Assessing the Maturity of Industrial Engineering as an Engineering Discipline

by
Thomas William Murphy

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Industrial Engineering
(Honors Scholar)

Presented May 29, 2020
Commencement June 2020

AN ABSTRACT OF THE THESIS OF

Thomas William Murphy for the degree of Honors Baccalaureate of Science in Industrial Engineering presented on May 29, 2020.

Title: Assessing the Maturity of Industrial Engineering as an Engineering Discipline.

Abstract approved:____

Javier Calvo-Amodio

Industrial Engineering is a broad discipline, with a wide range of definitions for the field and the knowledge areas that make up its parts. A conceptual gap exists between the definition of the field of Industrial Engineering and the definitions of each of these parts. To facilitate advancement of the field and to enable practicing industrial engineers to effectively choose problem solving approaches, a conceptual framework is necessary to organize and define the field of Industrial Engineering. This thesis utilizes a systemic approach to attempt creating such a framework based on the general stages of a scientific endeavor. The proposed framework would connect the knowledge areas to each other and to the field by connecting each knowledge area to specific stages of a scientific endeavor. The attempt to create such a framework was unsuccessful, due to a lack of sufficient and specific definition of the knowledge areas. The conclusion follows that Industrial Engineering is not a mature engineering discipline, due to the lack of clear definitions of the parts and relationships between the parts. Further work is necessary to develop the definition of Industrial Engineering and its related Body of Knowledge.

Key Words: Industrial Engineering, disciplinary maturity, systems science, Industrial Engineering ontology

Corresponding e-mail address: murphyth@oregonstate.edu

Assessing the Maturity of Industrial Engineering as an Engineering Discipline

by
Thomas William Murphy

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Industrial Engineering
(Honors Scholar)

Presented May 29, 2020
Commencement June 2020

Thomas William Murphy for the degree of Honors Baccalaureate of Science in Industrial Engineering presented on May 29, 2020.

APPROVED:

____

Javier Calvo-Amodio, Mentor, representing School of Mechanical, Industrial and Manufacturing Engineering

Hector Vergara, Committee Member, representing School of Mechanical, Industrial and Manufacturing Engineering

David Porter, Committee Member, representing School of Mechanical, Industrial and Manufacturing Engineering

Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Thomas William Murphy, Author

ACKNOWLEDGEMENTS

Thank you to Dr. Calvo for your mentorship through this endeavor and for guiding me through the process of researching and writing this thesis.

Thank you to Sage Kittleman and Malaia Jacobsen for the time and energy they have spent performing the coding for this thesis – this research would not have been possible without their contributions.

Thank you to Fr. Maximo Stock for helping me see where this thesis fits into the bigger picture of my life and for encouraging me to complete it.

Thank you to my parents for their support, love, and encouragement through my entire academic career.

Table of Contents

1 Introduction ... 1

1.1 Background ... 1

1.2 Problem Statement ... 3

1.3 Research Questions ... 4

1.4 General Hypotheses ... 4

1.5 Research Purpose ... 5

1.6 Research Objectives ... 5

1.7 Delimitations ... 5

1.7.1 Limitations ... 6

1.7.2 Assumptions ... 6

1.8 Relevance of this Study ... 7

1.8.1 Need for this Research ... 7

1.8.2 Benefits of this Research ... 7

1.9 Research Outputs and Outcomes ... 8

2 Literature Review ... 9

2.1 Introduction ... 9

2.2 Definitions of the field of Industrial Engineering ... 9

2.2.1 History of Definitions ... 9

2.2.2 Current Institute of Industrial and Systems Engineering definition ... 12

2.2.3 The Industrial Engineering Body of Knowledge ... 13

2.2.4 Accreditation Board for Engineering and Technology Criterion ... 14

2.3 The Knowledge Areas of Industrial Engineering ... 15

2.3.1 Work Design & Measurement 15
2.3.2 Operations Research & Analysis 16
2.3.3 Engineering Economic Analysis 17
2.3.4 Facilities Engineering & Energy Management 18
2.3.5 Quality & Reliability Engineering 19
2.3.6 Ergonomics and Human Factors 20
2.3.7 Operations Engineering & Management 21
2.3.8 Supply Chain Management 22
2.3.9 Engineering Management 23
2.3.10 Safety 24
2.3.11 Information Engineering 25
2.3.12 Design and Manufacturing Engineering 25
2.4 Systems Thinking and Ontologies 26
2.5 Stages of a Scientific Endeavour 28
2.6 Gap in Literature 31
2.7 Conceptual/Theoretical Model 32
3 Methodology 35
3.1 Introduction 35
3.2 Research Design 35
3.2.1 Type of Research 35
3.2.2 Research Focus 35
3.2.3 Qualitative Methods 36
3.2.4 Quantitative Methods 37
3.2.5 Research Hypotheses Restated 37
3.3 Collection and Treatment of Data 38

3.3.1 Data Collection 38
3.3.2 Treatment of Data 39
3.4 Methodological Issues 39
3.4.1 Reliability 39
3.4.2 Validity 39
3.4.3 Replicability 40
3.4.4 Bias 40
3.4.5 Representativeness 41
3.5 Research Constraints 41
4 Results 43
4.1 Introduction 43
4.2 Data Collection 43
4.2.1 Design of Data Collection 43
4.2.2 Calibration Process 43
4.3 Data Analysis 47
4.4 Results from Study 50
4.4.1 Second Research Hypothesis 50
4.4.2 First Research Hypothesis 51
5 Conclusion 53
5.1 Features of this Research 53
5.2 Limitations of this Research 54
5.3 Findings from this Research 54
5.3.1 Findings for knowledge area alignment with stages 55
5.3.2 Findings for relationships between the knowledge areas. 56
5.3.3 Findings for maturity of Industrial Engineering discipline 56

5.4 Future Research Needs 56

6 References 58

6.1 References 58

6.2 Bibliography 60

7 Appendix A: Analysis Inputs and Outputs 62

LIST OF FIGURES

Figure | Page

Figure 1-1. Stages of a Scientific Endeavor (Rousseau, 2018a) 3

Figure 2-1. Stages of a Scientific Endeavor (Rousseau, 2018a) 29

Figure 2-2. A scientific discipline's typical activity level per field dimension (Rousseau, 2018a) 30

Figure 2-3. Principles relating different disciplinary stages. (Rousseau, 2018a) 30

Figure 2-4. A Typology for Systems Principles (Rousseau, 2018a) 31

Figure 2-5. Conceptualization of Current Industrial Engineering Maturity State 32

Figure 2-6. Conceptualization of Ideal Industrial Engineering Maturity State 33

Figure 4-1. Process for Calculating Inter-Coder Reliability 44

Figure 4-2. Data Analysis Process 48

Figure 4-3. Visualization of Knowledge Area Mappings 49

LIST OF TABLES

Table Page

Table 2-1. History of Industrial Engineering Definitions 10

Table 2-2. Decomposition of Industrial Engineering Definition 13

Table 2-3. Knowledge Areas of Industrial Engineering (IISE, 2019) 13

Table 3-1. Variables for Research Hypothesis 1 38

Table 4-1. Inter-Coder Agreement Results 44

Table 4-2. Knowledge Area Mapping to Stages of a Scientific Endeavor 48

Table 4-3. Normalized Knowledge Area Mapping to Stages of a Scientific Endeavor 49

Table 4-4. Knowledge area dominant stages and levels of alignment........................ 50

Table 4-5: Statistical Analysis of Alignment Levels 51

Table 7-1. Inputs of Coding Analysis 63

Table 7-2. Outputs of Coding Analysis 67

Chapter 1

1 Introduction

1.1 Background

The field of Industrial Engineering is today one of the broadest engineering disciplines, involving design and analysis on systems ranging in size and complexity from a single motion of a worker to international corporations (Pritsker, 1990). Frederick Taylor, who pioneered the field of scientific management which has evolved into Industrial Engineering, said that “The principle object of management should be to secure the maximum prosperity for the employer, coupled with the maximum prosperity for the employee (1911).” This simple definition of the field has evolved into the current definition from the Institute of Industrial and Systems Engineering (IISE, 2019):

> *Industrial engineering is concerned with the design, improvement and installation of integrated systems of people, materials, information, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems (IISE, 2019).*

This definition defines the field *intensionally* – that is, it gives the necessary and sufficient conditions for which the term “Industrial Engineering” applies (Rousseau, Billingham, & Calvo-Amodio, 2018). The Institute of Industrial and Systems Engineering has enumerated the knowledge areas and the concepts, methodologies, and tools they each contain in its Industrial Engineering Body of Knowledge, as have editors of Industrial Engineering handbooks. These lists serve as *extensional* definitions of the field, by listing all the knowledge that falls under the field of Industrial Engineering (Rousseau et al., 2018). Literature has also defined “Principles of Industrial Engineering,” such as Kambhampati

(2017), which divide the field conceptually, but are not directly linked to specific methods of application.

Industrial Engineering is a conceptual system, “a structured set of parts or elements, which together exhibit meaning that the individual parts do not” (Sillitto et al., 2018). Individually, each of the concepts, methodologies, and tools that make up the field of Industrial Engineering do not have the same meaning and purpose as they do in the context of the entire field. Given that Industrial Engineering is a conceptual system, systems science can provide a means for understanding the maturity of the field of Industrial Engineering, because systems science seeks to provide a vocabulary and principles for explaining the nature of complex systems (Rousseau, 2018b).

Systems science produces theories and models that help us think in systems; therefore, systems thinking is informed by the work of systems science. There are many applied systems thinking approaches, but Cabrera developed one using systems science and proper scientific methods. Cabrera (2006) defines ‘Systems Thinking’ as the application of a set of four rules. These rules were developed based on systems science knowledge and studies of human cognition. Systems thinking occurs when these rules are applied recursively to develop and refine a concept about a phenomenon. The four rules are:

1. **Distinction making**: making a differentiation between identity and other, what something is and what something is not, drawing the boundary between what is internal and what is external to the system or concept of interest.
2. **Interrelating**: linking concepts to one another by identifying causes and effects
3. **Organizing systems**: grouping or splitting concepts into larger wholes (systems) which are made up of smaller elements (parts)
4. **Perspective taking**: taking different points of view on a system of concepts to reorient the observation

The Institute of Industrial and Systems Engineering has drawn the boundaries of Industrial Engineering with its Body of Knowledge and organized it into smaller parts (from one perspective) by dividing it into knowledge areas.

A complementary perspective that can be taken is viewing Industrial Engineering as a scientific endeavor. Rousseau (2018a) presents a systemic architecture that divides any scientific endeavor into four general stages, each characterized by some "essence" and a typical output, as depicted in Figure 1-1..

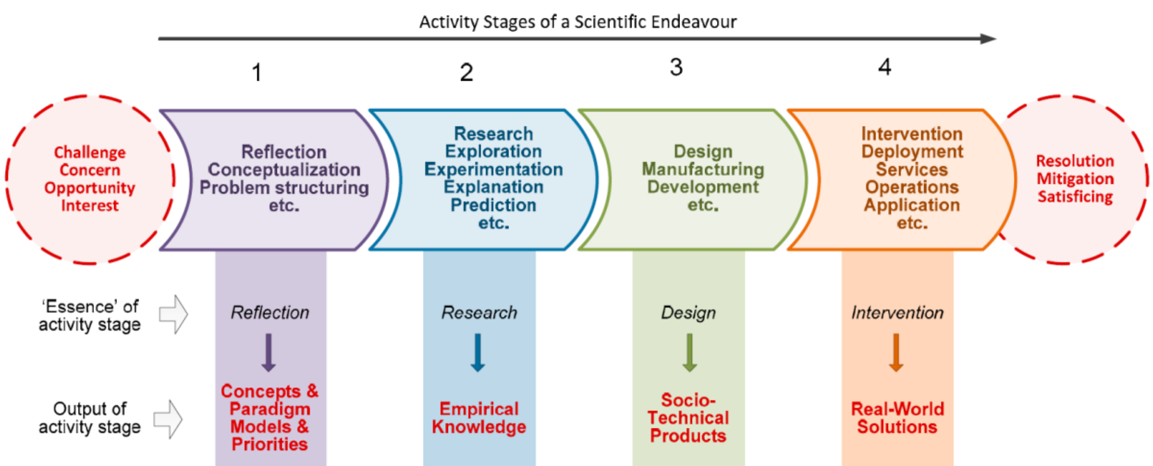

Figure 1-1. Stages of a Scientific Endeavor
(Rousseau, 2018a)

Rousseau proposes that though these stages are distinct, any given field, or part of a field, has one of these stages as its "essence" and involves lesser amounts of the activities involved in the other stages. All of the stages are interrelated: they share a common structure of methods, activities, and outputs; and the principles that are outputs from one serve as inputs to the next. Therefore, approaching Industrial Engineering from the perspective of this architecture could provide a framework for relating its knowledge areas.

1.2 Problem Statement

Though intensional definitions capture the core characteristics of Industrial Engineering by providing the necessary and sufficient conditions for which the term applies, it is always useful to have a comprehensive list of what knowledge areas and tools are considered within the boundary of the field of Industrial Engineering. For this purpose, the Institute of Industrial and Systems Engineering provides an extensional definition of Industrial Engineering that includes the concepts, methodologies, and tools within each knowledge area in the form of their Industrial Engineering Body of Knowledge. However, as complete as this definition is, it is limited only to listing what encompasses Industrial Engineering and lacks connections between knowledge areas and to the field of Industrial Engineering as a whole. Therefore, a gap exists between the definition of the entire field of Industrial Engineering and the definitions of each of its parts. There is a need to determine the relationships between these parts, and their relation to the field of Industrial Engineering. The completeness of the structure of these relationships can provide insight into the degree of maturity of the Industrial Engineering discipline.

1.3 Research Questions

1. What is the degree of maturity of the Industrial Engineering discipline?
   1.1. Can the relationships between the different knowledge areas of Industrial Engineering be established?
   1.2. Do the knowledge areas of Industrial Engineering align with specific stages of a scientific endeavor?

1.4 General Hypotheses

1. Industrial Engineering is a mature engineering discipline.
   1.1. The relationships between the different knowledge areas of Industrial Engineering can be established.
   1.2. The knowledge areas of Industrial Engineering align with specific stages of a scientific endeavor.

