

Review

Exploring Industrial Engineering Knowledge and Environmental Sustainability

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Abstract: This research identifies the relationship between industrial engineering and environmental sustainability knowledge components. A combination of a systematic literature review (SLR) and applied thematic analysis (ATA) is employed to uncover the pertinent literature associated with the purpose of this research. Whilst various forms of strategies, theories, methods, and practices were uncovered in each of the knowledge components, only a few were overlapping. These overlapping components include green supply chain operations, circular economy, and technology management. This study is the first in a series of studies contextualising industrial engineering knowledge in terms of its applicability to environmental sustainability. These results reveal concepts from industrial engineering and environmental sustainability knowledge components that can be used to systematically design methodologies or practically implement them in an industry or organisation. Methods and practices were a dedicated theme in the analysis, and these can be used by practitioners. A circle packing diagram is crafted using the IISE Body of Knowledge as a means of categorisation. This study considered industrial engineering as a catalyst in creating new forms of transdisciplinary knowledge areas. It also considers how industrial engineering knowledge can contribute to meeting environmental challenges.

Keywords: industrial engineering; environmental sustainability; transdisciplinary knowledge; systematic literature review; applied thematic analysis



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1. Introduction

Each industrial revolution has ensured progression through developmental changes that render societal gains. These societal gains are experienced in various sectors, ensuring economic growth and prosperity through technological advances. However, each revolution has also imposed an environmental burden which cannot go unnoticed. Urbanisation and industrialisation lead to high resource consumption and environmental pollution experienced in underdeveloped and developing countries [1,2]. This has been linked with environmental regulations which offset environmental degradation in African countries [3].

Industrial engineering finds itself at the forefront of innovation with a subconscious solution space comprising various theories, strategies, tools, and methods that apply to multidisciplinary environments and numerous sectors. The nature of these solutions appeals to a broad range of problems, such is the value and contribution of this discipline. The environmental challenges experienced by developing countries are extensive, ranging from waste generation, water and energy consumption, greenhouse gas emissions, pollution, and sanitation [4–6].

Sustainability has emerged in response to the growing advances made in the world. It comprises environmental, social, and economic pillars. These are first considered siloed (“Mickey Mouse” model), interrelated (triple bottom line model), and finally embedded in a bullseye model through improved understanding over time [7,8]. An approach used

to facilitate the balance of societal needs and environmental preservation is through environmental sustainability. Environmental sustainability (ES) is concerned with improving social welfare by protecting the sources of raw materials used in anthropogenic activities so as to sustain global life-support systems [9,10]. ES is often associated with transformations that meet the needs of current and future generations without compromising the health of ecosystems [11,12]. Environmental sustainability in this research will embody various strategies, theories, and methods. ES has the potential to enable socio-economic systems to function well and add value across environmental, social, and economic boundaries.

The industrial engineering (IE) discipline is a growing field that continues to apply multidisciplinary knowledge to solve complex problems. Complex problems are believed to be ill-defined with no clear problem definition and goal state [13]. The IE discipline designs, improves, and implements integrated systems comprising people, materials, energy, equipment, and information [14]. The Institute of Industrial and Systems Engineers defines industrial engineering as follows [15]:

“Industrial Engineering is concerned with the design, improvement and installation of integrated systems of people, material, information, equipment and energy. It draws upon specialised 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”.

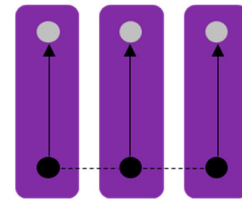
An industrial engineer is someone who can master various knowledge domains in order to creatively define, design, and refine solutions that maximise and balance value [16]. According to the resource-based theory, value is defined as an enabler for meeting customer needs and is associated with strengths within a firm [17,18]. The origins of the IE profession stem from industrial thinking from the industrial revolutions [19,20]. The profession has been recognised for its ability to improve the productivity, profitability, and efficacy of organizations using its versatile skillset and knowledge [21]. These skills and knowledge have a wide range of applications, from supply chain management to Industry 4.0 adoption.

