and modern armies, production then became more standardized, leading to multiple transformations of manufacturing [1].

In 17th-century Britain, several entrepreneurs began to apply steam power to manufacturing a variety of goods. After many iterations and inventions across the country, James Watt succeeded

in making a power steam engine that helped manufacturers move away from purely human processes to mechanically informed production. These steam engines made the production of goods more effective and efficient. Heated water created pressurized steam, transforming the heat into an energy feeding production system. During this epoch, textile manufacturing relied on workers who suffered from a host of troubles like long hours and hazardous working conditions, so mechanical production also allowed manufacturers to replace some human powered production. Watt's invention and related steam-powered developments resulted in a flurry of machines that marked the start of the industrial revolution. This event would later be categorized as Industry 1.0, the start of a series of revolutions in the manufacturing world [1, 2].

Following the explosion in steam power technology, entrepreneurs began to experiment with other energy production sources useful in manufacturing. For example, Thomas Edison introduced electricity as a viable option which helped manufacturers improve their systems and processes in the late 1870s. Refining Edison's ideas and prototypes, they began to adopt electricity as a main source of energy which resulted in the rise of mass production. Following the implementation of electricity, internal combustion engines were discovered and provided more opportunities for manufacturers to generate products. Simultaneously during this period communication among workers, customers, and manufacturers was improving due to the emergence of new ways of taking and conveying information. The telephone, telegraph, and improvements in transportation made the communication of goods and information much easier. Historians refer to this period as the Technological Revolution or Industry 2.0. Production lines began in the early 20th century and became more mechanical and autonomous. Factory floors looked completely different in the interwar period compared to a century prior to that. The main difference is the presence of more machines and electricity powering systems [1, 3].

After the Second World War, the advent of computers transformed manufacturing in significant ways. Machines could be taught using programming languages to perform tasks humans used to perform. The introduction of robotics to manufacturing also made manufacturing and production more efficient, thereby eliminating many human errors in the process. The implementation of scientific management tools through autonomous machines controlling production also helped eliminate many sources of waste. With the invention of advanced computers and programs as well, production of highly sophisticated goods increased. Computer systems made design and development of products much easier and assisted manufacturers in detecting defects much faster. Communication became more prevalent with the use of email systems and virtual working environments, and manufacturing floors in the 1970s-80s looked completely different from those seen in the 1920s-30s. One of the major differences was the presence of computer systems and machines running on instructed programs scripted prior to operations [4].

Since the 1990s, many technologies have witnessed tremendous developments and have been incorporated in manufacturing. Machine learning has allowed computers to make autonomous decisions that are independent of human intervention. Cloud computing has enabled manufacturers to store information and databases without investing in expensive storage spaces. Simulation applications have improved manufacturers' efforts to design and develop products more efficiently without the need to waste resources on testing various prototypes. Additionally, privacy and security frameworks have given manufacturers more safeguards to their spaces and proprietary information [5]. Today, additive manufacturing and virtual reality empower manufacturers to leverage technologies for more use. It is clear innovative technology has transformed production in several ways, leading to the present manufacturing era of Industry 4.0.

1.2 Industry 4.0 Overview

Advancements in manufacturing technologies by Industry 4.0 implementation have produced shorter product life cycles, marketing strategies, and client consumption dynamics which has opened doors to new opportunities for small and medium enterprises and posed new challenges [6]. For example, competitive advantage in these companies increases by appealing to the evolving audience of the product or operation in the form of marketing strategies. Positive changes brought on by Industry 4.0 approaches showcase company sustainability, production time, and customization options that attract larger target audiences. In the same manner, branding these organizations with respect to new optimizations in production erects a fuller picture of technological advantages and strengths for eager consumers. Furthermore, recent research reports that clientele development for companies implementing Industry 4.0 tactics results in higher satisfaction rates and connectivity with the enterprise, better local community health, and improved product use and storage time [7]. The use of technology in the workplace is ultimately changing the way businesses and their customers interact.

On another note, opportunities are presented for Industry 4.0 encompassing companies in opposition to their traditional counterparts. Increased profitability, productivity, and higher efficiency are noted by current research within companies utilizing higher methods of technological industrialization. Often, budgets for advanced manufacturing companies have also observed less cost distribution for employees, minimized hiring prices, more revenue with higher production rates, and lower repair costs due to involvement in current production hardware systems [8]. Similarly, productivity scores can shoot up with automated processes with the reduction of human error and implementation of structured design flows. Productivity can refer not only to material production, but also, in initiating precise output, to increasing labor satisfaction

and therefore effectivity and capital production [9]. Another opportunity presented by Industry 4.0 that has been observed is efficiency in return on investment, environmental emission reduction, and time management prosperities. Furthermore, outsourcing can be minimized, and task delegation and consolidation can be improved with technological advancements [10].

Similarly, businesses employing new technologies experience advantages within realms of flexibility, knowledge sharing, and decisiveness. Industry 4.0 implementing companies are able to offer employees more remote and hybrid work schedules, mechanical job-sharing opportunities, and compressed work hours [11]. The reduction of employees needed on the industrial line also gives managers the chance to budget higher salaries and retirement plans for their workers [11]. The less people on industrial lines translates into lower payroll [15]. The difference in the payroll from the original amount budgeted for paying too many workers and the new payroll amount excluding many of the line workers cod be used for a variety of purposes [13]. One of them is to increase pay for remaining workers [13]. Moreover, business executives can more readily share explicit and tacit information with their counterparts after implementing big data and operational systems. Consequently, this not only advances the enterprise, but the manufacturing sector as a whole [12]. In parallel, decisiveness within an organization has the chance to excel with the application of Industry 4.0 as timeliness and information processing increase planning and goal-setting tendencies in managerial staff [13].

Further, many challenges are posed around the implementation of new technologies in developing small and medium-sized enterprises. SMEs in developing countries tend to lack financial capital and expert knowledge to adopt new cutting-edge technologies [14, 15]. Some reported shortcomings of Industry 4.0 are gaps in technical abilities, data sensitivity, and security [14]. As automation processes increase, employers don’t always maintain the technical knowledge

needed to operate and calibrate the specifications of the machinery [15]. Team members responsible for systems in the industry must have adequate knowledge of both the manufacturing process as well as digital dexterity of the operations, being very detailed procedures on both fronts [15]. Additionally, it is difficult to implement systems of digital protection to maintain security of data in the machinery. Digital systems routed to the same network are reportedly very vulnerable to attack, making internet security workers in high demand within the field [3]. Further, businesses implementing Industry 4.0 must follow ownership, management, and privacy regulations to comply with corporate guidelines. This makes it difficult to maintain machinery that often requires third-party companies to repair technology, as it exposes data and allows more sensitivity than traditional methods [16].

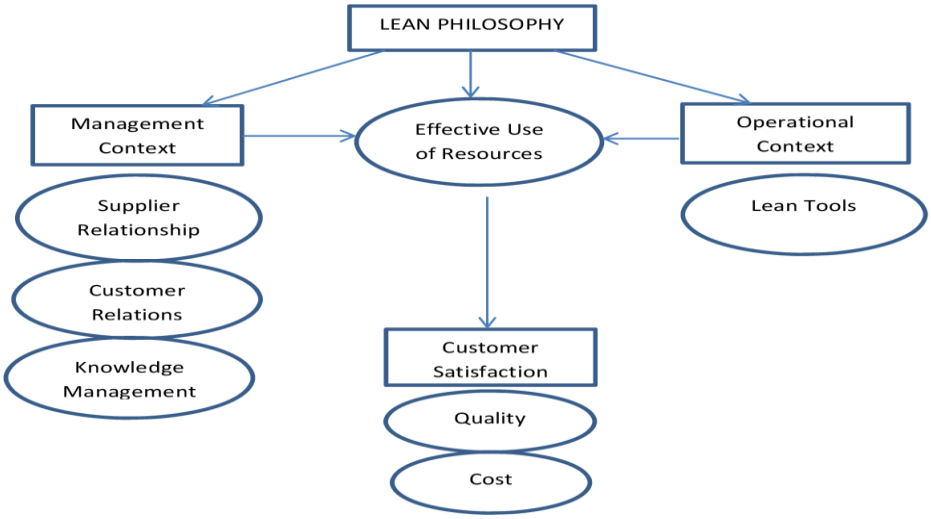
Additionally, culture change, business model considerations, and capital investments are obstacles for many small and medium-sized enterprises implementing Industry 4.0 [17]. Research reports that ensuring staff are prepared and trained for such transitions is critical in implementing more technological measures in a factory [4, 6]. Moreover, a hurdle posed for managers and business owners alike is the internal alignment decision of which strategies are most practical for the setting. A consensus of needed drivers within the industry helps staff become more receptive and open to learning new technological practices. In order to create strategies though, monetary investment is needed to initiate Industry 4.0 efforts [17]. It is difficult for small businesses to make this transition due to the funding supply that is required to implement many big technologies.

1.2.1 Industry 4.0 and Lean Manufacturing

Industry 4.0 manifestations (such as big data, automation, simulation, cybersecurity, and cloud computing) have proved to be operations that heavily increase line production in the manufacturing field [1, 3]. Techniques of LM include line balancing, value stream mapping, single

price flow, sorting, strengthening, shining, standardizing, and sustaining (5S), single-minute exchange of die (SMED), Kanban, just-in time (JIT) production, and total productive maintenance (TPM) [18]. Figure 1.1 summarizes the basic points of lean manufacturing philosophy.

Figure 1.1. Lean Philosophy



The implementation of Industry 4.0 improves lean manufacturing outcomes [1]. For instance, machine-to-machine communication enhances line balancing [19]. In a production line, operations are assigned optimally to workstations based on real-time autonomous communication allowed by sensors or robotics [3]. Overall, various industry 4.0 technologies improve the efficiency and effectiveness of manufacturing processes, the goal of lean manufacturing [20].

Industry 4.0 ameliorate lean manufacturing tools' implementation [21]. For instance, the positive gains from applying value stream mapping are larger in industry 4.0 contexts compared to legacy/traditional settings [22-24]. Data analytics assist in identifying bottlenecks much faster than human statistical informed approaches [25]. When data analytics is involved, the value stream map could be updated in real time. Such a reality is unattainable in traditional manufacturing settings [26].

Industry 4.0 maximizes efficiency by minimizing waste. The implementation of Industry 4.0 eliminates operational waste [27]. For instance, smart cloud cyber security systems minimize the dependence on manpower to secure facilities and information. Similarly, the application of simulation procedures eliminates the need for physical materials used for testing or assessment [28]. In addition, smart autonomous robots could solve bottlenecks on a production line using real data that is timely transferred between the various machines on the production system [29]. In sum, the achievement of lean manufacturing minimization of waste outcome is more probable when Industry 4.0 technology is implemented.

Sorting refers to discarding all unused materials in order to declutter manufacturing spaces while straightening depicts the act of placing items ergonomically and logically with reference to their respective place on the processing floor. Further, shining includes maintaining a clean work environment for both the safety of the staff and for the representation of the enterprise. Employers should then ensure that set standards for the organization workers and its processes are followed, taking the form of written plans, schedules, and charts delegating timelines among staff and then making sure these procedures are sustained [30]. Knowledge management thrives when these five guidelines are met in companies adopting lean manufacturing techniques because all dimensions of the production system are clear to both management and their staff. Employee involvement is crucial to this transition to Industry 4.0, as they play a huge role in buy-in and promotion of the enterprise [31-32]. Industry 4.0 implementation helps realize the 5S philosophy of lean manufacturing.

Industry 4.0 implementation improves the quality of production and products. The smart sensors and systems linked with products collect customers' feedback on the usability and functionality of products [33]. Such feedback could be funneled through big data technology

allowing the discovery of new areas of improvement. Relatedly, the sensors on the production floor help in minimizing product deficiencies. Industry 4.0 could utilize digital cameras and data processing systems to render autonomous decisions regarding product quality [34]. In food processing facilities, defects detection utilizes such advanced technologies making machines as decision makers in the process saving time while increasing value, the tenets of lean manufacturing [34].

Industry 4.0 facilitates the accumulation of benefits associated with Kanban or lean scheduling systems [16]. The integration of various systems by connecting them through shared networks, sensors, and data channels reduces delays through the improvement of information flow [35-37]. Systems and machines could communicate with each other at a much faster rate in Industry 4.0 settings compared to traditional contexts [38]. The utilization of cloud systems allows for more room to accommodate the large amount of data gathered.

Industry 4.0 helps manufacturers make product changes quickly through simulations and virtual reality technology [39]. Regularly, manufacturers attempt to improve the functionality and appeal of their products. To change one element, manufacturers need to invest in producing several prototypes for testing. In simulations, however, manufacturers save the resources otherwise spent on testing [40]. Further, virtual reality technology allows manufacturers to envision the future with better precision. The augmented reality software permits users to design products in highly visually appealing environments without the need to physically make them minimizing initial costs and processes involved with product quality assurance assessments [41].

Additive manufacturing, an enabler of industry 4.0, enhances the design of products across the manufacturing process [42]. The technology allows manufacturers to design, optimize, prototype, and print a product faster than a regular machine shop [43]. More importantly, to

produce several iterations with varying optimization levels of the same item, manufacturers could rely on additive manufacturing rather than traditional preparation methods [44]. Testing different prototypes in short amounts is afforded when the technology is deployed.

1.3 Research Scope

This thesis presents an Industry 4.0 implementation framework for manufacturers in developing countries. The framework is derived from a systematic review of challenges facing stakeholders at all levels when applying Industry 4.0 across all types of facilities. Additionally, expert opinions inform the construction of the framework, ensuring that it is deeply rooted in heuristic decision-making methods like interpretive structural modeling. Furthermore, the framework has been validated by using a questionnaire, see the questionnaire section on page 76 for more information, completed by experts on Industry 4.0 implementation within Saudi Arabia. The framework provides detailed recommendations for stakeholders on how to approach and execute Industry 4.0 in developing countries.

The proposed framework is also transferable and could be applied to small and medium-sized enterprises across developing countries. Additionally, the framework is a multidimensional depth of actions taken simultaneously at the institutional, constitutional, and structural levels. Implementing Industry 4.0 is not a strictly sequential process like a waterfall-based approach [46]. On the contrary, organizational changes coupled with legal and technologically innovative strategies along individual human capital developments are necessary requisites for making adoption of Industry 4.0 innovations implementation more probable and successful. This thesis applies mixed methods research in order to uncover a roadmap for ordinary stakeholders with little to no knowledge of Industry 4.0 or lean manufacturing. The project presents how Industry 4.0

implementation may influence lean manufacturing outcomes, including waste minimization, and increase customer satisfaction.

1.4 Research Motivations and Gaps

One of the motivations driving this research is the lack of representation for small and medium-sized enterprises from developing countries within the literature of Industry 4.0 implementation [47, 48]. Much of the existing studies focus on major industrial markets even when the research concerns developing countries. Emerging economies like Saudi Arabia are virtually absent from the industry 4.0 implementation literature [49]. The present analysis concentrates on applying a validated framework to these neglected markets like Saudi Arabia.

Another motivation is the lack of conceptual modeling on the relationship between Industry 4.0 enablers and lean manufacturing outcomes [1, 6]. Much of the research on both constructs focuses on one indicator or enabler rather than considering the overall impact each phenomenon plays on the other [7, 22]. More importantly, research on the relationship between lean manufacturing and industry 4.0 failed to incorporate the larger regulatory, technical, and human capital environments governing the contexts in which both are applied [4, 13, 25].

Existing frameworks on Industry 4.0 implementation have not been largely validated [1]. Typically, researchers propose a series of sequential steps that manufacturers need to implement to realize Industry 4.0's potential [6-9]. Such proposed productions are rarely tested or evaluated. This research uses a questionnaire in order to validate the proposed model generated from the quantitative and qualitative data analysis and collection strategies. The gap in this research is the limited number of practical Industry 4.0 implementation frameworks in developing countries.

1.5 Research Aims and Objectives

The aim of this research is to develop a framework for Industry 4.0 implementation for small and medium-sized manufacturers in developing countries. In this thesis, the word framework is defined as the collection of actions and changes stakeholders must take to move their facilities from one state, like traditional manufacturing, to a new state which is like smart lean manufacturing. Further, a framework is interchangeably used with the word model in this thesis. Note that this thesis is mainly concerned with the implementation of Industry 4.0 in lean manufacturing settings. To fulfill the aim of this thesis, the overall aim has been dissected into small, manageable objectives. The objectives of this research are as follows:

1) To identify associations between Industry 4.0 enablers and lean manufacturing in small and medium-sized enterprises using causal loop diagrams.
2) To develop an Industry 4.0 implementation framework using Interpretive Structural Modeling (ISM) and a focus group.
3) To validate the proposed framework via industrial expert judgment using surveys.

1.6 Research Questions

The rationale underlying the research questions is the missing information from the literature answering the proposed queries. The existing scholarship on Industry 4.0 offers insufficient information on the obstacles facing SMEs in the manufacturing sector implementing Industry 4.0. Further, the lean manufacturing research falls short on the provision of an adequate portrait of relationships linking Industry 4.0 enablers to lean manufacturing outcomes. By the same token, expert opinions in the developing world are not consulted on the best ways of overriding challenges to Industry 4.0 in their economies. Therefore, the research questions set forth in this thesis aim to generate information capable of remedying the gaps in the literature.

1) From the perspectives of experts on manufacturing in developing countries, what are the most important obstacles preventing stakeholders from implementing methods of Industry 4.0?
2) In what ways are Industry 4.0 enablers related to lean manufacturing outcomes?
3) How could manufacturers in developing countries implement Industry 4.0?
4) To what extent does the proposed framework of Industry 4.0 implementation meet the expectations of experts on manufacturing in developing countries?

Note that the answers to the proposed research questions are provided in the discussion and conclusions sections in chapter five.

1.7 Thesis Layout

This thesis is organized into large chapters. The present chapter constitutes an introduction providing an overview of the research context, aim, objectives, and layout. Chapter two features a systematic literature review generating the most widely cited challenges facing Industry 4.0 implementation for stakeholders. Additionally, chapter two supplies readers with the associations between Industry 4.0 enablers and lean manufacturing outcomes. Chapter two also summarizes the potential benefits of Industry 4.0 implementation for manufacturing. More importantly, however, it introduces readers to the limited literature on Industry 4.0 initiation in developing countries like Saudi Arabia.

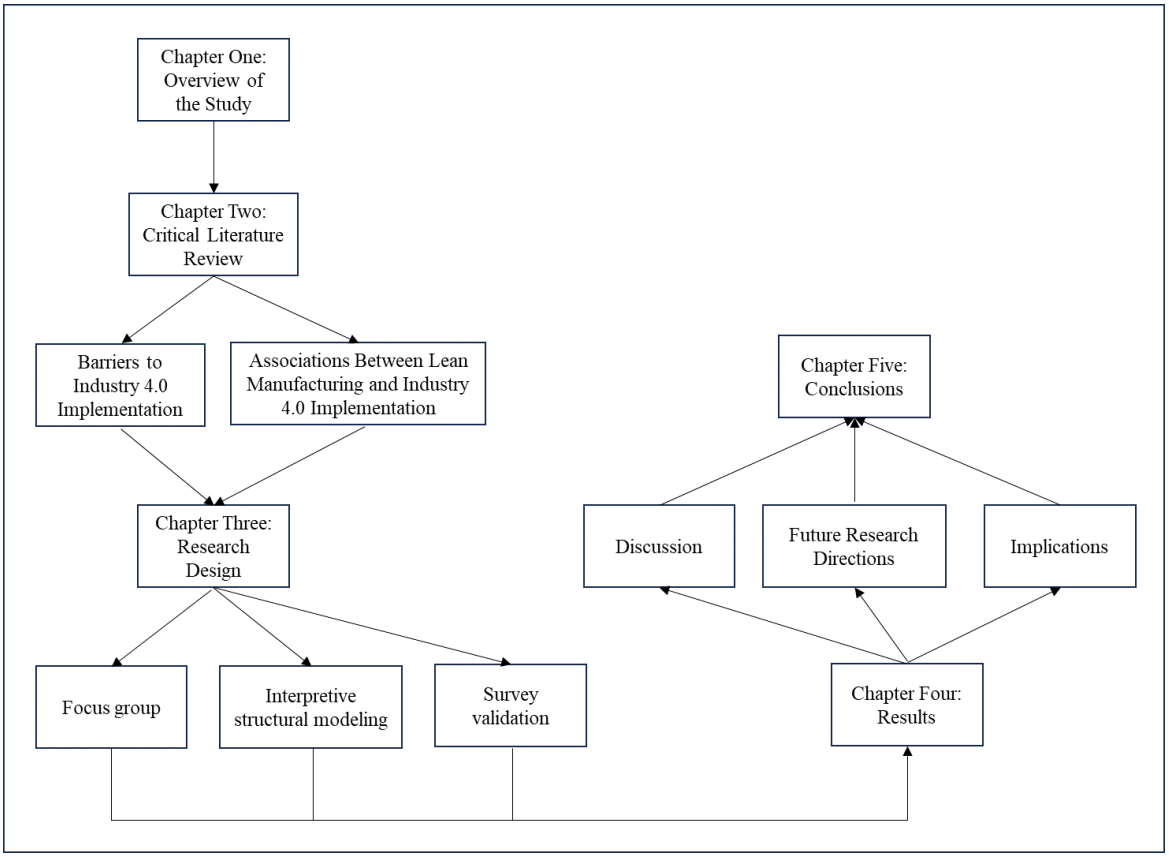
Chapter three of this thesis outlines the research methodology followed in order to fulfill the objectives of the study. The chapter begins with a discussion on the merits of performing mixed-method studies for generating reliable and valid data and findings that can be used by manufacturers in the real world. Subsequently, the focus group data collection method and thematic analysis are each rooted in the qualitative analysis technique that are introduced. Furthermore, interpretive structural modeling, as a quantitative strategy generating graphical

displays of decision-based frameworks, is outlined. Finally, the questionnaire developed to validate the constructed model using expert judgements is detailed.

Chapter four presents the results of the mixed-methods research design. On the one hand, the thematic analysis findings are displayed in tables and graphs. On the other hand, the ISM findings are represented by using matrices and graphical representations of the industry 4.0 implementation framework. Next, the survey-based descriptive statistical analysis is outlined to readers to showcase similarities and differences between current research and past studies.

Chapter five summarizes the main conclusions based on the mixed-methods research project. Additionally, the chapter features discussions on the relationship between observed findings in this research and those reported elsewhere in prior studies. Next, chapter five provides readers and stakeholders with numerous future research directions capable of generating more questions to cover intellectual and conceptual gaps in the field. Most importantly, the chapter clearly outlines the practical recommendations to all manufacturing stakeholders from the highest level of management to the lowest grades working on the manufacturing line. Relatedly, research implications are introduced to peak the interests of readers and commentators to improve the quality of research in this area. Figure 1.2 below shows the layout of this thesis.

Figure 1.2. Thesis Layout



Chapter Two

Literature Review

2.0 Introduction

This chapter introduces Industry 4.0 as it pertains to lean manufacturing. First, the associations between Industry 4.0 enablers and lean manufacturing outcomes are detailed, allowing readers to understand how each enabler is related to different aspects of lean manufacturing. Second, the barriers and challenges of Industry 4.0 implementation are introduced, giving readers an overview of the situation facing manufacturers in SMEs from developing countries. Third, the chapter outlines several Industry 4.0 implementations in Saudi Arabia to help understand how the technologies are applied in real-world contexts. Prior to this discussion, a general review of how manufacturers in SMEs have approached Industry 4.0 is supplied. Finally, a note on the potential implementation of Industry 4.0 is made in order to garner awareness of developments in the field.

2.1 Industry 4.0

2.1.1 What is Industry 4.0?

Researchers have not reached a consensus on a universal conceptualization of Industry 4.0 [25, 31]. Most authors refer to Industry 4.0 as the collection of devices, applications, software, hardware, and technologies that achieve production and performance standards in operational settings without consistent or frequent human interventions. The list of technologies, devices, and systems comprising Industry 4.0 is too long to be presented with full adequacy. Scholars often include cloud computing, big data analytics, internet of things, cybersecurity, autonomous robots, additive manufacturing, simulation software and hardware (virtual or augmented reality), and 3D printing. While such resources are non-exhaustive, Industry 4.0 includes other more niche

technologies that drive innovation and automation, like blockchain and artificial intelligence [1-3].

2.1.2 Defining Industry 4.0 Enablers

IoT internet of things, refers to the interconnected network of physical devices, vehicles, buildings, and other items embedded with electronics, software, sensors, and connectivity which enables these objects to collect and exchange data [4].

Big data refers to the five expanding characteristics of data including volume, velocity, variety, veracity, and value. Volume refers to the sheer amount of data being generated, velocity refers to the speed at which data is generated, variety refers to the wide range of data types and formats, veracity refers to mitigating the uncertainty and incompleteness of the data, and value refers to the potential insights and benefits that can be derived from the data [5].

Cloud computing is a technology that allows for the delivery of computing resources, such as storage, processing power, and software over the internet. This allows for on-demand access to shared resources and eliminates the need for organizations to maintain and manage their own physical infrastructure [6].

Cybersecurity refers to the practice of protecting devices, networks, and data from unauthorized access, use, disclosure, disruption, modification, or destruction. This includes protecting against cyber-attacks, data breaches, and other malicious activities [7].

Simulation is the imitation operation of a real-world process or system over time. It is typically used to model the behavior and performance of complex systems, such as manufacturing systems, transportation systems, and financial systems. Simulation can be used for a variety of purposes, including performance analysis, design optimization, and training [8].

Augmented Reality (AR) is a technology that overlays digital information, such as images, videos, or animations in the real world. It can be delivered through various devices, including smartphones, tablets, eyeglasses, and head-mounted displays [9].

Advanced Robotics refers to the use of advanced technologies, such as artificial intelligence, machine learning, and sensor fusion to create robots that can perform complex tasks in unstructured environments. These robots are typically capable of operating autonomously, with a high degree of flexibility and adaptability. They can be used in a wide range of applications, such as manufacturing, healthcare, logistics, and in service industries [10].

Additive Manufacturing (AM), also known as 3D printing, is a process of creating a physical object by adding layers of material, such as plastic, metal, or ceramic, one at a time. AM can be used to create a wide range of objects from simple prototypes to complex parts for industries such as aerospace, healthcare, and automobiles. It can be done using various technologies, such as Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) [11].

System integration is the process of combining multiple subsystems or components into a single, cohesive, system that can accomplish a specific task or function [12].

2.2 Industry 4.0 in Manufacturing

One of the less renowned conceptual elements of Industry 4.0 is its socio-political origins. The concept originated in Germany among members of a government council who believed that their economy and the country's industries must be world leaders [16-20]. Therefore, any integration and synchronization of physical and cyber systems needs to be aligned with the governments' vision. The investment in specific technologies that make industry 4.0 work best could be motivated by strategic decisions, placing firms in a competitive advantage construction

phase that enhances the country's leverage vis-a-vis its competitors. Also, the integration of manufacturing processes cannot be separated from human preferences that need to be aligned with technology integration in order to ensure maximal organizational alignment with desired objectives [16-20].

2.2.1 Areas of Industry 4.0 Research Interest

General literature on Industry 4.0 is vast. Four areas of interest with respect to Industry 4.0 have evolved in the past decade, however. The most explored area in Industry 4.0 is smart manufacturing. Researchers have explored how the adoption of a new technology leads to gains in effectiveness and efficiency. Further, the least examined area of research is how to make the workplace more digitized and smarter. Much of the writings on Industry 4.0 concern the implementation effect of a single technology on productivity or performance in one industry [21-23].

One perspective on Industry 4.0 is derived from the amount of digitization and automation desired in manufacturing facilities. On the one hand, few authors believe that Industry 4.0 is the full digitization and automation of production and supply chain processes. For them, manufacturing activities need to take place without human interference. On the other hand, another group of scholars believe that Industry 4.0 is the integration of physical and cyber systems in order to increase automation and digitization. In this scenario, humans take active roles in strengthening integration and facilitating the realization of manufacturing outcomes. One may find other scholars located on the continuum between those defining Industry 4.0 as full automation and those arguing that humans still play significant parts in making the shift from traditional manufacturing to smart production possible [24-28].

2.3 Conceptualizing Lean Manufacturing

Lean manufacturing refers to the minimization of waste, maximization of efficiency, boosting customer satisfaction, and improving the flow in enterprises [29]. Implementation of lean manufacturing is associated with the desire to lower costs, enhancing quality, and delivering services and goods in a timely manner to consumers [30]. Lean manufacturing is a dynamic process, and a philosophy driving the work of factories, workforce, and strategies [31]. The implementation of lean manufacturing goes hand-in-hand with the integration of Industry 4.0 [32]. Lean manufacturing assists in the improvement of standardization by using automated procedures and decreasing inventories to optimal levels through autonomous ordering systems [33]. Lean manufacturing reduces the need for excessive workforces by the incorporation of autonomous robots and utilization of advanced simulation models to better predict demand and thereby reduce extra manufacturing. The inspection of the relationships linking lean manufacturing with the pillars of Industry 4.0 is limited, and therefore deserves closer attention [34].

2.3.1 Benefits of Lean Manufacturing Implementation

Most of the resource-scarce manufacturers have resorted to lean manufacturing as a means to minimize operational costs, waste, product defects, and improve quality as well as customer satisfaction [44]. One of the mechanisms that help resource-scarce manufactures achieve their goal of optimal efficiency and effectiveness is the implementation of smart manufacturing. Lean manufacturing involves the reduction of human involvement in operations and the introduction of automatization [46]. Throughout this process, manufacturers integrate all their systems to formulate an intelligent whole that is capable of achieving affordable operations, superb products and services, minimal labor costs, and excellent customer feedback [63].

The next section highlights the benefits of implementing the nine pillars of Industry 4.0 and lean manufacturing with a focus on resource-scarce enterprises [51, 58]. Each section will provide a definition of one of the Industry 4.0 enablers and present its benefits with the different principles of lean manufacturing.

2.4 Understanding the Industry 4.0 Enablers in Lean Manufacturing

2.4.1 Lean Manufacturing and IIoT

The Industrial Internet of Things is best understood by using a six-dimensional structure that summarizes its varying and complex components [89]. These are industry sector, device location, connectivity, device characteristics, device technology, and user type. Industry sector refers to the vulnerabilities challenging an organization, factory, or their operational systems [90]. It is expected that the more advanced the sector, the more technologies, and systems it deploys. This creates layers of threats to every phase along the manufacturing process [91]. Industry sector and lean manufacturing has a negative association, and customer satisfaction will likely decrease with a manufacturer facing a myriad of threats to its facilities and processes. The more threats an industry sector faces, the more waste it will incur, making more people, costly security measures, and monitoring necessary to prevent and control risks. The higher the number of threats and the more severe they are, the more difficult process alignment [92]. Adding security and prevention measures complicates processes and makes them intricate and intractable on many occasions [93]. Higher numbers of threats and vulnerabilities prevent optimal continual improvement and flow. Therefore, more resources are needed to keep monitoring processes and update them to be congruent with technological advancements, which does not serve the lean manufacturing perspective [94].