1.5 Research Purpose

The purpose of this research is to assess the maturity of Industrial Engineering as an engineering discipline. This assessment will establish connections between the different knowledge areas of Industrial Engineering and the entire field that can serve as a guide to researchers, educators, students and practitioners. Currently, it is challenging to understand what Industrial Engineering is, so even those who study and practice the field might have a reductionistic understanding of the field. This research aims to develop a framework that provides a means for understanding the field of Industrial Engineering as a system of interconnected disciplinary areas, which will inform and guide future research, education, and practice of the field of Industrial Engineering.

1.6 Research Objectives

General objectives of this research are:

1. Provide a framework to catalog knowledge of the field of Industrial Engineering and each of its knowledge areas.
2. Link each knowledge area to the field as a whole using Rousseau's stages of a scientific endeavor as a framework
3. Develop an ontological framework to guide the selection of appropriate Industrial Engineering concepts, methods, techniques, and tools for a given problem.

1.7 Delimitations

This research focuses on developing a framework for relating the knowledge areas of Industrial Engineering, and therefore must adopt as inputs existing definitions of the field of Industrial Engineering and its knowledge areas. The Institute of Industrial and Systems Engineering's Industrial Engineering Body of Knowledge will serve as this input. The proposed framework will be validated through a coding process, where three coders apply the proposed framework to the field of Industrial Engineering.

Though Systems Engineering is considered a closely related field, its body of knowledge is maintained separately from that of Industrial Engineering (Board, 2019). Therefore, the current research will deal only with the field of Industrial Engineering, not Systems Engineering.

1.7.1 Limitations

A list of the limitations encountered during this research is presented below:

- The validation of the model was performed using a limited number of individual coders, due to time and resource constraints.
- The researchers involved are not experts in the field of Industrial Engineering, or in any particular knowledge area. They have the context of an undergraduate degree in Industrial Engineering and the additional research for this work.
- The background research on the different knowledge areas of Industrial Engineering was constrained by time, and so consisted of the following:
  - Review of a subset of between one and three of the sources referenced for each knowledge area in the Industrial Engineering Body of Knowledge
  - Synthesis of reviewed sources with the researcher's undergraduate Industrial Engineering education at Oregon State University

1.7.2 Assumptions

A list of the main assumptions of the proposed solution is presented below:

- This research assumes the Institute of Industrial and Systems Engineering's definition of the knowledge areas of Industrial Engineering presented in the Industrial Engineering Body of Knowledge are a complete and adequate representation of the field (IISE, 2019).
- This research assumes that the literature consulted to define each knowledge area is representative of the common research and practice of that knowledge area.

1.8 Relevance of this Study

1.8.1 Need for this Research

Much work has been done in defining and analyzing the field of Industrial Engineering, but not using a systemic approach. Such an approach would enable a better understanding of what the field is by defining the whole in terms of the relationships between its parts. At the same time, it allows for each of the parts to be understood in the context of the whole.

1.8.1.1 Theoretical Research Needs

The field of Industrial Engineering is defined currently through its practice. To facilitate advancement of the field, a conceptual model of the field is necessary to keep it centered and not grow disparate. A philosophical foundation is necessary to organize and guide the science, engineering, and practice areas of the discipline.

1.8.1.2 Practical Research Needs

Practicing industrial engineers are faced with a wide variety of problems, and have a great number of concepts, methods, techniques, and tools at their disposal to address these problems. The appropriate choice of approach is key to the successful resolution of a problem, but Industrial Engineering lacks a methodical way to choose an approach given a problem. The immediate practical benefit of this research is to provide a tool for practicing industrial engineers that provides guidance in effectively formulating and solving problems using the most appropriate concepts, methods, techniques, and tools from the Industrial Engineering Body of Knowledge.

1.8.2 Benefits of this Research

This conceptual model can serve as a guide to better inform and direct research decisions. The same conceptual model can help Industrial Engineering educators teach the different knowledge areas not as isolated parts, but rather present them in their appropriate context in relation to the entire field. By learning about Industrial Engineering within this structure, students will be better able to synthesize and appropriately apply what they have learned. For practicing industrial engineers, the framework will provide a means to determine the best concepts, methods, techniques, and tools to address a given problem.

1.9 Research Outputs and Outcomes

The primary outcome of this research is a validated framework establishing the relationships between the knowledge areas of Industrial Engineering. This framework will serve researchers, educators, students, and practitioners of Industrial Engineering in their work, enabling them to see their individual work in the context of the entire field. Additionally, a methodology will be created using this framework to match problems to appropriate Industrial Engineering concepts, methods, techniques, and tools.

Chapter 2

2 Literature Review

2.1 Introduction

The following literature provides an overview of the field of Industrial Engineering, its knowledge areas, relevant systems thinking theory, and a general model for the stages of a scientific endeavor. This model will be applied to the knowledge areas of Industrial Engineering to establish the relationships between the knowledge areas and an architecture of the entire field.

2.2 Definitions of the field of Industrial Engineering

This research attempts to establish the relationships between the knowledge areas of Industrial Engineering. Therefore, it is relevant to first establish the history and current definitions of the field of Industrial Engineering, to serve as a context for the current study.

2.2.1 History of Definitions

The commonly recognized "founder" of Industrial Engineering is Frederick Taylor, who wrote the book The Principles of Scientific Management in 1911. His definition of the field was based on the idea of maximizing prosperity for both employer and employee. Since this time, as the field has evolved, numerous different definitions have been presented. These are summarized in Table **2-1**. The definitions are presented here to show both how the field has evolved over time, but also to show that there have always been multiple definitions of Industrial Engineering, and they differ in fundamental ways.

The earliest version of the current Institute of Industrial and Systems Engineering definition was presented in 1955 by the American Institute of Industrial Engineers, and since that time has changed only slightly. In 1960, mention of 'systems of energy' was added to the definition, and in 2000, systems of 'men' was changed to systems of 'people' and mention of systems of information was added. This version of the definition is still used today.

Table 2-1. History of Industrial Engineering Definitions

YEAR	SOURCE	DEFINITION
1911	Frederick Taylor	The principle object of management should be to secure the maximum prosperity for the employer, coupled with the maximum prosperity for the employee (Taylor, 1911, p. 9).
1911	Frederick Taylor	"In the case of a more complicated manufacturing establishment, it should also be perfectly clear that the greatest permanent prosperity for the workman, coupled with the greatest prosperity for the employer, can be brought about only when the work of the establishment is done with the smallest combined expenditure of human effort, plus nature's resources, plus the cost for the use of capital in the shape of machines, buildings, etc." (Taylor, 1911, p. 11)
1911	Frederick Taylor	"… the greatest prosperity can exist only as the result of the greatest possible productivity of the men and machines of the establishment - that is, when each man and each machine are turning out the largest possible output…" (Taylor, 1911, p. 12)
1911	Charles Buxton Going	Industrial engineering is the formulated science of management. It directs the efficient conduct of manufacturing, construction, transportation, or even commercial enterprises — of any undertaking, indeed, in which human labor is directed to accomplishing any kind of work (Going, 1911, p. 1).

Table 2-1. History of Industrial Engineering Definitions

YEAR	SOURCE	DEFINITION
1955	American Institute of Industrial Engineers	Industrial Engineering is concerned with the design, improvement and installation of integrated systems of men, materials, and equipment. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems (Maynard & Zandin, 2001, p. 1.41).
1960	American Institute of Industrial Engineers	Industrial Engineering is concerned with the design, improvement and installation of integrated systems of men, materials, equipment, and **energy**. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems (Maynard & Zandin, 2001, p. 1.11).
1985	A. Alan B. Pritsker	The role of the industrial engineer is to integrate the skills of engineering with the tools of mathematics and computer science to formulate and build models for design, analysis, evaluation, and prediction (Pritsker, 1990, p. 8).
1990	A. Alan B. Pritsker	I interpret industrial engineering to be the process of improving total system performance as measured by economic measures, quality attainment, and environmental impacts, and how these relate to the benefit of mankind (Pritsker, 1990, p. 5).
2000-2019	Institute of Industrial and Systems Engineering	Industrial engineering is concerned with the design, improvement and installation of integrated systems of **people**, materials, **information**, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained

Table 2-1. History of Industrial Engineering Definitions

YEAR	SOURCE	DEFINITION
		from such systems (Maynard & Zandin, 2001, p. xix).
2001	Maynard's Industrial Engineering Handbook	Maynard defines Industrial Engineering as optimizing the utilization of human resources, facilities, equipment, tools, technologies, information, and the handling of materials to produce quality products and services safely and cost-effectively considering the needs of customers and employees (Maynard & Zandin, 2001, p. xix).

2.2.2 Current Institute of Industrial and Systems Engineering definition

The Institute of Industrial and Systems Engineering is commonly recognized professional society for the discipline of Industrial Engineering. Therefore, the current study will utilize its definitions as the basis for the current research. As mentioned previously in Chapter 1, the Institute of Industrial and Systems Engineering defines Industrial Engineering in the following way:

"Industrial Engineering is concerned with the design, improvement and installation of integrated systems of people, materials, information, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems" (IISE, 2019).

This intensional definition provides the necessary and sufficient conditions for something to be considered Industrial Engineering, in terms of the objectives, the types of systems analyzed, the knowledge applied, and the activities carried out in the practice of Industrial Engineering. These are presented in list form in Table 2-2.

Table 2-2. Decomposition of Industrial Engineering Definition

OBJECTIVES	SYSTEM TYPES	KNOWLEDGE	ACTIVITIES
Design	People	Mathematics	Specify
Improvement	Materials	Physical Science	Predict
Installation	Information	Social Science	Evaluate
	Equipment	Engineering Analysis	
	Energy	Engineering Design	

2.2.3 The Industrial Engineering Body of Knowledge

The Institute of Industrial and Systems Engineering also maintains a Body of Knowledge for the field of Industrial Engineering, providing an extensional definition by listing the essential information for Industrial Engineering. It is comprised of 12 knowledge areas, each of which are outlined with essential knowledge to "achieve a mastery in the field of Industrial Engineering" (IISE, 2019). The knowledge areas of the Body of Knowledge are listed in Table 2-3.

Table 2-3. Knowledge Areas of Industrial Engineering (IISE, 2019)

#	KNOWLEDGE AREA
1	Work Design & Measurement
2	Operations Research & Analysis
3	Engineering Economic Analysis
4	Facilities Engineering & Energy Management
5	Quality & Reliability Engineering
6	Ergonomics and Human Factors
7	Operations Engineering & Management
8	Supply Chain Management
9	Engineering Management
10	Safety
11	Information Engineering
12	Design and Manufacturing Engineering
13	**Related Topics**
13.1	Product Design & Development
13.2	System Design & Engineering

In the Industrial Engineering Body of Knowledge, each knowledge area is defined in few sentences, and the relevant knowledge is then listed in outline form. A list of references to textbooks with more information on each of the knowledge areas is provided.

The Industrial Engineering Body of Knowledge is maintained by a Content Review Board appointed by leadership within the Institute of Industrial and Systems Engineering. Three subject matter experts per knowledge area are responsible for maintaining the respective sections of the Body of Knowledge. The Body of Knowledge is updated by this Board in response to proposals for changes submitted by any Institute of Industrial and Systems Engineering member. (IISE, 2017)

The Industrial Engineering Body of Knowledge also presents a section of "Related Topics," which include Product Design & Development and System Design and Engineering (See Table 2-3). The full Body of Knowledge for Systems Engineering is maintained separately, and will not be considered as part of the current study (Board, 2019). Though the fields of Industrial and Systems Engineering are closely related and share areas of knowledge and application, the decision of their respective professional societies to separate the bodies of knowledge will be respected.

2.2.4 Accreditation Board for Engineering and Technology Criterion

The Accreditation Board for Engineering and Technology (ABET) is an organization that sets standards for accreditation of higher education programs for science and engineering. ABET has a set of criteria that apply to all engineering programs of study, and also a specific criterion that specifically applies to Industrial Engineering curriculum(ABET, 2019):

> The curriculum must prepare graduates to design, develop, implement, and improve integrated systems that include people, materials, information, equipment and energy. The curriculum must include in-depth instruction to accomplish the

> integration of systems using appropriate analytical, computational, and experimental practices.

This criterion is based on the Institute of Industrial and Systems Engineering definition of Industrial Engineering presented in Section 2.2.2.

2.3 The Knowledge Areas of Industrial Engineering

The following sections represent the twelve knowledge areas of Industrial Engineering defined in the Institute of Industrial and Systems Engineering Body of Knowledge. Each knowledge area will be summarized in reference to the definition in the Industrial Engineering Body of Knowledge and the literature reviewed for this study. These knowledge areas are the "parts" of Industrial Engineering that serve as the structure for the framework developed in the current research.

As noted in Section 1.7.1, the information presented in this part of the literature review represents a synthesis of the Industrial Engineering Body of Knowledge, research from sources referenced in the Body of Knowledge, and background and sources from the researcher's undergraduate Industrial Engineering curriculum at Oregon State University.

2.3.1 Work Design & Measurement

The Institute of Industrial and Systems Engineering defines the Work Design and Measurement knowledge area as follows:

> Work Design and Measurement covers the tools and techniques used to establish the time for an average worker to carry out a specified task at a defined level of performance in a defined work setting. The analysis associated with Work Design and Measurement focuses to create a standardized work environment that maximizes worker satisfaction and creates the best possible value for the enterprise and its customers (IISE, 2019).

An alternative definition of the knowledge area is “the design of jobs in their physical and social context (Konz & Johnson, 2008).” Turner describes the knowledge area as having the elements of determining standard time, a bottom-up approach starting with measurement, and adjustments leading to standards (Turner, Mize, & Case, 1987). Some representative tools and methods associated with this knowledge area include time studies, motion studies, line balancing, and workstation design. This knowledge area is well defined, with a relatively high degree of alignment between different sources on its definition.

2.3.2 Operations Research & Analysis

The Institute of Industrial and Systems Engineering defines the Operations Research and Analysis knowledge area as follows:

> Operations Research and the Management Sciences include a variety of problem-solving techniques focused toward improved efficiency of systems and support in the decision-making process. The realm of Operations Research involves the construction of mathematical models that aim to describe and/or improve real or theoretical systems and solution methodologies to gain real-time efficiency.
>
> The knowledge area of Operations Research is by its nature mathematical and computational. A fundamental basis in this knowledge area includes probability, statistics, calculus, algebra, and computing (IISE, 2019).