The knowledge of the industrial engineering profession offers itself as a remedy to the negative impact associated with each industrial revolution. Knowledge is cultivated, diversified, and disseminated in the literature. Industrial engineering knowledge has been classified according to various knowledge domains and application areas that are multidisciplinary in nature. Despite the inclusion of chapters discussing environmental law and clean manufacturing in the Handbook of Industrial Engineering [22], environmental sustainability has not been associated with a specific industrial engineering knowledge domain or application area. The Institute of Industrial and Systems Engineers (IISE) [23] details the industrial engineering body of knowledge as a composition of 14 knowledge areas. Another taxonomy for IE knowledge is the domains of industrial engineering (Salvendy [22]). However, the IE profession must be more focused on sustainability to remain relevant [21,24]. Furthermore, this profession holds the potential to provide a nuanced manner of addressing the environmental degradation imposed by industrial activities.

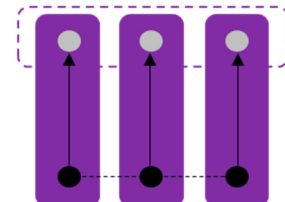
While this body of knowledge may seem promising, its structure prevents it from making systemic improvements to environmental concerns. According to Lang, et al. [25], sustainability issues require new ways of knowledge production and decision making, stressing the need for transdisciplinary research. Transdisciplinary research combines interdisciplinarity with a participatory approach by involving academics from unrelated disciplines and non-academics to create new knowledge and theories addressing complex research questions [26,27]. Figure 1 provides an overview of the evolution of research strategies shifting from disciplinary to transdisciplinary in nature.

Disciplinary

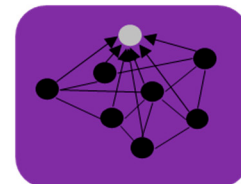
- Within one academic discipline
- Disciplinary goal setting
- Siloed between disciplines
- Development of new disciplinary knowledge and theory

**Multidisciplinarity**

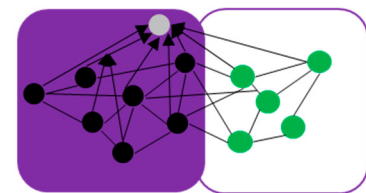
- Multiple disciplines
- Multi-disciplinary goal setting
- Loose cooperation of disciplines during knowledge exchange
- Disciplinary theory development

**Interdisciplinarity**

- Crosses disciplinary boundaries
- Common goal setting
- Integration of disciplines
- Development of integrated knowledge and theory

**Transdisciplinarity**

- Crosses disciplinary and scientific/academic boundaries
- Common goal setting
- Integration of disciplines and non-academics
- Development of integrated knowledge and theory among science and society

**Legend**

- | | | | |
|------------------------------|--|-------------------------------|--|
| • Discipline | | • Thematic umbrella | |
| • Non-academics | | • Academic knowledge body | |
| • Goal of a research project | | • Non-academic knowledge body | |
| • Movement towards goal | | | |
| • Cooperation | | | |
| • Integration | | | |

Figure 1. Transdisciplinary, interdisciplinary, multidisciplinary, and disciplinary overview redrawn from Tress et al. (2005) [26].

Although the industrial engineering profession is considered multidisciplinary, efforts to associate its theory with environmental sustainability are best explored by acknowledging research that would be transdisciplinary. An iconic transdisciplinary field of research is industrial ecology. This field focuses on the industrial metabolism focused on by industrial engineers, and environmental metabolism that concerns environmental managers [28,29]. An industrial system is perceived as an ecosystem that balances material, energy, and information flows [30,31]. Furthermore, it is also encouraged that engineers include interdisciplinary knowledge beyond what is strictly associated with the engineering domain [32]. Whilst giving recognition to the field of industrial ecology and its advances, the focus of this study will be to further industrial engineering knowledge and its association with environmental sustainability.

Despite the productivity achievements owed to the industrial engineering profession, it is yet to make noteworthy strides with regard to sustainable development [24]. There is research identifying that industrial engineering can contribute to the knowledge era [8]. In the knowledge era, traditional engines of wealth creation are eclipsed by the importance of intellect. More specifically, the industrial engineering knowledge area has made contributions by utilising Bayesian statistics for comparing energy efficiency gains as a proclaimed IE tool [24]. Lean and Green is also a hybrid knowledge domain that combines a well-established Lean theory domain focused on productivity, with environmental (green) considerations [33,34]. Notwithstanding these valuable insights from these researchers, there is limited research specifically focused on environmental sustainability practices as an initial starting point to ensure synergy between industrial engineering knowledge and environmental sustainability.