Device location refers to the desirable physical and cyber positioning of the tool, instrument, or technology. There is a positive association between device location and lean manufacturing. The more secure a device is in a manufacturing enterprise; the more confidence and assurance consumers have in the product and the company [95]. Appropriate arrangement of devices could potentially enhance flow improvement and smooth movement of products along manufacturing lines. The careful installment of devices in requisite spaces reduces the potential use of energy, workforce, and resources, thereby reducing waste. It is easier for a manufacturer to locate problems and ensure continued improvement if the devices are easy to locate, retrieve, and maintain [96].

Connectivity refers to the extent to which devices are linked with physical and cyber systems. There is a positive association between connectivity and lean manufacturing. The more connected devices are to computer and automated systems, the better identification of wasteful hot spots, which helps in minimizing initiatives to eliminate waste [97]. The better connectivity devices have with customers, the more interaction and engagement clients have with their products which results in better satisfaction. When more machine to machine and human to machine links are established in a manufacturing enterprise, the better alignment there is [94]. Human to machine communication, when functioning, helps avoid delays, and better identifies glitches to be addressed in a timely manner that guarantees better flow. Communication and collaboration also assist the manufacturer's endeavors to establish continued improvement throughout the enterprise. More information is shared, helping stakeholders identify optimal solutions and guaranteeing higher quality and more efficiency [96].

Device characteristics refer to the collection of functional abilities a machine, or individual part, possesses concerning the improvement of physical and cyber systems [94]. There is a positive

relationship linking device functionality and lean manufacturing. The more functions that devices have, the more capabilities manufacturers could achieve with them, and the less energy, workforce, and training are needed. This helps in reducing a number of waste sources [91]. The more functions devices have in a manufacturing process, the more likely alignment of processes is achieved. Devices may also communicate better, and faster, with other parts of the system thus increasing levels of collaboration and coordination. Device functionality influences the quality of products [92]. The more precise, reliable, and smart devices are the better products they manufacture. This increases the likelihood of harnessing better consumer satisfaction with the manufacturers' products and services [93].

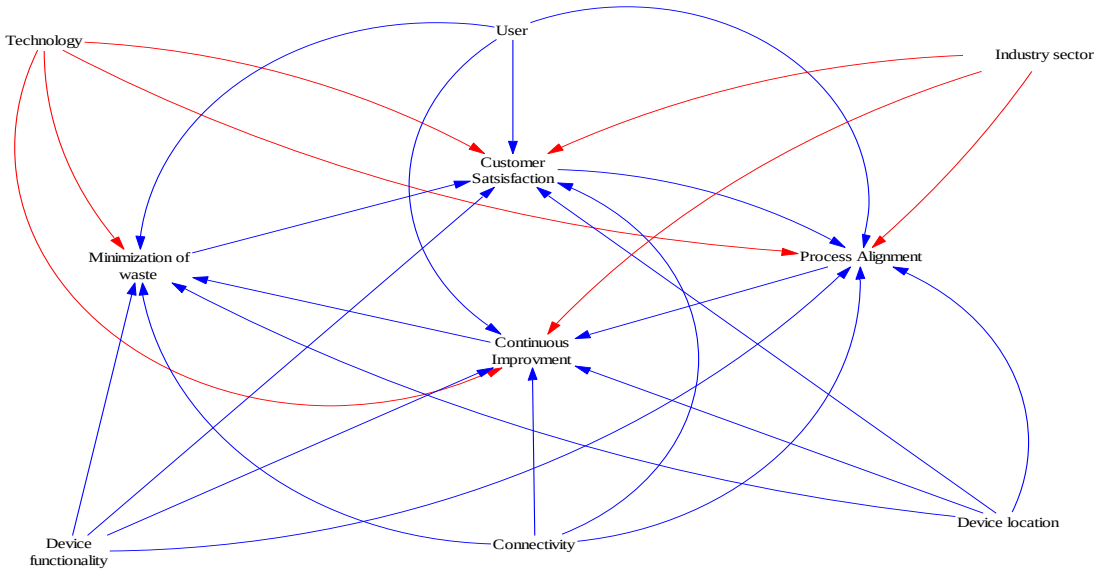
Device technology refers to the technical advancement of the tools, parts or systems used in the manufacturing process. There is an inverse relationship between device technology and lean manufacturing [94]. The more technical abilities a device needs, the higher workforce training and specialized expertise it requires for optimal functioning. Devices with higher technical functionality demands attention and increased customized maintenance [95]. These are therefore harder to integrate with the system. Further, highly technical devices tend to be costly and impractical in improving the flow of goods in a manufacturing facility [96]. Since the cost of investing in them is high, and their maintenance and integration require an additional cost, the products generated by them tends to be more expensive in comparison to standard counterparts which drives customers away and makes them less satisfied [97].

User characteristics refer to the ease and usefulness of the device or tool. The easier a device could be integrated into cyber and physical systems, the better integration it achieves, resulting in higher process alignment [98]. The more useful devices are perceived by the workers, the more likely they will learn how to use them and integrate them effectively into the

manufacturing process [94]. The ease of use and usefulness of devices in manufacturing influences the speed and flow of working with them. Workers will be more likely to produce more goods in a shorter period of time, achieving more efficiency and less waste. This will likely increase standardization and reduce defects, which will increase consumer trust in the product and the company [63].

Figure 2.1 summarizes the relationships between lean manufacturing and IIoT as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.1. Lean Manufacturing and IIoT



2.4.2 Lean Manufacturing and Big Data

Big data refers to the volume, variety, velocity, and veracity of the information collected by machines, systems, and humans in manufacturing. It also concerns the value, visualizations, and volatility of large amounts of information used in manufacturing processes and operations [43]. The variety of data refers to the depth of information gathered. This includes the number of

characteristics and measurements collected. The more information a system collects, the better decision-making capability for the manufacturer results [99]. Manufacturers that collect information on customer's preferences and usability statistics are more likely to generate better satisfaction rates with their products in comparison to others. Further, the more information stakeholders have in the operation and process the more likely they will resolve misalignment problems, guaranteeing better flow on production lines. More information also allows the manufacturer to identify sources of waste and propose robust solutions by addressing root causes [100].

Velocity refers to the speed of information gathering, storage, and analysis. There is a positive association between velocity and lean manufacturing. The faster the information gets to the system the shorter turnaround times are needed for identifying and addressing manufacturing problems [101]. This allows manufacturers to detect misalignment, waste, and inefficiencies at an earlier stage, thereby saving labor, energy, and workforce demands. The rapidity of data transfer also allows manufacturers the agility to respond to customers' demands, guaranteeing better satisfaction rates [102].

Veracity refers to the reliability, validity, and accuracy of information. There is a positive relationship between veracity and lean manufacturing [102]. Manufacturers with veracious information are capable of resolving misalignments with less cost and time when compared to their counterparts with noisy information. Further, manufacturers with accurate information on their processes and machines conserve more maintenance resources for their machines, thereby reducing waste. They are able to identify potential customers and their preferences, driving satisfaction higher with their products and future design and development projects. The collection

of usable and accurate information also helps stakeholders remove bottlenecks in processes and install continued improvement efforts [103].

Volume refers to the amount of information collected by sensors, systems, machines, or humans. The volume of information collected has a positive relationship with lean manufacturing, and the more information collected on customers and their preferences the more accurate model predicting consumer satisfaction results [104]. Additional information on machines and workers also improves the prediction of their needs. Volume assists in setting more accurate schedules for maintenance, as well as supporting the identification of training needs and potential future research and development building [102]. The more information collected on processes helps in their optimization, and the use of models to integrate varying cyber and physical systems. This helps improve the flow of products and goods by achieving continuous improvement [16].

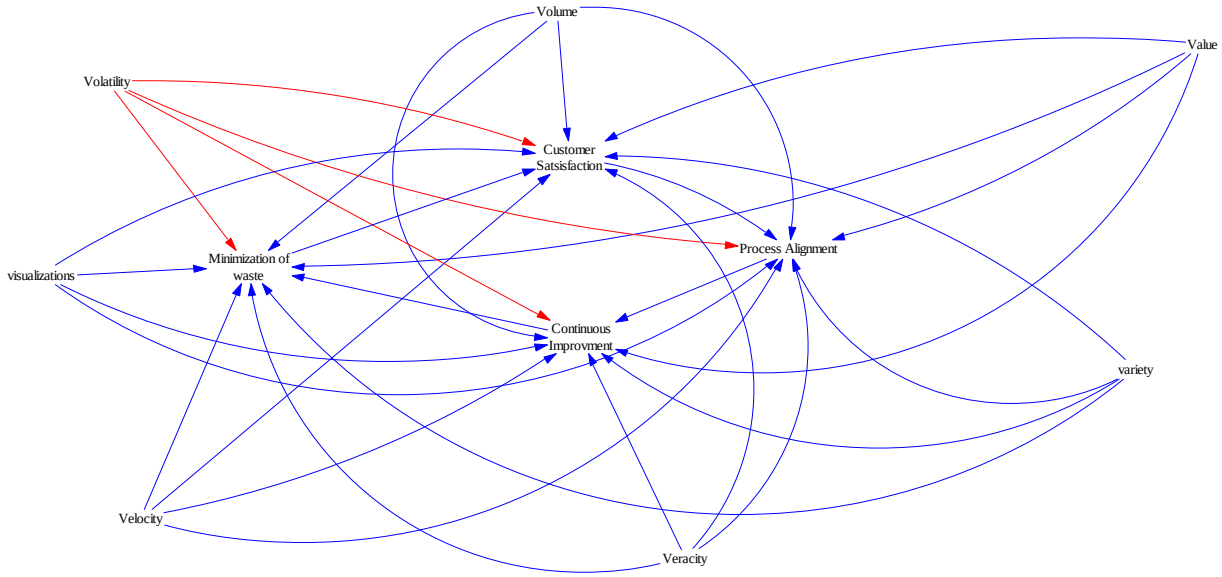
Volatility refers to the fluctuations in the gathering, receipt, storage, and analysis of information. There is a negative association between volatility and lean manufacturing. The more fluctuations in data gathering practices, the less likely accurate measurements are recorded [105]. This delays the identification of waste sources, process misalignments, customer needs, and improvement opportunities. Fluctuations of information requires more time, costs, and energy in streamlining them which makes them unusable for manufacturing improvement purposes. This necessitates the use of more resources rather than saving them [106].

The value of information refers to its usefulness and utility in the manufacturers' quest to realize its objectives. There is a positive relationship between value and lean manufacturing. The more meaningful the information gathered on consumers the more likely the manufacturer is able to identify sources of consumer satisfaction [101]. Richer data on products, devices, and processes ensures stakeholders are more able to optimize production, and flow. This assists the manufacturer

in integrating the varying process parts and establishing flow, which guarantees continual improvement effort [102]. Relatedly, visualizations of collected information constitute more valuable information to users. They summarize complex data in simple illustrations that help stakeholders and non-technical workers identify areas of potential improvement. Therefore, visualization and lean manufacturing are positively related [103].

Figure 2.2 summarizes the relationships between lean manufacturing and big data as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.2. Lean Manufacturing and Big Data



2.4.3 Lean Manufacturing and Cloud Computing

Cloud computing refers to the use of cyber and digital resources offered by the cloud in support of manufacturing operations. These applications in manufacturing focus on its costs, performance, security, reliability, flexibility, and management. There is a negative association between costs and lean manufacturing [107]. The investment in the cloud is expensive, and its maintenance requires prohibitive costs. This leads to higher waste in resources at the disposal of

the manufacturer, increasing costs added to the manufactured goods which in turn make them more expensive for consumers who are likely to express dissatisfaction [108].

Performance refers to the ability of the cloud to meet the expected objectives of the manufacturer. There is a positive association between performance and lean manufacturing. High performing, cloud-based, systems facilitate continuous improvement initiatives and efforts [109]. They increase the speed of data retrieval, sharing, and analytics capable of enhancing consumer satisfaction and process integration. Further, flexibility is positively related to lean manufacturing. Flexibility refers to the wide range of tasks and functions the cloud-based system is capable of performing. Increased flexibility allows stakeholders to get richer and more diverse information that allows them to better integrate their processes. This allows further opportunities to enhance process alignment [110].

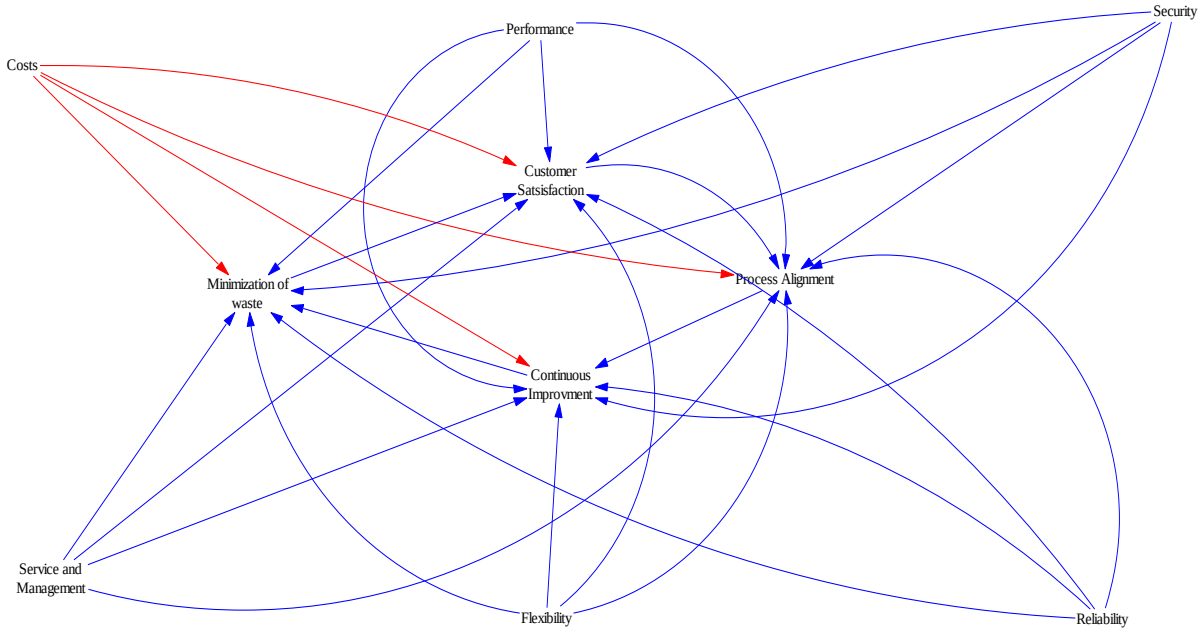
Security refers to the protection of information stored on the cloud. There is a positive association between security and lean manufacturing. Secured systems increase the confidence of consumers, which enhances their chances of being more satisfied with the manufacturer. Secure cloud-based infrastructure decreases data breaches and unauthorized access to information, which protects the competitive advantages of manufacturers and increases their market value [16, 104]. Secured cloud-based systems ensure the reliability, accuracy, and veracity of information to be used in continuous improvement initiatives. This helps decrease errors and increase successful opportunities for process realignment actions. Arising from this logic, there appears to be a positive relationship between reliability and lean manufacturing [77].

Cloud systems management refers to the operation of all resources relevant to the digital and cyber spaces that support the manufacturer's work. Effective cloud-system management is directly associated with lean manufacturing [102, 106]. It leads to better resources allocation and

minimizes information and workforce wastes related to the operation of cyber and digital systems. Cyber system management also establishes better interactivity and engagement with consumers, resulting in higher consumer satisfaction. By regulating the collection and storage of information it retains only relevant knowledge which streamlines continuous improvement and flow [47].

Figure 2.3 summarizes the relationship between lean manufacturing and cloud computing as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.3. Lean Manufacturing and Cloud Computing



2.4.4 Lean Manufacturing and Cybersecurity

Cybersecurity refers to the protection of information and its cyber and physical storage infrastructures. It is best understood by using the legal, organizational, technical, capacity, and cooperation framework [111]. Legal aspects of cybersecurity cover the regulatory, as well as ethical, nature of managing information in addition to the devices used to collect, store, and retrieve

it. The legal dimension of cybersecurity negatively affects lean manufacturing [102]. A lack of concrete and robust legal infrastructures protecting consumers and their privacy makes them less satisfied with the services and products offered by manufacturers. The inability of manufacturers to collect some crucial information on consumers, their preferences, and other ancillary variables make them less capable of optimally integrating their processes. This causes a lower chance of achieving optimal flow or continued improvement [104].

The technical dimension of cybersecurity refers to the robustness of machines and systems used to protect information. There is a positive relationship between the technical dimension of cybersecurity and lean manufacturing. Manufacturers are more likely to retrieve necessary information in a timely manner and without compromise when needed so as to improve flow or production processes [6]. They are confident in protecting their consumers' privacy and information, sending a positive message to their potential customers who are more likely to exhibit satisfaction with the manufacturer. The reliability, accuracy, and durability of cybersecurity technologies reduces unintended maintenance or waste costs associated with unreliable machines and systems [05].

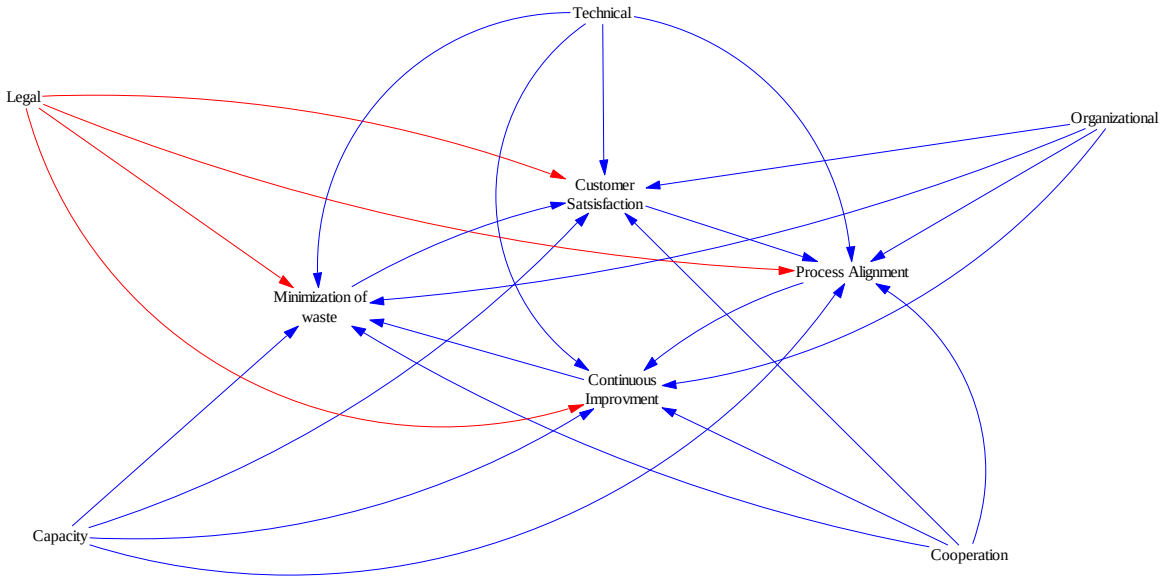
The organizational dimension of cybersecurity refers to the compliance of the workforce. As more employees are aware of the risks of cybersecurity, the more compliant they are with information policies. This is likely to decrease data breaches and increase customers' confidence in the manufacturers' workforce. It thwarts attempted phishing campaigns, which add security to the needed data for continuous improvement efforts. It saves incident intervention resources that would be deployed in case of a compromise [112].

Cooperation and capacity refer to the integration, and ability of the workforce, and systems to protect the information collected and stored. Higher levels of cooperation and capacity are

associated with enhanced lean manufacturing. Cooperation reduces the risk of data breaches, thereby minimizing the need for incident treatment resources. Capacity adds skills and abilities to the workforce, which enhances their risk assessments and incident avoidance. Capacity and cooperation are also reinforcing. They work together to decrease the chances of data breaches occurrence, which increases consumers' trust in the manufacturer [113].

Figure 2.4 summarizes the relationships between lean manufacturing and cybersecurity as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.4. Lean Manufacturing and Cybersecurity



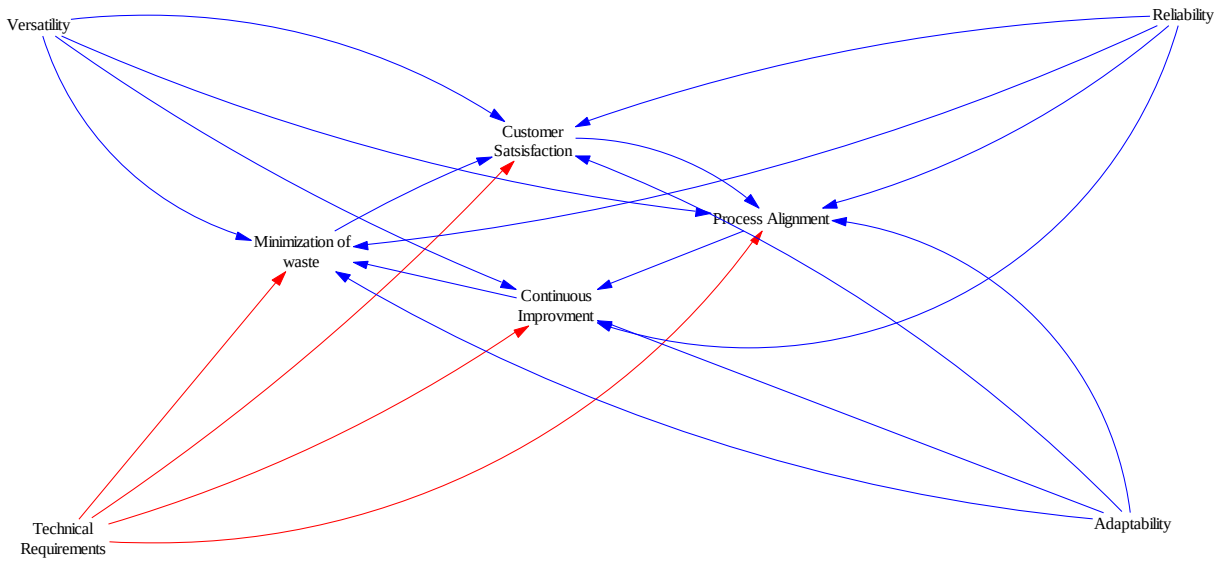
2.4.5 Lean Manufacturing and Simulation

Simulation is the modeling of real-world behaviors by using advanced applications. The use of simulation helps manufacturers achieve their lean manufacturing objectives. Ultimately, the more versatile the simulation platforms are the more capable is the manufacturer. The

manufacturer is also able to model many behaviors using versatile environments, thus saving materials and workforce costs [114]. Further, manufacturers may reengineer process improvements by using simulation models that help them identify optimal flow. This also supports manufacturers' journey of continuous improvement given the affordability of testing various processes that use simulation platforms. One of the drawbacks to some simulation technologies is their high technical requirements [115]. Some simulation software requires advanced expertise, and it is difficult to be integrated into the manufacturing operation which has a negative effect on lean manufacturing [113].

Figure 2.5 summarizes the relationships between lean manufacturing and simulation as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.5. Lean Manufacturing and Simulation

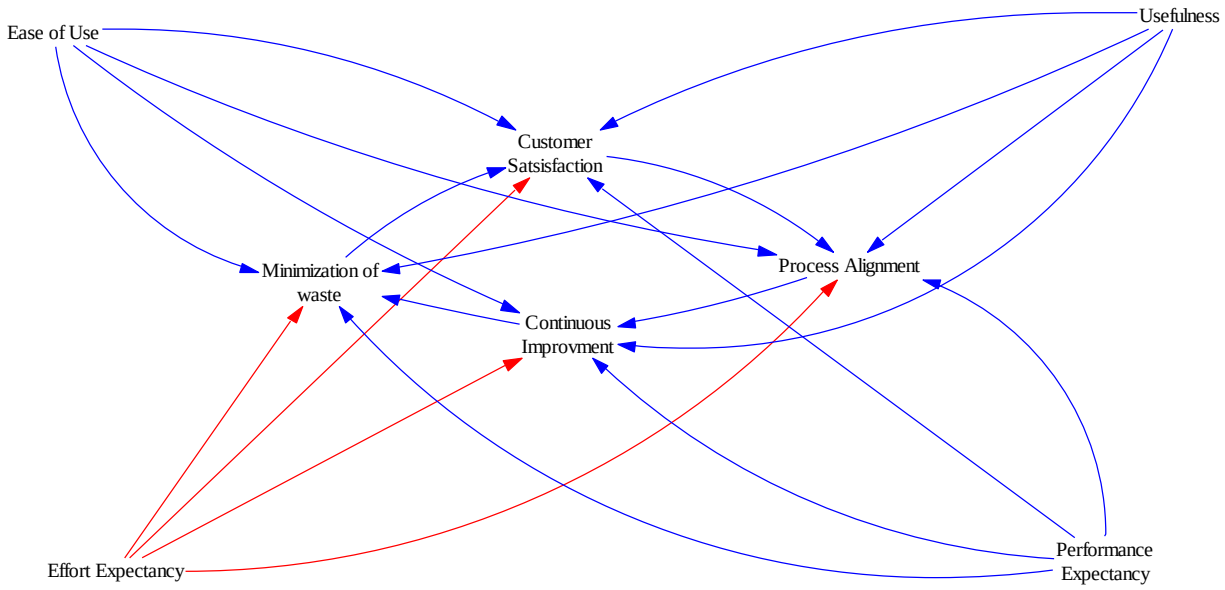


2.4.6 Augmented Reality and Lean Manufacturing

Augmented reality is an enhanced virtual environment allowing the user to interact with the surrounding setting. Utilizing a collection of equipment and tools used to enrich the experience of the user, additional elements can be added to the natural environment virtually. It is best understood through technology acceptance models in manufacturing [116]. There is a positive relationship between augmented reality and lean manufacturing. The easier the augmented reality tools are, the more likely manufacturers will adopt them. Meanwhile, the less effort associated with the technology to be learned and implemented the more likely it is it will be deployed [112]. There is a positive association between augmented reality and lean manufacturing. Easy to use, and low effort expectancy technologies will be more frequently used by the workforce, helping them identify sources of waste. This use will also allow workers to address operational bottlenecks [43]. Customers may interact with the manufacturers' products and offer customized feedback, resulting in higher levels of satisfaction. In addition, if the augmented reality technologies are perceived to be highly performing, the manufacturer is likely to adopt them which helps achieve its lean manufacturing mission [80].

Figure 2.6 summarizes the relationships between lean manufacturing and augmented reality as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.6. Lean Manufacturing and Augmented Reality



2.4.7 Lean Manufacturing and Autonomous Robots

Autonomous robots are machines programmed to achieve a task or a collection of functions in the manufacturing process. They are best analyzed using the four dimensions defining their use in manufacturing: space, ubiquity, functionality, and piloting. Space refers to the amount of available land or territory occupied by robots [117]. There is a negative relationship between space and lean manufacturing. Autonomous robots need more space to achieve their tasks and are difficult to integrate into small manufacturing enterprises. Crowding presents the most pressing challenge to many manufacturers in integrating robots into their operations. On the one hand, robots will require the investment in updating the layout of the production line. This consumes a colossal number of resources. An alternative is to use vertical multi-functioning robots that work from above rather than traveling to the ground floor. This type of technology, however, is costly [118].

Ubiquity refers to the prevalence of robots used in a manufacturing enterprise and is positively associated with lean manufacturing. The use of many robots to achieve most

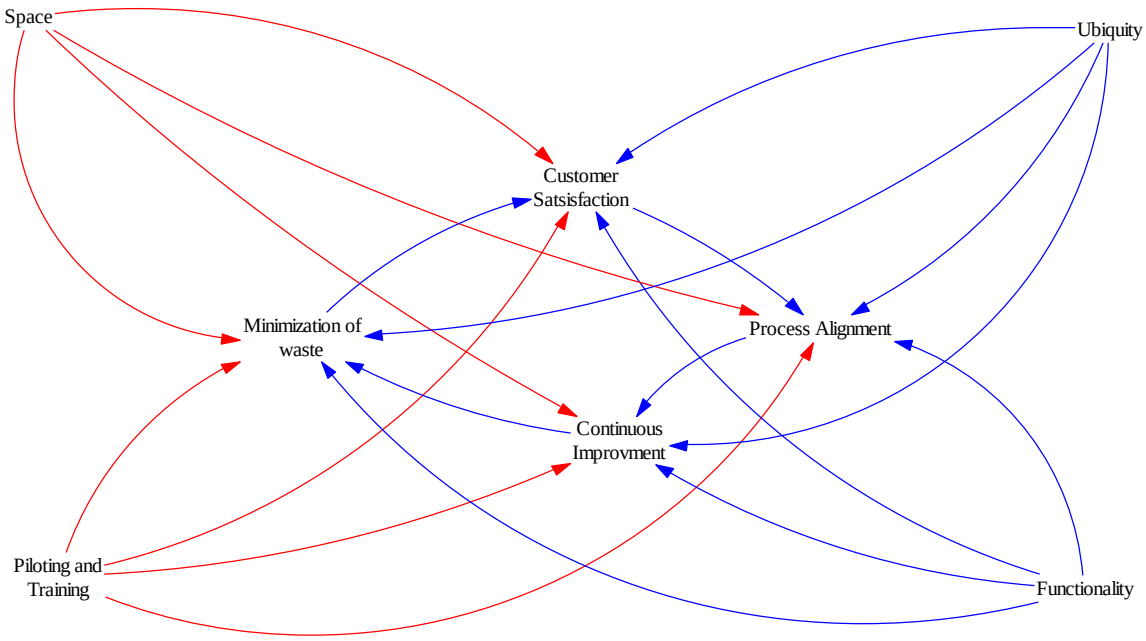
manufacturing needs reduces the reliance on humans which saves both labor and cost. Use of many robots on the floor both increases standardization and mitigates the occurrence of errors and defects on the production line. This helps the manufacturer achieve a better integration level as well as flow improvement [119].

Functionality refers to the ability of autonomous robots. There is a positive relationship between functionality and lean manufacturing. Intelligent robots are capable of identifying risks and potential errors, and act to prevent them. This minimizes potential maintenance and intervention resources. More capable robots also reduce dependence on various human skills needed to optimally run the operation. Autonomous robots are likely to generate products that meet consumer requirements and produce high levels of satisfaction [120].