An alternative definition of the knowledge area is “…a scientific approach to decision making that seeks to best design and operate a system, usually under conditions requiring the allocation of scarce resources (Winston & Goldberg, 2004, p. 1).” Winston goes on to describe this scientific approach, saying “The scientific approach to decision making usually involves the use of one or more mathematical models. A mathematical model is a mathematical representation of an actual situation that may be used to make better decisions or simply to understand the actual situation better (Winston & Goldberg, 2004, p. 1).” In his definition of the knowledge area, Frederick Hillier addresses the two key terms, *operations* and *research*. *Operations* is the area of application – operations research is applied to “problems that concern how to conduct and coordinate the operations (i.e., the activities) within an organization (Hillier & Lieberman, 2015).” *Research* concerns the approach taken, which resembles the scientific method (Hillier & Lieberman, 2015).

Some characteristic methods of operations research include linear programming, nonlinear programming, heuristics, simulation, and queuing systems. This knowledge area is well-defined, with a specific set of methodologies generally accepted as constituting the knowledge area.

2.3.3 Engineering Economic Analysis

The Institute of Industrial and Systems Engineering defines the Operations Research and Analysis knowledge area as follows:

> Engineering economics is a specific knowledge area of economics focused on engineering projects. Industrial Engineers need to understand economic viability of any potential problem solution (IISE, 2019).

The fundamental question asked in this knowledge area is whether engineering projects are economically viable – whether they make or save enough money to warrant their capital investments (Sullivan, Wicks, & Luxhoj, 2003, p. xi). Problems are broken down into their constituent components to make analysis possible (Newnan, Eschenbach, & Lavelle, 2012). Due to the complexity of the analysis process, engineering economic analysis is typically only applied in situations of significant investments, benefits, or risks.

Some characteristic methods in engineering economic analysis include cash flow analysis, cost-benefit analysis, comparisons between alternatives, cost accounting. A key concept applied in most analyses is the time value of money. This knowledge area is well-defined, with a clear scope and set of knowledge and methods that fall within that scope.

2.3.4 Facilities Engineering & Energy Management

The Institute of Industrial and Systems Engineering defines the Facilities Engineering & Energy Management knowledge area as follows:

> Facilities Engineering is concerned with the arrangement of physical resources to support the optimal production and distribution of goods and services. Energy Management includes the planning and operation of energy required in facilities to support the production and distribution of goods and services. Their close interrelationship accounts for their knowledge topic described in a common section (IISE, 2019).

This single knowledge area combines two closely related, but separate areas of knowledge. Facilities Engineering deals with problems including the location, sizing, and layout of facilities, while Energy Management focuses on the design and integration of different types of energy and utilities necessary to operate facilities. Tompkins describes the knowledge area as follows: "Facilities planning determines how an activity's tangible fixed assets best support achieving the activity's objective (Tompkins, White, Bozer, & Tanchoco, 2010, p. 6)." When intentionally designing a facility, it is important to have the primary objective in mind, so all other decisions can be subordinated to that goal. These decisions can happen on different levels of detail, ranging from the geographic location of the facility to the micro-layout of a particular work area within the facility. The smallest level of detail, the layout of individual workstations in the facility, falls under the Work Design knowledge area (IISE, 2019).

Some characteristic methods involved in Facilities Engineering and Energy Management are charts and diagrams depicting flow between different elements of an activity (from-to chart, flow process chart, activity relationship chart), as well as algorithms to design and improve a facility layout. Energy Management deals largely with technical knowledge of the different types of energy systems and the codes and regulations associated with them. The Facilities Engineering portion of the knowledge area is well defined, with recognized methods and scope, but the Energy Management portion of the knowledge area is not well-defined, with few of the listed methodologies in the Institute of Industrial and Systems Engineering Body of Knowledge pertaining specifically to Energy Management.

2.3.5 Quality & Reliability Engineering

The Institute of Industrial and Systems Engineering defines the Quality & Reliability Engineering knowledge area as follows:

> Quality Engineering covers the tools and techniques employed that help to prevent mistakes or defects in manufactured products or service processes that avoids problems when delivering solutions or services to customers. A closely related knowledge area is Reliability Engineering. These concepts are used to determine the ability of a system or component to function under stated conditions for a specified period of time (IISE, 2019).

The primary goal of Quality Engineering is to minimize defects and mistakes in products and services. Reliability engineering has a similar goal but focuses on maintaining and improving the systems which support the production of products and services. Quality Engineering can be divided into two main subsections: monitoring and control. This distinction between control and monitoring is emphasized by Hines (Hines & Montgomery, 1980). Quality monitoring methods collect data through different statistical methods to determine the current state of the activities of interest. It is the important and necessary first step in any quality engineering intervention, because actions cannot be taken to improve quality without first knowing the current state. Quality control deals with the methods by which levels of quality are improved and maintained. This can be achieved through changes to the process itself, or by pairing interventions with monitoring methods. Quality control can also be addressed at an institutional level, through systems like Lean and Six Sigma. These systems aim in part to improve quality by implementing cultural and organizational practices and systems among the workers in an organization.

Some characteristic methods of quality engineering are control charts and acceptance sampling. This knowledge area is well defined within the quality control portion, but there are some elements included, such as Lean and Six Sigma, which would arguably fit better into different knowledge areas. This inclusion could confuse the definition of this knowledge area.

2.3.6 Ergonomics and Human Factors

The Institute of Industrial and Systems Engineering defines the Ergonomics and Human Factors knowledge area as follows:

> Ergonomics and Human Factors as a field of research and practice is concerned with the design and analysis of equipment and devices that fit the human body and its cognitive abilities. The knowledge area includes contributions from anthropometry, statistics, psychology, physiology, biomechanics, industrial design, graphic design, operations research, and other disciplines. It is the study of designing equipment and devices that fit the human body and its cognitive abilities. The areas of emphasis are: Physical Ergonomics, Cognitive Ergonomics, and Organizational Ergonomics (IISE, 2019).

The underlying principle in this knowledge area is that if work systems and their components are designed with the capabilities and limitations of their human workers in mind, the performance of the resulting system will be better than otherwise (Pulat, 1992). This is analogous to principles from General Systems Theory, as Pulat explains: “For any system to function effectively, the two major prerequisites are: (1) the components must have been designed properly, and (2) the components must function together cohesively toward a common goal" (1992). As distinguished in the Institute of Industrial and Systems Engineering definition, ergonomics can focus on the physical aspects of humans and systems, the cognitive and information processing abilities of humans, or how humans work together in organizations. An important distinction to make for this work is that between the Work Design and Ergonomics knowledge areas. The difference between the two is the principles on which the analysis is based: work design focuses on the time and production aspects of work, while ergonomics focuses on designing the work to fit the human. There is some overlap in that human ergonomic limitations influence elements of work design analysis.

Some characteristic elements of physical ergonomics are anthropometrics and work capacity and fatigue. Cognitive ergonomics applies knowledge of human information processing to design displays and controls. This knowledge area is well-defined, although it has some overlap, especially in the organizational ergonomics area, which is encompassed in more depth in the Engineering Management knowledge area.

2.3.7 Operations Engineering & Management

The Institute of Industrial and Systems Engineering defines the Operations Engineering & Management knowledge area as follows:

> Operations Engineering and Management is an area of technical management dealing with the design and analysis of production and service processes. From an Industrial Engineering viewpoint this knowledge area employs tools and techniques to ensure business operations function efficiently, using as few resources as needed, and effectively in meeting customer requirements (IISE, 2019).

This knowledge area can be summarized as the management of the logistics necessary to make business operations function properly. Much of the activities involved are those of forecasting, planning, and control, but the knowledge area also encompasses areas of management. This is not a well-defined knowledge area, due to its broadness in scope. One of the referenced textbooks in the Body of Knowledge lists the following areas as all being a part of production management (Nahmias, 1993):

1. Inventory
2. Production scheduling and control
3. Equipment selection and replacement

4. Maintenance
5. Size and location of plants
6. Plant layout and structure
7. Quality control and inspection
8. Traffic and materials handling
9. Methods

These areas overlap heavily with the facilities design knowledge area, especially items 5,6, and 8. Item 7 falls under the quality and reliability engineering knowledge area. The area of supply chain management is contained within this knowledge area but is also given its own knowledge area in the Body of Knowledge. There is also a great deal of overlap with the engineering management knowledge area, with topics such as project management and organizational issues being included in the list of topics. Though these topics may be related to this knowledge area, they are not necessarily part of it, but rather are applied in the practice of the other activities which are specific to this knowledge area. The combination of overlap with other knowledge areas and the broadness of this knowledge area make it poorly defined.

2.3.8 Supply Chain Management

The Institute of Industrial and Systems Engineering defines the Supply Chain Management knowledge area as follows:

> Supply Chain Management (SCM) covers the movement, production, and storage of raw materials, work-in-process inventory, finished goods, and services from point of origin to point of consumption or use. Suppliers, manufacturers, intermediaries, stores, and service enterprises are involved in delivery of products and services to end customers in a supply chain (IISE, 2019).

Blanchard defines a supply chain as “the sequence of events that cover a product's entire life cycle, from conception to consumption” (Blanchard, 2010). Supply Chain Management is the management of this sequence of events from this high-level perspective. Though this sequence of events encompasses activities within other knowledge areas of Industrial Engineering, what differentiates it is the level of analysis: Rather than focusing on the individual stages of the activities, supply chain management focuses on the interaction and the high level decisions needed to design and operate a supply chain. There are three major focuses within supply chain management, based on its definition in the body of knowledge: financial, logistical, and relationships. The financial dimension deals with the decisions of cost, such as make-buy analysis and value determinations. The logistical dimension deals with the operational decisions of how to execute the supply chain, particularly between different parts of the organization and between internal and external elements of the supply chain. Blanchard lists the five primary processes on which a supply chain is built as the following: Inbound logistics, operations, outbound logistics, sales/marketing, and service (Blanchard, 2010). This broad focus differentiates it from operations management, which focuses on the operations of one element of the supply chain at a time. Finally, the relationships dimension deals with managing relationships at both ends of the supply chain, both suppliers and customers.

This knowledge area is well defined because it is defined both in scope and level of analysis, and though the scope includes elements of other knowledge areas, it is clear what activities are considered a part of this knowledge area, and what is merely related and applied knowledge.

2.3.9 Engineering Management

The Institute of Industrial and Systems Engineering defines the Engineering Management knowledge area as follows:

> Engineering Management is a focused area of management dealing with the application of engineering principles to business practice. Whereas Operations Engineering and Management focuses on the design and analysis of production and service processes, Engineering Management deals with the technical business side of the organization (IISE, 2019).

Engineering Management, by its nature, touches every part of an organization, because it deals with the business aspects of the operations. While most other knowledge areas of Industrial Engineering focus on the technical and operational aspects of organizations, Engineering Management focuses on the management of the business which supports all these technical operations. Some representative areas of Engineering Management include strategic management, project management, and performance measurement. While management is not typically considered an engineering discipline, rather a business discipline, what differentiates engineering management is the approach and methodologies of management: it applies the quantitative and qualitative methods of engineering to the practice of management (Morse & Babcock, 2007). The area of engineering management is well-defined, though elements of it overlap with other knowledge areas. Its differentiation of being focused on the business aspects of the organization puts it at a broader level of analysis than the other knowledge areas.

2.3.10 Safety

The Institute of Industrial and Systems Engineering defines the Safety knowledge area as follows:

> Occupational Safety Engineering addresses the origins or workplace accidents, regulations and management practices towards mitigating hazard exposures, preventing harm and reducing liability. Safety engineering also addresses methods and measures for recognizing and controlling workplace physical hazards, as well as approaches for dealing with accidents and facilitating recovery (IISE, 2019).

Safety Engineering, though an important consideration in the practice of Industrial Engineering, is not a well-defined knowledge area. The Body of Knowledge lists the different areas of safety as a perspective and overview, laws and regulations, hazards, and management. The idea of ‘safety’ makes it more of a set of knowledge considered in the practice of other areas of engineering rather than an independent knowledge area.

2.3.11 Information Engineering

The Institute of Industrial and Systems Engineering defines the Information Engineering knowledge area as follows:

> Information Engineering is an approach to planning, generating, distributing, analyzing and using collection of data in systems to facilitate decision making and business communication (IISE, 2019).

Information Engineering is an important yet very broadly defined knowledge area within Industrial Engineering. The length of the definition of the knowledge area of the Body of Knowledge itself is indicative of this: there are 17 different sub-areas within the knowledge area, and many of these sub-areas overlap with other knowledge areas, dealing with the specific aspects of those knowledge areas as they pertain to information engineering. Laudon describes Information Engineering as the engineering of the information technology necessary to support processes, and comments that it can be analyzed as a process itself (2004). Though the knowledge area is well-defined, it runs the risk of being too broad and including topics that would more appropriately belong in the bodies of knowledge of related knowledge areas of Industrial Engineering or different disciplinary fields, such as computer science.

2.3.12 Design and Manufacturing Engineering

The Institute of Industrial and Systems Engineering defines the Design and Manufacturing Engineering knowledge area as follows:

> Design and manufacturing engineering focuses on tools and techniques to conceptualize, engineer, produce, and qualify physical products across feature-scales, production quantities, and application domains. From an industrial engineering viewpoint, this knowledge area is concerned with the development, optimization, and standardization of methods to transform raw materials into

functional products to satisfy the applications' and stakeholders' requirements in the most time and cost efficient manner (IISE, 2019).

This knowledge area was added to the Industrial Engineering Body of Knowledge in the 2019 update and was listed as a "Related Topic" in previous versions of the Body of Knowledge (IISE, 2016). The topics in this knowledge area are relevant to Industrial Engineering but are also considered primarily important knowledge for the disciplines of Manufacturing and Mechanical Engineering. Its inclusion as one of the knowledge areas of Industrial Engineering risks blurring the boundary between Industrial Engineering and its related fields, thus weakening the definition of both.