For the profession to remain relevant, this field of study must be explored. The industrial engineer will redefine environmental issues and sustainability [21]. This research takes this unique stride by investigating the degree to which environmental sustainability knowledge can be linked with industrial engineering knowledge in its all-encompassing fashion.

2. Research Question, Aim, and Objectives

The over-arching research question is as follows: What is the relationship between industrial engineering knowledge and environmental sustainability knowledge?

The aim of this research is to conduct a systematic literature review to establish and categorise the applicable forms of strategy, theory, methods, and practices that embody industrial engineering knowledge and environmental sustainability.

This is further segmented into the following research objectives:

1. Identify which are the most prominent forms of industrial engineering knowledge that promote environmental sustainability.
2. Determine the most prominent forms of industrial engineering and environmental sustainability strategies, theories, methods, and practices.
3. Identify overlapping knowledge components associated with industrial engineering and environmental sustainability.

3. Research Method

To achieve this aim, a systematic literature review (SLR) and thematic analysis have been performed. An SLR is a rigorous method that can be used to identify, evaluate, and synthesise a large body of literature in a reproducible fashion [35]. In contrast, a thematic analysis is used to perform a textual analysis of the literature filtered from the SLR into defined themes that are coded using the atlas.ti software platform, version 24.1.1. It is commonly used to code and annotate bodies of unstructured data. This caters for textual data categorisation for qualitative analysis. In a similar approach followed by Mangaroo-Pillay, et al. [36], the SLR comprises the following steps (illustrated in Figure 2), which are cast in respective phases.

Each step from this method has been acknowledged using the subsections that follow. The technical detail and result from each step are elucidated.

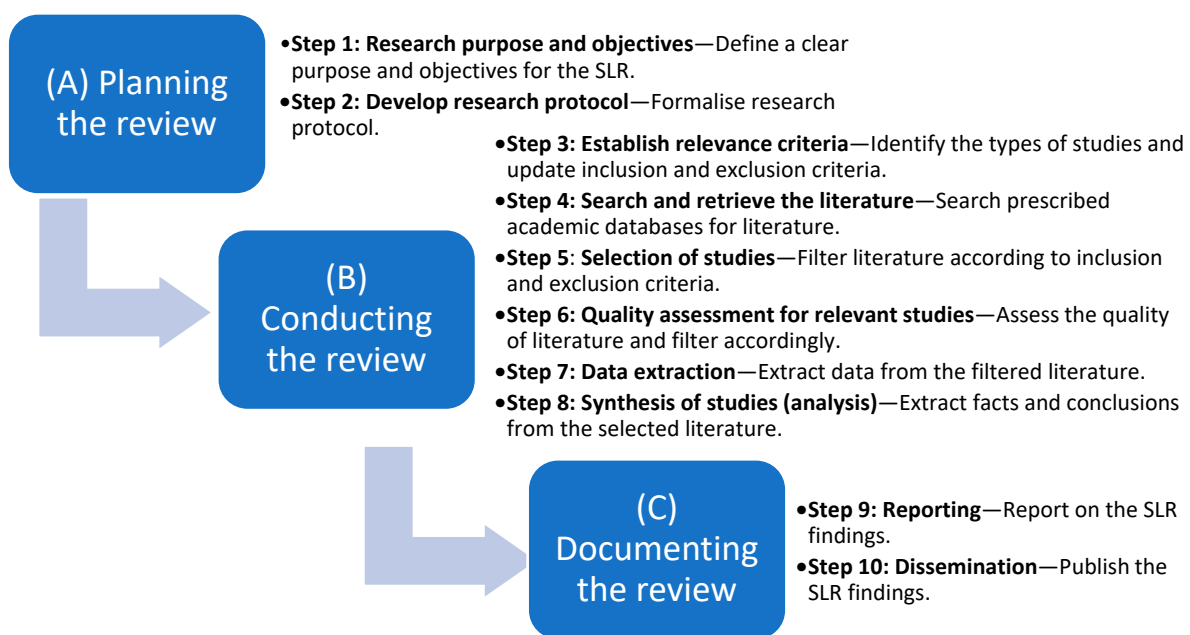


Figure 2. SLR process from Albliwi et al. (2014) [37].

4. Results and Findings

4.1. Step 1: Research Purpose and Objective

The aim of this research is to establish and categorise applicable forms of strategy, theory, methods, and practices that embody industrial engineering knowledge and environmental sustainability knowledge. The objectives are to (1) identify the prominent forms of industrial engineering knowledge that promote environmental sustainability and (2) synthesise the forms of industrial engineering and environmental sustainability strategies, theory, methods, and practice.