Piloting is the process of adopting, integrating, and using autonomous robots in production. This process is dynamic and costly, requiring the training of the workforce on how to interact with robots and avoid duplication. More importantly, it involves trying out varying available options from the market. Manufacturers spend significant costs and time in identifying the most appropriate robots for their operation. This is likely to result in waste, more training, and less efficient integration in the short run [121].

Figure 2.7 summarizes the relationships between lean manufacturing and autonomous robots as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.7. Lean Manufacturing and Autonomous Robots



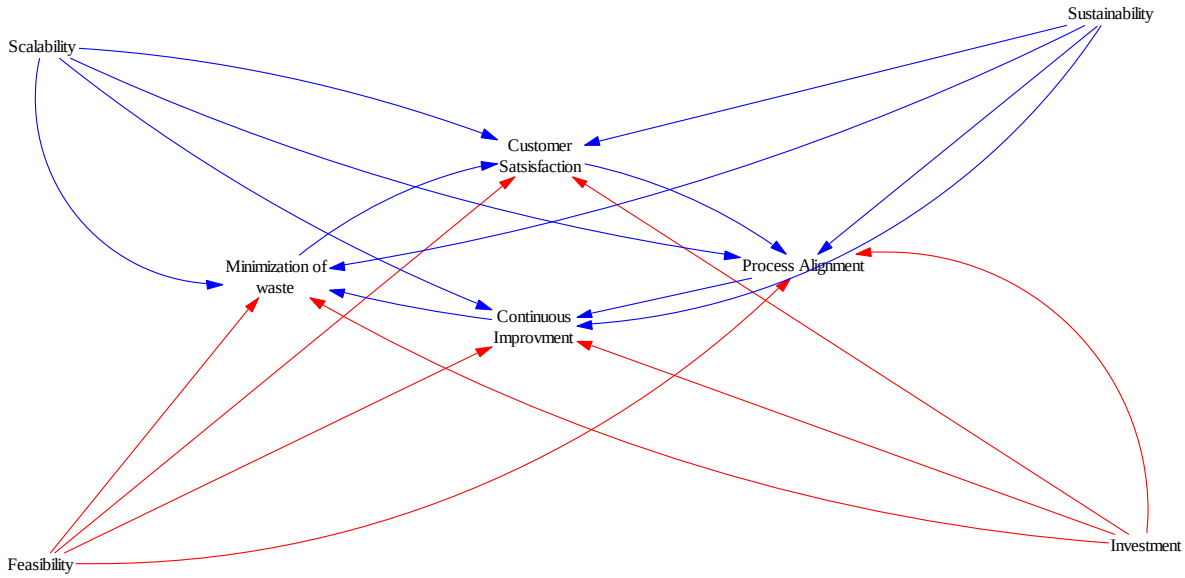
2.4.8 Lean Manufacturing and Additive Manufacturing

Additive manufacturing refers to the creation of high dimensional objects by the disposition of materials, such as 3D printing. Its application within manufacturing is best understood in four dimensions: scalability, sustainability, feasibility, and initial investment. Scalability refers to the enlargement of existing arrangements to meet higher demands [77]. Scalability is positively associated with lean manufacturing. Customers may also utilize additive manufacturing technologies to customize them, thus increasing their satisfaction [108]. In addition, additive manufacturing saves a great number of resources by minimizing the amount of waste used in producing real prototypes. Sustainability refers to the preservation of systems, devices, technologies, and tools for future use. This helps manufacturers achieve the objectives of lean manufacturing. Sustainability entails the minimization of resources, costs, and energy [109].

Feasibility refers to testing, piloting, and trying additive manufacturing technologies. This is negatively associated with lean manufacturing. Assessments of potential benefits of additive manufacturing tools take time and incur significant costs. They necessitate advanced technical expertise [120]. It takes trial and error to identify the appropriate technologies best fitting for the operation, which negatively impacts efficiency. Investing in additive technologies is expensive and inversely related to lean manufacturing in the short run. Purchasing new systems, training individuals how to use them, or hiring consultants all use scarce resources [48].

Figure 2.8 summarizes the relationships between lean manufacturing and additive manufacturing as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.8. Lean Manufacturing and Additive Manufacturing



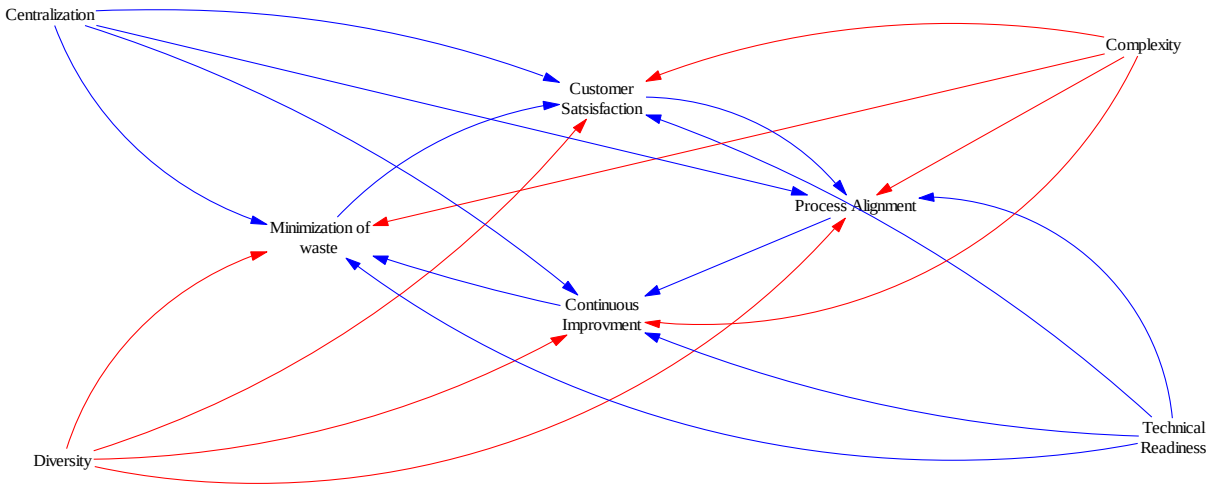
2.4.9 Lean Manufacturing and System Integration

System integration refers to the increased connectivity and linking of physical and cyber systems in manufacturing operation. Integrating systems helps manufacturers achieve lean manufacturing [118]. The more connected systems are within an operation, the easier the detection

of waste sources and customer needs. Alternatively, the more diverse and technically advanced systems are the harder their integration is. Therefore, it is best for manufacturers to standardize their systems and tools in order to guarantee higher degrees of standardization. This results in enhanced continuous flow and improvement at all levels of the operation [36].

Figure 2.9 summarizes the relationships between lean manufacturing and system integration as mentioned above. Note that blue arrows represent positive relationships, and red arrows represent inverse relationships between the variables in the figure.

Figure 2.9. Lean Manufacturing and System Integration



2.5 Benefits of Industry 4.0 on Lean Manufacturing

2.5.1 IIoT and Lean Manufacturing

Industrial Internet of Things (IIoT) is concerned with the implementation of the internet of things by the manufacturing sector. It integrates information and communication technologies with existing operational infrastructure utilized by manufacturers. Operational systems include production control systems, labor management protocols, and the machinery installed in the

enterprise. IIoT also pertains to the collection, storage, and analysis of data and its transfer between all existing systems and machines across the operation.

The implementation of IIoT has shown significant decreases in operational wastes, meeting lean manufacturing's main desired outcome. Beier, Niehoff and Xue noted the additional value of IIoT for environmental sustainability [16]. Their survey demonstrated how the increasing implementation of IIoT improved the use of renewable energy resources, operational cost efficiency, and sustainability awareness among business and government leaders. Scilimati et al. demonstrated how the use of IIoT decreases operational costs and retains optimal effectiveness, thereby satisfying all the requirements of environmental monitoring missions [35]. The study also investigated the feasibility and implementation of autonomous vehicles connected to a multitude of Internet of Things (IoT) devices in order to collect, transmit, analyze, and interpret readily gathered data from the environment. For instance, the movement, speed, and size of objects occupying a roadway while the vehicle is in motion are gathered by smart sensors. The authors argued that such advancements eliminated the need for patrolling agents as well as expensive hardware equipment across stations throughout the environment while satisfying the needs of the industry's customers.

The implementation of IIoT has yielded improved flows of goods, services, and operations across manufacturing sectors. Balaji, et al., highlighted the potential role of IIoT in improving value flow by manufacturing operations [36]. They argued that IIoT devices and connectivity allows for the construction of digital value stream maps that capture the dynamic interaction among the various components of the operation, a lean manufacturing principle. Researchers have also conceptualized the potential of IIoT in resolving complex operational processes in traditional manufacturing. Munín-Doce et al. suggested that IIoT presents a solution to the myriad of

communication problems impacting the shipyard industry [37]. Further, Saxena et al., demonstrated how IIoT could assist foundries in molding unconventional castings and replenishing materials without human intervention [38]. Mayer et al. documented how research laboratories and research education providers utilize IIoT to create an enriched education experience for learners [39]. The authors suggested that education service providers could leverage IIoT to eliminate operational wastes by achieving a leaner organization and improved flow of services.

2.5.2 Big Data and Big Data Analytics

Big data analytics are tools that collect, transmit, store, and intelligently analyze information. They are commonly utilized across manufacturing processes to facilitate machine-to-machine communications and are used by experts to identify areas of operational waste, non-value-added procedures, and to enhance design and development. These tools are also integrated into the cloud and connected with all systems in the manufacturing operation. The data stored is valuable, and helps manufacturers achieve customer satisfaction and reach new markets.

Deployment of big data in manufacturing has assisted stakeholders in achieving lean manufacturing. Cui et al. concluded that the increasing utilization of data analytics and big data tools in manufacturing has enhanced operational sustainability as well as resource sharing by reducing waste across the manufacturing stages [40]. Majeed et al., proposed a framework that integrated big data analytics into smart manufacturing in order to improve the products' beginning of life stage [41]. The authors reported a noticeable decrease in energy consumption, as well as an increase in product quality once big data is linked to smart manufacturing. Dai et al., highlighted the increased utilization of big data tools in IIoT [42]. The authors suggested that big data allows manufacturers to understand customers' needs and helped them improve satisfaction and boost future business.

Use of big data in manufacturing is also associated with the minimization of waste and the enhancement of customer engagement. Belhadi et al., analyzed data from 201 industry practitioners in North Africa to investigate the effect of big data on manufacturing performance [43]. The structural equation modelling findings demonstrated a direct, positive, relationship between big data and lean manufacturing. Further, there was a positive association observed between big data applications and the performance and sustainability of manufacturing processes and products. Kozjek et al., indicated that the investment in big data training, software, and hardware is associated with long-term business growth [44]. The authors argued that the use of big data engages customers in the product design and development stages. Ge et al., suggested that big data improves automation, intelligent decision-making, and predictions across all manufacturing stages [45]. In their view, this helps manufacturers reduce the amount of time and materials, thereby maximizing the output of all operations.

2.5.3 The Cloud and Lean Manufacturing

The cloud is a data warehouse storing information linked with sources like sensors, machines, robots, computers, systems, and other devices used by manufacturers. Intelligent systems retrieve the data and use it to communicate decision altering processes in the operation. Machines rely on the deposited information to communicate with each other. The cloud represents a safe repository of necessary data used by manufacturers for all types of purposes like production, marketing, client management, and supply chain control.

The implementation of the cloud is associated with enhanced performance in enterprises that apply lean manufacturing. Lu and Xu demonstrated how cloud-based manufacturing systems help stakeholders meet on-demand customer requests [46]. Manufacturers allow their customers to place orders, monitor their development, and participate in their customization through cloud-

based manufacturing features. Kumar and Vaishya suggested that cloud applications help manufacturers decrease unnecessary stock [47]. Further, the cloud helps manufacturers optimize the frequency of production, thereby meeting the exact demands of the market and avoiding overproduction. Novais et al., conducted a survey of 260 companies in Spain to investigate the effects of using the cloud on lean manufacturing management practices [48]. The authors found that companies utilize the cloud to support their logistics operations, improving flow and avoiding delays that directly impact business performance. Krishnaiyer and Chen, investigated the potential of devising Kanban cloud-based systems to support key decisions across manufacturers [49]. Their results indicated that cloud-based Kanban systems guarantee higher degrees of operational flow, optimal ordering of materials, and more efficient resource allocation. Caggiano proposed a cloud-based system that allows manufacturers to coordinate complex operational processes with minimal human intervention [50]. Barenji, suggested the potential of cloud-based systems for increasing the coordination between enterprise resource planning systems and manufacturing execution systems of manufacturers [51]. This helps eliminate potential misunderstandings that could lead to waste and delays in the production process.

2.5.4 Cybersecurity and Lean Manufacturing

With increased reliance on database systems, a pressing priority of manufacturers has been the security of their information infrastructures. Cybersecurity is the collection of measures taken to protect digital assets on the cloud across manufacturers' systems. Cybercrime is on the rise and phishing attacks have rapidly increased in recent years. The frequency of data breaches has also risen with a clear need for security, education, training, and education programs bolstering the security of information systems in the manufacturing sector.

Cybersecurity measures help manufacturers accelerate their realization of lean manufacturing potential. Zarreh et al., noted that cybersecurity programs help manufacturers implement total productive maintenance for their goods, thus achieving higher customer satisfaction [5253]. Dawson reviewed the literature on cybersecurity and lean manufacturing in the United Kingdom (UK) and concluded that vulnerability assessments and risk evaluations help manufacturers identify opportunities for incident detection and raise consumers' trust in their products [54]. Corallo et al., concluded that the implementation of cybersecurity measures by manufacturers safeguarded cloud-based systems [54]. This leads to increased levels of integrity, reliability, and consistency of information and its availability for use when needed. Bajaj and Akhilesh, suggested that training programs on cybersecurity provided to the manufacturing workforce guarantee fewer human errors associated with data breaches [55]. This increases employees' recognition of the vulnerabilities and risks as well as makes them invested in ensuring the consistent flow of goods and achieving better lean manufacturing.

Cybersecurity investment by manufacturing operations enhances operational and process flow. Kosmowski, indicated that the application of routine cybersecurity checks and vulnerability assessments achieves better operational flow as well as performance [56]. The safety evaluations need to be regular and consistent, penetrating all information and operation technology deployed within the enterprise. Da Silveira Dib et al., concluded that without sufficient investment in cybersecurity, manufacturers have a higher chance of failing to meet sustainable operations and jeopardizing their survival in an increasingly competitive market [57]. Iaiani et al., suggested that increased awareness and training of the manufacturers' workforce requires many processes to improve the flow of goods and increase both streamlining and standardization [58].

2.5.5 Simulation and Lean Manufacturing

Simulation represents a real model, process, or product by using digital tools and software. It enhances the visualization of operational processes. This helps formulate optimal flows and streamline of products. Simulations allow the reengineering of production process testing and the feasibility of multiple options. It permits manufacturers to view whether the investment in new technologies or equipment is desirable or conducive. Simulations also equip manufacturers with the ability to estimate costs, manpower, and technology required to produce an optimal number of products and meet market demands.

Simulations help manufacturers fulfill their aspirations of achieving lean manufacturing in several respects. Mourtzis, suggested that simulation allows manufactures to validate new processes and remove potential areas of waste [59]. Similarly, simulations provide valuable tools for the detection of non-value-added processes that deplete scarce resources in the manufacturing operation. Zhang et al., indicated that modelling and simulation allow manufactures to test customers' desirable features and requested additions to existing products [60]. The available tools also permit manufacturers to experiment with new features without the need to invest in expensive labor or material. Garwood et al., displayed how manufacturers could utilize simulation to save energy costs in operations, thereby decreasing the costs and increasing efficiency [61].

Simulations constitute an asset for manufacturers to achieve lean manufacturing principles. Ojstersek et al., showed how simulations assist manufacturers in achieving social, as well as environmental, sustainability. Simulation tools assist manufacturers in conducting environmental impact investigations, which boosts their compliance with new regulations as well as bolsters their reputation among existing and potential customers [62]. Baumer-Cardoso et al., confirmed the utility of simulations in making lean practices more sustainable in the manufacturing sector [63].

The analysis indicated how simulations identify areas of weaknesses in lean practices and how to strengthen them by using modelling and simulations. Teerasoponpong and Sopadang, suggested that simulations present a planning tool for small and medium size manufacturers, helping them eliminate unnecessary operational bottlenecks by visually and interactively graphing production processes [64].

2.5.6 Augmented Reality and Lean Manufacturing

Augmented reality is a collection of devices that allow the viewing of a system or component in high dimensional fashion. Manufacturers who have employed AR technology in delivering training to their workforce have found that distance learning becomes easier to administer and offers an enriched experience. AR has also exposed technicians to the complex systems underlying the machines' work which has aided in their capability for future maintenance. With AR, technicians are also able to communicate with staff located in other manufacturers in ways that facilitate their work.

Augmented Reality (AR) has been associated with improved workflow, standardization, and product design in addition to customer satisfaction. Gonzalez-Franco et al., suggested that the use of AR reduces costs associated with training and human resource development in manufacturing enterprises, thereby eliminating exorbitant costs, and increasing standardized training in order to deliver more effective performance [65]. Egger and Masood demonstrated how AR is increasingly being employed by manufacturers to resolve these and other process flow challenges [66]. The authors further suggest that workers become more aware of non-value-added processes once they are exposed to the dynamic flow allowed by digital AR tools. Bottani and Vignali, indicated that AR not only improves such training in manufacturing, but also resolves many classical challenges associated with product development, design, and assembly [67].

Viewing all dimensions in an interactive format ultimately allows engineers opportunities to improve designs as requested by clients and increase customer satisfaction, a core objective of lean manufacturing.

AR use improves manufacturing process control and ensures smoother flow of steps along the manufacturing process. Uva et al., indicated that AR technologies allow for customized product design and development [68]. Interactive AR simulations provided to customers engage them in the process of determining the parameters of their products and generate increased levels of satisfaction and loyalty. Zhu et al., demonstrated how the use of AR technology provides technicians the opportunity to interact with Digital Twin systems [69]. This allows technicians to better view how data is collected, stored, and utilized in order to ensure a more efficient human-to-machine interface in smart manufacturing. Drouot et al., suggested that the use of AR technology and clear instructions improved process control [70]. In their experiment comparing AR with non-AR viewing of operational processes, the authors suggested there were no adverse effects associated with AR. The finding conforms to expectations that AR proves to be better in viewing the operation process.

2.5.7 Autonomous Robots and Lean Manufacturing

Autonomous robots have been in use in manufacturing for decades. They help workers with many simple and complex tasks. With the advent of advanced machine learning, robots have assumed more control over key production phases. Autonomous robots and unmanned machines communicate with each other to achieve manufacturing goals. They have become cheaper and within reach of many manufacturers, thus reducing the cost of hiring, training, and retaining a skilled workforce. Autonomous robots are also expected to grow in manufacturing along with the increasingly digitized rise of smart factories across sectors.

The implementation of autonomous robots eliminates areas of waste and adds standardization to the manufacturing operation. El Asmar et al., suggested that autonomous robotic vehicles could help manufacturers eliminate waste in plants [71]. Autonomous robots minimize the extensive time required to transport material from one place to another. They offer logistics solutions to workers involved in the use of many parts and materials when manufacturing customized products and designs. Saxena et al., indicated that robots could help foundries in the completion of complex castings [38]. Autonomous robots could transfer hazardous materials easily between stations and potentially achieve standardization in delivering highly complex tasks like pouring appropriate amounts of molten material into cavities.

The use of autonomous robots increases the efficient and effective flow of products in manufacturing. Vukorep, demonstrated the value of using cable-driven robots in easing, facilitating, and expediting the manufacturing process of products [73]. Liaqat et al., concluded that autonomous mobile robots assist complex operations by eliminating delays in the design and production of goods [74]. Patel et al., suggested that autonomous robots within the IIoT setting are capable of rectifying errors in the design and production process, thereby avoiding defects. Intelligent robots are able to make decisions immediately and address any unexpected deviation from the specified production process [75]. Khan et al., concluded that the use of autonomous robots in food packaging achieved much higher cost-efficiency and standardization of products compared to the use of trained humans [76].

2.5.8 Additive Manufacturing and Lean Manufacturing

Additive manufacturing (AM) is the process of generating a prototype by using innovative technologies. Those technologies include computer aided design (CAD), 3D printing, and digital direct design (DDM). This allows manufactures to produce more flexible and customizable goods

that are easily sketched on computerized files and fed into the technology to be produced. This presents limitless opportunities for manufacturers to save on operational costs, intensive human labor, and excess material use. It also provides manufacturers with a more agile ability to meet the increasing and changing demands of their customers by producing customized products.

The implementation of AM accelerates the realization of the lean manufacturing principal objective of waste elimination. Ghobadian et al., conducted a review of AM's adoption in the manufacturing sector and suggested that if it is brought to a full extent, AM will deliver superb performance by not only reducing waste but also reaching optimal lean manufacturing results [77]. Singamneni et al., demonstrated the increasing application of AM in the aviation industry. The authors concluded that AM is a "true messiah" to the complex sector [78, p.22]. AM provides companies with digital solutions to the costly materials and labor investments required to generate new products and has been proven to attend to customers' satisfaction by engaging the patron through the ordering, manufacturing, and delivery phases (a long sought after goal by lean manufacturing practitioners) [79].

The application of AM to manufacturing has enhanced products' quality and met increasing expectations of customers. Prasittisopin, et al., concluded that AM in the construction industry is capable of reducing material use by 10% and increasing energy savings by 30%, thus adding more value to the products delivered [80]. Delic and Eyers analyzed data from 124 medium and large size automotive industry leaders in Europe and found that AM increases flexibility of companies' supply chains, which positively improves the firms' performance [81]. Costa et al., highlighted the importance of AM in meeting the highly customizable and personalized needs of customers in the ceramics industry, showing how AM allows manufactures to readily model highly personalized objects requested by their patrons [82].

2.5.9 Vertical and Horizontal System Integration and Lean Manufacturing

Vertical integration refers to the blending of physical and virtual systems, allowing rapid responses to change in the environment. Horizontal integration concerns the building of strong and closely related networks that add value to the operation. Both types of integration help manufacturers standardize their systems, establish better predictability of markets, and eliminate information and operation wastes. System integration allows stakeholders to more easily identify opportunities of growth and strengthen areas of weakness.

System integration has been demonstrated as a strategy for waste elimination. Chen highlighted how integration is associated with more intelligent manufacturing and minimized manufacturers' reliance on intensive human labor [83]. Tao et al., indicated that cyber-physical systems integration increases manufacturers' efficiency by eliminating non-value-added processes by replacing them with automated intelligent procedures [84]. Zhou et al., concluded that the integration of systems in manufacturing results in increased implementation of artificial intelligence that reduces human intervention and allows machines to avoid erroneous ordering or dispatching of needed materials or products [85].

Physical-cyber system integration is celebrated as another tool helping manufacturers become leaner. Lee et al., demonstrated the value of Digital Twin, the merging of cyber and physical systems, in lowering design and development costs while increasing standardization across the manufacturing operation [86]. The authors suggested that Digital Twins is expected to rise, and eventually be capable of achieving the main goal of lean manufacturing: waste elimination. Penas et al., concluded that physical-cyber integration systems implementation in manufacturing reduces operational bottlenecks and automates the optimal streaming of goods and achieving more efficiency and effectiveness [87]. Harrison et al., indicated that a sustainable

physical-cyber system integration model is capable of eliminating waste, engaging customers throughout the manufacturing process, and achieving optimal flow that satisfies the expectations of lean manufacturing [88].

2.6 Manufacturing in Developing Countries SMEs

There has been a renaissance in the manufacturing sector across developing countries. Sub-Saharan African countries have seen the highest gains in employment between 1990 and 2018 across twelve sectors (i.e., agriculture, mining, manufacturing, public utilities, construction, trade, transport, business services, finance, real estate, government services, and other services) because of the expansion of manufacturing activity [122]. Similarly, middle income countries across the globe have witnessed an upsurge in the number of textiles, fisheries, agriculture, and mineral manufacturers. Further, automation and digitization in manufacturing have exponentially increased among SMEs globally. One potential explanation for this observation is the availability and accessibility of affordable technologies like simulations, additive manufacturing applications, and data analytics tools. Simultaneously, network sharing has assisted in discriminating helpful information about the proper usage of technologies in specific manufacturing settings [122, 123].

Manufacturing in the developing world lags behind advanced nations in several respects. On the one hand, SMEs in the developing world have limited adoption of intelligent manufacturing systems compared to their counterparts in industrialized nations. Limited availability of funding, lagging technology infrastructures, and shortages of skilled labor all contribute to the stunted growth of cyber-physical integration across the manufacturing sector of developing countries. Furthermore, inadequate awareness concerning long-term benefits in investing financial resources in Industry 4.0 technologies has prevented stakeholders in developing countries from adopting smart manufacturing techniques and strategies. In a similar vein, insufficient exposure to the

implementation of advanced applications of Industry 4.0 technologies has led to minimal incorporation of such techniques across developing world manufacturing facilities [123, 124].

2.6.1 Emerging Trends in SME Manufacturing

One of the emerging trends in manufacturing across developing countries is the superiority of large firms over small and medium sized enterprises [124]. SMEs typically have low budgets and high shortages of sufficient labor to meet manufacturing production goals [123, 124]. On the contrary, large manufacturing firms can invest in technological solutions by reducing production costs and increasing output levels that offset the market share of SMEs in the same sectors [122]. One of the innovative strategies SMEs have adopted to counter the high control of large enterprises is the initiation of Industry 4.0 technologies. Such technologies have the potential to increase manufacturing value-added products while decreasing costs associated with traditional labor-intensive manufacturing procedures [122]. Notwithstanding SMEs endeavors in making their production smarter via technology, larger firms still hold the superior position in deploying all kinds of technology investments across their manufacturing portfolios and generate more revenue while driving down their operational costs [122-124].

Innovation across manufacturers in developing countries is low. One culprit is top management resistance for purchasing and deploying sophisticated technologies and machines to modernize legacy manufacturing systems. Furthermore, the absence of incentives, whether from government agencies or trade associations, has generated an apathy concerning smart manufacturing. Further, the great number of infrastructure challenges (whether in technical readiness or personnel preparation) have slowed down the industry 4.0 manufacturing wave across developing countries. A holistic framework incorporating every key stake holder in the process of

making manufacturing more autonomous and digital is needed to foster smooth transitions from old manufacturing practices to novel production systems [122, 123, 125].

2.7 Challenges of Implementing Industry 4.0 in Manufacturing SMEs

2.7.1 Prohibitive Costs

Investment in Industry 4.0 is costly. Manufacturers purchase the latest technologies, train their personnel in using new systems, and redesign their workspaces to become compatible with the physical-cyber infrastructures installed. At every step of Industry 4.0 implementation, a new cost is introduced. More importantly, there has been confusion about the return on investment brought by the application of Industry 4.0 solutions to manufacturing problems. Such an environment has discouraged the majority of stakeholders invested in small and medium sized enterprises [126]. Manufacturers' decision to replace legacy systems with smart production lines requires large-scale training of the workforce. Hiring and retaining talented individuals that are competent in running and maintaining advanced technological systems has proven to be a challenge for all industries in the modern era. In developing countries, manufacturers need to address deficient network readiness and technology infrastructure problems which adds further costs to the implementation of Industry 4.0 [127]. While many experts have recommended the gradual cheaper routes to the adoption of Industry 4.0, every stage of the process depletes existing financial resources that could be spent elsewhere.

Stakeholders are largely unfamiliar with the potential benefits of Industry 4.0 for their enterprises in the long run. Savings on production, maintenance, and the human workforce are still unclear to many managers and owners which makes the move to Industry 4.0 less attractive. Initial investment in Industry 4.0 is colossal, also making investors less likely to approve it because of the intangible benefits conceptualized to them by smart manufacturing advocates [139]. More

importantly, economic forecasting of Industry 4.0's potential return on investment is governed by several uncertainties that create further complications on the part of stakeholders and managers before authorizing any Industry 4.0 investment [40]. Transforming operations in radical ways like Industry 4.0 scares people in positions of power, fearing disruptions in their enterprises.

2.7.2 Absence of Talent in the Workforce

Industry 4.0 implementation also requires advanced technical expertise to manage effectively and efficiently the various cyber, as well as smart physical, technologies across the manufacturing enterprise [128]. Evidence indicates a shortage of knowledge workers capable of running sophisticated interconnected networks, sensors, and machines in the manufacturing world. Increasingly competitive markets also present a challenge to manufacturers trying to attract talent from other lucrative sectors like information technology. Manufacturing jobs typically require physical presence on the premises, and knowledge workers today prefer to work from home using remote access systems. The highly non-synchronized systems and machines also demand specialized knowledge that traditional education institutions cannot provide [129]. Therefore, manufacturers face real challenges in staffing if they decide to invest in Industry 4.0 solutions [128]. Additionally, manufacturers need to cross-train existing workforces on new systems, environments, and machinery. Many employees do not possess the necessary backgrounds to make them ready for the new change(s).

2.7.3 Information Security and Privacy Concerns

Implementing Industry 4.0 exposes manufacturers to a heightened risk of falling victim to cyberattacks [130]. The increased interconnectivity of devices presents potential threats of being hacked or compromised. Smart systems place previously unconnected machines on the cloud or the web which exposes their information to potential cyber criminals. Industry 4.0 systems

oftentimes require upgrades or additional installations from the web as well [131]. Such activities increase the chances of manufacturing systems being attacked by malware or denial of service threats. The emerging regulatory frameworks for information management may expose manufacturers to risks of clients' data sharing problems. Systems collect large amounts of information that are constantly transferred among smart machines without the potential consent of clients or even workers at the manufacturers [130]. Detection and defense against cyberattack in Industry 4.0 environments are more difficult given the numerous technologies and machines involved in the process.

2.7.4 Unclear Regulatory Environments

Implementation of Industry 4.0 also poses several legal challenges to manufacturers. Smart manufacturing requires the insertion of third-party services that help enterprises streamline their cyber and physical systems [132]. Inclusion of parties presents potential liability concerns. Services and products furnished to customers become more complex by having more than one party contributing to the quality and characteristics of the end materials [133]. Therefore, the distribution of risk is unclear, and regulations are insufficient to protect manufacturers from claims. More importantly, intellectual property rights become more blurred when many parties enter the manufacturing process. Additionally, manufacturers are at the mercy of regulators when matters come to artificial intelligence, machine learning, and cybersecurity [132]. Courts have ruled in differing ways in the past, introducing confusion to manufacturers on how to draft clear policies. The unclear regularity infrastructure governing Industry 4.0 implementation makes manufacturers less willing and more hesitant to develop smart ways of conducting business [133].