2.4 Systems Thinking and Ontologies

The task of understanding and relating knowledge contained in the field of Industrial Engineering is large and complex, and systems thinking provides a means for approaching such complex tasks. The field of Industrial Engineering is a conceptual system, that is, a structured set of ideas, theories, and methods, which together exhibit meaning that the individual parts do not (Sillitto et al., 2018). Given this understanding, we can approach the task of understanding and relating the different knowledge areas of industrial engineering from a systemic perspective. To take this systemic perspective, it is first necessary to understand what it means to think systemically.

Derek Cabrera defines 'Systems Thinking' as the application of a set of four rules. These rules were developed based on systems science knowledge and studies of human cognition. Systems thinking occurs when these rules are applied recursively to develop and refine a concept about a phenomenon. The four rules are:

- **Distinction making**: making a differentiation between identity and other, what something is and what something is not, drawing the boundary between what is internal and what is external to the system or concept of interest.
- **Interrelating**: linking concepts to one another by identifying causes and effects
- **Organizing systems**: grouping or splitting concepts into larger wholes (systems) which are made up of smaller elements (parts)

  Perspective taking: taking different points of view on a system of concepts to reorient the observation (Cabrera, 2006)

Systems science provides a set of principles that can aid in ontology development. Rousseau, Billingham, and Calvo-Amodio (2018) propose a framework to apply systems thinking to creating ontologies of systems. An ontology is an "explicit specification of a conceptualization", a technical vocabulary which makes explicit an abstraction of reality (Gruber, 1993). For such an ontology to function well, it must be a system, and "for systems to function as wholes, their parts must work together in a coherent way, otherwise instabilities would arise to undermine the integrity of the system and its wholeness would break down" (Rousseau et al., 2018). Coherent functioning of the parts of an ontology depends on both the relationship of the parts with each other and the relationship of the whole with the environment surrounding it. Creating an ontology of Industrial Engineering, defined as a conceptual system, can yield insights into the maturity of the discipline.

However, to effectively define an ontology for Industrial Engineering, it is first necessary to set the boundary of the disciplinary field being defined. Researchers must identify a "spectrum of relevance" for the ontology, which manages the scope and ensures the ontology has clear limits. When defining such a spectrum of relevance, it is important to maintain a coherent balance between the categories within the scope of the ontology and the categories outside the scope. This is the distinction between the system and its environment, between what is considered a part the system and what is not considered a part of the system. If this boundary is not clearly and appropriately defined, the result can be an isolation of the disciplinary domain from its closely related fields. A discipline that is too broadly defined has too much overlap with its related fields, while a discipline that is too narrowly defined lacks the closeness necessary to make relationships with other fields (Rousseau et al., 2018). The existing boundaries for the field of Industrial Engineering come in the form of the definitions discussed in Section 2.2, both intensional (Section 2.2.1) and extensional (The Industrial Engineering Body of Knowledge, Section 2.2.3).

Having defined the boundary of a disciplinary field, a consistent and coherent definition of the parts falling within that boundary is also necessary. It is critical that any term in an ontology always has unique meaning, so it can be clearly distinguished from other terms. As a disciplinary field changes and terms are added, it may be necessary to adjust the definition of other terms to maintain uniqueness and coherent relationships. Terms and definitions cannot be updated in isolation, but rather must be defined and re-defined in the context of the entire disciplinary field. Each term is related to other terms in the ontology, and these relationships must be considered when definitions are updated. Such relationships can be better defined if a “network of categories” is created “in which the relationships and interdependencies between the categories are made explicit, easy to trace, and open to assessment.” (Rousseau et al., 2018) The Industrial Engineering Body of Knowledge serves as a list of the parts of Industrial Engineering for this research, so this perspective on the definition of terms in an ontology will be applied to the Industrial Engineering Body of Knowledge to assess the coherence and maturity of the engineering discipline.

2.5 Stages of a Scientific Endeavour

David Rousseau (2018a) presents a series of activity stages as a standard structure of any ‘scientific endeavor’. These stages are reflection, research, design, and intervention. They are depicted below in Figure 2-1. They provide a systemic architecture for any disciplinary field. Each stage has typical activities, one of which is chosen as the 'essence' for each stage and has some kind of output from its activities.

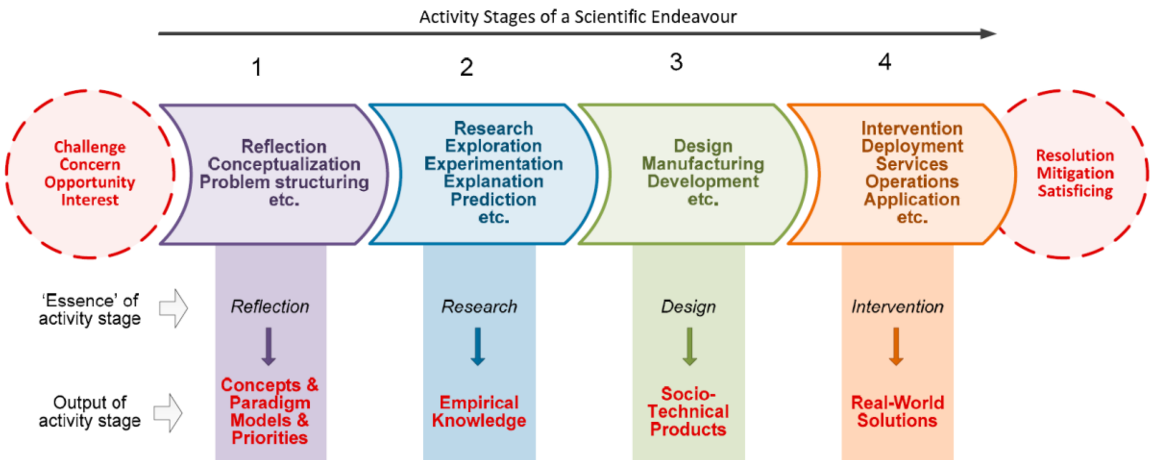

Figure 2-1. Stages of a Scientific Endeavor
(Rousseau, 2018a)

Any scientific discipline can employ activities from all four stages, but typically has a focus on one of the stages (also referred to as 'field dimensions'), as depicted in Figure 2-2. Figure 2-2 also shows the linkage between the stages of reflection, research, design, and intervention, and how they correspond to the fields of philosophy, science, engineering, and practice (respectively). These terms are used analogously in the following figures.

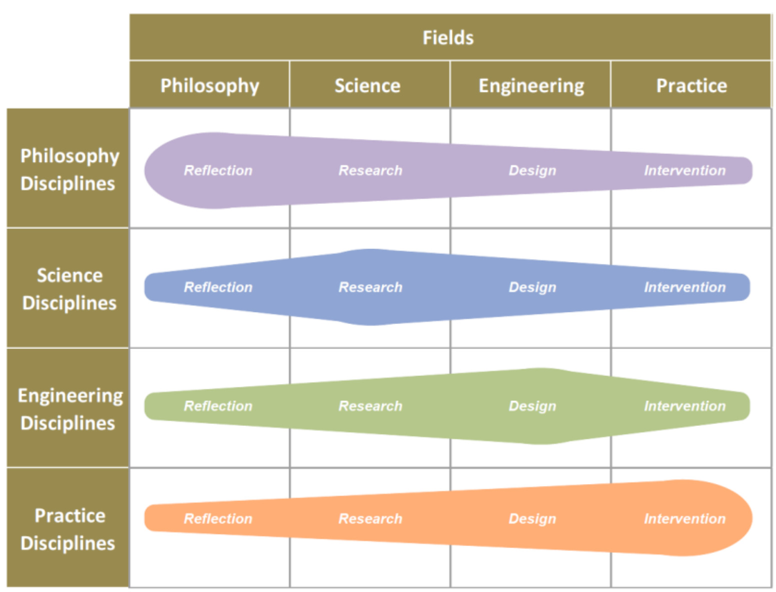

Figure 2-2. A scientific discipline's typical activity level per field dimension (Rousseau, 2018a)

What links the different stages together is the principles that are inputs and outputs from each stage. For example, the output of reflection activities are worldview principles and research principles, which are necessary inputs for research activities. These relationships are depicted in Figure 2-3, and the specific principles associated with each state are listed in Figure 2-4, with examples from the field of systemology.

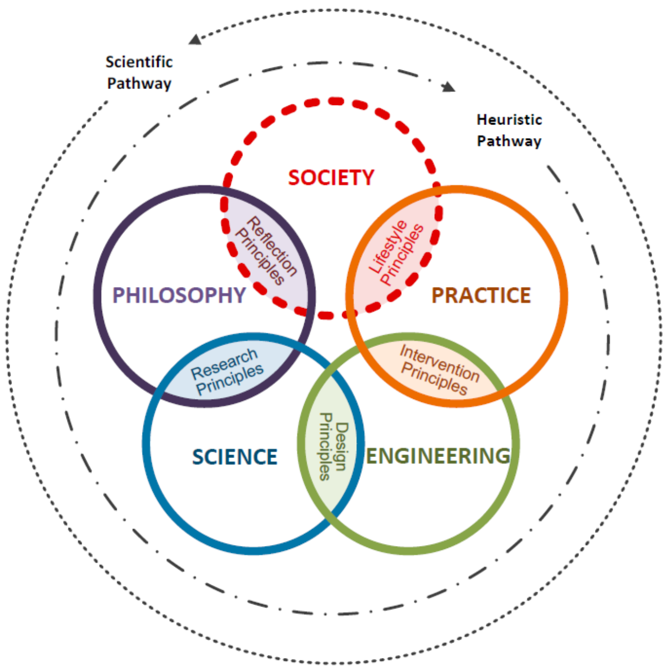

Figure 2-3. Principles relating different disciplinary stages. (Rousseau, 2018a)

Stage	Key Questions	Subtypes of Principles	Examples of Systems Principles
Reflection	What is the issue?	Focus Principles	estabish clear boundaries
	What is the context?	Perspective Principles	systems are conditioned by systemic relationships
	What might happen?	Exploration Principles	systems change in a network balancing way
	Why does this matter?	Evaluation Principles	systemic changes have causes and consequences
	What are the risks/uncertainties?	Confidence Principles	we can only influence the systems we recognize
	What can/should we do?	Actioning Principles	dance with the systems; respect the stakeholders
Research	What is it? What is it like?	Classification Ps	systems, boundaries, relationships
	Where does it occur?	Ecological Ps	almost everything is part of a greater system
	How does it work?	Functionality Ps	emergent properties entail submergence
	Why does it work this way?	Optimization Ps	explore emergence/submergence interplay
	How did it get like this?	Developmental Ps	systems emerge from stable relationships
	How did it arise?	Evolutionary Ps	balance technical and social needs
Design	What should it be like?	Conceptualization Ps	hierarchical organization provides robustness
	How could it work?	Functional Design Ps	stability via setpoint and negative feedback
	Why should it work this way?	Design Optimization Ps	minimise resource use, maximize effectiveness
	How can we provide it?	Manufacturing Ps	integrate simpler systems to make complex ones
	Is there a better way to do this?	Innovation Ps	open systems create integration opportunities
	How can we sustain it?	Maintenance Ps	maintenance and repair depend on systems too
Intervention	Can we preserve it?	Prevention Ps	protect the hyper-nodes
	Can we change it back/recover it?	Restoration Ps	restore its structure and relationships
	Can we make it grow/multiply?	Expansion Ps	protect the systems it depends on
	Can we change it?	Transformation Ps	adjust the internal and/or external relationships
	Can we get hold of it?	Establishment PS	leverage relationship: supply - demand systems
	Can we get rid of it?	Dismantling Ps	cut at the joints in the hierarchical structure

Figure 2-4. A Typology for Systems Principles
(Rousseau, 2018a)

2.6 Gap in Literature

The gap in current literature is an approach of defining the field of Industrial Engineering from a systemic perspective. Definitions exist of the field of Industrial Engineering as a whole (Section 2.2), and of its parts (Industrial Engineering Body of Knowledge, Section 2.3). However, there is a disconnect both between the whole and the parts, and a lack of interrelationships between the parts. To adequately define the field, it needs a clearly defined boundary with respect to its closely related fields, and parts that are defined uniquely and in relationship with each other. It is clear from the analysis presented in Section 2.3 that the knowledge areas were defined in isolation from one another. This isolated perspective will likely result in a siloed and parallel development of the knowledge areas and lead to a disjointed Body of Knowledge. Though some relationships are described, there exists a high potential for confusing knowledge areas due to overlapping definitions. There are also unclear distinctions between related fields, such as Design and Manufacturing engineering. In the most recent revision of the Industrial Engineering Body of Knowledge, Design and Manufacturing Engineering is included as one of the knowledge areas of Industrial Engineering, but the scope of this knowledge area is so broad that it can be considered a disciplinary field by itself.

2.7 Conceptual/Theoretical Model

The current maturity state of Industrial Engineering is as follows:

- Multiple inconsistent definitions exist for the field, including different subsets of the knowledge areas defined in the Industrial Engineering Body of Knowledge.
- The knowledge areas within the Body of Knowledge have overlaps.
- Some knowledge areas are not sufficiently defined.
- Knowledge and terms included in existing Industrial Engineering definitions overlap with those of related disciplinary fields.

A conceptualization of this current state is depicted graphically in Figure 2-5.