2.7.5 Integration Challenges

The application of Industry 4.0 necessitates the integration of various production systems across a facility. Each system may have varying technical and maintenance characteristics requiring parties interested in Industry 4.0 to reconfigure a few or all platforms in order to ensure synchronization [134]. Assembling a unitary platform where all systems communicate with each other timely and consistently without glitches is a cumbersome task [135]. Manufacturers may need to invest in new systems by replacing their legacy protocols and procedures to create compatible environments for Industry 4.0. Special skills are required to ensure the streamlining of all systems to function in their expected fashion within a unified, smart, manufacturing framework [134]. Such an integration proves to be demanding on all levels, including financial and human resources as well as management. More importantly, the synchronization of systems needs to avoid data breaches or untimely transfers of information, which is a complex endeavor on the part of manufacturers [135]. Therefore, creating a cyber-physical environment where everything functions in a desirable manner is a serious challenge for any manufacturer thinking about the implementation of Industry 4.0.

2.7.6 Management Resistance

Investment in Industry 4.0 constitutes a major change in how manufacturers perform tasks and generates a great deal of organizational resistance to novel methods of production and handling manufacturing tasks [136]. Evidence indicates that stakeholders dislike change, especially when return on investment is unclear. Workers fight any change to the way work has been conducted for years. Personnel defaults to the ways organizations have conducted business and reject proposals for changing workstations and workspaces. Industry 4.0 implementation changes all stages of production, however. Employees may lose their jobs because of increased automation and reliance

on robotics, making the idea of smart facilities unattractive for many within the manufacturing industry. Operations managers unfamiliar with technological potential refuse to alter the ways business has been conducted. Managers like routines and stability, avoiding radical changes like the application of machine learning and artificial intelligence on the production line [137]. In sum, resistance to Industry 4.0 implementation is prevalent across all levels of the manufacturing industry.

2.7.7 Insufficient Technology Infrastructure

Investing in Industry 4.0 needs a ready technical infrastructure capable of handling the high-level technologies featured in smart facilities. Many manufacturers have limited access to internet connectivity such as those located in rural communities or developing countries. Further, many facilities lack the electric and power infrastructure necessary to support cyber-physical integration [4]. Relatedly, manufacturers may not have access to sufficient energy levels and maintenance systems required to buttress the operation of smart manufacturing operations. Today, manufacturers struggle to locate the requisite human capital needed to steer the application of Industry 4.0 applications [138]. The absence of connectivity, access to technology, personnel versatile in technical integration, and funds to make facilities technology-ready for Industry 4.0 all present infrastructure-related challenges to manufacturers interested in adopting Industry 4.0 solutions in their facilities.

2.7.9 Natural Disasters

Earthquakes, floods, tornados, cyclones, and electrical shutdowns all negatively impact manufacturing operations. Industry 4.0 implementation is prone to natural disasters more than traditional facilities [141]. On the one hand, glitches, cyberattacks, and service cutoffs present serious challenges to the interconnected networks powering smart manufacturing. On the other

hand, extreme heat or cold conditions affect the technological and power infrastructure providing power to the cyber and physical systems running operations [142]. Additionally, investing in plans addressing potential disasters is costly.

2.7.10 Workplace Disruptions

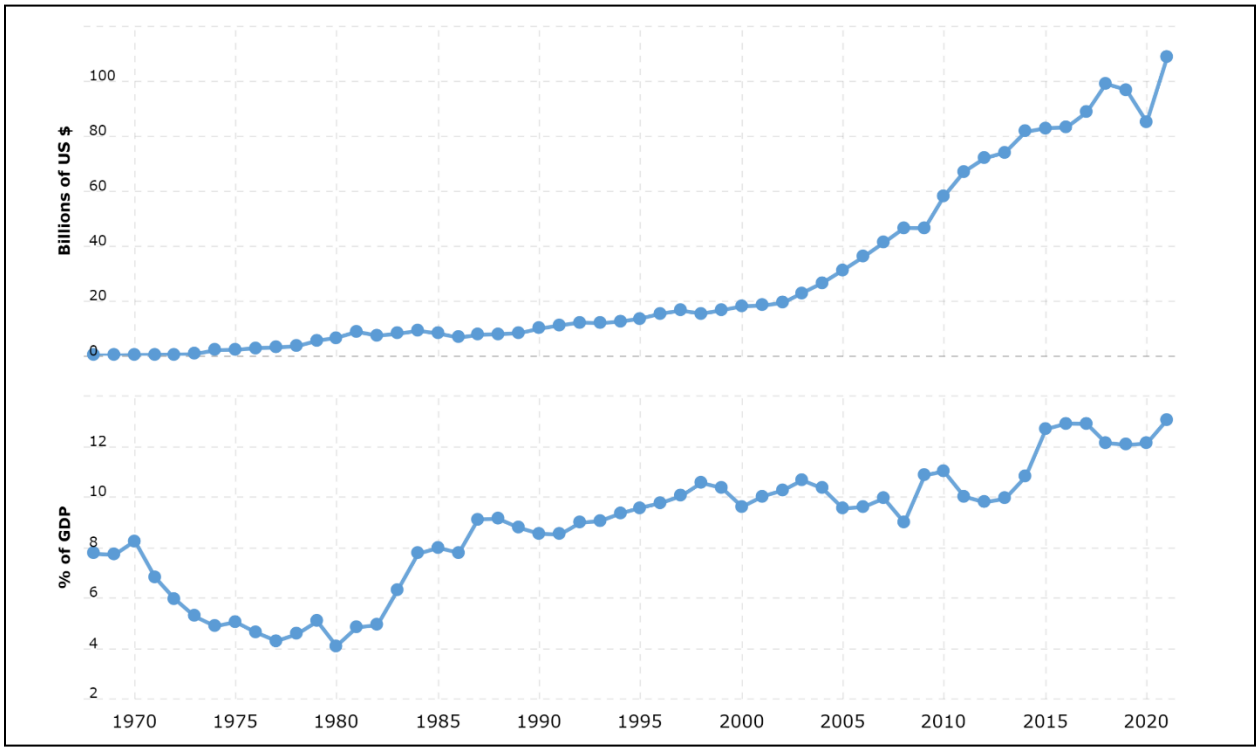
Industry 4.0 applications require modifications to the workspace, workstations, and personnel. At a rudimentary level, Industry 4.0 translates into more automation and less human interventions in the manufacturing process [143]. On a more advanced level, robots move freely around facilities and complete manufacturing tasks while communicating with intelligent systems. Such changes generate several challenges to manufacturers. First, people whose jobs will be lost because of automation and digitization will likely organize and fight the change. Further, managers will resist the redesigning of manufacturing floors because of perceiving ineffectiveness and inefficiencies [144]. Stakeholders have a difficult time imagining digitally sophisticated workplaces replete with sensors, machines, and systems which makes investment in Industry 4.0 more unattainable.

2.8 Case Study

2.8.1 Manufacturing in Saudi Arabia

Saudi Arabia's manufacturing sector has grown exponentially in the past few decades. As a percentage of the gross national product, the manufacturing contribution to the Saudi economy reached about 14% in 2021, a move of ten percentage points compared to 1980. Simultaneously, the raw dollar amount of the manufacturing sector in Saudi Arabia reached its peak around $110 billion in 2021 (see Figure 2.10)**.** This is about a five-fold increase compared to 1980, signaling the growth of manufacturing in the country [145].

Figure 2.10. Manufacturing Output in Saudi Arabia (World Bank, n.d.)



While the Kingdom of Saudi Arabia relies on oil sales to replenish its revenues, the country has made significant strides with respect to the manufacturing sector. First, the manufacturing sector contributes about 10% to the entire GDP in 2021, an increase from low digits only two decades ago. Over time, the annual growth rate of the manufacturing sector in the country reached 7.5% in 2021, the highest in the past few decades. The Ministry of Industry and Mineral Resources also issued more licenses for plants in 2021 compared to the previous year, coinciding with a 14% increase in manufacturing licenses awarded to applicants last year. Such trends point to the booming future of manufacturing in Saudi Arabia, especially given the subsidies provided by the government in hopes of fully diversifying the economy [146-148].

Governments of developing countries, such as Saudi Arabia, have realized the strategic importance of private-sector manufacturing in boosting economic strength and competition. The Saudi Industrial Development Fund has approved over 1500 medium range loans for competitive

and aspiring enterprises. In the past decade, the fund authorized about $28.5 billion in loans to support attempts by established enterprises to strengthen and diversify their manufacturing practices. In 2020 alone, the fund distributed around $4.5 billion on bolstering industrial development across several sectors, including non-oil and petroleum related industries. The largest beneficiary from the loans are ambitious small and medium sized enterprises that proved their competitiveness by achieving economic growth in the past decade [149, 150].

2.8.2 Implementation of Industry 4.0 in Saudi Arabia SMEs

One line of research on Industry 4.0 implementation in Saudi Arabia concerns its impact on many types of firms' outcomes. Some scholars investigated the integrated effect of Industry 4.0 technologies and lean manufacturing on a sample of plastic and petrochemical companies. Using self-reported questionnaires from 112 manufacturers in Saudi Arabia and Structural Equation Modelling, the authors reported positive effects by Industry 4.0 on all measures of sustainability. One of the cutting-edge applications of Industry 4.0 in Saudi Arabia is Siemens MindSphere platform. The cloud based IoT system allows all stakeholders to connect their systems, products, teams, and machines together, and has been implanted in more than a single Saudi industry. Outcomes from the various applications have been successful in improving the effectiveness and efficiency of the work performed [151, 152].

Another area of research on Industry 4.0 in Saudi Arabia is the potential for the innovative technologies to change work settings. A researcher indicated that Industry 4.0 adoption across sectors is expected to grow. Such an increase would result in altering workspaces, placing higher demands on skilled workers proficient in the use of high-tech devices and applications. The increased interest in the potential of Industry 4.0 has initiated several public-private partnerships to advance the application of Industry 4.0 across sectors. Saudi government programs have

stimulated the adoption and implementation of digitization by offering funds for the enhancement of efficiency and use of cutting-edge technologies [153-155].

The Saudi 2030 vision aims to invest a colossal number of resources in diversifying the manufacturing sector in the country. One of the bold steps the government of Saudi Arabia has taken is the investment in the purchase of new technologies like autonomous robots and additive manufacturing to be used across industries. The government also has subsidized programs for new investments in Industry 4.0 technologies. Such moves come amidst increasing investment in research and development activity across all domains in order to improve the adoption and implementation of Industry 4.0 [75, 152, 156].

One of the on-going endeavors encouraging the adoption and implementation of Industry 4.0 in Saudi Arabia is the funding of innovative projects through incubation and acceleration programs. The Innovation Center has been established to ameliorate the acceleration of Industry 4.0 implementation by new businesses in Saudi Arabia. New government commissions established after the passage of the 2030 Vision focuses on the purchase, integration, and application of new technologies and processes to improve efficiency and effectiveness across the board. The government has also partnered with reputable consulting firms to found advisory boards that review existing practices and recommend new guidelines to ensure the technology-driven implementation of business processes [157-160].

2.8.3 VISION 2030 and Manufacturing Future in Saudi Arabia

Funding from the Saudi Arabian government is making advancements in smart manufacturing regarding artificial intelligence and machine learning. These AI devices contain narrowed intelligence that can perform specific tasks with expertise that can be difficult for corporations to find. Artificial intelligence uses past data to predict future outcomes and act

accordingly. This method eliminates emotional and personal bias in businesses that traditional manufacturing cannot completely cease. Saudi Arabia is also funding businesses to study machine intelligence to further modernize the country by creating devices that are as smart as a human in the realms of language, imaging, and computational functioning and reasoning. Higher intelligence in manufacturing machinery contributes to reduced risks for workers in factories, faster service for customers, and more accurate operations. Modernization is surpassing augmentation in Saudi Arabia, where AI systems can function on their own in a manufacturing setting opposed to needing specific commands to collaborate with one another. AI tools are leading smart manufacturing tools in saving companies money and allowing virtual assistance and are constantly being advanced. Saudi Arabia is working further to implement super intelligent devices that will eventually outsmart humans in both functional and interpersonal environments, promising a long-term, modern, work domain for the country [161-163].

Another method of smart manufacturing that Saudi Arabia is currently implementing to modernize the nation are big data tools such as time-sensitive networking (TSN). TSN allows quicker access to information as control systems are linked in real time, enabling information transfer between various networks. This method of big data access is easy to implement as long as the communication interfaces on devices are synchronized. TSN ultimately permits Saudi technology sectors to employ advanced ethernet systems such as 5G, allowing more nodes to be utilized at once. The modernization of Saudi Arabia is also advancing with the implementation of open platform communications united architecture (OPC-UA) in big data. OPC-UA administers security in confidential technological systems by encrypting and authenticating the data at the source instead of building firewalls. This introduces big data use efficiency in many work environments where interoperability can be secured, allowing collaboration between diversified

vendors and platforms. The convergence of operative and information technology in big data also contributes to the modernization of smart manufacturing in Saudi Arabia. Collecting data from open-source cloud storage in technological fields has been advanced due to Saudi Arabia's investment in big data OT/IT combination services like Klynveld Peat Marwick Goerdeler (KPMG) professional companies. IT systems prove to strengthen such efficiency in companies by analyzing data imported from actuators, machines, plants, lines, and sensors instead of gaging them individually [164-166].

Additionally, Saudi Arabia is modernizing their economy by popularizing smart manufacturing methods such as mass customization. With transparent customization, individual clients receive unique services and products without knowing that the goods have been customized for them. This strategy is enhanced as algorithms for observing media users are improved and manufacturers are able to analyze and advertise within their audience's interests without direct communication. Smart manufacturing by this method allows businesses to supply a specific product to a niche audience, limiting expenditures on an array of products that depend greatly on the state of the economy. Another type of customization, cosmetics, helps Saudi manufacturers to mass-produce products while greatly appealing to their clientele. Customers are more likely to pay for personalized goods, but companies can decrease their expenditure on product creation by developing a base product that can be personalized in many ways. Strong relationships with consumers are created when mass customization is utilized, leading to customer loyalty, reviews, and referrals. Moreover, collaborative customization increases the modernization of Saudi manufacturing as it allows the production of a standard product that users or buying companies can alter on their own. The time to market can be significantly improved, shipping requirements can be generalized, and companies can specialize in one quality good or service by utilizing this

method. Mass customization is a modern form of interaction with the clientele that ensures cost advantages [167-169].

2.9 Methodology Literature Review

Prior to holding focus groups or conducting questionnaires, this study began with a comprehensive literature review. The purpose was to identify key factors affecting the implementation of Industry 4.0 in manufacturing facilities operating in the developing world. Numerous large databases, like the web of science and Scopus, were searched for relevant articles, and hundreds of articles were initially identified. After reading the full abstracts, about 128 empirical papers were reviewed. Ten factors were recurring across more than 83% of these studies. These were: prohibitive costs, absence of talent in the workforce, information security and privacy concerns, unclear regulatory environments, integration challenges, management resistance, insufficient technology infrastructures, unclear return on investment, natural disasters, and workplace disruptions.

Few terms were selected to search the databases for relevant articles. The terms included "Industry 4.0 Barriers in Developing Countries, "Industry 4.0 Obstacles in Developing Countries, and "Industry 4.0 Challenges in Developing Countries." Once the hundreds of articles were initially identified, only those articles that looked at barriers/obstacles for implementation were included. Many of them focused on experts' opinions or performed literature reviews. Each of the included papers concluded more than a single factor.

2.10 Digitization vs. Digitalization

Digitization and digitalization are related, yet different. Digitization refers to the transformation of objects into codes or digital values. For instance, when a user scans an image, the content does not change, however, the image is stored on the machine with a labelled number

or series of values. Digitalization is changing organizational processes from human to object or human to human into human to machine enabling devices to collect and process information. Digitalization is moving the organization tables or offices to virtual spaces where interactions of systems create new models and change.

2.11 Conclusion

This chapter has summarized the most commonly cited barriers to Industry 4.0 implementation in developing countries by SMEs. The chapter has also discussed the relationships between the various enablers of Industry 4.0 with different dimensions of lean manufacturing. Subsequently, readers have been acquainted with how manufacturers of SMEs have implemented the different technologies of Industry 4.0 with an emphasis on developing countries. The case of Saudi Arabia has augmented this discussion by exhibiting how authors have researched the implementation of Industry 4.0 in various facilities within SMEs across the country. A note on the frameworks leading to the implementation of Industry 4.0 and their potential was also introduced. The gap in the literature is the absence of realistic frameworks guiding stakeholders in implementing Industry 4.0 in lean manufacturing settings across developing countries like Saudi Arabia. Additionally, the associations between Industry 4.0 enablers and lean manufacturing outcomes have not been adequately investigated.

Chapter Three

Methodology

3.0 Introduction

This chapter introduces the mixed methods approach and stages of the present study. At a fundamental level, since the way to construct reality has several paths, this research utilizes the interpretive research paradigm [212-214]. Based on such an understanding, a mixed methodology is used to triangulate quantitative and qualitative information in order to reach a more accurate portrayal of the real world and the phenomenon under investigation, which is preferred over other approaches [214]. A comparison between the qualitative as well as the quantitative results is performed to ensure the consistency of observed patterns in the mixed methods studies [214]. The chapter outlines the systematic literature review guiding the problem identification and description underlying this research. Industry 4.0 implementation in developing countries comprises the primary research area of this project. A humanistic approach that follows these practices from the field guides the strategy for choosing appropriate data collection and analysis methods. A humanistic approach refers to the use of qualitative self-reported data by participants to describe a social phenomenon like the implementation of Industry 4.0 in lean manufacturing. Therefore, three distinct data collection techniques were used: 1) focus groups, 2) descriptive data for interpretive structural modeling, and 3) survey responses (see chapter four for more information). Based on the quantitative and qualitative methods of data collection, a series of data analysis strategies were followed. Those were thematic analysis of focus group information, interpretive structural modeling based on experts' ratings of factored data, and descriptive statistics based on questionnaire-response data. All approaches complement each other by providing a different lens for considering the same phenomenon.

3.1 Research Paradigm

3.1.1 Philosophy of Science

This research utilizes the interpretive paradigm of scientific investigation. One of the underlying assumptions is that reality cannot be reached using a single approach. More importantly, reality may have several faces or manifestations. Further, using more than a single method to analyze the same phenomenon generates more information that contributes to finding the truth in an outcome. In a similar vein, the truth about an outcome like Industry 4.0 implementation is multifaceted and multidimensional. In no way, shape, or form do the outcomes reached in this or any other research become truly deterministic.

Interpretive researchers uncover the social constructions concerning concepts or practices in the environment surrounding us. Expert opinions then reflect their perceptions based on the extensive experiences they have accumulated throughout their lives. Further, qualitative data has important value in informing us about how factors relate to each other and produce real-world observable outcomes. Additionally, the researcher affects every procedure performed throughout the research process. All in all, interpretive research produces a more realistic view of the phenomenon under investigation.

3.1.2 Mixed Methods Research

The simple definition of mixed-methods research is the collection of both qualitative and quantitative data for analysis within one study [213]. These studies have become increasingly common within the social sciences, as the use of both types of data makes results more difficult to disprove. These designs entail slightly different constructs than typical studies, including the composition of a research question, open and close-ended data, and interpretation of results with regard to both qualitative and quantitative aspects of the project [214, 216]. More specifically, data

should be collected, integrated by sequence, or embedding, and prioritized based on the application of the research questions. Procedures should be thoughtfully aligned, as sometimes it is more appropriate to institute multiple phases in the study with a mixed-method design. Procedures should be thought about by using multiple lenses with respect to worldview application, as well as precisely applying them to the conduction of the study [217]. One pertinent goal of these designs is to ensure a well-rounded analysis of the research topic.

Using mixed-methods research also helps to analyze data on a deeper, more personal, approach than simply using quantitative methods and the addition of qualitative data helps prevent the overgeneralization of data conducted in qualitative studies [215]. This allows data to be more applicable to larger, more diverse, audiences. Mixed-methods research is needed if there is an insufficient amount of data, an insufficient source, or if initial results need to be explained more thoroughly. Mixed-methods designs are also useful for generalizing the findings of a study, enhancing the results of a study, and supporting theoretical viewpoints [217].

There are two main categories of mixed-method designs: sequential and concurrent [213]. Sequential constructs are best used when there is an unequal emphasis on the qualitative or quantitative aspects of the study [216]. It is also good to use sequential processes when one set of data must be collected, using the other collection as a basis. The three sub-categories of sequential design are explanatory, exploratory, and transformative. Explanatory designs are used when data is first collected in a quantitative way, but qualitative analysis is used secondarily as the rationale. Exploratory research should be employed when greater insight is needed on the topic, so qualitative data collection is performed before quantitative. Lastly, sequential transformative designs are helpful when theoretical lenses are more important than the methods as a framework [216].

Concurrent designs are best utilized when both types of data are closely related or are easily collectible at the same time [215, 217]. Types of concurrent designs include triangulation, concurrent nesting, and transformative methods [213, 214]. Concurrent triangulation is helpful when the relationships between variables need to be accurately defined [216]. Nested designs are prominent when data is collected simultaneously but more weight is given to either the qualitative or quantitative part of the design [217]. Transformative measures are best installed when the data is being used to represent a perspective for theories or social ideas.

3.2 Sampling and Participants

This research has used a snowball sampling strategy to identify experts for participation in the research. When "samples with the target characteristics are not easily accessible" this strategy is suitable [24, p.763]. First, the researcher reached out to a factory owner in southern Saudi Arabia who operates a small water bottle facility. The owner has informed the researcher that he invested in many technologies to modernize manufacturing in the facility. One example is the adoption of sensors that capture defective bottles by using cameras and imaging detection software. The system operates autonomously and removes any detected defective bottle from the manufacturing line. When asked by the researcher, the owner recommended participants who own or operate facilities that also adopted innovative Industry 4.0 technologies. A list of ten names was prepared. The researcher asked the owner to participate in the focus group to be held once all six participants were identified and agreed to partake in the research, and following approval, the researcher began reaching out to potential participants.

3.2.1 Snowball Sampling

Snowball sampling is a non-probability-based sampling technique. Therefore, the estimates provided through this sampling strategy cannot be generalized to describe the general

population. Snowball sampling is an appropriate method to be used when the intended population of the research is difficult to reach or be identified. Members of the intended population assist researchers in finding more participants that meet the sample criteria set by the researcher. In this research, the population is experts on the implementation of Industry 4.0 technologies in manufacturing facilities operating in the developing world. Unfortunately, lists containing a sufficiently large number of this population are oftentimes unavailable, and if existent, are inaccessible to the researcher.

Snowball sampling is also suitable for studies targeting populations that constitute 2% or less of the general population. While official statistics on the prevalence of experts on Industry 4.0 implementation in manufacturing facilities in the developing world are absent, the likelihood this population is less than 2% in developing countries is high. Such a decision is reached by observing the low manufacturing capacity of most developing nations. Further, the rarity of applying Industry 4.0 in manufacturing supports the conclusion that experts on Industry 4.0's actual application in manufacturing across the developing world are seldom to be found. Based on this logic, the researcher chose Saudi Arabia, a growing economy with a burgeoning manufacturing sector to be the country for this analysis.

Saudi Arabia is home to more than 10,000 manufacturing facilities as of the summer of 2022. While the Covid-19 pandemic, investors' hesitation, and slow economic growth defined the general atmosphere in the production sector across the country, manufacturing accounted for about $300 million in recent estimates published by the General Authority for Statistics. Small and medium-sized manufacturing facilities comprise a sizable proportion of the country's manufacturing map. Saudi Vision 2030, an ambitious economic development plan, has also funded local manufacturing since 2017. Additionally, new manufacturing facilities have been

implementing the latest technologies as many have been constructed in the past ten years. Other established manufacturers have invested in technology to increase efficiency and keep up with the increasing competition from other firms or markets. Therefore, Saudi Arabia represents an appropriate case to identify potential participants for this research.

3.2.2 Identification of Experts

The researcher reached out to a small factory owner in Najran, Saudi Arabia, asking for potential participation in the research. Once the approval was secured, the researcher asked the factory owner to prepare a list of potential participants. The owner was asked to only include the name of people who own or operate small to medium-sized factories and have implemented Industry 4.0 technologies. Nine technologies were listed for the owner to help him identify the names. These were: the internet of things, simulations, big data, cybersecurity, 3D printing, additive manufacturing, robotics, smart sensors connected to other technical systems, and physical/cyber integration. The owner was asked to list as many names as possible, resulting in a list of ten people who own or operate factories across Saudi Arabia.

Each contact on the list was called using the information supplied by the first participant, the owner of the water bottling facility. Seven individuals indicated that they have not heavily invested in industry 4.0 technologies, and therefore they do not feel confident to provide valuable information to this research. Three individuals indicated that they have applied for some form of Industry 4.0 in their facilities.

One of them purchased a cloud-based data management system and a cybersecurity platform to help the facilities better protect consumer information. This individual owned a medium-sized factory that produced dairy products for national and regional wholesalers. The second individual owned a small factory that manufactures date cookies in northern Saudi Arabia,

and indicated they invest in big data analytics services. His goal was to identify potential markets in the West for his booming product which has already been exported to 19 nations. He indicated that for every purchase, the system collects much information and generates profiles of similar buyers by using a regularly updated database of small and medium grocery store chains in 158 countries. The third owner operated a factory that produced customized furniture for wealthy clients. Since each product is made to exacting standards, the owner invested heavily in smart sensors. The sensors are connected to machines that stop working autonomously when the sensor detects misspecification on the product used on the line. The defect is then augmented on a screen to the operator with pre-formatted messages on what to do next.

Once the initial three owners agreed to participate in the research, each of them was asked to recommend one name to recruit more individuals to partake in the research. Three more individuals were identified. One of them apologized, stating that he is sick and dealing with health-related issues. The remaining two individuals accepted the invitation. One of them operated a facility that manufactures paint and indicated that in early 2022 he invested in a new system that detects machine downtime. The system is prepared by a German manufacturer and is used to self-collected information about the operation of the machine and then suspend its operation for maintenance when a need arises. Lastly, the second individual operates a facility that manufactures small frames of plywood used in construction. While the facility gets its raw materials from other countries, it uses newly purchased processors to make the frames ready to be used in commercial and residential buildings. The owner invested in sensors that detect dimensions and sizes when preparing the frames, and the systems display defects on a screen while instructing operators how to adjust the position of the materials fed into the processor in order to guarantee perfect dimensionality.

All participants in the study are males. They are also all owners of their facilities who have high levels of expertise in manufacturing. Each of these experts are natives from Saudi Arabia though they have extensive world travel and speak English fluently. All owners came from their industries, previously working for several manufacturers. Table 3.1 provides an overview of experts, products, and industry 4.0 technology used.

Table 3.1. Overview of Experts

Owners	**Products**	**I 4.0**
Khaled Alyami	Water Bottles	Industrial Internet of Things
Mohammed Alwaela	Dairy Products	Cloud Computing
Ali Alamri	Food and Beverages (Date Cookies)	Big Data Analytics
Fahad Albalawi	Customized Furniture	Smart Sensors and 3D Printing
Saeed Alahmedi	Paint	Industrial Internet of Things
Salman Alotaiwi	Plywood	Industrial Internet of Things and Simulation

Notes. Pseudonyms are used for the owners listed above.

3.3 Data Collection

3.3.1 Focus Group

Focus groups are appropriate data collection methods for gathering input from a small number of people with similar characteristics. Further, focus groups present efficient techniques to obtain information from a limited number of individuals (between 5 and 10) in the same setting. Additionally, when participants come from the same context, culture, and setting, focus groups are likely to provide in-depth information about the phenomenon because participants feel comfortable seeing similarities in profiles that elevate levels of trust. Focus groups are safe discussion forums where every participant feels free to contribute to the ongoing debate. This research held an online

focus group via Zoom with the six Saudi factory owners who are experts on Industry 4.0 implementation in small and medium enterprises.

The moderator of the focus group was the researcher. One reason behind this choice is the high expertise level of the researcher in Industry 4.0 and manufacturing. Further, the researcher is a Saudi citizen who is fluent in both Arabic and English and is familiar with the manufacturing environment in the country. Such factors have created a sense of trust, making participants more likely to furnish important information from their experiences in implementing Industry 4.0 in manufacturing. The moderator allowed for a few breaks throughout the session. During the break, some notes were recorded to capture important themes along with vibrant discussions. Since the focus group took place via Zoom, there was minimal need for a second moderator who handles logistics. Two of the participants objected to the Zoom videoconference being recorded, therefore the session was not recorded. Nevertheless, the moderator secured permission for a transcription of the answers by having each participant record his voice without the use of video features. Each participant used the WhatsApp recording feature to share the answers once the focus group was complete.

The first portion of the focus group was meant to familiarize participants with the topic. Afterward, the moderator began with the following statement "Welcome to the 2-hour focus group session on Industry 4.0 implementation in manufacturing in the developing world…. Today, we will discuss the important factors that drive or inhibit the adoption of Industry 4.0 technologies in manufacturing facilities." The moderator then began by having each participant introduce himself and his experience in manufacturing. Once every participant introduced himself, the moderator showed all participants the nine technologies considered to be Industry 4.0 mentioned in the sampling section above.

Once participants established familiarity with Industry 4.0 technologies, the moderator shared the following statement on the most cited factors in the literature affecting manufacturers' decision to invest in Industry 4.0. The moderator stated, "based on an extensive review of the literature, the following factors were found to be linked with the decision of a manufacturer to invest in Industry 4.0." This was followed by displaying a list of the 10 factors outlined previously. Then, the moderator shared a word document exhibiting a table with all participants. The table included the names of factors listed in a column and a row, and the moderator asked all participants to take a look at the document. Once every participant noted his familiarity with all the factors, the moderator began asking questions to officially begin the focus group content discussions.

The moderator asked each participant to consider the bivariate relationship linking each of the 10 factors for the implementation of Industry 4.0. For instance, the moderator asked participants to indicate the type of relationship linking cost and workplace disruptions. The types of relationships were explained to participants. There were four choices available to choose from per bivariate relationship. These were one-directional linking Industry 4.0 implementation to the factor, one-directional linking the factor to Industry 4.0 implementation, two-directional linking both variables together, and nonexistent (indicating an absence of a relationship). The moderator instructed each participant to indicate his choice before justifying it to ensure that everyone provided a determined relationship. Once all choices were taken, participants were allowed to discuss their choices for 7 minutes per bivariate relationship. This amount of time allowed each individual to indicate his logic behind the determination of the association provided earlier.

The moderator took note of each participant’s choice per bivariate relationship. Once discussions for all relationships were complete, the moderator informed all participants that he will share the results of the focus group with all of them. Based on the result, the moderator constructed

a model that describes Industry 4.0 implementation in manufacturing. The survey solicits participants' perceptions of the model. All participants agreed to complete the survey via WhatsApp.