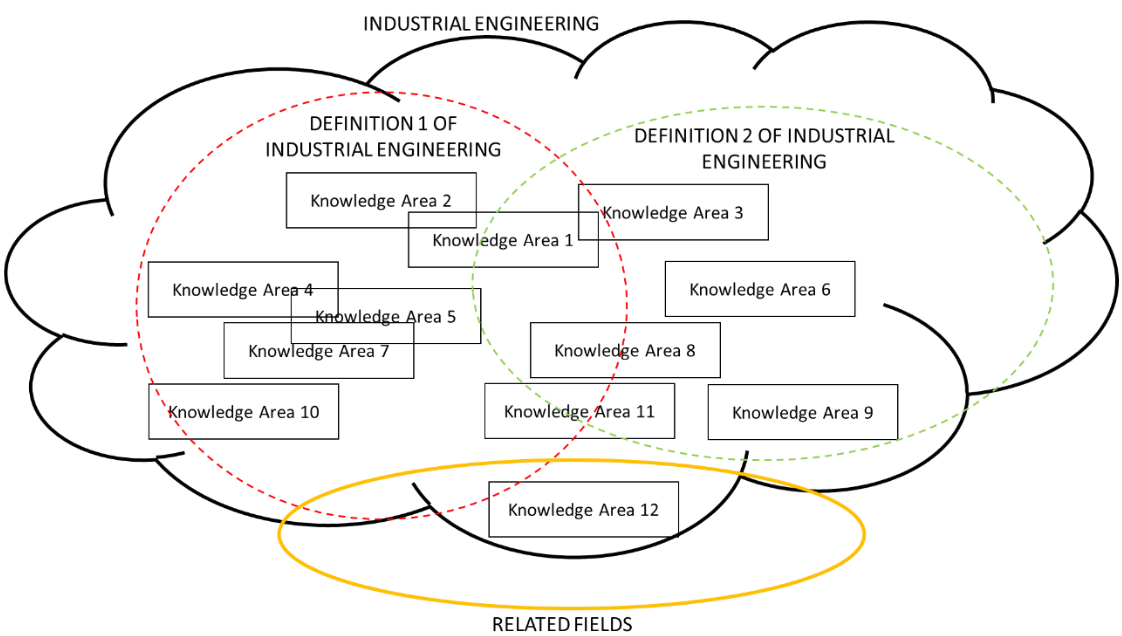

Figure 2-5. Conceptualization of Current Industrial Engineering Maturity State

To approach the definition of a broad and complex field such as Industrial Engineering from a systemic perspective, a set of categories is necessary to organize the parts of the system. Though the ABET criterion mentioned in Section 2.2.4 was a candidate for analyzing the field, Rousseau's framework of the Stages of a Scientific Endeavour presented in Section 2.5 can best serve as such a set of categories for the field of Industrial Engineering. Ideally, Industrial Engineering would have a single definition with distinct knowledge areas, categorized according to this framework. This ideal state is depicted graphically in Figure 2-6.

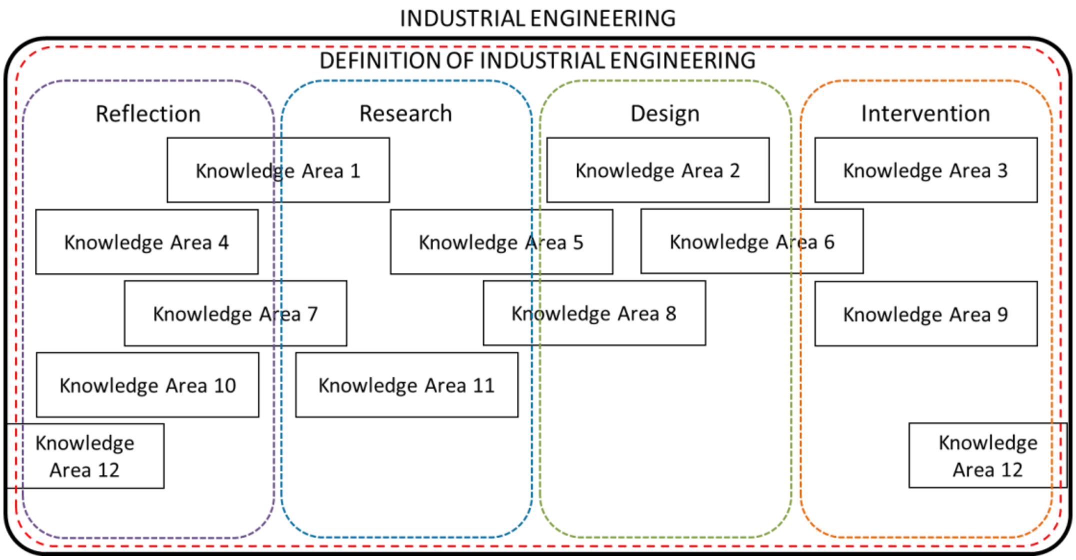

Figure 2-6. Conceptualization of Ideal Industrial Engineering Maturity State

Figure 2-6 shows a single definition of Industrial Engineering which corresponds with the reality of the field. Within it, the knowledge areas do not overlap, and are categorized according to the different stages of a scientific endeavor proposed by Rousseau. The knowledge areas could fit into two different stages, because the principles which are outputs from one stage are inputs to another, and society forms a link between Reflection and Intervention (see Figure 2-3).

The goal of the current research is to demonstrate the current state of the field by applying Rousseau's framework of the stages of the scientific endeavor to the knowledge areas of Industrial Engineering as defined in the Body of Knowledge. As Industrial Engineering is a scientific endeavor, its activities should correspond with the four stages presented by

Rousseau. Therefore, it can serve as a means of organizing the knowledge areas of Industrial Engineering.

Chapter 3

3 Methodology

3.1 Introduction

The purpose of this chapter is to outline the methodology utilized in this research. This includes the research design, the testable research hypothesis, the collection and treatment of data, and methodological issues and constraints.

3.2 Research Design

This research seeks to determine the relationships that exist between the different knowledge areas of Industrial Engineering. The work will be guided by Rousseau's (2018a) model for the activity stages of a scientific endeavor, applied within the context of the knowledge areas of Industrial Engineering.

3.2.1 Type of Research

This research used a combination of qualitative and quantitative methods. The qualitative portion of the research involved a coding analysis to map the knowledge areas of Industrial Engineering to the four stages of a scientific endeavor, and the quantitative portion of the research involved the analysis and treatment of the results of this coding data. This combined approach was chosen due to the complexity of the conceptual ideas being investigated. It was not possible to directly perform a quantitative analysis on the concepts and knowledge that are the subject of the research, so the coding analysis served to provide data which could then be quantitatively analyzed.

3.2.2 Research Focus

The focus of this research is to organize the knowledge areas of Industrial Engineering by determining how they correspond to a common set of stages of any scientific endeavor.

These stages are described and defined in Section 2.5: reflection, research, design, and intervention. This organization will both give a means to explicitly show the relationships between the knowledge areas, and the degree of alignment between coders will help to demonstrate how well defined the knowledge areas are in themselves.

3.2.3 Qualitative Methods

The qualitative portion of the research was undertaken through a coding process where the concepts, methods, techniques, and tools within each knowledge area of Industrial Engineering were assigned to the four stages of a scientific endeavor by three independent coders, based on their knowledge of the field of Industrial Engineering and a set of guidelines and reference materials provided to all of the coders. The items to be coded will be the top-level outline items of each knowledge area in the Industrial Engineering Body of Knowledge. The top-level outline items are chosen as the items for coding for two reasons: firstly, because it is the only level of outline item consistently present through all the knowledge areas of the Body of Knowledge, and secondly, because coding lower levels of the outline would be impractical given the time constraints of this research. These items will each be associated by the coders with two of the four stages of a scientific endeavor that most closely match the activities described by the items. Two stages will be coded due to the principles linking pairs of stages, as discussed in Section 2.5 and depicted in Figure 2-3.

The coders will go through a calibration process to align on their understanding and methods for coding. This process will consist of the coders coding a subset of the Industrial Engineering Body of Knowledge, comparing the results, discussing the discrepancies, and agreeing on common understandings of terms and procedures to facilitate a higher degree of alignment. This calibration process will repeat as many times as necessary to attain the desired degree of alignment between coders.

3.2.4 Quantitative Methods

The quantitative methods will consist of an analysis of the results of the qualitative coding analysis. First, the degree of alignment between the coders will be analyzed, to determine the internal validity of the results. Then, the results for each knowledge area will be aggregated to determine both how well the knowledge areas are defined, and which stages of a scientific endeavor they most appropriately correspond to. The results will also be aggregated to define the field of Industrial Engineering in terms of the stages of a scientific endeavor.

3.2.5 Research Hypotheses Restated

The hypotheses proceed conceptually in the order stated in the introduction, but for experimental purposes, the first is dependent upon the second, so hypotheses will be addressed in the opposite order in the following sections.

Second Research Hypothesis

The knowledge areas of Industrial Engineering align with specific stages of a scientific endeavor.

'Alignment' is quantified as at least 80% of the items within a knowledge area being associated with the two dominant stages of a scientific endeavor for that knowledge area. The level of 80% is selected on the assumption that the alignment is an exhibition of the power law, specifically the Pareto Principle: the core principles of a knowledge area should correspond with 80% of the content. Many natural phenomena have been demonstrated to follow power law distributions (Newman, 2005).

Variables: $X_{i,j}$: percentage of KA i coded to the j^{th} ranked stage

$$H_0: \frac{1}{12}\sum_{i=1}^{12}(X_{i,1} + X_{i,2}) < 80\%$$

$$H_1: \frac{1}{12}\sum_{i=1}^{12}(X_{i,1} + X_{i,2}) \geq 80\%$$

First Research Hypothesis

The relationships between the different knowledge areas of Industrial Engineering can be established.

The knowledge areas would be related by being precedents or antecedents to each other, which could be determined through the correspondence of the knowledge areas to the stages of a scientific endeavor.

$$H_0: \forall\, KA_I \in \{IE\}, \nexists\, \{KA_P, KA_O\} : KA_P \xrightarrow[influences]{} KA_I \xrightarrow[influences]{} KA_O$$

$$H_1: \forall\, KA_I \in \{IE\}, \exists \{KA_P, KA_O\} : KA_P \xrightarrow[influences]{} KA_I \xrightarrow[influences]{} KA_O$$

Table 3-1. Variables for Research Hypothesis 1

VARIABLE	MEANING
$\boldsymbol{KA_I}$	Knowledge Area of Interest
$\boldsymbol{IE}$	Field of Industrial Engineering
$\boldsymbol{KA_P}$	Precedent Knowledge Area
$\boldsymbol{KA_O}$	Output Knowledge Area

3.3 Collection and Treatment of Data

3.3.1 Data Collection

The coding process will consist of the coders utilizing the Industrial Engineering Body of Knowledge and a set of instructions which includes figures defining the different codes being assigned to the items being coded. The coders will input their data into a spreadsheet in which they select two stages to associate with each of the items being coded.

I considered using the ABET criterion (Section 2.2.4) as a framework and guide to my coding, but determined that it was not specific enough to add meaningful value to the research. The criterion provides an intensional definition of the field similar to the Institute of Industrial and Systems Engineering definition and seem to be based on that definition. It would be redundant to include these criteria as part of the research.

3.3.2 Treatment of Data

The data from the coders will be compiled into a single spreadsheet for analysis. Their codes for each of the items will be compared to determine the level of inter-coder agreement. The data will be aggregated to assess the quality of the definition of each knowledge area. By observing the level of agreement on stages of a scientific endeavor present for each of the knowledge areas, it will be possible to assess whether the knowledge area is well-defined.

3.4 Methodological Issues

This section discusses how the four primary methodological issues of reliability, validity, replicability, and bias were addressed in the current research.

3.4.1 Reliability

The primary concern of reliability in the current study is in the qualitative coding analysis. For the study to be reliable, a desired level of agreement must be reached between the coders. This will be attained through the calibration process outlined in Section 3.2.3, and the development of a defined process for coders to follow.

3.4.2 Validity

Both internal and external validity are relevant to the current research. For the research to be internally valid, the data collected must be consistent, enabling conclusions to be drawn within the current study. Internal validity was ensured through a consistent methodology and set of resources for the coders, and through the calibration process which aligned the coders on knowledge and way of thinking about the topic.

The external validity of the research deals with its applicability to the real world outside the current study. The object of the research, the Industrial Engineering Body of Knowledge, is compiled by recognized experts in the field of Industrial Engineering and is the accepted standard for defining the field of Industrial Engineering, making it the most valid basis for research assessing the field of Industrial Engineering.

3.4.3 Replicability

The methodology presented sufficiently details how other researchers may replicate the findings from this research, using the same information as the basis for the coding analysis and following the same methodology. The one variable that cannot be made replicable in the current study is the knowledge levels of the coders: with different coders, their differing knowledge about Industrial Engineering may affect the results of the research.

The methodology is general enough that it could be replicated with different inputs, with small modifications to account for structure and organization of knowledge. This would enable similar research to be done assessing the maturity of other disciplinary fields using their bodies of knowledge.

3.4.4 Bias

The four areas of bias to address are sampling, instrumentation, response, and researcher. Sampling bias is not a concern with the present research because the entire Body of Knowledge was included in the study, so sampling was not necessary. The instrumentation for the study was the coding analysis, which was objective and concrete. Response bias is not relevant to the current study because it does not involve human subjects.

Researcher bias is relevant, given that the coders are all Industrial Engineering students who focused their studies on the area of Engineering Management. A student's perspective on the field will differ greatly from that of a practicing engineer or an academic expert, but this perspective and bias is acceptable and desired, given one of the applications of this research is in Industrial Engineering education. The fact that the coders are Engineering Management focused could have impacted the results of the coding, because the area of engineering management is a perspective through which the rest of the field of Industrial Engineering can be analyzed. Their shared perspective could have led to a higher level of inter-coder agreement than would have been achieved with coders with a more diverse background in Industrial Engineering. The coders were also much more familiar with some knowledge areas than with others, which could mean that their mappings are more accurate and valid for the knowledge areas with which they were more familiar than for those with which they were unfamiliar.

3.4.5 Representativeness

The research is representative because it samples the entire field of Industrial Engineering, rather than picking a subset. One concern with representativeness is that the research only looks at one group's Body of Knowledge of Industrial Engineering (Institute of Industrial and Systems Engineering). There are no other bodies of knowledge that exist in the same breadth and depth, with consistent updates. This made the Institute of Industrial and Systems Engineering Body of Knowledge the best selection for the current research.

Since the primary researcher and coders are students studying Industrial Engineering, this research is representative of a students' perspective of the discipline of Industrial Engineering, not that of a practicing engineer or an expert.

3.5 Research Constraints

This research was constrained both in its scope and depth, and by the knowledge of the researcher and the coders. It would be preferable to have a larger number of coders to have a wider sampling of perspectives on the field of Industrial Engineering, but the time constraints and level of research did not allow for more coders to be involved. Another constraint is the knowledge of the researcher. Having completed an undergraduate Industrial Engineering education, the researcher has familiarity with the field, but does not possess the knowledge or experience of a practicing Industrial Engineer or Industrial Engineering faculty member. Expert knowledge would have enhanced the research by providing a more informed background to make decisions and assessments about the best way to conduct the research.