3.3.2 Survey Method

This research used a questionnaire to gather experts' feedback on the constructed model by describing the relationships between the factors and Industry 4.0 implementation. The survey contained several measures asking the six experts whether the model accurately reflected their perceptions of the associations linking the variables or not. Further, the survey asked participants to indicate their agreement levels with regard to several statements describing the model. More importantly, many items on the questionnaire asked participants to rate descriptor statements demonstrating the designation of each factor within the newly developed model.

All participants completed the survey using WhatsApp. The researcher shared a copy of the questionnaire shown under the subtitle of Questionnaire in Chapter 3. Each response was collected by the researcher and inserted into a spreadsheet on IBM SPSS. It took participants an average of 15 minutes to complete the survey. The shared copy was accessible through Google Forms. Survey items were written in English, and the researcher was available to answer any questions concerning the clarity of all items within the research.

Notice that all items on the survey utilize a feeling thermometer response type. Compared with traditional Likert-based measurement, feeling thermometers are capable of producing more variation and accurate interval-level data. Respondents are not restricted to 4, 7, or 10 categories, but could choose any number between 0 and 100, making their self-reported data more representative of the true score on the set of variables measured. Further, when descriptive statistics are used, it is more appropriate to have more than a limited number of categories to construct

means and medians. Further, more variation within each variable allows inferential models to better detect statistical relationships linking variables.

3.3 Data Analysis

3.3.1 Interpretive Structural Modelling

Interpretive Structural Modelling (ISM) Is a heuristic tool providing descriptive information concerning an interdisciplinary phenomenon. To a large extent, the method relies on expert knowledge gained through practice and experience to aid applied decisions in organizations. Oftentimes, researchers mine the literature on a specific topic or elicit tacit knowledge from a small group of individuals who are considered expert researchers and practitioners within their own field. Then, researchers combine the information collected to formulate tables and graphs that summarize the driving and dependent forces within a specific domain.

In the year 2020, more than 1200 peer-reviewed articles were published using ISM as a research strategy, confirming the popularity of the technique. About 71% of all papers published using ISM are generated in India, the US, China, the UK, and Iran, testifying to the far-reaching limits of the methodology all over the world. Within the field of manufacturing, the method has been applied to study many topics, especially new practices within the domain. Previously, the method has been applied to analyzing Industry 4.0 use in factories. Nevertheless, none of these studies focused on the developing world or small and medium-sized enterprises.

ISM supplies decision-makers with structures of variables affecting a specific phenomenon. Based on available scholarly information and feedback from experts, matrices of interrelations are constructed and then converted into graphical representations of the associations. Based on the output of ISM, researchers may resort to the use of MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée á un Classement, i.e., cross-impact matrix multiplication applied

to classification) to classify all variables into dependent, independent (driving), linking, or autonomous. Such classification helps decision makers ascertain their affordances for change underlying conditions that generate desired outcomes in the area of application concerned.

ISM follows a series of steps to be performed. First, the researcher needs to specify a set of variables or elements that explain the main outcome. This identification could be achieved either by conducting a thorough review of the literature or by asking a set of experts in the field. In this research, the main phenomenon of interest is Industry 4.0 implementation**.** The main purpose of this research is to identify the factors that affect decision-makers' adoption and implementation of Industry 4.0 in factories located in the developing world. A comprehensive review of relevant research identified 10 distinct factors that have been widely cited across several studies. The ten factors are prohibitive costs, absence of talent in the workforce, information security and privacy concerns, unclear regulatory environments, integration challenges, management resistance, workforce resistance, unclear return on investment, natural disasters, and workplace disruptions.

The second step in ISM is the creation of the Structural Self-Interaction Matrix (SSIM). SSIM is a correlation-like matrix with all identified factors listed in a column and a row. The researcher inserts a relationship linking each factor with the other. Four choices are available: factor 1 only directly influences factor 2, factor 2 only directly influences factor 1, factor 1 and factor 2 are both related and influence each other, or factor 1 and factor 2 are unrelated. Each relationship is translated into a universal letters system as V, A, X, or O respectively in the matrix. The choice of relationships relies on either the overarching consensus of experts or the thorough literature review conducted by the researcher. To better help readers understand the four choices of relationships, the following rules were prepared to guide this research. Based on the literature review, the researcher prepared the SSIM matrix in the ISM analysis.

The third step in preparing the ISM output is the construction of the reachability matrix. Here, the researcher replaces the universal letters V, A, X, or O with either 0's or 1's. If the relationship in the SSIM was X, and both variables affect each other, then the value in the reachability matrix is 1. If the relationship in the SSIM was O, there is an absence of relationships, and the O's are then replaced with 0's in the reachability matrix. A variable within itself is considered to have a reciprocal relationship with itself, and therefore the diagonal values of the reachability matrix will be 1's. All Vs, one-directional relationship from factor 1 to other factors will be replaced with 1's. All one-directional relationships linking other factors to factor 1, the As, will be replaced with 0's. The following rules were conducted in this research to prepare the reachability matrix.

For each variable in the reachability matrix, two values are calculated. Driving power is the sum of 1's and 0's along the rows of each variable. Dependence power is the sum of 1's and 0's along the columns of all variables. Since there are 10 factors in this research, the driving and dependence values will not exceed 10. Then, transitive relationships are checked in the reachability matrix to ensure that all relationships are accounted for.

Partitioning of variables, four sets of variables, are then estimated. First, the reachability set consists of the variable itself and all factors it impacts directly. Second, the antecedent set consists of the variable itself and all factors impacting that variable in unidirectional form. The interaction set consists of the variable itself and all other factors shared by the reachability and antecedent sets. Lastly, the level set consists of the similarities between the reachability set and the interaction set.

Within the partitioning of variables to determine the level, the researcher looks at the reachability and intersection sets. If they are identical, then the variables within both sets constitute

the top level. Then, these variables are removed from the determination of the next level. The process continues until each variable is given a level in the hierarchy.

Once all levels are identified, a digraph is created to represent the hierarchy of variables in graphical form. All variables are written in rectangular boxes. Each set of variables within the same level is linked with each other using arrows moving horizontally across the same level. Then, once the next level variables are introduced to the diagram, they are vertically linked with the level preceding them. Each variable is then linked with all variables in the level placed on top of it in the hierarchy. The process continues until all variables are linked with their respective factors, and the final product represents the digraph of the ISM model describing relationships among the original factors.

Finally, a classification of variables into autonomous, dependent, driving, or linking is performed using the MICMAC approach. Each variables' driving and dependence powers are considered to determine the classification. Two axes are prepared, each corresponding to the driving of dependence powers. Then, variables are placed in one of the four quadrants depending on their scores. The final diagram shows the placement of all variables, informing decision makers about the power of each original factor and explaining the phenomenon under investigation.

3.3.2 Thematic Analysis

Thematic analysis is used to identify patterns within qualitative data. The researcher mines the textual information collected to generate summative and interesting themes that describe the corpus in succinct ways. Each theme represents a general idea with subcomponents, all corresponding to an overall thought [219]. While there are several ways to conduct thematic analysis, the most compressive way is the six steps (sections) following [219].

3.3.2.1 Build familiarity. The researcher needs to build familiarity with the data prior to conducting the thematic analysis. For this research, the corpus of text is represented by the extensive notes taken by the researcher throughout the focus group. A total of 13 pages of notes recording verbal and non-verbal observations were prepared as the input for this research. As an initial step, the researcher read the manuscript twice in two distinct ways to be familiar with the information. First, the 13 pages were distributed to different elements of the focus group. Each participant was given a distinct section and all his comments were organized following this strategy. Next, the researcher read all 13 pages at once without organizing the text in the section. The two readings took place on separate days and times to ensure sufficient time to digest the material.

3.3.2.2 Generate Initial Codes. Once familiarity was established, the researcher began the second step by generating initial codes. The 13-page manuscript distributed to each participant was taken as the input of this step. As the researcher read the manuscript, initial codes were built. For instance, if participant 1 indicated that “to me, costs are the most important factor," a code called "cost importance" is constructed. Each sentence was taken on its own in the manuscript. If new ideas were generated, new codes were built. Each participant possessed a separate table of codes. Notice that many of the initial codes were represented in each participant’s table.

3.3.2.3 Construction of Themes. New themes represent a set of related codes. To accomplish this step, each participant’s table of codes was read twice. Then, themes per participant were constructed by placing all related codes into the same theme. Once a list of themes per participant was prepared, a universal list of themes for all participants was made by eliminating redundant themes across the six lists. The product was a list of themes that represented all observations from the six participants.

3.3.2.4 Reviewing Themes. To better guarantee the accuracy of the new universal themes list, a number of exercises were taken. First, the researcher reread the manuscript to ensure that all the themes within the list are represented in the text. Second, the researcher handed the list of themes and the manuscript to an independent researcher who is an expert in qualitative research. The resulting outcome was that the independent researcher confirmed the accuracy of all extracted themes, finding they were sufficiently represented in the text of the data. Next, the researcher counted the frequency of statements corresponding to each theme on the list. Each theme was at least represented by 10 statements, adding confidence to the universal list of themes extracted.

3.3.2.5 Defining Themes. Once the universal list of themes established credibility and confirmability, the researcher defined each theme describing its self-reported domains by the participant. Each domain was also defined within each theme to supply readers with a fine-grained list of patterns describing the verbal and non-verbal textual data of the focus group. A conceptual map of themes connecting them to their domains was also prepared to graphically convey interrelationships among themes to readers.

3.3.2.6 Write Up. The writing of thematic analysis results focused on explaining the meaning, relevance, and impact of each theme. Results were presented in both tabular and graphical formats to explain the most interesting patterns observed within the text. Clear definitions of themes and domains were provided to readers to help them distinguish between extracted patterns. Rich excerpts from the focus groups were utilized to illustrate the meanings of the theme and how participants expressed them throughout the session.

3.4 Survey Data Analysis

Descriptive statistics were used to summarize the results of the follow-up survey. Means and standard deviations for each item on the survey were reported in a table. Then, each

participant's feeling thermometer scores per item were displayed using bar graphs. Summary statistics per item were provided, including minimum, maximum, mean, and standard deviations. Variability graphs, including box plots, were shown to describe the differences in responses observed in the data.

3.5 Summary

This chapter described the mixed-methods approach used to complete the research on Industry 4.0 facilitators and barriers in small and medium sized enterprises in emerging economies like Saudi Arabia. First, the chapter fully detailed the way experts have been chosen to conduct the focus group and the survey in order to fulfil the methodology of the research. The selection of participants has been outlined and justified by the fact that each expert has extensive profiles in the manufacturing sector within the Saudi economy. The chapter provides information on how the focus group data was analyzed by using thematic analysis. Further, the design and development of the follow-up survey and its descriptive analysis were discussed in detailed terms to allow readers an understanding of every step involved in the analysis process. Further, the interpretive structural modeling procedure was furnished to readers describing each phase along the investigation. The chapter highlighted the merits of the mixed-methods approach and the rationale behind the interpretive research methodology.

Chapter Four

Results

4.0 Introduction

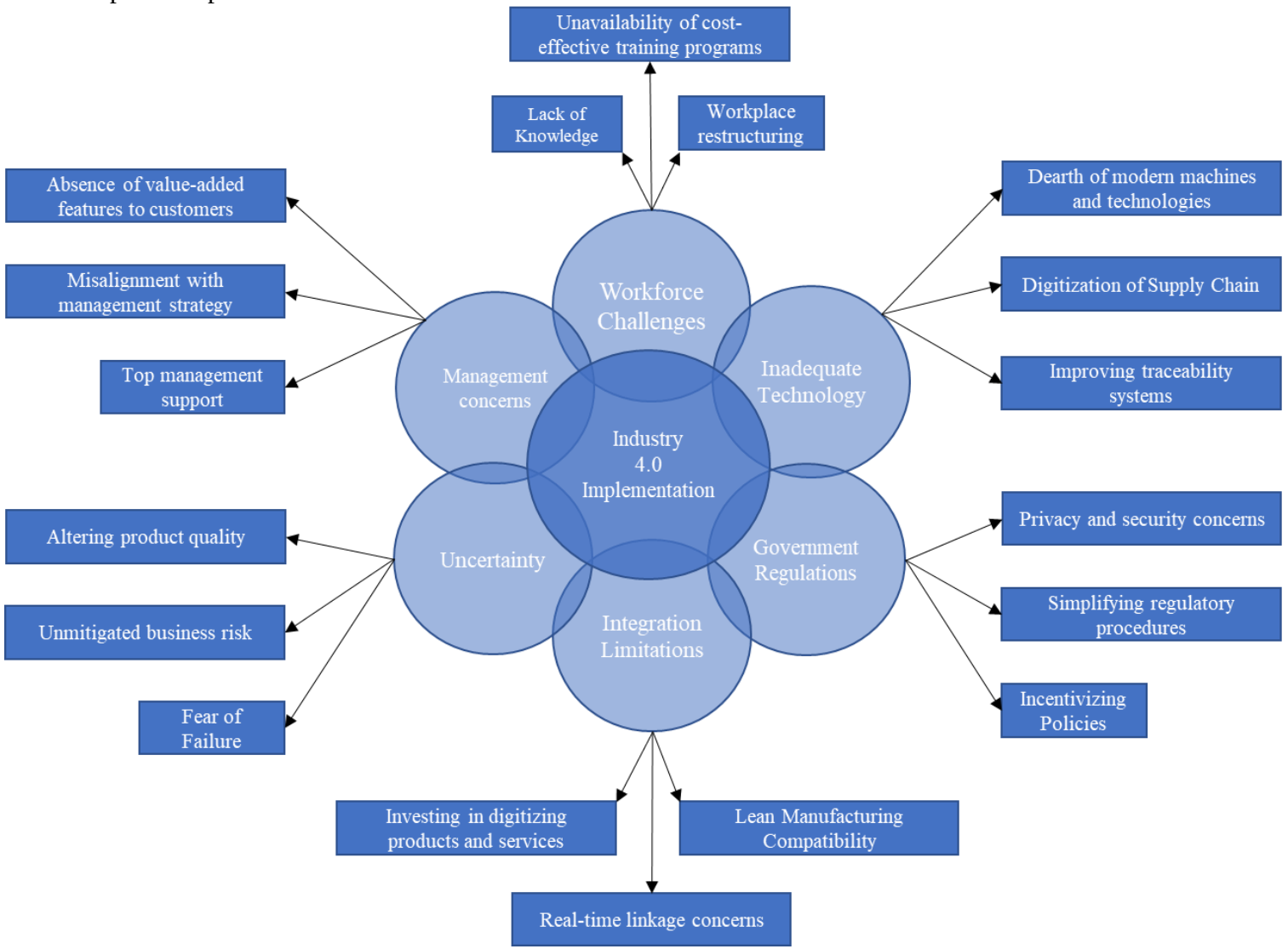
This chapter demonstrates the results of several qualitative and quantitative analyses performed throughout this research. The discussion begins by showcasing the thematic understandings concluding that the six experts were concerned with six themes: workforce challenges, management concerns, uncertainty, integration limitations, government regulations, and technology challenges. Each theme has subcategories that represent its multidimensionality. Following the conceptual mapping of themes and their dimensions, input matrices for the ISM analysis were presented. The matrices presented the driving independence powers of each variable by using expert readings. Additionally, a questionnaire was developed to validate initial perceptions by the experts. Note that results are all analyses confirmed by one another's findings. Details of each analytical approach and its sub-components were provided to readers guaranteeing a better chance for replication.

4.1 Thematic Analysis

There are six themes that decribe experts' opinions on the implementation of Industry 4.0 in developing and emerging countries like Saudi Arabia. Prior to the presentation of themes, note that cost was discussed in all of the reported themes, and therefore was not interpretted as a separate theme. The underlying six themes by experts toward focus questions are: workforce challenges, management concerns, uncertainty, integration limitations, government regulations, and technology challenges. Within each theme, there are several categories that describe the various manifestations of the them. Table 4.1 contains all themes, and their corresponding coding categories found across responses of all experts. Note that a category was identified as a recurring

element within the responses by experts during the focus group session. Each element or coding category was mentioned by at least 3 experts to be considered as such. Figure 4.1 displays the themes and their categories graphically, showing their relationship with Industry 4.0 implementation.

Figure 4.1. Conceptual Map



4.1.1 Theme One: Workforce Challenges

One of the recurring concerns of all experts throughout the focus group is an unprepared workforce for handling the shift to Industry 4.0 [227]. Experts unanimously agreed that there is a shortage of talent in the marketplace that is compatable with required skills demanded by the high, technologically savvy, machines that enable Industry 4.0 to materialize. Similarly, expert 3 indicated that many workers, as well as leaders, are unaware of the basic value and benefits of Industry 4.0, presenting a serious challenge for its implementation. Similarly, the availability of affordable training workshops for Industry 4.0 technologies is limited. Many investors are disuaded from investing in new technologies because of high costs associated with human capital investment. The fear of job loss because of increased automation inside factories makes many workers unwilling to support the shift to Industry 4.0. Experts indicated that there is a general concern among their workers that eventually all human labor will be eliminated by autonomous technology. They echoed the need for performing training for all workers in order to increase their awareness about the need of human capital even if all elements of manufacturing within a plant becomes smart.

4.1.2 Theme Two: Management Concerns

All experts referred to management support as a critical success factor for the adoption and implementation of Industry 4.0 (Rosin et al., 2020). Expert 6 suggested that many managers believe that Industry 4.0 does not bring value to customers, and therefore it should not be implemnted. Such a view only considers the machine-to-machine interaction, and ignores the many benefits technological advancement offers to product design and service delivery as expert 2 argued. Lack of top management support for any change in manufacturing strategy or approach leads to failure in realizing desired outcomes. All stakeholders across all divisions must believe in

the value of Industry 4.0 to achieve its long-term benefits. Managers need to allocate financial resources, sufficient time, and leave room for experimentation. Experts concluded that owners and managers at all levels need to be well informed and engaged in the change from traditional to high tech manufacturing. Detailed project management procedures are needed to ensure that the investment yields its expected objectives in a timely manner.

4.1.3 Theme Three: Uncertainty

Many experts referred to uncertainty as an important factor that prevents investors and leaders from implementing Industry 4.0. Expert 1 argued that many people are afraid of failures. In the manufacturing world, stories of devastating investments spreads quickly and thwarts the aspirations of many entrepreneurially-oriented individuals. Many experts coined business risk as a major driving force in making investors reluctant to implementing Industry 4.0. The financial, human, and technological investment carries several unmitigated business risks that could outweigh perceived benefits for a considerable proprotion of individuals in the manufacturing world. One of the most important areas of concern communicated by experts is product quality. Some experts believe that increased automation and the elimination of human validation may alter the quality of products. Such a scenario means consumer disatisfaction translated into lower sales. Therefore, few experts considered unpiloted investment in technology to be inept.

4.1.4 Theme Four: Integration Limits

Experts also noted the significance of appropriate physical, cyber, and remote integration of all components in order to ensure the success of Industry 4.0 implementation. Expert 4 emphasized the readiness level of facilities prior to making any shifts. He suggested that manufacturers implement Lean Manufacturing in order to test their plants' integration levels prior to any major investment in Industry 4.0 technology or systems. Another important limit of

integration is the inability to connect highly contexualized machines with smart digital systems to produce real-time information. Oftentimes, manufacturers have specific systems designed to meet their own needs, and once integrated into larger autonomous technologies, much reengineering is required which prevents an easy transition. Further, the failure to incorproate Industry 4.0 investment into the organizations' overarching strategic plan is likely to lead to other disastorous failures according to a few experts. The actual gains of Industry 4.0 must be delineated in a strategy that is compatible with the organizations' overall direction. Similarly, the experts unanimously advocated for active top management support in order to ensure the success of Industry 4.0. When everyone at the top of the pyramid genuinely believes in the value of the investment, more resources, tolerance, and persistence are fueled in the journey of shifting legacy systems to modern Industry 4.0 platforms. Few experts reported the need for making products and services smart. Such a call is motivated by the ease of connectivity created with sensors and linking technologies between floor machines and manufactured goods.

4.1.5 Theme Five: Government Regulations

Some experts signaled the necessity of incentivizing the role of governments in order to accelerate the implementation of Industry 4.0. On the one hand, Industry 4.0 is associated with colossal financial investments and governments have a stake in developing local manufacturing sectors so they can become more efficient and effective. One proposition made by an expert is the institution of subsidized programs by government agencies overseeing manufacturing policies to increase interest in the area [150]. Experts indicated their disatisfaction with contemparary government regulations concerning purchasing large technological devices from foreign firms. One expert provided an illustration where he reported the need to complete too many forms on paper. Further, he needed to explain current regulations to government officials who were not even

aware of the law. The rise of privacy concerns also discourages several investors from making products smart. Government regulations are frequently unclear in many instances on what legal information could be collected and what is not. Further, when systems are smarter they by default collect information from users' machines. Such information could prove legally challenging if consumers challenged manufacturers on their ability to access such information in courts.

4.1.6 Theme Six: Technology Challenges

Century old legacy systems are common in developing world manufacturing facilities. Experts agreed that for Industry 4.0 solutions to be implemented, new technologies need to be installed across all stages of the manufacturing process. Modern machinery helps in integrating the various parts of the process better than archaic assembly lines or machines. Numerous experts alluded to the insufficient prevalence of digitized supply chain systems across small and medium sized enterprises and the developing world. Starting with digitization at the supply chain level increases the chances of implementing more Industry 4.0 in reference to the experts' opinions. Few experts indicated the importance of enhancing traceability technologies for products. Such an improvement would pave the way for further investment in Industry 4.0. Another challenge shared by experts is the difficulty in designing compatible technical infrastructures that support Industry 4.0 implementation. Energy, connectivity, human resources, and device availability requirements are high for Industry 4.0 applications to be successful, and in many situations, such prerequisites are difficult to secure in the developing world.

Table 4.1 presents the themes, their codes and illustrations. There are six themes describing experts' responses to the focus group concerning Industry 4.0 implementation. The themes are: workforce challenges, management concerns, uncertainty, integration limits, government

regulations, and technology challenges. Each of the themes have several codes. Note that each theme was supported by an illustration from all experts.

Table 4.1. Themes and Coding Categories

Theme	Codes	Illustrations
Workforce Challenges	Lack of Knowledge	Expert 3 stated “If I have an honest conversation with the employees at my plant about Industry 4.0, the most educated amongst them would not even know what it is, let alone others working on the assembly line.” Expert 4 stated " you got to realize we are in Saudi Arabia. Wages for manufacturing jobs here are not the highest. Therefore, the talented individuals would not be here. Most of our workers do not understand the returns on investing in Industry 4.0"
	Unavailability of Cost-Effective Training Programs	Expert 5 stated that “Imagine I invest in purchasing new machines and assembly lines for my plant. The new machines require good training. If I hire 2 or 3 people that quit within a year, then I am in a hostage like situation where I cannot let them go before training others. If you shop around, you will find good training programs, but the price tag is too prohibitive.” Expert 1 stated " to my knowledge, Arabic language training on Industry 4.0

		technologies is very limited, and that is if it is even available."
	Workplace Restructuring	Expert 2 reported that “one of my line supervisors told me that if we keep purchasing machines that work on their own, we will have hard time convincing any good worker to stay. The overall impression I got is that many workers believe that machines will eventually replace them. I think it is good to do some education for workers on future work structures.” Expert 6 stated " there is a general fear of jobs loss. Workers are hesitant to commit because technology is taking over."
Management Concerns	Absence of Value-Added features for customers	Expert 6 stated “for us, Industry 4.0 is about machine-to-machine transaction. It simply helps machines detect errors in other machines, and autonomously handle the issue. Customers do not care about our factories; they care about their products. In many industry leaders’ opinions, Industry 4.0 does not add value to customers’ experience”. Expert 1 reported " if I buy more machines, I need to price my goods higher in the market. I'm unsure if consumers really would

		benefit from the use of such machines."
	Misalignment with management strategy	Expert 2 indicated that “when I try to make any change in my organization, I consider the short, medium, and long-term strategies within my mission and vision. Industry 4.0 will change many faces of a facility; it must be incorporated into the larger strategic management plan.” Expert 3 stated " there is a constant struggle with management with any decision involving the purchase of machines. There's a fear of shifting the strategy."
	Top management support	Expert 5 explained that “top management needs to be plentiful and materialistic in real financial investments. Top leaders like owners or operation managers need to communicate the change to workers and believe in it. They need to award more paid hours for learning, be tolerant of affordable losses, and most importantly positive about the implementation of Industry 4.0.” Expert 4 said "alienation is an inevitable outcome. Many mid and senior managers, those who you really rely on, would not like the complete digitization idea."

Uncertainty	Fear of Failure	Expert 1 suggested “the worst thing ever for an investor is a huge failure. Investing in the unknown is something undesirable in any industry. Fortunately, many factories are owned and operated by experts who appreciate the role of technology. Others are not, they are afraid of failures. Industry 4.0 is a large animal many are not daring to touch.” Expert 2 indicated "when you talk to American investors in fairs, they got mixed opinions on the returns. No one is certain about the outcomes here."
	Unmitigated business risk	Expert 6 stated that “investing in Industry 4.0 is too risky for many in the manufacturing world. You pay a lot of money and train some people in advanced use of technology without really knowing if you need it or not Many things could go wrong when you purchase all the stuff associated with Industry 4.0.” Expert 4 stated" once the risk is taken, it is impossible to undo the change. I am not fully convinced that this is a good risk to take in current markets. I am afraid that industry 4.0 is another buzz thing like floating ideas once in a while."

	Altering product quality	Expert 5 reported that “when machines make a product, they are consistent. Are they quality? If we eliminate human checks, the answer may be no. If our products are not good, no one will buy them. Machines and smart technologies make our costs lower, but do they play with the quality, maybe, if yes, it is disastrous.” Expert 6 stated " The bottom line here is that such machines produce high quality products customers would buy. Si far, not everyone believes in this."
Integration Limitations	Lean Manufacturing Compatibility	Expert 4 stated “without proper integration, Industry 4.0 is doomed to failure. One of the easier ways to pave the road for the shift from traditional manufacturing to Industry 4.0 is the implementation of Lean Manufacturing to improve integration as a whole in a facility”. Expert 5 reported "I invested in different technologies in the past ten years alone. Would this industry 4.0 work well with my systems? I am not sure about this."
	Real-time linkage concerns	Expert 6 stated that “linking digital systems with physical machines to produce real-time usable information to make autonomous decisions

	Investing in digitizing products and services	is the most difficult endeavor to achieve in Industry 4.0." Expert 2 stated " I attended a workshop on big data recently. The Expert mentioned a concern with updating the information momentarily. The issue is that systems have varied infrastructures." --- Expert 1 claimed that "once our products are linked with sensors, the implementation of Industry 4.0 becomes easier to me, you can't really ask for Industry 4.0 without making your stuff smart. Everyone likes the smart thing nowadays, and it makes it much easier for you to get and test new technologies, and eventually implement Industry 4.0." Expert 3 reported " I got to fill my plant with sensors and tracking devices. Is that easy? No. But, a full integration with industry 4.0 requires it, and I'm uncertain about the actual viability of integration. "
Government Regulations	Incentivizing Policies	Expert 5 indicated that "to facilitate the transition into Industry 4.0, governments need to provide subsidies to manufacturers interested in innovation." Expert 1 said " the government constantly changes policy and advice.

		We are afraid of buying something that would be banned or heavily regulated."
	Simplifying regulatory procedures	Expert 6 indicated that "I wanted to get some licenses to purchase new machines from Russia and China. Government officials were not even aware of the regulations we have. We need to educate them on all procedures associated with technology purchases. Also, they have too many unnecessary forms that are not online. This needs to change for us to have it easy to make Industry 4.0 investments." Expert 2 suggested " the worry of obtaining licenses is real. We got to ensure that all agencies are on board with us. It is simply too complex."
	Privacy and security concerns	Expert 3 concluded that "our government is very active in the area of privacy. It is a newly growing area of legislation. If we trace anything, we have to make sure we do it right. Even when we make our products smart, they track information, sometimes the law is unclear about what to collect and what not to collect. We could be in a gray area many times." Expert 4 indicated " the whole cyber-attacks issue

		scares everyone now. More online technologies make your business probe to more risks. The government here is very tough now on data breaches."
Technology Challenges	Dearth of modern machines and technologies	Expert 1 “when I ask you to walk into all the factories in the nearby area, and then go to Germany and observe their facilities, you notice one stark difference is technology. We cheap out on purchasing great functioning technology. They do not. To have Industry 4.0, we have to be realistic and assess how much technology we possess.” Expert 2 stated " technology is a challenge. We fund our operations out of pocket. Banks here are not as liberal as those in the US. They won't fund expansions. Therefore, technology is more limited here."
	Digitization of Supply Chain	Expert 3 stated that “we tend to forget the need for a good supply chain in the manufacturing world. When we digitize the supply chain, we make the first shift to Industry 4.0. We must make our machines able to choose for us. Disruptions killed many businesses today, using digital systems can help.” Expert 5 suggested " look at my neighbor making furniture during Covid 19. His business died because he could not get

		the wood needed. Globally, the supply chain was disrupted."
	Improving traceability systems	Expert 4 concluded that "making products smart requires traceability. Many manufacturers we have today in our vicinity do not simply trace their products. Some investment needs to be made in this area to make our factories ready to adopt any form of Industry 4.0." Expert 6 explained " we do not have the technology nor the supply chain. We need a lot of investment to improve things like smart products or even tracing our own goods."

4.2 ISM Results

Table 4.2 summarizes the six experts' views on the bivariate associations between the identified ten factors affecting Industry 4.0 implementation in the manufacturing sectors of developing countries. If five or more experts assigned the same designation to a relationship, that relationship was presented in Table 4.2. For instance, five experts decided to choose O to explain the association between prohibitive costs and workplace disruptions denoting an absence of direct impact between the two variables. Table 4.2 also represents the highest levels of agreement among the experts concerning all relationships, and therefore will be used to guide the remaining parts of the ISM analysis. Note that differences among experts amounted to less than 10%. In all relationships, at least five experts gave the same designation describing the association between a

pair of variables. Again, note that the following explanations describe each letter's meaning in the SSIM matrix.

Table 4.2. Structural Self-Interaction Matrix (SSIM)

	10	9	8	7	6	5	4	3	2	1
1 Prohibitive Costs	O	O	X	V	V	O	O	O	V	—
2 Absence of Talent in the Workforce	X	O	O	V	X	O	O	V	—	—
3 Information Security and Privacy Concerns	O	O	O	A	A	X	X	—	—	—
4 Unclear Regulatory Environments	O	O	O	O	O	A	—	—	—	—
5 Integration Challenges	X	O	V	A	X	—	—	—	—	—
6 Management Resistance	X	O	X	V	—	—	—	—	—	—
7 Insufficient Technology Infrastructures	V	O	X	—	—	—	—	—	—	—
8 Unclear Return on Investment	O	O	—	—	—	—	—	—	—	—
9 Natural Disasters	V	—	—	—	—	—	—	—	—	—
10 Workplace Disruptions	—	—	—	—	—	—	—	—	—	—

Note. Letter designations are obtained from Karadayi-Usta (2019) and provided below:

1) V: (i, j) entrance becomes 1, whereas (j, i) entrance becomes 0,

2) A: (i, j) entrance becomes 0, whereas (j, i) entrance becomes 1,

3) X: (i, j) entrance becomes 1, whereas (j, i) entrance becomes 1,

4) O: (i, j) entrance becomes 0, whereas (j, i) entrance becomes 0.