Chapter 4

4 Results

4.1 Introduction

This chapter presents the details of the data collection, analysis, and results as outlined in the methodology in the previous chapter. Section 4.2 details the design and execution of the data collection process. Section 4.3 details the data analysis process. Section 4.4 presents the results of the tests of the research hypotheses.

4.2 Data Collection

4.2.1 Design of Data Collection

The data for this research was collected using the qualitative methods described in Section 3.2.3. The items to be coded were the top-level outline items of each knowledge area of Industrial Engineering, referred to in this research as “methodologies.” A list of these methodologies can be found in Appendix A.

4.2.2 Calibration Process

To develop and refine the coding process, the researcher went through a series of calibration rounds with three coders. In each calibration round, a subset of the methodologies was coded, the results were compared and analyzed, and then the coders met to discuss discrepancies, align on definitions of concepts, and determine any changes necessary for future coding. The output of each calibration round was a new set of procedures for the next round of coding. The level of agreement in each coding round was assessed using Krippendorf’s Alpha, a reliability coefficient which represents the degree to which the different coders were able to agree on the distinctions between the different stages assigned to each coding item (Krippendorff, 2011). When tentative conclusions are acceptable, an agreement level of 67% is desired (Krippendorff, 2004). The level of agreement was calculated based on the stages, with the coder's selection of one or more stages being translated into a binary yes/no coding of each of the four stages for purposes of calculating Krippendorf's Alpha. The level of agreement for each individual stage was calculated, and these four values were averaged to calculate an overall level of agreement for each round. The process flow diagram in Figure 4-1 depicts the process for calculating inter-coder agreement. A summary of the inter-coder agreement values for the experiment can be found in Table 4-1.

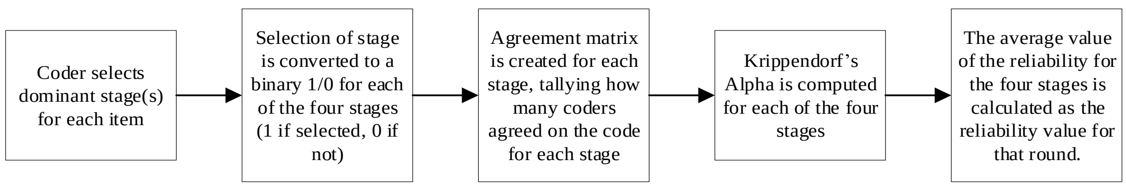

Figure 4-1. Process for Calculating Inter-Coder Reliability

Table 4-1. Inter-Coder Agreement Results

		CODING ROUND			
		Calibration 1	**Calibration 2**	**Calibration 3**	**Full**
# METHODOLOGIES		24	11	12	136
STAGE	**Reflection**	21%	52%	66%	32%
	Research	12%	36%	22%	33%
	Design	28%	51%	62%	42%
	Intervention	17%	-11%*	15%	28%
AVERAGE		**20%**	**32%**	**41%**	**34%**

*The negative inter-coder agreement value is a result of one coder assigning "Intervention" for most items when the other two coders did not.

The first calibration round coded a subset containing 24 of the 136 methodologies to be coded, 2 from each of the 12 knowledge areas of Industrial Engineering. For each of the methodologies, the coders utilized the following process:

1. Locate the methodology in the Industrial Engineering Body of Knowledge. Look at the list of concepts/tools listed under that methodology and recall any knowledge of that methodology from coursework.

2. Reference Figure 2-4. A Typology for Systems Principles (Rousseau, 2018a). Using the Key Questions, Subtypes of Principles, and Examples of Systems Principles, determine which question best describes the given methodology.

The questions that the coders selected each corresponded to one of the four stages of a scientific endeavor. The result of the first coding round was a level of agreement of 20%, which is well below the desired level of 67%. It was concluded that often, more than one question or stage could fit an item being coded, which contributed to the disagreement. There were similar questions present in the different stages, so using questions as the sole criteria for coding was not sufficient. It was also necessary to align on how to define each of the items, and in what context to consider the coding (education, research, or practice of Industrial Engineering).

The second calibration round coded a subset containing 11 of the 136 methodologies to be coded, from 11 of the 12 knowledge areas of Industrial Engineering (12 were intended, but an error omitted one of them from the coding, and the omission was determined to have an insignificant impact on the results). For each of the methodologies, the coders utilized the following process (key changes underlined):

1. Locate the methodology in the Industrial Engineering Body of Knowledge. Look at the list of concepts/tools listed under that methodology and recall any knowledge of that methodology from coursework. This list of concepts/tools should be considered as the requisite knowledge to apply that methodology, not necessarily as a definition of the methodology itself (in other words, focus on the methodology itself rather than the concepts/tools listed below).
2. Reference Figure 2-4. A Typology for Systems Principles (Rousseau, 2018a) . Using the Key Questions, Subtypes of Principles, and Examples of Systems Principles, determine which stage and question that best describe the given methodology. Consider how the methodology is *applied* in the *practice* of Industrial Engineering.

3. If the choice cannot be narrowed to a single stage and question, they can be selected as "Question 2," but a second question is not required.

In this second round of coding, the definitions of the terms and in what context they were to be considered for coding was further specified. The coding process was also changed so that the coders first select a stage for the methodology, and then a question within that stage. This process aligned better with the structure of the model, because it is more natural to first select a broader category (the stage) and then a more specific category within that (the question). The coders were also given the option of selecting a second stage and question for each methodology, if more than one applied. The result of the second coding round was a level of agreement of 32% - an improvement from the first round, but still far from satisfactory. It was concluded that a better definition of the stages was necessary, and that having the option of coding a second stage was contributing to disagreement: it should be specified whether to always code one stage per methodology or always code two.

The third calibration round consisted of 12 of the 136 methodologies to be coded, 1 from each of the 12 knowledge areas of Industrial Engineering. For each of the methodologies, the coders utilized the following process (key changes underlined):

1. Locate the methodology in the Industrial Engineering Body of Knowledge. Look at the list of concepts/tools listed under that methodology and recall any knowledge of that methodology from coursework. This list of concepts/tools should be considered as the requisite knowledge to apply that methodology, not necessarily as a definition of the methodology itself (in other words, focus on the methodology itself rather than the concepts/tools listed below).
2. Reference Figure 2-1. Stages of a Scientific Endeavor (Rousseau, 2018a) defining each of the stages, and Figure 2-4. A Typology for Systems Principles (Rousseau, 2018a). Consider how the methodology is *applied* in the *practice* of Industrial Engineering.

a. Using the definitions of the stages, select the two dominant stages for the given methodology. The order of the two stages/questions is not significant, the two will be treated equivalently.
b. Using the Key Questions, Subtypes of Principles, and Examples of Systems Principles, determine which question best describes the given methodology within each of the two stages selected.

In this third round of coding, the key changes were the addition of an additional figure to reference, giving a more concrete definition of the four stages for the coders to refer to, and the mandatory selection of two stages for each methodology. The rationale for selecting two stages per methodology is detailed in Section 2.7. The result of this round of coding was an increased level of agreement of 41%. It was determined in the discussions that the main issue in the disagreement now was not the process or the coding, but rather the definitions of the methodologies to be coded. The lists and details present in the Industrial Engineering Body of Knowledge were not sufficient to have a clear and consistent definition and idea of each methodology between the three coders. Because of this, it was decided to proceed with the full coding of all the methodologies.

The results of the full round of coding are presented and analyzed in the following sections.

4.3 Data Analysis

This section details the steps taken to analyze and aggregate the raw data from the coding analysis to make it possible to test the research hypotheses.

For each of the 136 items coded, each of the coders provided two stages and their corresponding questions. The questions were ultimately determined not to be necessary given the scope of the present research, and so are omitted from the analysis. For each of the items, the number of codes mapped to each stage was tallied, giving a value for each of the four stages between 0 and 3, corresponding to the number of coders who agreed that item corresponded strongly with the given stage. The codes assigned to each value were then aggregated to the knowledge area level for analysis. The process flow diagram in Figure 4-2 depicts the process for calculating analyzing the data. The raw data and the results of this analysis are included in Appendix A.

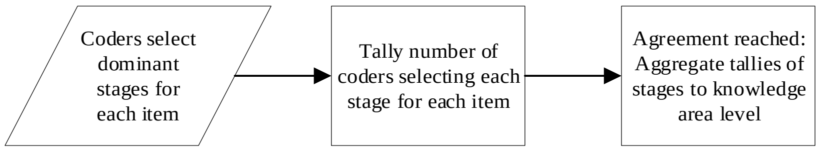

Figure 4-2. Data Analysis Process

With the results of the analysis described, the data for each of the twelve knowledge areas was aggregated, resulting in a count of how many items were coded to each stage for each of the knowledge areas (see Table 4-2). Because the number of items per knowledge area differs, these counts were normalized to a percentage (see Equation 1), with the numerator being the number of items coded to each stage, and the denominator being the total number of items for a given stage (see Table 4-3 and graphical depiction in Figure 4-3).

Table 4-2. Knowledge Area Mapping to Stages of a Scientific Endeavor

KNOWLEDGE AREA (KA_i)	REFLECTION ($n_{i,1}$)	RESEARCH ($n_{i,2}$)	DESIGN ($n_{i,3}$)	INTERVENTION ($n_{i,4}$)	TOTAL (N_i)
01 - WORK DESIGN AND MEASUREMENT	8	31	33	6	**78**
02 - OPERATIONS RESEARCH AND ANALYSIS	5	40	37	2	**84**
03 - ENGINEERING ECONOMIC ANALYSIS	43	34	9	10	**96**
04 - FACILITIES ENGINEERING AND ENERGY MANAGEMENT	3	14	18	1	**36**
05 - QUALITY & RELIABILITY ENGINEERING	20	31	21	12	**84**
06 - ERGONOMICS AND HUMAN FACTORS	12	23	38	5	**78**
07 - OPERATIONS ENGINEERING & MANAGEMENT	14	11	28	25	**78**
08 - SUPPLY CHAIN MANAGEMENT	7	2	13	14	**36**
09 - ENGINEERING MANAGEMENT	12	6	16	14	**48**
10 - SAFETY	7	6	7	4	**24**
11 - INFORMATION ENGINEERING	10	30	45	17	**102**
12 - DESIGN AND MANUFACTURING ENGINEERING	2	29	36	5	**72**

Equation 1. Normalization of data to percentages

$$N_i = \sum_{s=1}^{4} n_i$$

$$X_{i,s} = \frac{n_{i,s}}{N_i} \times 100\%$$

Table 4-3. Normalized Knowledge Area Mapping to Stages of a Scientific Endeavor

KNOWLEDGE AREA (KA_i)	REFLECTION $(X_{i,1})$	RESEARCH $(X_{i,2})$	DESIGN $(X_{i,3})$	INTERVENTION $(X_{i,4})$
01 - WORK DESIGN AND MEASUREMENT	10%	40%	42%	8%
02 - OPERATIONS RESEARCH AND ANALYSIS	6%	48%	44%	2%
03 - ENGINEERING ECONOMIC ANALYSIS	45%	35%	9%	10%
04 - FACILITIES ENGINEERING AND ENERGY MANAGEMENT	8%	39%	50%	3%
05 - QUALITY & RELIABILITY ENGINEERING	24%	37%	25%	14%
06 - ERGONOMICS AND HUMAN FACTORS	15%	29%	49%	6%
07 - OPERATIONS ENGINEERING & MANAGEMENT	18%	14%	36%	32%
08 - SUPPLY CHAIN MANAGEMENT	19%	6%	36%	39%
09 - ENGINEERING MANAGEMENT	25%	13%	33%	29%
10 - SAFETY	29%	25%	29%	17%
11 - INFORMATION ENGINEERING	10%	29%	44%	17%
12 - DESIGN AND MANUFACTURING ENGINEERING	3%	40%	50%	7%

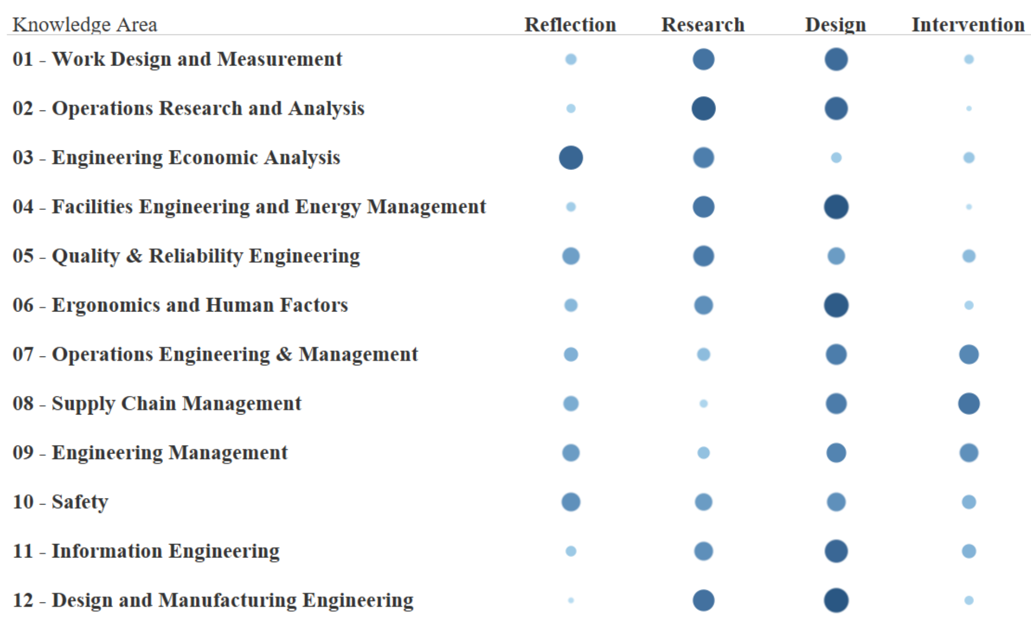

Figure 4-3. Visualization of Knowledge Area Mappings

It was then necessary to select the two dominant stages for each of the knowledge areas, determined by the two highest percentages in Table 4-3. The sum of these two percentages constituted the overall level of agreement on that knowledge area's place within the stages of a scientific endeavor (see Table **4-4**).