Table 4.3 represents the reachability matrix of all variables based on the structural self-interaction matrix. Within this matrix, each letter describing a relationship is changed to 0 or 1. Transformations helps in constructing summary indices that describe the power of each variable. Two particular features are of interest to ISM researchers, the driving and dependence powers of each variable. Driving power determines how much leverage each variable possesses in influencing other variable to occur. Dependence power refers to the number of variables needed to cause the concerned variable to occur. Each of the two powers per variable is shown at the end of the row and column corresponding to the variable.

Table 4.3. Reachability Matrix

Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Driver P.**
1 Prohibitive Costs	1	1	0	0	0	1	1	1	0	0	5
2 Absence of Talent in the Workforce	0	1	1	0	0	1	1	0	0	1	5
3 Information Security and Privacy Concerns	0	0	1	1	1	0	0	0	0	0	3
4 Unclear Regulatory Environments	0	0	1	1	0	0	0	0	0	0	2
5 Integration Challenges	0	0	1	1	1	1	0	1	0	1	6
6 Management Resistance	0	1	1	0	1	1	1	1	0	1	7
7 Insufficient Technology Infrastructures	0	0	1	0	1	0	1	1	0	1	5
8 Unclear Return on Investment	1	0	0	0	0	1	1	1	0	0	4
9 Natural Disasters	0	0	0	0	0	0	0	0	1	1	2
10 Workplace Disruptions	0	1	0	0	1	1	0	0	0	1	4
Dependence Power	2	4	6	3	5	6	5	5	1	6	43/43

Tables 4.4 - 4.8 demonstrate the various iterations conducted to reach the final levels of the ISM model. Note that a level is found when the intersection and reachability sets are identical. Once a level is identified, its components are removed from the reachability matrix. This process is followed until all levels are extracted. The levels will be used in designing the final ISM figure.

Table 4.4. Partitioning of Variables (Iteration 1)

Parameters	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,6,7,8	1,8	1,8	
2	2,3,6,7,10	1,2,6,10	2,6,10	
3	3,4,5	2,3,4,5,6,7	3,4,5	1
4	3,4	3,4,5	3,4	1
5	3,4,5,6,8,10	3,5,6,7,10	3,5,6,10	
6	2,3,5,6,7,8,10	1,2,5,6,8,10	2,5,6,8,10	
7	3,5,7,8,10	1,2,6,7,8	7,8	
8	1,6,7,8	1,5,6,7,8	1,6,7,8	1
9	9,10	9	9	
10	2,5,6,10	2,5,6,7,9,10	2,5,6,10	1

Table 4.5. Partitioning of Variables Iteration 2

Parameters	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,6,7	1	1	
2	2,6,7	1,2,6	2,6	
5	5,6	5,6,7	5,6	2
6	2,5,6,7	1,2,5,6	2,5,6	
7	5,7	1,2,6,7	7	
9	9	9	9	2

Table 4.6. Partitioning of Variables Iteration 3

Parameters	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,6,7	1	1	
2	2,6,7	1,2,6	2,6	
6	2,6,7	1,2,6	2,6	
7	7	1,2,6,7	7	3

Table 4.7. Partitioning of Variables Iteration 4

Parameters	Reachability Set	Antecedent Set	Intersection Set	Level
1	1,2,6	1	1	
2	2,6	1,2,6	2,6	4
6	2,6	1,2,6	2,6	4

Table 4.8. Partitioning of Variables Iteration 5

Parameters	Reachability Set	Antecedent Set	Intersection Set	Level
1	1	1	1	5

Table 4.9 Partitioning of Variables (Variable Levels)

Levels	Parameters	Variable Names
1	3,4,8,10	3 Information Security and Privacy Concerns 4 Unclear Regulatory Environments 8 Unclear Return on Investment 10 Workplace Disruptions

2	5,9	5 Integration Challenges 9 Natural Disasters
3	7	7 Insufficient Technology Infrastructures
4	2,6	2 Absence of Talent in the Workforce 6 Management Resistance
5	1	1 Prohibitive Cost

The ISM model in Figure 4.2 summarizes the experts' concerns about the adoption of Industry 4.0 in manufacturing. Unclear return on investment and regulatory environment, workplace disruptions, and the need to secure information and assets constitute the first level of variables in the industry 4.0 framework. In the second layer of concerns, experts place importance on the considerations for natural disasters and integration challenges. Once such concerns are remedied by proposals for Industry 4.0 adoption, experts believe that insufficient technology infrastructures influence the implementation phase. Once the technology barrier is addressed, management challenges are dealt with in the form of internal management resistance and the absence of a talented workforce capable of implementing the change. Finally, all the variables are linked to cost, which determines a great deal of the adoption movement.

Figure 4.2. Interpretive Structural Model

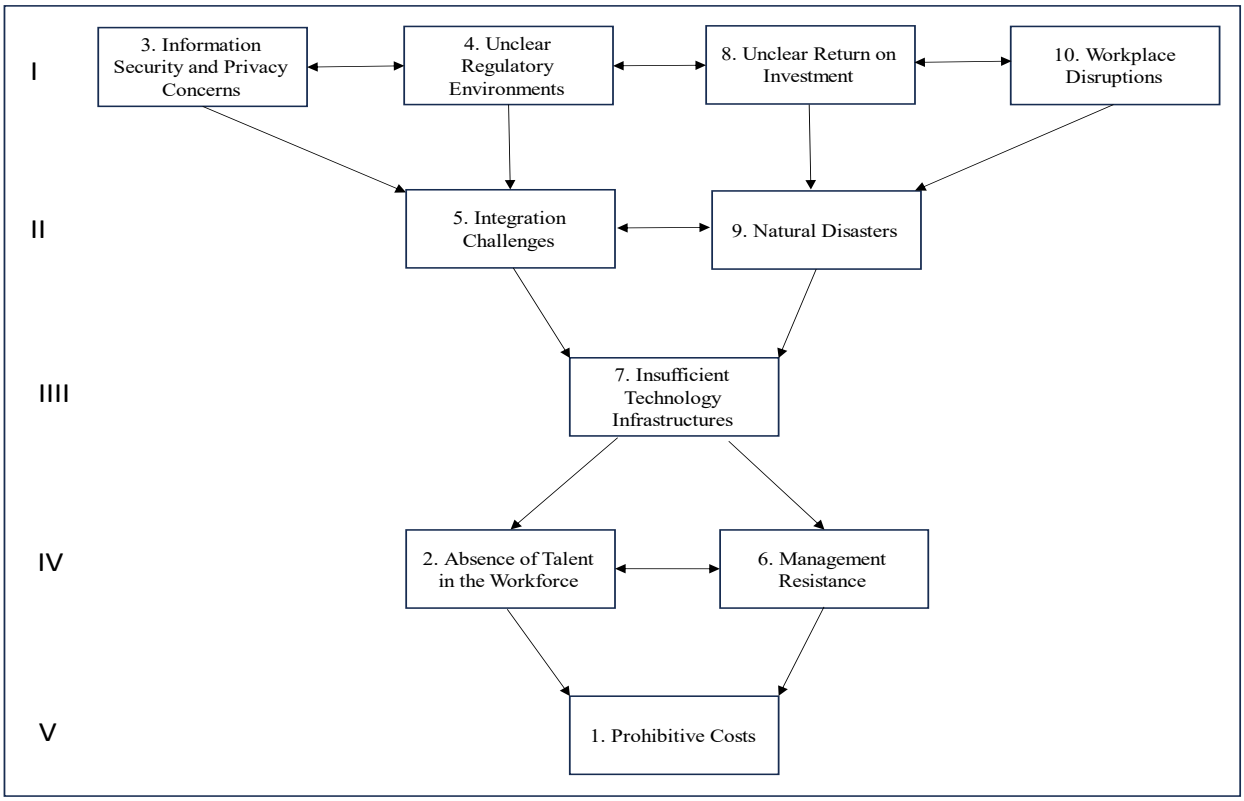
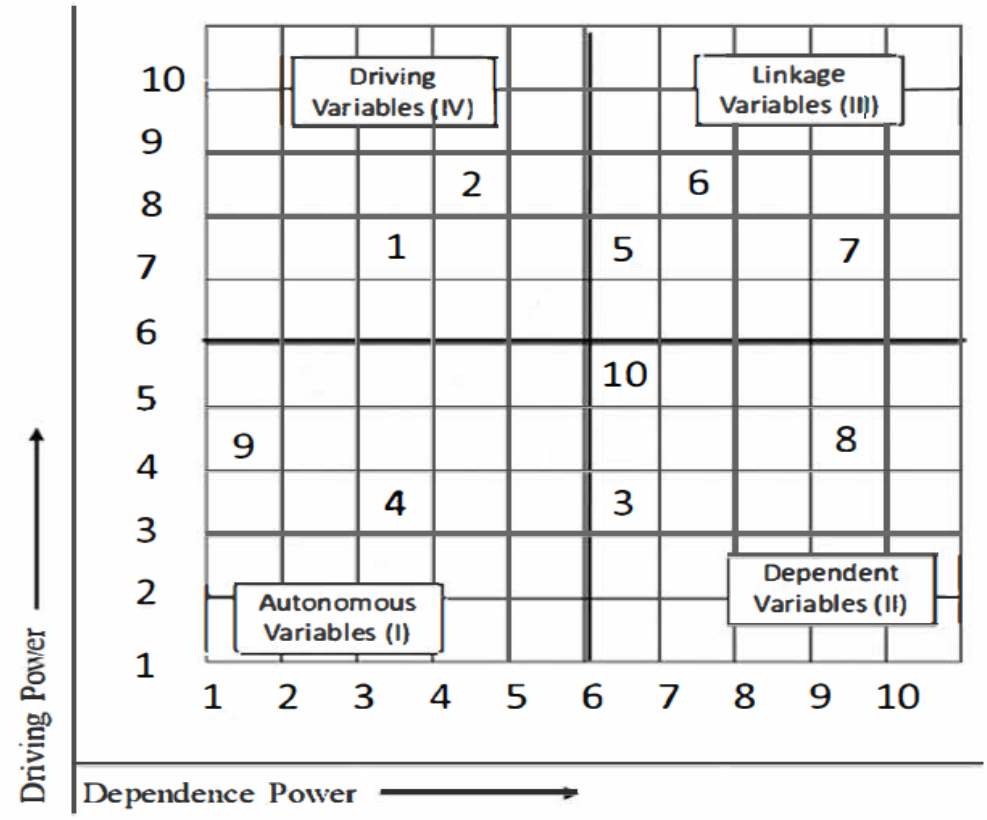


Figure 4.3 shows the distribution of factors based on driving and dependence powers. Natural disasters and unclear regulatory environments are independent of other factors. These two factors are autonomous. Prohibitive costs and science skills of talent in the workforce have high driving powers and low dependence power. The two variables cause many others to occur. Integration challenges, management resistance, and technology infrastructure inadequacy are linking variables. These three variables have high driving and high dependence powers. They link many variables together in the implementation of Industry 4.0. Unclear return on investment, workplace disruptions, and information security concerns are highly dependent on other factors. These three factors are affected by many factors included in the analysis. They possess low driving power and high dependence power.

Figure 4.3. Cluster of Variables



4.2.1 Survey Data Analysis

Figure 4.4 presents means and standard deviations for experts' ratings of the accuracy of relationships leading to the construction of the ISM model. Note that each statement asked experts to rate whether the relationship connecting Industry 4.0 implementation to the factor is accurate or not on a thermometer ranging between 0 and 100, with higher scores corresponding to more accuracy. All expert means exceed 80 on a 0-100 scale. Simultaneously, all standard deviations are at or below 20. Such a result indicates that experts rated all relationships leading to the construction of the model as being accurate. Further, the variation in responses is low, suggested by the small ranges in the standard deviations.

Figure 4.4. Standard Deviations of Experts' Ratings

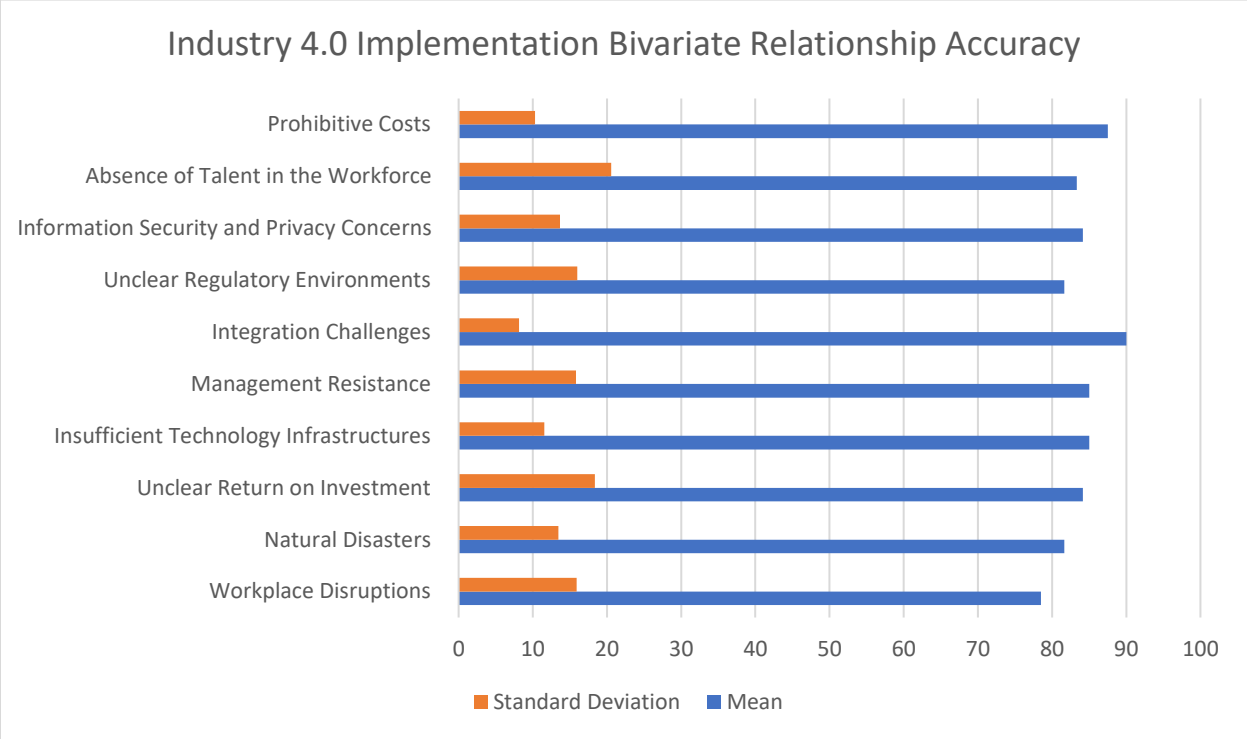


Figure 4.5 demonstrates the average agreement levels of all experts with five statements that describe the ISM model's accuracy. Examining all five means, one finds that they are at or exceed 80 on an agreement scale that ranges between 0 and 100 with higher scores corresponding to further agreement. The evidence is clear that experts believe that the ISM model is accurate. Looking at the standard deviations for each statement, one notices the low ranges indicating an overall agreement level for all statements among all experts.

Figure 4.5. Average Agreement Levels of All Experts with Five Statements

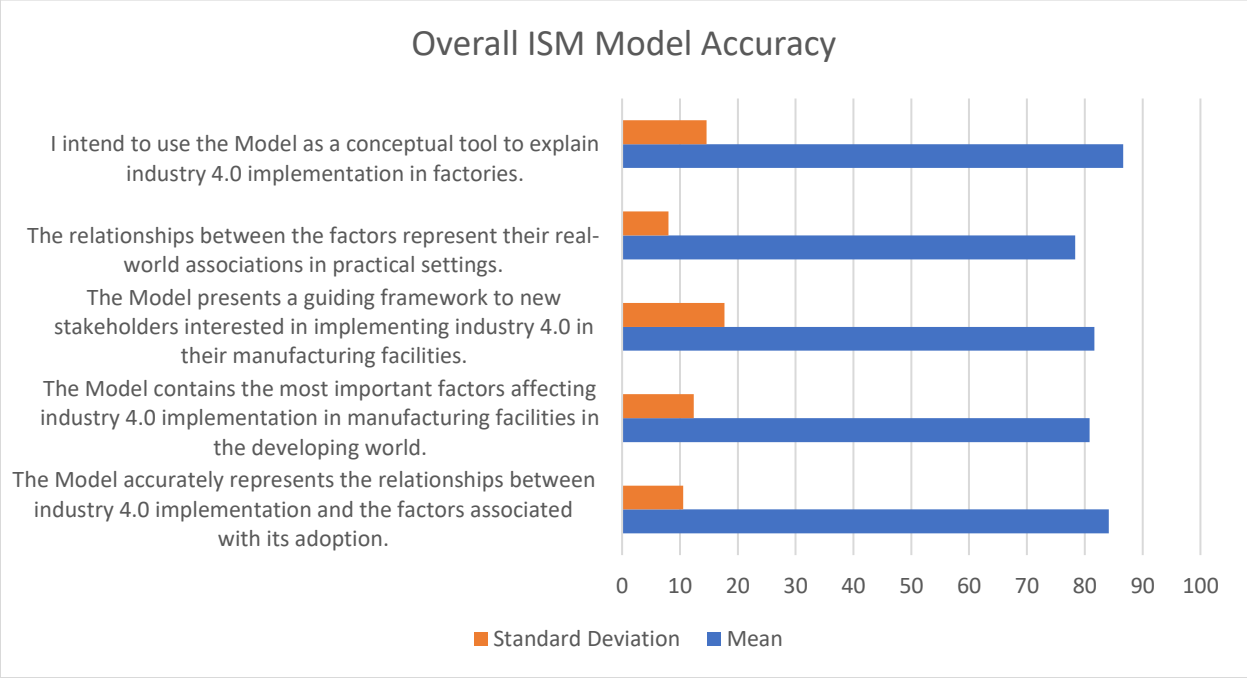


Figure 4.6 displays the means and standard deviations of experts' ratings of the placement of variables such as driving, dependent, autonomous, or linking based on ISM results. It appears that all means are at or exceed 80 on a scale ranging from 0-100, with higher scores indicating that the description of the variable is accurate. Overwhelmingly, experts believe that the designations of variables are accurate according to the ISM analysis. Such evidence supports the overall conclusion that the ISM results describe the underlying logics of experts. All standard deviations are relatively low, indicating a general agreement on the placement and designation of variables.

Figure 4.6. Standard Deviations of Expert Ratings

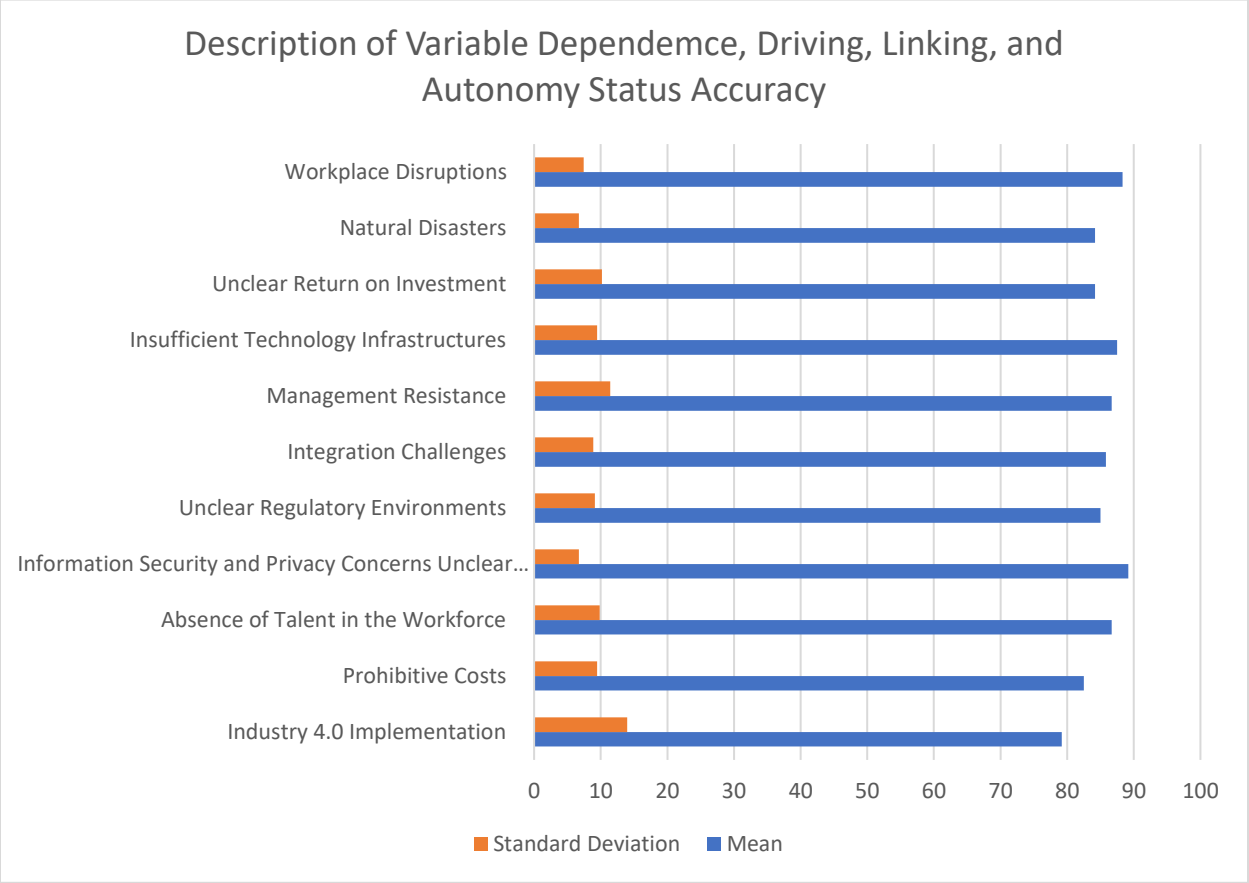


Figure 4.7 displays the boxplots based on the average of each experts' rating of the ten statements describing the relationship between Industry 4.0 and the ten identified factors. Each average ranges between 0 and 100. While there is considerable variation within each experts' responses to the ten statements, all experts rated the statement at 50 or above. The pattern alludes to a general agreement with the supplied statements describing the relationships. Despite the 40-50 ranges observed in many experts' average ratings of the ten statements, more accurate measures of variation like Interquartile Range (IQR) reflect a lower level of variability in responses. Based on this evidence, it is concluded that experts did not vary considerably when rating the ten relationships describing the directionality of association linking Industry 4.0 and the ten identified factors.

Figure 4.7. Experts' Average Ratings on Ten Statements

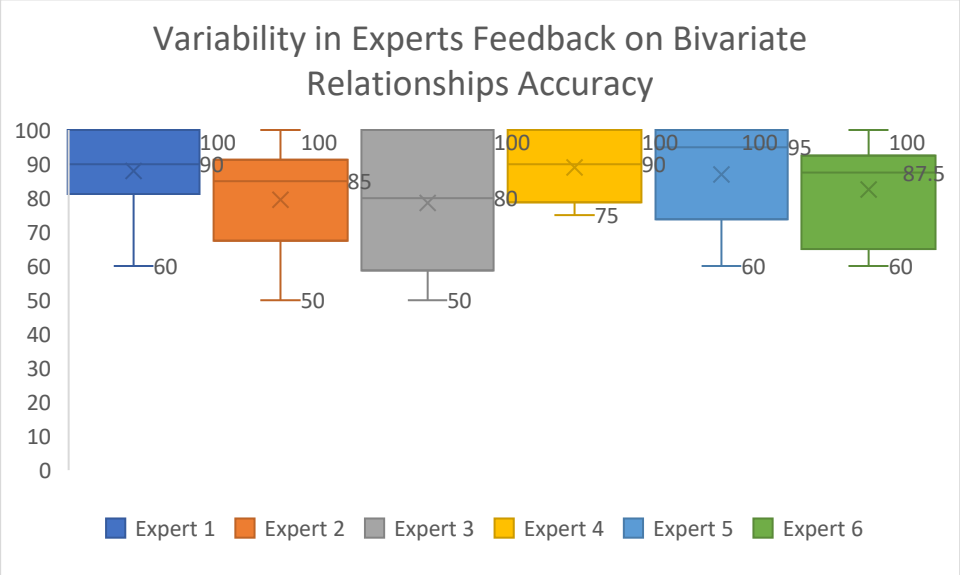


Figure 4.8 displays the average ratings on five statements after asking the experts whether they believe the ISM model constructed is accurate or not. Results show that the ranges in each expert's ratings of the five statements are moderately high. For instance, expert 1 and expert 5 gave ratings that range between 65 and 100, indicating some level of variability. Nevertheless, considering IQRs, the level of variability decreases which leads to the conclusion that all experts relatively believe that the ISM model results are trustworthy and recommended to be used by practitioners.

Figure 4.8. Experts' Average Ratings on Five Statements

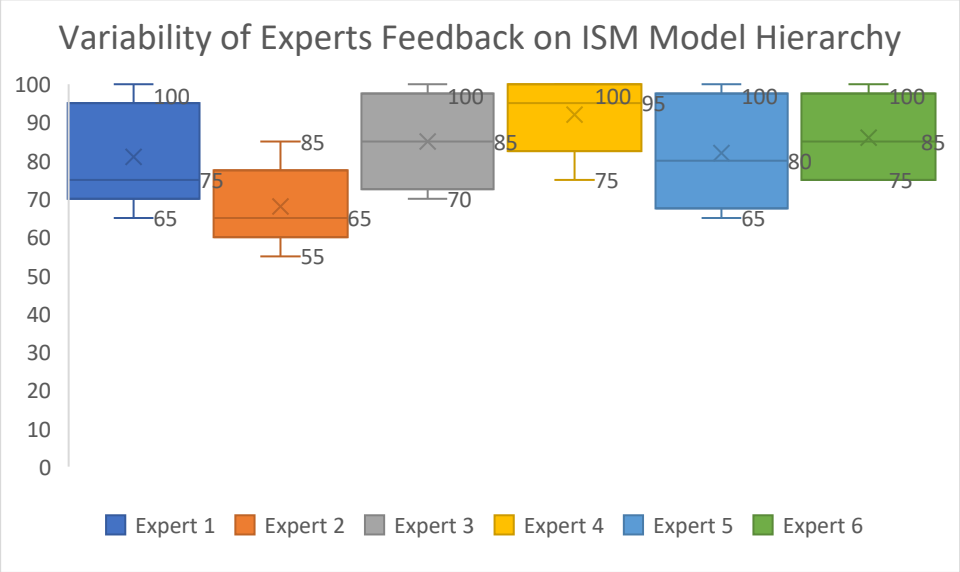


Figure 4.9 demonstrates the boxplots based on each experts' average score of eleven statements describing whether each variable included in the analysis has driving, dependent, autonomous, or linking designation. While some of the ranges could be considered moderate, indicating a modicum level of variability, more fine-grained measures of variation like IQRs conclude that much variability is absent from experts' ratings. For instance, experts 1, 4, and 6 rated all eleven statements between 75 and 100 on a scale ranging from 0-100, with higher scores corresponding to more agreement.

Figure 4.9 Expert Average Score on Eleven Statements

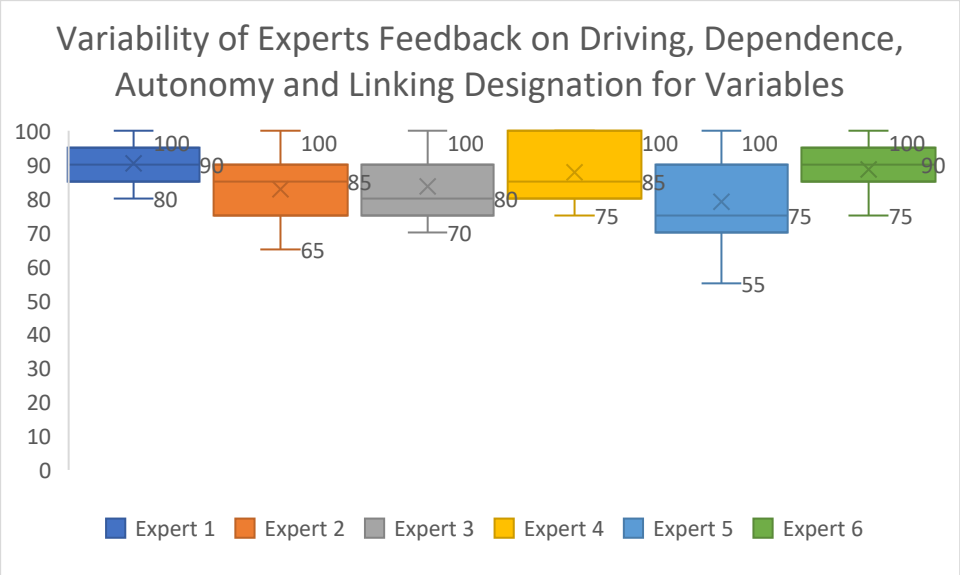
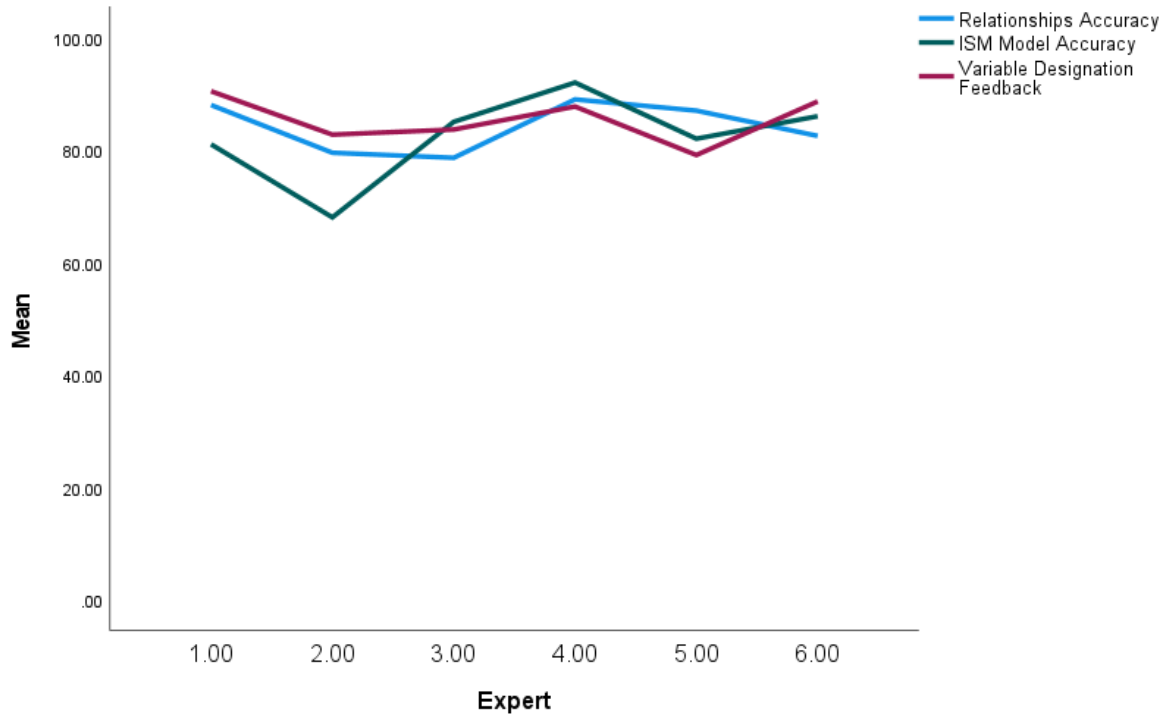


Figure 4.10 shows a multiple line chart demonstrating the average score of all experts on three variables: relationship accuracy, ISM model accuracy, and variable designation feedback. Relationship accuracy refers to whether experts believe that the associations linking Industry 4.0 to the identified ten factors reflect their perceptions or not. The figure indicates a relatively high accuracy score, above 80 on a scale ranging from 0-100 for all experts. ISM model accuracy asks experts whether the hierarchical figure constructed through ISM reflects their overall thinking about Industry 4.0 implementation and the ten factors or not. Evidence suggests that overall, all experts believe that the model reflects their underlying logic regarding the ten factors and Industry 4.0 implementation. Expert 2 possessed the lowest score on ISM model accuracy, which was the only score below 80 on a range between 0-100. Variable designation feedback refers to whether the placement of the variable on the two-axis figure is correct or not from the perspective of experts. All experts seem to have relatively high agreement levels with the designation of variables as linking, autonomous, driving, or dependent.

Figure 4.10. Average Score of All Experts on Three Variables



4.3 Summary

This chapter presented results from all three qualitative and quantitative methods employed throughout this research. First, the thematic analysis responses were presented in a table along with specific excerpts taken out from experts' comments throughout the session. Next, the relationships among the themes and their subcategories were conceptually mapped in a graphical format showing how each theme is related to its sub-themes. Following the qualitative analysis of the focus group text, the quantitative information obtained from all experts pertaining to associations between identified factors influencing Industry 4.0 implementation was used to construct matrices as inputs for the ISM analysis. Following the recommended sequence of analytical steps within the ISM framework, structures and variables were identified and constructed, conveying the driving independence powers for each of the variables considered. Subsequently, the follow-up questionnaire responses were used to validate initial expert ratings of

factor associations as well as the model constructed after completing the ISM investigation. Each set of results supported each other in more than one single capacity, confirming the reliability and validity of the methodology followed in conducting this research.

Chapter Five

Discussion

5.0 Introduction

This chapter presents the discussion of results of this research. A conversation with past research sheds light on the meaning and significance of the findings in this research. Thus, the main results are discussed in terms of corroborating or disconfirming prior research findings. Further, the theoretical and practical implications are presented to showcase where the study findings lie with respect to prior literature. Finally, a note on the contributions of the current study is furnished to allow readers the opportunity to explore the significance of the research.

5.1 Discussion

Results in this analysis confirm earlier findings on Industry 4.0 implementation research. Many researchers have reported the multidimensional, complex, web of variables influencing the implementation of Industry 4.0. Further, authors have argued that unclear expectations, needs, anticipated outcomes, and returns made manufacturers hesitant to adopt Industry 4.0. Further, legal challenges associated with new technology implementation and privacy have been extensively discussed in the literature. Similarly, a plethora of integration challenges to existing infrastructures and processes have been highlighted as important barriers to the adequate implementation of Industry 4.0. Shortages of skilled laborers and experts on Industry 4.0 implementation in manufacturing have contributed to the stunted adoption of the technology. The present research, however, differed from past research by highlighting the equivalent importance of all themes in the process of Industry 4.0 adoption. Cost is not the only factor nor the most important in many contexts. Industry 4.0 implementation is at best a complex phenomenon requiring many actors to collaborate on gradual integration of technology into processes [171, 195, 196].

The findings in this investigation contradict earlier results on factors affecting Industry 4.0 integration. In most analyses, costs seem to be the most important variable preventing stakeholders from pursuing the new technology. Further, past studies have placed more importance on management-related factors in comparison to workplace-related variables. The present study argued that potential workspace disruptions and workforce talent management are more important when compared to management concerns. More importantly, the present research establishes that unclear expectations, needs assessments, returns on investments, and future directions constitute the single greatest inhibitor to the realization of Industry 4.0 implementation. Current findings in this manuscript using the ISM method suggest that many variables government regulation, security and privacy concerns, workplace distribution, and unclear return investment carry equivalent weights in determining Industry 4.0 destiny within developing countries manufacturers [197, 198].

Findings from this research departs from earlier research in the same area with respect to the most important factors preventing Industry 4.0 implementation. In a study using several experts on developed and developing countries manufacturing sectors, Raj et al., reported that the lack of digital strategy and scarcity of resources were the most influential factors in determining the implementation of Industry 4.0 [182]. In this research, unclear return on investment and workplace disruption were more salient in the ISM analysis more than management-related attributes. Further, the thematic analysis demonstrated the equivalent importance of all six themes. Management or strategy-level variables were not more or less important to individual or institutional level characteristics. One of the key takeaways from this research is that many variables are of equal importance in determining Industry 4.0 application in manufacturing settings in developing countries [182, 199, 202].

Findings in this study are inconsistent with past research on the most influential variables for explaining the adoption of Industry 4.0. Unlike Masood and Sonntag who reported that financial and knowledge constraints are the most salient factors in the process, this study found otherwise [178]. This analysis points to the importance of all relevant variables, including often neglected one's line regulation, security, privacy, and workplace disruption. On a more important note, workplace disruption is observed as being just as significant as costs given their influence on the feasibility of any Industry 4.0 implementation. Similarly, the present analysis illustrates how the factors are important for all sectors regardless of facility type, maturity, or resources. Such findings extend to developing countries similar to Saudi Arabia [178, 203, 204].

Contrary to popular belief, suggesting that Industry 4.0 implementation is an orderly procedure defined by sequential changes, this investigation highlights the complexity and multidimensionality of Industry 4.0 application in developing economies. If a manufacturing facility began with one domain of changes, like technology updates, it will be doomed to failure because management resistance, integration challenges, and workplace disruptions all affect the process of change equally. Such a reality leads stakeholders to confront challenges of Industry 4.0 implementation at many levels. Multiple changed initiatives going in motion together are needed to successfully shift manufacturing floors from outdated legacy systems to smart, innovative, enterprises. More importantly, structured processes of change that require specification of resources and meticulous requirements fail the auspicious endeavors of ambitious decision makers attempting to modernize their facilities. A better approach for Industry 4.0 implementation is a flexible, dynamic, method that implements a series of changes on multiple fronts. With timely spontaneous decision-making abilities meeting arising needs without traditional delays [205-207].

Congruent with prior studies, this research found that radical and revolutionary changes in organizations are more likely to materialize in shifts toward Industry 4.0. Field visits to manufacturing plants in Italy have found that having forward-looking organizational cultures (like envisioning workplaces with minimum human interventions and zero waste) leads to the adoption of Industry 4.0. Further, provision of intensive, consistent, and frequent training on the use of sophisticated machinery and lean production makes workers more likely to agree with workplace changes, making manufacturing floors smarter. In a similar vein, the implementation of several Industry 4.0 technologies simultaneously at different levels of the organization, like virtual reality, simulations, and animations, prepares supervisors and managers for implementing larger and more effective digital tools and platforms. Evidence from developing countries has concluded that endless top management support in the form of financial backing and logistics assistance results in more effective Industry 4.0 initiatives [197, 208, 209].

Consistent with prior manufacturing success stories, the present analysis documents the significance of personnel as well as organizational resilience mechanisms in supporting Industry 4.0 implementation. Marcucci et al.'s case studies indicated that the most effective applications of Industry 4.0 faced numerous survival threats along their journey and were deeply defended by aspiring leaders and their teams, making them realities on the ground. Prior surveys of managers at facilities that implement sophisticated digital technology and their production in supply chain management indicated that uncertainty is the most vicious enemy through the success of Industry 4.0. Personnel, regardless of their post, should have a unified vision of successful implementation for Industry 4.0 regardless of the many challenges they face [204, 210, 211].

5.2 Future Directions

Future researchers are encouraged to examine the dynamic and interactive associations linking the barriers or facilitators of Industry 4.0. Much of the available research agenda on Industry 4.0 implementation in developing countries, including this study, examines direct relationships between a set of factors and the implementation of a single or more technology representing Industry 4.0. Such research expects that relationships between one or a set of factors and implementations are independent from each other. An expectation in the manufacturing environment is also untenable. Many variables are at work simultaneously leading to interaction in the industry 4.0 setting. Therefore, researchers need to develop more realistic models to test the predictors of implementation. For instance, moderation and mediation analyses may provide information about the most conducive conditions leading to successful implementation. Further, such investigations allow researchers to observe whether the interaction of two variables is significant in explaining variance in implementation among a set of cases [182, 184-186].

A predominant theme in the literature on Industry 4.0 implementation is the conducting of literature, systematic, or scoping reviews. Much of this work is theoretical in nature. Authors survey the literature for case studies implementing a single or more than one technology in a specific or universal setting. While information generated from such reviews are helpful in grounding researchers' and practitioners' ideas, they lack practical implications for manufacturers' day-to-day operational work. Little experimental work in developing countries concern the implementation of one or more Industry 4.0 techniques. Even if authors tried to examine how some manufacturers implemented technology in their manufacturing processes, they are limited to mostly soft technologies like simulations or software-based applications such as analytics or virtual reality. The examination of how smart machine sensors, robots, or additive manufacturing

equipment is implemented is inadequate. Future researchers are urged to perform more experimental oriented research on Industry 4.0 implementation in the manufacturing industry. Real-world case studies must be better delineated showing interested stakeholders how actual implementation took place [177, 184-186].

Available assessments for Industry 4.0 implementation are not context sensitive. For instance, the evaluation of technical knowledge and infrastructure should not be the same in an advanced economy like Germany and an emerging manufacturing market like Saudi Arabia. Implementing the same assessment frameworks is inappropriate given the large gaps between clusters in countries. Here, the framework refers to the unified way or standard assessment agencies or parties use to evaluate the readiness of a factory or plant to integrate industry 4.0. Similarly, the framework also refers the methodology followed by parties or organizations to assess the technology readiness of a factory to adopt Industry 4.0. Industry experts need to modify their frameworks (methods or assessment tools) when evaluating the readiness of factories located in emerging economies. Such methods need to be less stringent and more flexible. For instance, one factory in Southern Saudi Arabia could possess some of the requisite technology infrastructure appropriate for integrating one or more of the Industry 4.0 application. A German expert should not deem the factory not ready because it does not possess one or more of the non-essential technology tools. The standards shall not be the same given the large gaps characterizing the economies.

Future researchers need to develop validated readiness assessment per technology accounting for the level of economic and manufacturing development. Each technology readiness within Industry 4.0 could be measured by using several indicators. The choice of the indicators must be informed by the country and industry. Future researchers need to perform on the ground

humanistic research to generate the potential list of useful indicators for each country being investigated [187, 188].

5.3 Theoretical Implications

Many analysis findings lend support to the relevance of the unified theory of acceptance and use of technology (UTAUT) in explaining effective Industry 4.0 implementation. UTAUT calculates that individual-level perceptions and behaviors influence actions taken by decision-makers in manufacturing settings. For instance, performance expectancy, effort expectancy, and peer pressure all affect readers choices of implementing new strategic plans like investment in technology. Another driver of technological advancement is the prospective idea of efficiency and financial success. All experts indicated that individual level variables are important in determining whether or not Industry 4.0 implementation is successful. On the one hand, work force challenges include how employees feel about their employers' implementation for workplace changes like the introduction of automation systems. On the other hand, workers at factories are influenced by their managers' attitudes toward new policies like the adoption of Industry 4.0 implementation. Ultimately, any proposed theoretical framework predicting Industry 4.0 outcomes should examine individual level attributes with respect to several stakeholders like employees and managers [170]

Results from the qualitative phase of this project supports an emerging review in the practice of Industry 4.0 implementation literature, citing the role of institutional theories and explaining the rise of business' adoption of revolutionary technologies. One of the theories that has been recently cited in clarifying why some manufacturers choose to implement Industry 4.0 is the resource-based view (RBV). RBV argues that successful companies in the marketplace are endowed with long standing, robust, competitive advantages, placing them ahead of their counterparts within the same sector. In practical terms, experts advocated for the positive influence

of a prior exposure that technology implementation makes smooth during transitions from traditional to transformational manufacturing processes. In other words, companies with prevalent technology and high levels of innovative platform fluency experience less problems in integrating advanced technologies within their manufacturing systems. This perspective pushes researchers to incorporate institutional-level variables in constructing parsimonious models to explain successful variation within Industry 4.0 implementation in developing countries [171].

The interpretive model of results points to the importance of the overarching management structure and approach in determining the effectiveness of Industry 4.0 implementation. Such a finding relates to the potential rule of management theory, explaining difference across Industry 4.0 implementation cases within developing countries. Leadership styles moving from strict transactional scientific management in schools to more laissez-faire transformational approaches generate differences in observed outcomes concerning Industry 4.0 implementation. Firms with high levels of control over innovation and professional management tend to be slower in adopting Industry 4.0 technologies compared to agile transformational management-run organizations. Levels of decision-making echelons determine how and whether Industry 4.0 applications would proceed in the manufacturing setting. On the one hand, when multiple-tier approvals are required for the purchase and employment of new technology, a slower pace of implementation occurs. On the other hand, hierarchy in an organizations' future decision-making protocol efficiency leads to an easier path to the realization of Industry 4.0 implementation [172].

Survey results demonstrated the importance of the interaction between individual level attributes and organization level characteristics in determining Industry 4.0 integration into manufacturing facilities. Such findings corroborate the theoretical emphasis on acceptance features and the adoption and implementation of new technologies in novel ways or new settings. In

practical terms, worker, manager, and key stakeholder acceptance of a specific technology is directly related to the cultural climate of the organization. More specifically, trust, reciprocity, and collaboration define the work culture of an organization and the actions specified by top management or first-line supervisors will be smoothly implemented. Relatedly, flexibility, autonomy, and independence of workers as well as their units in manufacturing facilities increases innovative and entrepreneurial actions leading to the integration of digital solutions after production line and manufacturing processes. One of the emerging conclusions is that the framework of Industry 4.0 application in developing countries should reflect multilevel interactions between the different actors and institutions involved in the implementation, planning, and execution [173].

One of the common themes reported in both the qualitative and quantitative findings in this research is the rule of formal institutions in driving or halting Industry 4.0 implementation. Government regulation is one of the main significant factors that facilitates the realization of Industry 4.0 implementation across manufacturers. When liability is minimal and the law is clear, firms are more likely to take risks like purchasing cloud computing services and data intelligent systems. Governmental incentives in the form of tax cuts or matching grants influence the frequency and intensity of implementing Industry 4.0. Certainty in legal processes and precedents set clear paths for organizations for implementing new platforms or processes without the fear of colossal damages. Furthermore, attention from government officials attracts supporters from all walks of life, collecting more streams of funding for industry-use and technological advancements. With such a pivotal role played by formal institutions, theorists of Industry 4.0 must incorporate explicit variables with clear, measurable, outcomes for the operationalization of institutions [174].

The present analysis has introduced the inductive dimension to the theorizing of Industry 4.0 implementation. Listening to experts from the field informs the practical integration of new technologies into legacies or traditional processes on the production floors. Such a view contradicts much of the existing models that rely on the deductive approach to modeling integration. One of the main problems associated with the deductive approach is the initial heavy requirement for changes and upgrades to systems, protocols, and workplace layouts. Similarly, the deductive view of Industry 4.0 implementation assumes perfect collaboration of all human and machine components in facilities. The resulting outcome is a dearth of practical inductive frameworks guiding the real work of decision makers in their day-today operations. Furthermore, the absence of sensitive approaches to cultural contexts makes deductive solutions lacking at best. Future theorizing requires more attention to the interactive dynamic settings that define factory floor issues, including but not limited to, the diversification of decisions makers, long-term investments, and futuristic installments of workplace procedures. Static models predicting Industry 4.0 move to become more stochastic by incorporating real-life patterns and interactions [175].

There has been ample support for the compilation of systems and activity theories to implement technological interfaces in the manufacturing industries of developing countries. The framework first enforces the understanding of consequences for all workers once Industry 4.0 adaptions are undertaken, followed by the assessment of worker and community opinions of industrial modernization. On one hand, this approach supports the autonomy of all staff and their region, gaining momentum, encouragement, and funding from outside stakeholders for technological learning and initiation. On the other hand, managerial power and business ownership is diminished by the consideration of the working class's opinions. These judgements can then be considered in the implementation of lean manufacturing techniques, analyzing the extent that

Industry 4.0 can be taken in terms of financial, social, and environmental considerations. The approach promotes a unified strategy toward business growth, supporting endeavors that will benefit not only the executives, but the entire manufacturing business line: production floors, suppliers, and consumers [176].

Frameworks such as the fuzzy analytic hierarchy process (FAHP) utilize a multitude of layers to merge the multi-faceted structure of small and medium enterprises with Industry 4.0 utilization. Exemplified by productivity and revenue analyses, businesses were able to identify stronger solutions for conflicts in manufacturing which can be divided into legitimacy, rationality, feasibility, and controllability sectors. By means of validity, companies inaugurate budgets and compensation plans to ensure safety and efficiency for all staff with the initiation of lean manufacturing in the workplace. Managerial staff must ensure that the emotional appeal of their workers and that they can function alongside automated counterparts. Furthermore, businesses must question their economic and environmental stance and whether the implementation of Industry 4.0 is feasible and sustainable. Likewise, if public participation and emergency response preparation standards are not underlined, the controllability of the technological system may be breached. The establishment of higher computational services within an establishment must outweigh traditional resources for the support and enactment of Industry 4.0 [177].

The aforementioned theories of industry 4.0 implementation bring many factors of importance to the forefront. All authors remarked that the initiation of horizontal technological development relies on an expansive network of internal and external individuals, ranging from government officials to factory floor workers. Suggested frameworks reflect the knowledge of business success that lean manufacturing entails without overlooking the theoretical risks that are enveloped with any instigation of infrastructural change. Similarly, Industry 4.0 implementation

was noted to be an inductive strategy, evolving business development from traditional structures to enterprises with competitive advantage. Although emerging countries have reflected a disadvantage in technological advancement, research suggested that cultural considerations may allow a diversified Industry 4.0 strategy that succeeds in its home economy. Further, feasibility, adaptability, and individuality must be encased in advanced industrial plans in order to bring lean manufacturing to businesses for the sake of effectivity of Industry 4.0 implementation from both a quantitative and qualitative standpoint.

5.4 Practical Implications

The results arising from this study informs the practice of manufacturers in their endeavors to increase digitization and cyber-physical integration in their facilities. Several within reach initiatives on the part of manufacturers are presented in the ISM model, helping in moving away from legacy operations to smart production and control. The model indicates that insufficient technology infrastructure presents a real challenge for many in their quest for achieving effective Industry 4.0 implementation. Practically, the findings suggest a need for the evaluation of facilities' readiness for the adoption of a specific technology. Manufacturers need to generate checklists of technology requirements to ensure that updates are made prior to making any major shifts in operations. The identification of equipment, digital devices, training, and requisite infrastructures need to be formally conducted. Gradual changes with realistic deadlines need to occur where the infrastructure is introduced in several phases to safeguard the continuity of the operation. Small changes need to first be implemented to show everyone the value of technology integration into the existing operations. Investments in the implementation of Industry 4.0 should be gradual and performed by trusted third party partners. Clear metrics and periodic progress reviews need to be in place to ensure the timely and smooth implementation. Once a number of

related changes to the technical infrastructure are made, operations could be moved away from old ways of performing tasks to technology integrated business performance operations [177, 178].

Manufacturers interested in Industry 4.0 need to invest in the demonstration of the value of implementing smart technologies to increase cooperation. Resistance to change is a major hurdle in the way of successful implementation. Stakeholders could mandate everyone at the facility perform training showcasing the value of Industry 4.0 integration. More importantly, successful case studies within the same domain need to be repeatedly and consistently communicated to top managers, as well as workers, to sway resistant elements from preventing the implementation of Industry 4.0. Internally, recruitment efforts could focus on attracting talent that is competent in advanced technology integration and equip them to assume management positions. Further, retention strategies could be linked to performance criteria related to the incorporation of Industry 40. Similarly, manufacturers could contract third party vendors to visit their facilities and demonstrate the power of their technologies. Resistance to Industry 4 0 could be mitigated by increasing action-based research projects to solve operational problems facing facilities through investment in technology-informed solutions [22, 179].

Government regulation prevents a recurring theme in the facilitating of the creation of an Industry 4.0 robust sector of industries. Manufacturers could pressure governments to increase funding and incentives for the adoption of novel technologies. Trace associations and manufacturing groups could lobby governments to create new industrial zones that are fully equipped with ready to implement technology infrastructures. When legislation passes to regulate manufacturing, stakeholders need to specify liability clauses to better guide decisions made by manufacturers concerning Industry 4 0 implementation. Further, government agencies at all levels need to establish standards for technology integration in order to increase industrial alignments

within sectors. In cases where regulations are unclear, manufacturers need to get further guidance on how to proceed with the implementation of Industry 4.0. Guidance must be linked with clear illustrations of successful practices [22, 178].

Improving readiness across all levels is an inevitable change that manufacturers need to perform to improve Industry 4.0 implementation. Performance-based trainings on how to use adopted technologies need to be given to all workers. Additional workshops must be required to win over laborers and supervisors to technology changes that must be taken in the journey of Industry 4.0 implementation. The recruitment of new staff needs to be sensitive toward finding talented personnel who are well versed in novel technologies use. The incremental incorporation of technologies creates a more accepting and ready culture for implementing Industry 4.0 technologies. The replacement of necessary outdated equipment and production lines with smart devices exposes workers to the utilization of novel devices and processes, making them better prepared for the total shift into a comprehensive cyber-physical integration period [31, 180, 181].

One important implication arising from the findings across this research is the potential use of Industry 4.0 to improve consumer satisfaction. Manufacturers need to examine how the adoption of technologies improves their services or products in ways that make their clients more satisfied. Manufacturers could implement vetted ideas in the design and development phases, naming products smarter, and appealing to customers. Further, manufacturers could attempt to link existing problems learned via user experience surveys and addressing them through technologies. Exploration of technology integration into products that increase their usability and decrease their problems are key approaches in incorporating Industry 4.0 into manufacturing [124, 182].

Strategic planning with respect to Industry 4.0 implementation needs to be a priority for manufacturers. Currently, many SMEs in developing countries do not have explicit strategic plans

to integrate technologies in their operations. Specific actions with timeliness and measurable outcomes tasked to specific personnel members must be fully detailed. Operating reviews that occur periodically need to happen in order to ensure the implementation of the plan. Resources in the form of funding and staff must be funneled to teams working on Industry 4.0 integration. Plans should also be realistic with respect to objectives and timeliness [22, 180].

SMEs in developing countries have downplayed the importance of privacy and security of infrastructures involved in their production systems. Such a fact is driven by inadequate resources and cultural orientations resistant to funding non-essential components in production. Many managers prioritize other needed processes or equipment purchases over cybersecurity. This research has demonstrated the importance of cybersecurity in any integration attempts by digitization and automation. Manufacturers need to analyze their processes and identify security needs that need to be addressed by available, affordable, solutions in their respective markets. For instance, securing databases containing client information concerning the usability of devices or private information is an imminent priority that many firms need to take in a serious way. This requires investment in personnel training and the purchase of sophisticated technologies designed for protecting client records. Resolving such challenges increases customers' confidence in the products offered by the manufacturers [181, 183].

Partnering with smart manufacturers is an option for aspiring firms aiming to implement smart production. Getting the expertise necessary for successful installation of smart production lines and agile processes serves the benefits of all manufacturers. This approach allows the discovery of integration challenges and identifying feasible solutions that have been addressed elsewhere in the sector. Public policymakers in the manufacturing sector could improve collaboration by starting new initiatives aiming to advance smart systems. Offering incentives

constitutes an effective strategy to recruit interested stakeholders in assisting their peers in advancing the local industrial sector while generating revenue from knowledge sharing activities [183].

Current decisions being executed by managers in the industrial field of developing countries mostly support the traditional methods of manufacturing. Although business owners in the SME sector understand the importance of advancing their companies technologically, research states that the initial financial investment is difficult for managers to implement without promising evidence from data showing success with utilization of robotic, automated, processes. Researchers also explore manager hesitancy with regards to short-term and long-term benefits for their company, arguing that the down payment for lean manufacturing methods is often too hefty for SMEs in developing countries to understand the future means. Managerial staff also debate the effects that digitalization may have on their workers and human-based approaches to the work atmosphere. Research suggests that business owners and leaders must make controversial decisions where aspects of their businesses will not be supported by all community members while implementing new technological standards [177, 179].

Research also examines the role of workers, customers, and government officials to assess the practical implication of Industry 4.0 in growing SMEs. Many employees would be pushed out of their positions with the implementation of automation in factories, raising unemployment rates further in such developing countries. Researchers state that the need for employers to open other doors for population employment would highly increase the support for technological measures within the public. Customers are observed to be fond of the idea of Industry 4.0 measures, as it increases the accuracy, customization, and speed that they are able to consume their manufactured goods. Further, government officials are making decisions in favor of technological advancements

because they can put forward initial expenses for the welfare of the systematic approach Industry 4.0 entails. Examples of this include electronic voting systems, increased tax revenue from businesses benefitting from Industry 4.0, and large databases to analyze country statistics and economic issues [124, 178].

Overall, this section expands upon research dictating the practicality of Industry 4.0 implementation by means of facility readiness, funding, training, planning, resources, partnerships, policy makers, suppliers, and consumers of SMEs in developing countries. There are many shortcomings and obstacles to technological advancements in these industries that authors have examined. With closer analysis, these hurdles can be subdued by business owners, advancing the competitive advantage of manufacturing companies in the long-term. From a practical standpoint, authors noticed the opportunities presented with the implementation of Industry 4.0 measures across the developing world, and how its furtherment will shorten wealth disparities between them and prospering nations. IoT, automation, lean manufacturing, and cybersecurity aspects of Industry 4.0 can eliminate human error and ensure company growth and success in the developing world.

5.5 Contribution

The main contribution in this research is that the implementation of Industry 4.0 is not strictly sequential, being comprised of meticulously designed steps applied in order. The ISM model, based on expert ratings of relationships between widely cited factors contributing to Industry 4.0 implementation, demonstrates the simultaneous implementation of several steps at many levels across the factory or the organization interested in implementing Industry 4.0. First, on the personnel and floor sides, workplace disruptions are to be fully discussed and visualizations of smart facilities need to be explicitly drawn. Second, at the same time, management and leadership need to consider the clear articulation of the return on investment brought by Industry

4.0. During this stage, the IT team conducts a thorough analyses of privacy and security of facilities systems to help in implementing Industry 4.0. Legal teams need to coordinate with government agencies and officers, ensuring compliance prior to any investment. All such steps do not take place each at a time, but rather are conducted in the same timeframe. Such a scenario allows the manufacturer to have a more holistic and realistic view.

The foregoing discussion notes the failure of existing models to provide facility owners and managers with sophisticated and detailed frameworks for implementing Industry 4.0. Most available models promote the analysis, development, testing, and evaluation approach. The waterfall modelling technique is widely used, starting with measurement or identification of needs. Then, prototypes are made, or alternatives are specified. Subsequently, testing or deployment of a specific technology for a particular use is followed. Such a perspective demands that the stakeholder has complete information about the problems and the future returns of the industry 4.0 implementation. Nevertheless, this is an untenable assumption. Stakeholders may order the wrong technology or prescribe inaccurate solutions because of limited knowledge. Therefore, existing models are insufficiently detailed and require unrealistic expectations from everyone, making them misleading.

Currently proposed models for Industry 4.0 implementation are parochial. Authors ask owners or managers to identify a specific need with a particular technology that is capable of solving the problem. For instance, the implementation of virtual reality for delivering training or education could qualify as an Industry 4.0 example. The use of a single technology does not lead to Industry 4.0 implementation, and the implementation of Industry 4.0 is a way of work. Which addresses workplace, technical infrastructure, and organizational features simultaneously in the

proposed ISM Model. The implementation of several technologies together helps in the realization of the industry 4.0 vision.

The clear majority of Industry 4.0 frameworks lack specificity, but the demonstrated ISM model presents change in ordinary, simple, language understood by factory owners in developing countries. For instance, many models instruct interested parties in Industry 4.0 to analyze, measure, control, or evaluate without providing details on what specifically is being targeted. The ISM model presented here apprises owners and managers of the actions needed and at what level. For instance, workplace disruptions refer to everything deemed important to the workplace environment in case of Industry 4.0 being implemented. Further, most models draw too many arrows, linking way too many vaguely specified constructs. Factory owners become confident once they are introduced to hierarchical figures with simple words linked with arrows. The ISM model is simple in the way stakeholders look at each box and understands immediately the actual meaning and realm of action.