Table 4-4. Knowledge area dominant stages and levels of alignment

KNOWLEDGE AREA (KA_i)	PRIMARY STAGE ($j = 1$)	SECONDARY STAGE ($j = 2$)	PRIMARY STAGE % ($X_{i,1}$)	SECONDARY STAGE % ($X_{i,2}$)	LEVEL OF ALIGNMENT ($X_{i,1} + X_{i,2}$)	MEETS 80% THRESHOLD?
01 - WORK DESIGN AND MEASUREMENT	Design	Research	42%	40%	82%	Yes
02 - OPERATIONS RESEARCH AND ANALYSIS	Research	Design	48%	44%	92%	Yes
03 - ENGINEERING ECONOMIC ANALYSIS	Reflection	Research	45%	35%	80%	Yes
04 - FACILITIES ENGINEERING AND ENERGY MANAGEMENT	Design	Research	50%	39%	89%	Yes
05 - QUALITY & RELIABILITY ENGINEERING	Research	Design	37%	25%	62%	No
06 - ERGONOMICS AND HUMAN FACTORS	Design	Research	49%	29%	78%	No
07 - OPERATIONS ENGINEERING & MANAGEMENT	Design	Intervention	36%	32%	68%	No
08 - SUPPLY CHAIN MANAGEMENT	Intervention	Design	39%	36%	75%	No
09 - ENGINEERING MANAGEMENT	Design	Intervention	33%	29%	63%	No
10 - SAFETY	Reflection	Design	29%	29%	58%	No
11 - INFORMATION ENGINEERING	Design	Research	44%	29%	74%	No
12 - DESIGN AND MANUFACTURING ENGINEERING	Design	Research	50%	40%	90%	Yes
				Average	**76%**	**No**

4.4 Results from Study

The following section states the results of the tests of the two research hypotheses stated in Section 3.2.5.

4.4.1 Second Research Hypothesis

$$H_0: \frac{1}{12}\sum_{i=1}^{12}(X_{i,1} + X_{i,2}) < 80\%$$

$$H_1 : \frac{1}{12} \sum_{i=1}^{12} (X_{i,1} + X_{i,2}) \geq 80\%$$

The average level of agreement for the field of Industrial Engineering as a whole is 76%, which is below the specified threshold of 80%. Therefore, the null hypothesis cannot be rejected, meaning that there is not enough evidence to conclude that the knowledge areas of Industrial Engineering align with specific stages of a scientific endeavor.

$$\frac{1}{12} \sum_{i=1}^{12} \left(X_{i,1} + X_{i,2}\right) = 76\% < 80\% \therefore \mathit{Fail\ to\ reject}\ H_0$$

The results of a basic statistical analysis are presented in Table 4-5. The variance is not large enough to have a significant impact on the conclusions, and the mean and median are close to each other, indicating that the data is relatively uniformly distributed.

Table 4-5: Statistical Analysis of Alignment Levels

STATISTIC	VALUE
AVERAGE	75.88%
VARIANCE	1.20%
ST. DEV.	10.95%
MIN	58.33%
1ST QUARTILE	66.59%
MEDIAN	76.60%
3RD QUARTILE	83.76%
MAX	91.67%

4.4.2 First Research Hypothesis

$$H_0 : \forall\ KA_I \in \{IE\}, \nexists\ \{KA_P, KA_O\} : KA_P \xrightarrow[influences]{} KA_I \xrightarrow[influences]{} KA_O$$

$$H_1 : \forall\ KA_I \in \{IE\}, \exists \{KA_P, KA_O\} : KA_P \xrightarrow[influences]{} KA_I \xrightarrow[influences]{} KA_O$$

Because the individual knowledge areas cannot be conclusively mapped to the stages of a scientific endeavor, the relationships between the knowledge areas cannot be established. Therefore, the null hypothesis cannot be rejected, meaning that the relationships between the knowledge areas of Industrial Engineering cannot be established.

$$Decision\ on\ Second\ Research\ Hypothesis \Rightarrow$$

$$\nexists\ \{KA_P, KA_O\} : KA_P \xrightarrow[influences]{} KA_I \xrightarrow[influences]{} KA_O \forall\ KA_I \in \{IE\}$$

$$\therefore Fail\ to\ reject\ H_0$$

Chapter 5

5 Conclusion

5.1 Features of this Research

The purpose of this research was to assess the maturity of Industrial Engineering as an engineering discipline by developing a framework to connect the different knowledge areas, serving as a means for understanding the field as a system of interconnected parts which would guide and inform future research, education, and practice in the field of Industrial Engineering. The research attempted to achieve the purpose through the following objectives but was not successful in achieving all of them.

1. *Provide a framework to catalog knowledge of the field of Industrial Engineering and each of its knowledge areas.*
   - The proposed framework was detailed in Section 2.7, based on Rosseau's stages of a scientific endeavor applied to the field of Industrial Engineering
   - Figure 2-6 depicts the desired state of the framework.
2. *Link each knowledge area to the field as a whole using Rousseau's stages of a scientific endeavor as a framework*
   - Through the coding analysis described in chapter 3 and its results presented in chapter 4, an attempt was made to link the knowledge areas to the field as a whole using the stages of a scientific endeavor as a framework
   - This attempt was unsuccessful due to the lack of a clear definition of the knowledge areas, making it impossible to conclusively link each of them to stages of a scientific endeavor.
3. *Develop an ontological framework to guide the selection of appropriate Industrial Engineering concepts, methods, techniques, and tools for a given problem.*
   - Because the attempt to link the knowledge areas to the field failed, it was not possible to create the proposed ontological framework beyond dispute.

- Despite the unsuccessful attempt to conclusively define the framework, a preliminary structure for such a framework was created. The level of agreement was near the defined threshold, which means the framework created can serve as a guideline.

5.2 Limitations of this Research

The findings in the following section should be considered in the context of the following limitations of this research, which were first presented in Section 1.7.1.

- The validation of the model was performed using a limited number of individual coders, due to time and resource constraints.
- The researchers involved are not experts in the field of Industrial Engineering, or in any particular knowledge area. They have the context of an undergraduate degree in Industrial Engineering and the additional research for this work.
- The background research on the different knowledge areas of Industrial Engineering was constrained by time, and so consisted of the following:
    - Review of a subset of between one and three of the sources referenced for each knowledge area in the Industrial Engineering Body of Knowledge
    - Synthesis of reviewed sources with the researcher's undergraduate Industrial Engineering education at Oregon State University

5.3 Findings from this Research

The findings from this research do not support the research questions and general hypotheses. The questions and hypotheses were first presented in sections 1.3 and 1.4, respectively, and are restated below.

Research Questions

1. What is the degree of maturity of the Industrial Engineering discipline?

1.1. Can the relationships between the different knowledge areas of Industrial Engineering be established?

1.2. Do the knowledge areas of Industrial Engineering align with specific stages of a scientific endeavor?

General Hypotheses

1. Industrial Engineering is a mature engineering discipline.
   1.1. The relationships between the different knowledge areas of Industrial Engineering can be established.
   1.2. The knowledge areas of Industrial Engineering align with specific stages of a scientific endeavor.

The research questions are presented in their natural conceptual order but must be answered in reverse order experimentally. The following sections address the findings of this research in this reverse order.

5.3.1 Findings for knowledge area alignment with stages

The second hypothesis (1.2) was not supported by the results of the coding analysis presented in section 4.3. The results of the analysis indicate that all of the knowledge areas do not align with specific stages of a scientific endeavor. Of the 12 knowledge areas, 5 meet the threshold of 80% of their content aligning with the two dominant stages of a scientific endeavor. For the entire field, an average of 76% of the items within the knowledge areas align with the two dominant stages in each knowledge area.

These results have implications for both the structure and definition of the field. The failure to align could be attributable to the broad nature of the knowledge areas, making it difficult to map them to specific stages of a scientific endeavor. Furthermore, it was identified that some knowledge areas lack sufficient definition, leading the coding analysis to not accurately reflect the reality of the scope of the knowledge areas.

5.3.2 Findings for relationships between the knowledge areas.

The first hypothesis (1.1) was not supported by the results of the coding analysis presented in section 4.3. The results of the analysis indicate it is not currently possible to establish the relationships between the knowledge areas of Industrial Engineering. Because the knowledge areas could not be mapped to the stages of a scientific endeavor (see findings in Section 5.3.1), it is not recommended to use this as a framework for relating the knowledge areas.

5.3.3 Findings for maturity of Industrial Engineering discipline

The main hypothesis was not supported by the results of the research, because its two sub-hypotheses were not supported by the results (see findings in sections 5.3.1 and 5.3.2). A discipline can be considered mature when its constituent parts are clearly defined and thus their boundaries and interrelationships can be established. The tests of the research hypotheses show that the parts cannot be related to the whole field or to each other through a framework based on the stages of a scientific endeavor. Therefore, I conclude that Industrial Engineering is not a mature engineering discipline.

5.4 Future Research Needs

Future research is necessary to develop and build upon the results of this thesis. The findings of this work primarily point to the insufficient definition of the field of Industrial Engineering and its parts. Therefore, future work should focus on further developing the definition of Industrial Engineering and its related Body of Knowledge. This could be done through a panel of experts performing a Delphi Method study. The design of the study should be such that the knowledge areas are developed in relationship with each other rather than in siloes. The focus should be on reaching consensus among experts on the modern definition of Industrial Engineering and what constitutes its Body of Knowledge, and the perspective and focus for each of its knowledge areas with respect to the stages of a scientific endeavor. The current Body of Knowledge is a taxonomy of the concepts and knowledge considered relevant to the discipline of Industrial Engineering. It is necessary to clarify and redefine the purpose of the Body of Knowledge. I propose that the discipline of Industrial Engineering would be better served by a body of knowledge that is more than just a taxonomy: it should be a document which stands on its own and summarizes the principles upon which Industrial Engineering and each of its knowledge areas are based. There exist Industrial Engineering handbooks which provide such a summary of the field, but they are written and compiled by individuals, not a centralized governing body such as the Institute of Industrial and Systems Engineering. The output of this research would yield a framework for organizing and understanding knowledge in any field, which could yield insights as to how Industrial Engineering should be structured.

Chapter 6

6 References

6.1 References

ABET. (2019). Criteria for Accrediting Engineering Programs, 2019 - 2020. Retrieved from https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/

Blanchard, D. (2010). *Supply Chain Management Best Practices* (2nd ed.). Hoboken, NJ: John Wiley & Sons, Inc.

Board, S. E. (2019). The Guide to the Systems Engineering Body of Knowledge (SEBoK). In R. J. C. E. i. Chief) (Ed.), (v. 2.1 ed.). Hoboken, NJ: The Trustees of the Stevens Institute of Technology.

Cabrera, D. A. (2006). *Systems Thinking*. Ithaca, NY, USA: Cornell University.

Going, C. B. (1911). *Principles of industrial engineering*: McGraw-Hill Book Company.

Gruber, T. R. (1993). A translation approach to portable ontology specifications. *Knowledge acquisition, 5*(2), 199-221.

Hillier, F., & Lieberman, G. J. (2015). *Introduction to operations research* (Tenth ed.). New York, NY: McGraw-Hill Education.

Hines, W. W., & Montgomery, D. C. (1980). *Probability and statistics in engineering and management science* (2nd ed.). New York, NY: John Wiley & Sons.

IISE. (2016). Industrial Engineering Body of Knowledge. In: Institute of Industrial and Systems engineers.

IISE. (2017). Body of Knowledge Policies & Procedures. In: IISE Governing Board.

IISE. (2019). Industrial Engineering Body of Knowledge. Retrieved from https://www.iise.org/Details.aspx?id=43631

Kambhampati, V. S. S. N. R. (2017). *Principles of Industrial Engineering.* Paper presented at the IIE Annual Conference. Proceedings.

Konz, S., & Johnson, S. (2008). Work Design: Occupational Ergonomics. In (Seventh ed.). Scottsdale, AZ: Holcomb Hathaway.

Krippendorff, K. (2004). Reliability in content analysis: Some common misconceptions and recommendations. *Human communication research, 30*(3), 411-433.

Krippendorff, K. (2011). Computing Krippendorff's alpha-reliability.

Laudon, K. C. (2004). *Management information systems : managing the digital firm* (8th ed.). Upper Saddle River, N.J.: Pearson Prentice Hall.

Maynard, H. B., & Zandin, K. B. (2001). *Maynard's industrial engineering handbook* (5th ed.). New York: McGraw-Hill.

Morse, L. C., & Babcock, D. L. (2007). *Managing Engineering and Technology* (4th ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Nahmias, S. (1993). *Production and operations analysis* (2nd ed.). Homewood, IL: Richard D. Irwin, Inc.

Newman, M. E. (2005). Power laws, Pareto distributions and Zipf's law. *Contemporary physics, 46*(5), 323-351.

Newnan, D. G., Eschenbach, T. G., & Lavelle, J. P. (2012). *Engineering Economic Analysis* (11th ed.). New York, NY: Oxford University Press.

Pritsker, A. A. B. (1990). *Papers - Experiences - Perspectives*. West Lafayette, Indiana: Systems Publishing Corporation.

Pulat, B. M. (1992). *Fundamentals of industrial ergonomics*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Rousseau, D. (2018a). On the architecture of systemology and the typology of its principles. *Systems, 6*(1), 7.

Rousseau, D. (2018b). Three general systems principles and their derivation: Insights from the philosophy of science applied to systems concepts. In *Disciplinary convergence in systems engineering research* (pp. 665-681): Springer.

Rousseau, D., Billingham, J., & Calvo-Amodio, J. (2018). Systemic semantics: A systems approach to building ontologies and concept maps. *Systems, 6*(3), 32.

Sillitto, H., Martin, J., Dori, D., Griego, R. M., Jackson, S., Krob, D., . . . McKinney, D. (2018). SystemDef13MAy18.docx. In *Working Paper of the INCOSE Fellows Project on the Definition of "System"*. San Diego, CA, USA: INCOSE.

Sullivan, W. G., Wicks, E. M., & Luxhoj, J. T. (2003). *Engineering Economy* (12th ed.). Upper Saddle River, NJ: Pearson Education, Inc.

Taylor, F. W. (1911). *The Principles of Scientific Management*: Harper & Brothers.

Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). *Facilities Planning* (Fourth ed.). Hoboken, NJ: John Wiley & Sons, Inc.

Turner, W., Mize, J. H., & Case, K. E. (1987). Introduction to industrial and systems engineering. In (2nd ed.). Englewood Cliffs, N.J.: Prentice-Hall.