One of the most important contributions of this research is that Industry 4.0 implementation is a flexible, affordable, and easily integrated process for many traditional facilities. Many manufacturers and stakeholders believe that implementing Industry 4.0 means the complete restructuring of the manufacturing floor or the entire plant. Such a characterization is untrue. Today, many technologies, like advanced sensors that could be connected to smart data analytics platforms with affordable monthly subscriptions, could be used to collect data on many processes or products and generate automatic reports for decision makers to consider in their meetings. Further, simulation software is affordable and makes the design and development of new products more feasible, especially when linked to more readily available 3D printing technologies. Learning how to use such systems is also available on the internet, costing nothing or only nominal fees in

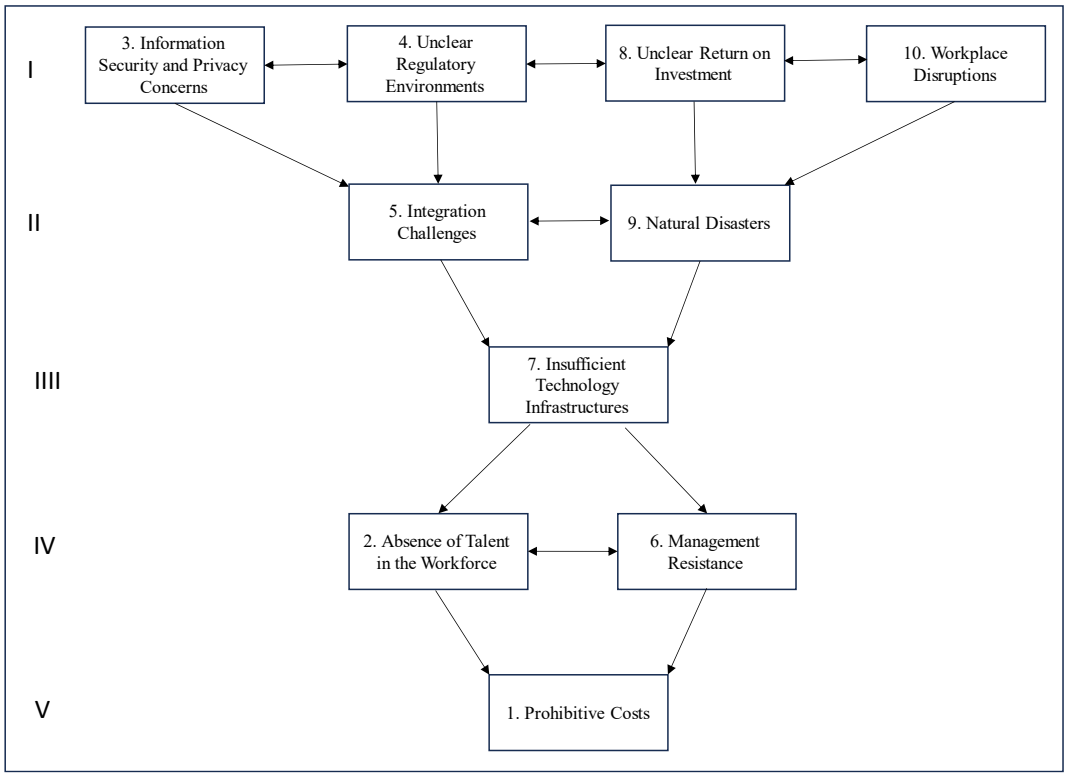
many cases. Industry 4.0 implementation does not mean the complete overhaul of all procedures, lines, and processes, it is simply the introduction of smart technology gradually into the production systems of facilities.

The present study contributes to the design and development of conceptual models guiding the implementation of Industry 4.0 in manufacturing settings. Much of the existing models in the literature specify a series of steps stakeholders must go through sequentially to reach a given outcome. A waterfall approach is followed by most authors where the business requirements determine operational, technical, and system/subsystem needed changes. Once changes are made, then thorough testing to evaluate the changes proceeds. Such a process necessitates hefty resources that are unavailable to the vast majority of SMEs. Therefore, the highly structured and reasoned models prove to be of little to no utility to manufacturers. The current research proposes instead that a scalable flexible framework that suits the differing needs of manufacturers across developing countries is followed.

One of the distinct features concerning the agile model for Industry 4.0 is its decentralization. Each unit determines what is needed and pursues the technology best suiting its needs. In SMEs, small units deal with specific tasks that could be achieved by using affordable Industry 4.0 solutions. Such a defining criteria saves a tremendous amount of time consumed in traditional decision-making processes. Also, the available budgets for the units are used for this investment rather than ad hoc expenses, unless top stakeholders quickly act by authorizing necessary funds for the implementation. The implementation of decentralized technology planning will likely resolve integration problems since implementing teams would seek digital solutions that suit the manufacturing process in their plant.

Figure 5.1 is the proposed framework by the author of this dissertation based on the ISM analysis. Note that the first level represents the factors that immediately affect decision makers' investment choice in Industry 4.0. Investors consider information security risks, unclear return on investment, Uncharted regulatory government environment, and the changes to their workplace. Interested manufacturers in Industry 4.0 consider all of the four factors simultaneously. Then, investors consider the integration challenge with existing systems, as well as external threats like natural disasters. On the third level, investors begin to think about technology infrastructure supporting their decision to adopt Industry 4.0. Subsequently, the investors consider staffing and the availability of workforce while working through management acceptance. Finally, investors consider prohibitive costs. Thus, the framework of factors and their ordering in the decision-making process of Industry 4.0 proposed by the dissertation author is presented in Figure 5.1.

Figure 5.1. Proposed Framework



Chapter Six

Conclusions

6.0 Introduction

This chapter introduces readers to the most important conclusions found in this project. Next, each conclusion is illustrated with respect to past relevant research, providing rich discussions on its implications and practical application. The results observed throughout the research impact existing theoretical models by outlining why and how Industry 4.0 is implemented. More importantly, the inferences made in this manuscript impact the conceptual undertaking of many schools of thought while attempting to improve Industry 4.0 in manufacturing. Relatedly, the findings are discussed with relation to their applied implications. Such discussions concern how Industry 4.0 implementation is manifested on manufacturing floors. Future research directions are detailed, guiding the work of ambitious researchers trying to make manufacturing smarter and more efficient in developing countries. Most importantly, this chapter outlines the most notable limitations that faced the researcher when he conducted the study and allows future researchers an opportunity to appreciate the multiple choices available to them when performing research on the topic.

6.1 The Problem Statement Restated and Objectives

The primary problem driving this research project is the paucity of studies on Industry 4.0 implementation in emerging economies like Saudi Arabia. More specifically, the implementation of Industry 4.0 by SMEs in non-industrialized nations is a missing theme in the literature on Industry 4.0 adoption. A nuanced problem addressed in this study is the absence of theoretical links between lean manufacturing and Industry 4.0 enablers. Finally, the existence or available of

flexible frameworks for interested investors or manufacturers in emerging markets to implement Industry 4.0 are absent in the vast scholarship on Industry 4.0.

The main objective in this research is the development of an Industry 4.0 implementation framework suitable for emerging economies like Saudi Arabia. Further, the framework would be validated by experts' opinions through a questionnaire. In doing so, the author set two ancillary objectives. First, the identification of barriers for the implementation of Industry 4.0 in developing countries was conducted. Second, the theoretical links between industry 4.0 enablers and lean manufacturing outcomes were reported.

6.2 Recapitulating the Methodology

This research used a mixed methods approach. The interpretive research paradigm organized the choices of data collection, analysis, and interpretation. First, the focus group method was used to collect experts' views on Industry 4.0. The information collected from the focus group was both quantitative and qualitative. The quantitative information allowed the author to utilize the Interpretive Structural Modelling technique. The qualitative information furnished the data necessary for the thematic analysis. Further, the survey methodology though a close ended questionnaire was used to validate the results of the ISM analysis.

6.3 Summary of Findings

The qualitative information collected from experts throughout this research noted the prevalence of six themes in the industry 4.0 implementation process within the developing countries context. These themes are workforce barriers, insufficient technology, unclear government regulation, integration problems, management concerns, and uncertain outcomes. Workforce barriers included, but were not limited to, finding, and retaining necessary skilled manpower in order to operate Industry 4.0 machines and integration. Management concerns

covered a wide array of issues, chiefly resistance to change and the devotion of adequate resources for making Industry 4.0 implementation achieve its goals. Uncertainty touched on a broad range of problems like unspecified returns on investment and the real need for establishing the case for Industry 4.0 in a particular context. Inadequate government regulation concerns challenges arising from potential privacy and information security liabilities. Insufficient technology infrastructure refers to the readiness of facilities for integrating new machinery and systems. Currently, a large proportion of facilities in developing countries operate using old technology that is inappropriate for running smart manufacturing operations. Integration problems arise from the lack of compatibility of various machines, processes, and systems facilities within their manufacturing operations. The analysis found that all themes were represented by all experts despite operating in different sectors. More importantly, the salient nature of the themes remained consistent even across all included sectors. Such an observation makes one conclude that all of the six themes carry important weight in affecting Industry 4.0 implementation.

The present investigation concluded that variables in the ISM study that the unclear returns on investment, government regulation, workplace disruptions, and information security and privacy, constitute the most important factors in determining Industry 4.0 implementation. Additionally, the analysis found natural disasters and integration challenges in the second level of the ISM study. The third level factors affecting Industry 4.0 implementation were insufficient technology infrastructure. The fourth level of the factors affecting Industry 4.0 implementation was management resistance and the absence of talent in the workforce then the fifth level was the prohibitive cost. The set of aforementioned factors seems to be equally important at the same level for the implementation of Industry 4.0.

This research reported equal or near equivalence of importance of many factors in determining Industry 4.0 implementation. For instance, the thematic analysis found all six themes to be evenly distributed in the six experts' answers. Many variables possessed the same level in the ISM model results. In many cases, experts indicated that stakeholders needed to award attention to more than a single factor simultaneously.

While this research found financial and knowledge-related factors as important variables in driving the implementation of Industry 4.0, their impact was equal or less salient when compared to other factors. Regulatory frameworks and institutional processes were significant factors in affecting Industry 4.0 implementation. The institutional practice of determining returns on investment or managing uncertainty were the most influential factors. Physical changes to the layout of the manufacturing space and updating existing technology constituted important variables considering the potential lack of compatibility or integration across systems at facilities.

The present analysis also reported a multidimensional model for Industry 4.0 implementation in developing countries. This model incorporates multiple layers as well as stakeholders without specifying a hierarchical or orderly structure. The highly contextual manufacturing facilities prevalent across developing countries require the implementation of simultaneous initiatives to bring Industry 4.0 into realization. Such an observation renders existing step-by-step implementation models incapable of meeting realistic expectations and outcomes within manufacturing floors in small and medium size enterprises across emerging economies like Saudi Arabia.

One of the conclusions emerging from this research is the importance of organizational-level variables in explaining Industry 4.0 implementation. On the one hand, management resistance support is one of the critical success factors in realizing the potential of Industry 4.0

implementation. Otherwise, workforce readiness seems to be a pivotal attribute for making or breaking Industry 4.0 initiatives. The current investigation highlights the importance of workers' acceptance of Industry 4.0. Without the internal buy-in from users and workers, Industry 4.0 is inevitably going to fail on many levels. Overall, the emphasis on organizational survival as well as efficiency shifts priority from making new lines of production to improving existing production systems by making them leaner and less wasteful. In some, organizational climates as well as culture present a key factor in determining the success of Industry 4.0 implementation.

This study suggests the need for organizational resilience to sustain Industry 4.0 implementation efforts. the concept of resilience refers to endless top management support as well as repeated integration attempts that may fail at times in bringing expected benefits to manufacturers. A holistic approach to Industry 4.0 implementation shielded by resilience from all units across manufacturers is not only a sufficient condition for effective implementation but also an accessory-driving force realizing the vision of smart manufacturing. Unlike other processes, similar to business reengineering or process deconstruction, Industry 4.0 is a colossal undertaking touching every department and person working within a manufacturing facility.

A less noticeable ramification of Industry 4.0 implementation is the phenomenon's effect on domestic and foreign regulatory frameworks. International trade associations and economic organizations accept numerous standards for technology purchase, transfer, and deployment in the manufacturing sector across the globe [200, 201]. Compliance with the best practices, whether governmentally mandated or privately encouraged, presents an important area of consideration for manufacturers interested in implementing Industry 4.0. The present analysis demonstrated not only the relevance of privacy and security in-laws within domestic economies but also international legal doctrines governing transnational business interactions. Such a conclusion calls for more

emphasis to be placed on the role of formal and informal institutions in regulating the arrangements governing how Industry 4.0 implementation plays out in the international arena.

6.4 Limitations and Constraints

Like any empirical research investigation, this project suffers from numerous limitations. First, the focus group session was constrained by time. Industry 4.0 implementation is a complex topic involving many variables and processes. Sessions of a few hours cannot suffice to generate the wealth of information needed to summarize all the factors potentially affecting the implementation of Industry 4.0 technologies. Also, the focus group was restricted to males providing insights on manufacturing technology implementation in Saudi Arabia. While most manufacturing experts in the Kingdom are males, some females have made headlines in national news as successful entrepreneurs in the smart manufacturing realm. The female perspective is missing from the responses in the focus group. This could lead to missing out on some important factors that are emphasized by female industry experts more than males.

Second, practical challenges in the data collection procedures defined several stages in this research. On the one hand, having the experts complete the variable relationship matrices and the survey was an uneasy undertaking. Several reminders were sent to experts ensuring their timely cooperation. More importantly, while the experts returned all data instruments timely, such information could have been completed inaccurately. The assumption that all experts filled out the questionnaires and matrices accurately is made by the researcher, decreasing data quality problems. Further, experts may have exercised social desirability with respect to survey items. They may prefer to be seen as legitimate sources by not changing their perceptions concerning relationships given by them at the focus group. Therefore, the high agreement ratings with the survey items may appear close to the initial ratings.

Third, the conclusions and inferences of this research are limited by the design of the study. One sample of experts participated at a single point in time, making this project cross-sectional. This type of study provides correlational statements concerning variable associations. One may not construct causal statements based on cross-sectional research. The statements and conclusions reached in this study provide snapshots of the relationships among the variables. Such relationships may differ from one time period to another or one geographic cluster to another.

Fourth, social desirability may have influenced the information provided by experts during the focus group session. For instance, when one expert said that workplace disruptions is an important factor for implementing Industry 4.0, two others agreed immediately. Experts desire to be observed as legitimate sources of information on a topic like Industry 4.0. Disagreement with others may be interpreted as a lack of competency in an area, and therefore experts may have avoided disagreeing statements. Relatedly, when answering survey questions on the designation of variables as linking, autonomous, driving, or dependent, experts exhibited high agreement levels with the ISM results. Such an outcome may have been caused by the desire to agree with the researcher for a multitude of reasons like making the researcher appear to be an authority on the subject matter.

Fifth, the number and type of limitations provided to experts as inputs to the ISM analysis were choices that could have altered the results in the research. Reviews of the literature identified many factors that could influence Industry 4.0 implementation. In some cases, authors determined that there are 15 or more factors that affect Industry 4.0. While an extensive number of factors is helpful and seems to be more representative and realistic, experts have limited time to discuss all identified factors. One focus group would be insufficient if the number of factors is too large. Further, when experts attempt to assign relationships between the factors, it would be unrealistic

on the part of researchers to expect an expert to spend many hours on the task. The level of burden would be too high. Nevertheless, the choices determining the inputs for the analysis influences some of the output observed after conducting the study.

Sixth, the low number of experts prevented the researcher from using statistical models like correlational or regression analysis. A large sample is needed for performing ordinary least squares to test the effect of each identified factor on the industry 4.0 implementation outcome. Relatedly, the data collected throughout this research is perceptual. It represents the attitudes of individuals, and not the actual outcomes observed. Therefore, the conclusions and inferences made throughout this research are only pertinent to the conceptions and perceptions rather than actual observed metrics or indicators.

6.5. Reflections on the Research

The overarching tone in the literature on Industry 4.0 implementation in developing countries is celebratory. Naturally, economies endowed with low human and financial capital exhibit aggressive stories of success in manufacturing. One of the important missing pieces, however, is the assessment of quality in implementation. Little attention by past researchers has been devoted to the quality of how manufacturers have adopted and implemented certain technologies in their countries. Future studies are recommended to generate several frameworks that accurately reflect the quality of implantation [182, 190].

While many frameworks provide general guidance on how manufacturers ought to structure their Industry 4.0 implementation, the models lack specific planning tools to help interested stakeholders manage the process. Future researchers need to link framework steps or phases with measurable baseline, current, and end state goals with specific timeliness. Planning guides help stakeholders monitor the progress of every step and identify ways to remove barriers

facing successful implementation. Further, the assessment of states provides a wider perspective to the reality of Industry 4.0 application in a specific case. Future researchers need to spell out how decision makers need to utilize such planning instruments with respect to applying the recommended steps in the transformation plan [186, 187].

One key to the success of Industry 4.0 is conducive public policies and government regulations. Across developing countries, variation in the implementation of Industry 4.0 exists. The link between features in public policies and success of Industry 4.0 is neglected in the research. Future researchers are encouraged to explore opportunities arising from public-private partnerships. Similarly, researchers are urged to examine specific policies like tax incentives or subsidies and the innovation or diffusion of Industry 4.0 solutions across the manufacturing sector. Such knowledge helps policymakers better guide the transformation process from traditional to smart manufacturing in emerging globalized economies [192, 193].

With the rise of too many Industries 4.0 technologies that are applicable to manufacturing, decision makers have become less clear concerning useful options. Future researchers may help industry leaders by identifying those proven technologies with respect to specific sectors. Further, studies in particular industries showing the most commonly adopted technologies needs to be commissioned in order to document the success of some technologies over others in given contexts. Similarly, technologies need to be classified with respect to clear criteria to help decision makers generate decisions as to what would work best for their own enterprises [191, 194].

While surveys of the literature and systematic reviews fill the body of scholarship on barriers and facilitators of Industry 4.0 implementation, few meta-analyses have been conducted. The power of meta-analyses is in linking a specific technology or an enabler with a particular manufacturing outcome. Further, researchers could code moderators to examine under what

conditions such relationships are more salient when compared to others. Future researchers need to conduct meta-analyses linking each of the technologies in the industry 4.0 movement with a host of manufacturing outcomes in order to better understand the best choices available to manufacturers [186, 189, 192].

Future Researchers are recommended to utilize more robust research designs capable of capturing causal associations between the predictors of effective Industry 4.0 implementation and lean manufacturing outlines. Much of the current research utilizes cross-sectional research methods or single case studies. Despite the value of such research studies in uncovering success stories, they fail to generalize findings across sectors and cases. More longitudinal research is needed to further our understanding about actual associations between critical success factors and theorized outcomes [192, 194].

This section has discussed the independent factors influencing Industry 4.0 implementation both internally and externally. Components such as environment, simulations, industrial infrastructure, and budgeting play a role in both extending and impeding the growth of technology spread worldwide. Furthermore, economic factors ultimately pose different barriers to the implementation of Industry 4.0 in developing countries like Saudi Arabia, with consideration to importation and skilled labor for technological advancement. Literature reviews are also still limited with respect to lean manufacturing execution frameworks despite composing the majority of theoretical approaches (which also neglect details and specifications of developing industrial sectors). Despite the disadvantages faced by emerging nations compared to their advanced counterparts, over time more meta-analyses and data will be recorded and continue facilitating Industry 4.0 expansion across both public and private sectors in Saudi Arabia.

6.6 Summary

One of the main problems facing manufacturers is the dearth of easy to implement frameworks for industry 4.0 implementation. Many existing models necessitate transformational changes that are prohibitive to the budgets. Workplaces, job structures, and technology of most manufactures in developing countries. Initial investment in changing many infrastructures is a prerequisite to many frameworks being more effective. Such an approach is unrealistic at best. Manufacturers in developing countries need to follow simple solutions that shift their manufacturing from traditional approaches to smart frames in an accessible manner. Future researchers could develop more fine-grained guidelines to assist manufactures in making their enterprises smarter. One of the best ways in this domain is the provision of detailed steps with specific actions linked with timelines and variables. Such steps need to specify affordable technology options with realistic personnel demands [186-189].

An apparent disconnect between the research on Industry 4.0 implementation and the factors leading to its adoption in developing countries is the negligence of social and behavioral aspects of the phenomenon. Past research has established that Industry 4.0 is a diffusion-related phenomenon. If one factory in an area decided to import and implement smart technologies, neighboring factories are likely to implement similar technologies. Many papers published on Industry 4.0 minimally incorporate the social and cognitive elements of the matter. Most researchers underestimate the personal or individual connection to Industry 4.0 as an innovation related behavior. The outcome of such marginalization has been overemphasized technology-related variables and factors that take humans out of the implementation process to a large extent [189-191].

This chapter presented the main conclusions of this research. The inferences were discussed with relevance to prior research. Additionally, findings were presented within theoretical models and frameworks related to Industry 4.0. Practical implications based on observed conclusions were spelled out fully for stakeholders in order to guide their work in the field. Future research recommendations were demonstrated for potential authors interested in advancing the area of Industry 4.0 implementation within developing countries. The most challenging limitations preventing the smooth performance of the research were outlined. In sum, this chapter situated the findings from this research in the larger context of Industry 4.0 implementation.

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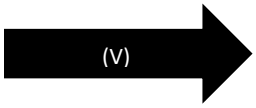
Appendix

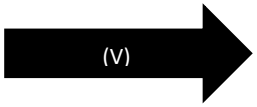
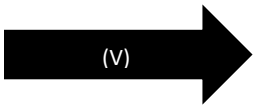
Questionnaire

On a feeling thermometer—this is a common type of scales used in questionnaires capturing respondents' perceptions more accurately compared restricted Likert scales—ranging from 0 (not accurate at all) to 100 (very accurate), how accurate does the following matrix represent your conception of each bivariate relationship linking Industry 4.0 implementation and the 10 factors discussed in our earlier focus group?

Note that Table A.1 represents the bivariate relationships between prohibitive cost and all other factors. These relationships represent the overall ratings of the six experts. The relationships are used to validate whether the experts agree on the results of the ISM model or not to inject more confidence in the results found through this research.

Table A.1. Bivariate Relationships

Variable 1	**Direction**	**Variable 2**	**Accuracy Score (0-100)**
Prohibitive Costs		Workplace Disruptions	
Prohibitive Costs		Natural Disasters	
Prohibitive Costs		Unclear Return on Investment	
Prohibitive Costs		Insufficient Technology Infrastructures	

Prohibitive Costs		Management Resistance	
Prohibitive Costs		Integration Challenges	
Prohibitive Costs		Unclear Regulatory Environments	
Prohibitive Costs		Information Security and Privacy Concerns	
Prohibitive Costs		Absence of Talent in the Workforce	
V: Right-sided, A: left-sided, X: both-sided, O: no relationship.			

On a feeling thermometer ranging from 0 (strongly disagree) to 100 (strongly agree), please indicate your score per statement below:

1. The model accurately represents the relationships between all factors related to Industry 4.0 implementation.

2. The model contains the most important factors affecting Industry 4.0 implementation in manufacturing facilities within the developing world.

3. The model presents a guiding framework for new stakeholders interested in implementing Industry 4.0 in their manufacturing facilities.

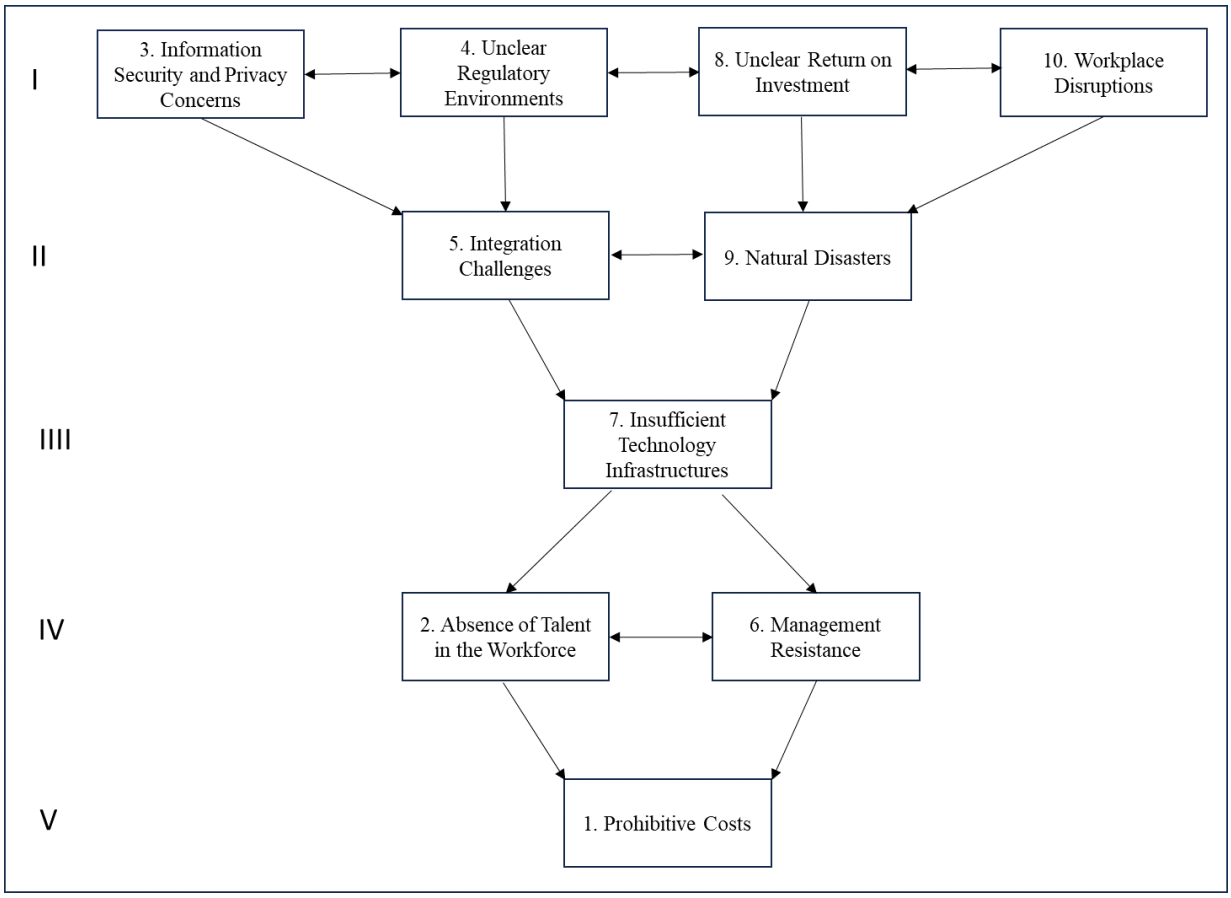
4. The relationships between the factors represent their real-world associations in practical settings.

5. I intend to use the model as a conceptual tool to explain Industry 4.0 implementation in factories.

The five statements were rated by each expert. Each rating is a subjective self-reported score representing the degree of agreement with the statement by the expert. Note that the expert

had the option to choose any number between 0 strongly disagree and 100 strongly agree. Figure A.1 represents the model extracted from the ISM analysis based on the input of the experts. The entire procedure of reaching this model is fully detailed in the results chapter.

Figure A.1. ISM-based Model of Variables

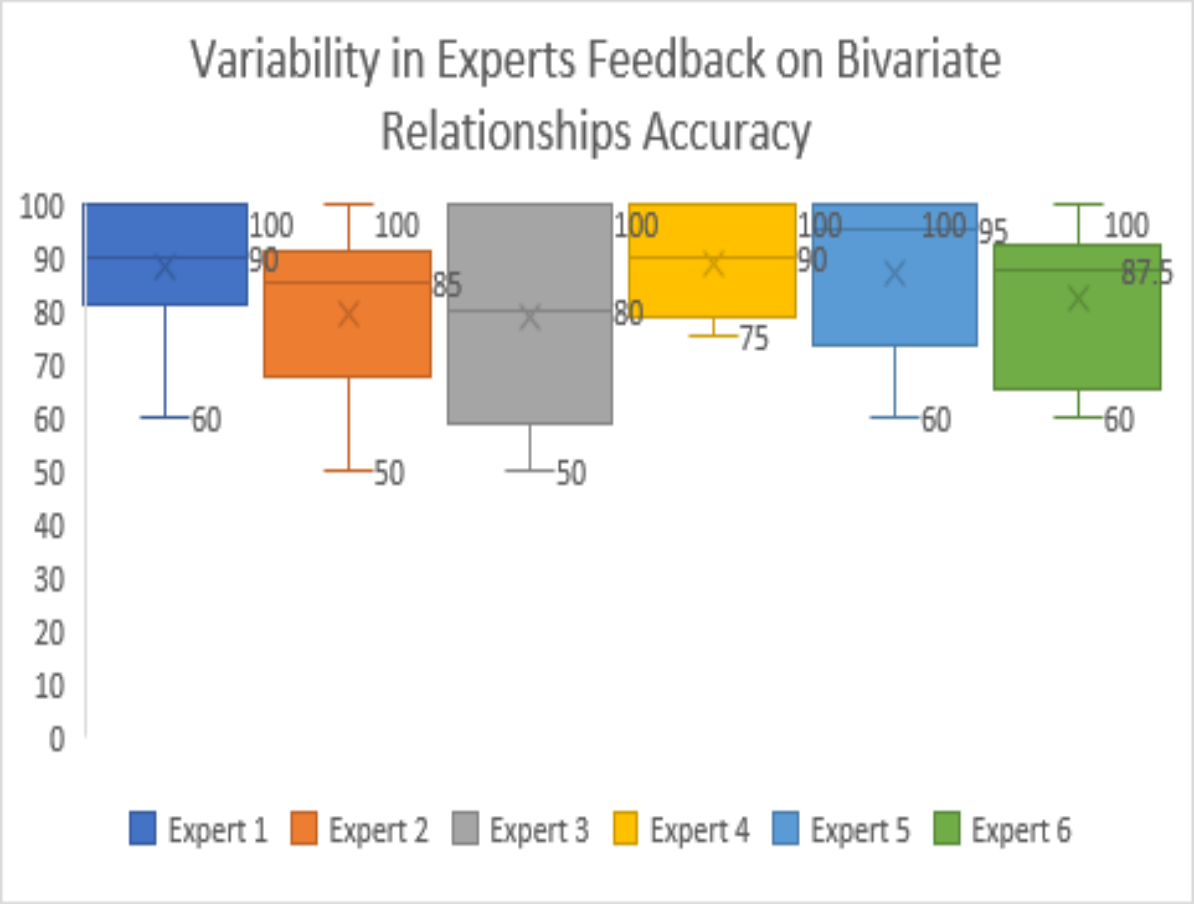


On a feeling thermometer ranging from 0 (extremely incorrect) to 100 (absolutely correct), rate the correctness of the following statements based on the location of each factor on the driving and dependence axes shown in Figure A.2. Below are the definitions of four different types of variables used in this study:

- Autonomous Variables: They are independent of other variables.
- Driving variables: They cause a change in other variables.
- Dependent variables: They rely on other variables to be changed.

- Linking variables: They connect variables together.

Figure A.2. Cluster of Variables



Below are helpful definitions that could be referred to when responding to the following statements:

1. Cost is an autonomous variable.

2. Talent in the workforce is an autonomous variable.

3. Information security is a dependent variable.

4. Regulatory is an autonomous variable.

5. Integration is a driving variable.

6. Management resistance is a linking variable.

7. Technology infrastructures are an autonomous variable.

8. Return on investment is an autonomous variable.

9. Natural disaster is an autonomous variable.

10. Workplace disruption is a dependent variable.