Winston, W. L., & Goldberg, J. B. (2004). *Operations research: applications and algorithms* (Vol. 3): Thomson Brooks/Cole Belmont.

6.2 Bibliography

Diemer, H. (1921). *Factory organization and administration*: McGraw-Hill.

Eschenbach, T. G. (2003). Engineering economy : applying theory to practice. In (2nd ed.). New York, NY: Oxford University Press.

Kapur, K. C., & Lamberson, L. R. (1977). *Reliability in Engineering Design*: John Wiley & Sons.

Lima, R. M., Mesquita, D., Amorim, M., Jonker, G., & Flores, M. A. (2012). An analysis of knowledge areas in industrial engineering and management curriculum. *International Journal of Industrial Engineering and Management, 3*(2), 75-82.

McGinnis, L. (2002). A brave new education. *IIE Solutions, 34*(12), 27.

McNamara, C., & Troncale, L. (2014). *SPT II.: How to Find & Map Linkage Propositions for a GTS from the Natural Sciences Literature.* Paper presented at the Proceedings of the 56th Annual Meeting of the ISSS-2012, San Jose, CA, USA.

Moore, B., Calvo-Amodio, J., & Junker, J. (2017). Applying a Framework for Complementarist Intervention Approaches to Service Organizations to Achieve a Sustainable Holistic Management Model. *Systemic Practice & Action Research, 30*(5), 487-513. doi:10.1007/s11213-016-9403-6

Natarajan, S., Kumar, A., Chaudhuri, S. R., Ramanujam, N. M., Banerjee, R., Banerjee, A., & Patwari, P. (2019). How Do Knowledge Domains Come Together in Systems? In *Systems Engineering in Context* (pp. 137-150): Springer.

Sloane, E. H. (1945). Reductionism. *Psychological Review*, *52*(4), 214--223.

Taylor, G. D. (2009). *Introduction to Logistics Engineering*. Boca Raton, FL: CRC Press.

Troncale, L. R. (1978). Linkage Propositions between fifty principal systems concepts. In *Applied general systems research* (pp. 29-52): Springer.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (Third ed.). Upper Saddle River, NJ: Prentice-Hall Inc.

Appendix A

7 Appendix A: Analysis Inputs and Outputs

Table 7-1 presents the list of items from the Industrial Engineering Body of Knowledge that served as inputs for the coding analysis, divided by knowledge area.

Table 7-2 presents the output of the coding analysis, the count of how many coders coded each item to each stage.

Table 7-1. Inputs of Coding Analysis

Knowledge Area	Outline Item to be Coded
Work Design and Measurement	Uses of Standards
	Time and Motion Study
	Pre-Determined Time Systems
	Work Sampling
	Learning Curve
	Line Balancing
	Service Applications
	Use with Labor and Unions
	Workstation Design
	Worker Capacity Analysis
	Analysis Tools
	Job Analysis
	Wage Surveys
Operations Research and Analysis	Operations Research
	Linear Programming (LP)
	Transportation Problem
	Linear Assignment Problem
	Network Flows and Optimization
	Deterministic Dynamic Programming
	Integer Programming
	Nonlinear Programming
	Metaheuristics
	Decision Analysis and Game Theory
	Modeling under Uncertainty
	Queuing Systems
	Simulation
	Fundamentals of Systems Dynamics
Engineering Economic Analysis	Value and Utility
	Classification of Cost
	Interest and Interest Formulas
	Cash Flow Analysis
	Financial Decision Making Among Alternatives
	Replacement Analysis
	Break-Even and Minimum Cost Analysis
	Evaluation of Public Activities
	Accounting and Cost Accounting
	Depreciation and Depreciation Accounting
	Income Taxes in Economic Analysis
	Estimating Economic Elements
	Estimates and Decision Making

Table 7-1. Inputs of Coding Analysis

Knowledge Area	Outline Item to be Coded
	Decision making involving risk
	Decision Making Under Uncertainty
	Analysis of Construction and Production Operations
Facilities Engineering and Energy Management	Facilities Location
	Facilities Sizing
	Facilities Layout
	Material Handling
	Storage, Warehousing, and Distribution
	Plant and Facilities Engineering
Quality & Reliability Engineering	Quality Concepts
	Quality Fundamentals
	Control Charts and Process Capability
	Lot acceptance sampling
	Rectifying inspection / auditing
	Design of Experiments
	Regression
	Response Surface Methodology
	Lean Six Sigma
	Change Management
	Reliability Fundamentals
	Reliability Testing
	Failure Analysis
	Maintenance
Ergonomics and Human Factors	Ergonomic Basics
	Organizational and Social Aspects of System Design
	Anthropometric Principles in Workspace and Equipment Design
	Work Capacity and Fatigue
	Design of the Thermal Environment
	Design of Repetitive Tasks
	Design of Manual Handling Tasks
	Design for Standing and Sitting
	Vision, Light and Lighting
	Hearing, Sound, Noise and Vibration
	Human Information Processing, Skill and Performance
	Displays and Controls
	Human-machine interaction, human error and safety
Operations Engineering & Management	Operations Planning
	Project Management
	Planning and Control for Manufacturing Systems / Projects
	Production Scheduling
	Inventory Management & Control
	Capacity Management

Table 7-1. Inputs of Coding Analysis

Knowledge Area	Outline Item to be Coded
	Materials Requirements Planning
	Purchasing / Supply Chain
	Maintenance Management & Control
	Organizational Issues
	Product Lifecycle Management
	Operational Metrics
Supply Chain Management	Supply Chain Management Fundamentals
	Building Competitive Operations, Planning, and Logistics
	Reverse logistics
	Managing Product Flow
	Managing Customer Relationships
	Managing Supplier Relationships
Engineering Management	Customer Focus
	Leadership, Teamwork, and Organization
	Shared Knowledge Systems
	Business Processes
	Resource and Responsibility
	Strategic Management
	Human Resource Management
	Project Management
	Organizational Level Performance Measurement
Safety	Perspective and Overview
	USA Laws and Regulations
	Hazard Recognition, Evaluation and Control
	Safety and Health Management
Information Engineering	Differentiating Data and Information
	Systems Concepts
	Information Requirements for Organizations
	Designing Information Outputs
	Data Processing Overview
	Data Base Concepts
	Logical Data Organization
	Physical Data Organization
	Storage and Processing
	System Analysis
	System Design
	System Evaluation & Justification
	Controls
	Forms, Programs, and Procedures
	System Implementation
	Management Considerations for the Information System
	Data Analytics

Table 7-1. Inputs of Coding Analysis

Knowledge Area	Outline Item to be Coded
Design and Manufacturing Engineering	Engineering Design
	Fundamentals of Materials
	Solidification-based Manufacturing Processes
	Material Removal Processes
	Forming-based Processes
	Particulate Processing
	Joining Processes
	Additive Manufacturing (AM)
	Biomedical Manufacturing (BM)
	Micro and Nano-scale Manufacturing
	Manufacturing Planning
	Manufacturing Systems

Table 7-2. Outputs of Coding Analysis

KA	Methodology	Reflection	Research	Design	Intervention
Work Design and Measurement	Uses of Standards	1	2	2	1
	Time and Motion Study	0	3	3	0
	Pre-Determined Time Systems	0	3	3	0
	Work Sampling	1	3	2	0
	Learning Curve	2	1	2	1
	Line Balancing	0	2	3	1
	Service Applications	1	2	3	0
	Use with Labor and Unions	1	1	3	1
	Workstation Design	0	3	3	0
	Worker Capacity Analysis	1	2	3	0
	Analysis Tools	0	3	3	0
	Job Analysis	0	3	2	1
	Wage Surveys	1	3	1	1
Operations Research and Analysis	Operations Research	0	3	3	0
	Linear Programming (LP)	0	2	3	1
	Transportation Problem	0	3	3	0
	Linear Assignment Problem	0	3	2	1
	Network Flows and Optimization	0	3	3	0
	Deterministic Dynamic Programming	0	3	3	0
	Integer Programming	0	3	3	0
	Nonlinear Programming	0	3	3	0
	Metaheuristics	0	3	3	0
	Decision Analysis and Game Theory	3	2	1	0
	Modeling under Uncertainty	1	3	2	0
	Queuing Systems	0	3	3	0
	Simulation	1	3	2	0
	Fundamentals of Systems Dynamics	0	3	3	0
Engineering Economic Analysis	Value and Utility	3	2	1	0
	Classification of Cost	2	2	2	0
	Interest and Interest Formulas	2	2	1	1
	Cash Flow Analysis	3	3	0	0
	Financial Decision Making Among Alternatives	3	1	2	0
	Replacement Analysis	3	2	0	1
	Break-Even and Minimum Cost Analysis	3	3	0	0

Table 7-2. Outputs of Coding Analysis

KA	Methodology	Reflection	Research	Design	Intervention
	Evaluation of Public Activities	3	2	0	1
	Accounting and Cost Accounting	3	1	0	2
	Depreciation and Depreciation Accounting	2	2	0	2
	Income Taxes in Economic Analysis	2	3	0	1
	Estimating Economic Elements	3	2	0	1
	Estimates and Decision Making	3	3	0	0
	Decision making involving risk	3	2	1	0
	Decision Making Under Uncertainty	3	2	0	1
	Analysis of Construction and Production Operations	2	2	2	0
Facilities Engineering and Energy Management	Facilities Location	2	1	3	0
	Facilities Sizing	0	2	3	1
	Facilities Layout	0	3	3	0
	Material Handling	0	3	3	0
	Storage, Warehousing, and Distribution	0	3	3	0
	Plant and Facilities Engineering	1	2	3	0
Quality & Reliability Engineering	Quality Concepts	0	2	3	1
	Quality Fundamentals	2	3	1	0
	Control Charts and Process Capability	1	3	1	1
	Lot acceptance sampling	2	3	0	1
	Rectifying inspection / auditing	2	1	2	1
	Design of Experiments	2	3	1	0
	Regression	2	3	1	0
	Response Surface Methodology	2	3	1	0
	Lean Six Sigma	1	1	2	2
	Change Management	2	0	1	3
	Reliability Fundamentals	0	2	3	1
	Reliability Testing	2	2	1	1
	Failure Analysis	2	3	1	0
	Maintenance	0	2	3	1
Ergonomics and Human Factors	Ergonomic Basics	2	1	2	1
	Organizational and Social Aspects of System Design	3	0	3	0
	Anthropometric Principles in Workspace and Equipment Design	1	2	3	0
	Work Capacity and Fatigue	0	2	3	1
	Design of the Thermal Environment	1	2	3	0

Table 7-2. Outputs of Coding Analysis

KA	Methodology	Reflection	Research	Design	Intervention
	Design of Repetitive Tasks	0	2	3	1
	Design of Manual Handling Tasks	0	2	3	1
	Design for Standing and Sitting	0	2	3	1
	Vision, Light and Lighting	1	2	3	0
	Hearing, Sound, Noise and Vibration	1	2	3	0
	Human Information Processing, Skill and Performance	0	3	3	0
	Displays and Controls	1	2	3	0
	Human-machine interaction, human error and safety	2	1	3	0
Operations Engineering & Management	Operations Planning	2	1	2	1
	Project Management	2	0	1	3
	Planning and Control for Manufacturing Systems / Projects	0	1	3	2
	Production Scheduling	0	1	3	2
	Inventory Management & Control	0	2	3	1
	Capacity Management	0	1	3	2
	Materials Requirements Planning	0	2	3	1
	Purchasing / Supply Chain	1	0	3	2
	Maintenance Management & Control	0	0	3	3
	Organizational Issues	3	0	0	3
	Product Lifecycle Management	2	0	3	1
	Operational Metrics	1	3	1	1
Supply Chain Management	Supply Chain Management Fundamentals	1	1	2	2
	Building Competitive Operations, Planning, and Logistics	1	1	3	1
	Reverse logistics	0	0	3	3
	Managing Product Flow	1	0	3	2
	Managing Customer Relationships	2	0	1	3
	Managing Supplier Relationships	2	0	1	3
Engineering Management	Customer Focus	2	0	2	2
	Leadership, Teamwork, and Organization	1	1	2	2
	Shared Knowledge Systems	1	1	3	1
	Business Processes	0	1	3	2
	Resource and Responsibility	3	0	2	1
	Strategic Management	3	0	1	2

Table 7-2. Outputs of Coding Analysis

KA	Methodology	Reflection	Research	Design	Intervention
	Human Resource Management	1	0	2	3
	Project Management	3	0	0	3
	Organizational Level Performance Measurement	1	3	1	1
Safety	Perspective and Overview	2	3	1	0
	USA Laws and Regulations	2	0	3	1
	Hazard Recognition, Evaluation and Control	1	2	2	1
	Safety and Health Management	2	1	1	2
Information Engineering	Differentiating Data and Information	2	3	1	0
	Systems Concepts	1	3	2	0
	Information Requirements for Organizations	0	2	3	1
	Designing Information Outputs	2	1	3	0
	Data Processing Overview	0	3	3	0
	Data Base Concepts	1	3	2	0
	Logical Data Organization	1	2	3	0
	Physical Data Organization	0	1	3	2
	Storage and Processing	0	2	3	1
	System Analysis	0	3	3	0
	System Design	1	2	3	0
	System Evaluation & Justification	1	1	2	2
	Controls	0	0	3	3
	Forms, Programs, and Procedures	0	1	3	2
	System Implementation	0	0	3	3
	Management Considerations for the Information System	1	0	2	3
	Data Analytics	0	3	3	0
Design and Manufacturing Engineering	Engineering Design	1	2	3	0
	Fundamentals of Materials	0	3	3	0
	Solidification-based Manufacturing Processes	0	3	3	0
	Material Removal Processes	0	2	3	1
	Forming-based Processes	0	3	3	0
	Particulate Processing	0	3	3	0
	Joining Processes	0	3	3	0
	Additive Manufacturing (AM)	0	3	3	0
	Biomedical Manufacturing (BM)	0	3	3	0

Table 7-2. Outputs of Coding Analysis

KA	Methodology	Reflection	Research	Design	Intervention
	Micro and Nano-scale Manufacturing	0	3	3	0
	Manufacturing Planning	1	0	3	2
	Manufacturing Systems	0	1	3	2