4.2. Step 2: Develop Research Protocol

To achieve the aim and objectives of this research, the research protocol was designed as in Table 1. Each search component, specification, and rationale are clearly detailed.

Table 1. SLR search protocol.

Search Component	Specifications	Rationale
Keywords	Industrial Engineering, Environmental Sustainability.	Key terms relevant to the purposes of this study.
Platforms	Science Direct, Scopus, IEEE Explore, Web of Science, EBSCO host, Emerald Insight.	Reputable academic databases accessible to the researcher.
Search strategy	“Industrial Engineering” AND “Environmental Sustainability”.	Boolean operator for the union of the content. Wildcards are not considered.
Time frame	No lower bound, until October 2023.	Structured so as to unveil all available literature.
Inclusion criteria	Publications discussing theory, concepts, methods, strategies, and techniques that achieve or promote environmental sustainability.	Screen publications to conform with the scope of the study.
Exclusion criteria	Publications that are not in English, undergoing review. Curriculum design papers.	Protect the academic integrity and ability to analyse the research publications according to the aim of this study.
Quality assessment criteria	Remove all duplicates and filter according to papers relevant to the research aim.	Filter literature according to aspects beyond those in the inclusion and exclusion criteria.

It is also important to note that various databases were used within EbscoHost: Academic Search Complete, Applied Science and Technology, Business Source Complete, EconLit, E-Journal, Environment Complete, Greenfile, and Water & Oceans Worldwide.

4.3. Step 3: Establish Relevance Criteria

Through an iterative process of evaluating the cumulated search results and relevance of each topic, the inclusion and exclusion criteria were refined and are presented in Table 1.

4.4. Steps 4 to 6: Search, Selection, and Quality Assessment of the Literature

Following the aim of the research, only the literature relating to industrial engineering and environmental sustainability was considered to gain an understanding of this focused research area. The search strategy considered the abstracts of the initial set of reputable publications. The exceptions to this were Science Direct and Scopus, and their functionality facilitated collective searches on the title, abstract, and keyword. For the information sources and methods, a multi-database searching approach was employed in which no study registries were included. Online resources were accessed and subjected to abstract and title screening, followed by a full-text reading. No citation searching was adopted in the search strategy.

During the search and selection process, an initial cumulated literature search result of 95 publications was obtained. The results from each database were imported into an Excel file that was used to screen the data. CSV exports and manual copy and paste functionalities were used on the various databases to populate the aforementioned spreadsheet. The six duplicated research papers were first removed before title and abstract screening for relevance according to the prescribed eligibility criteria. The eligibility criteria were a product of the inclusion and exclusion criteria that removed certain forms of the literature as part of a rigorous synthesis method. After removing 58 publications, 31 were subjected to full-text reading. Eight publications were removed from this sample since they did not meet the eligibility criteria. Many of these publications were excluded since they were housed within engineering education or belonged to other engineering disciplines. The full search strategy and search filters are provided in Table 2, accompanied by the total records with deduplications removed.

Table 2. SLR search string strategies for the identification of relevant studies.

Search Database	Search String	Results
Science Direct	"Industrial Engineering" AND "Environmental sustainability"	1
Scopus	(TITLE-ABS-KEY ("Industrial Engineering") AND TITLE-ABS-KEY ("Environmental sustainability"))	37
IEEE Explore	("Abstract":Industrial Engineering) AND ("Abstract":Environmental sustainability)	20
Web of Science	"Industrial Engineering" (Abstract) and "Environmental sustainability" (Abstract)	3
EbscoHost	AB Industrial Engineering AND AB environmental sustainability	30
Emerald Insight	abstract:"Industrial Engineering" AND (abstract:"Environmental sustainability")	4

The PRISMA statement 2020 can be incorporated since this study serves as an original systematic literature review and may serve as the underpinning approach used to identify, select, appraise and synthesise studies [38]. More recently, the work by Rethlefsen, et al. [39] provides an extension to the PRISMA-S statement, which contains a more current checklist. A combination of these two PRISMA checklists has been employed in this study.

To reduce the study's risk of bias, the filtering and results were reviewed by two researchers. This systematic process is visualised in Figure 3 using the standard PRISMA approach by detailing the manual filtering between the cumulated results from the initial search and the final set of publications subjected to thematic analysis.

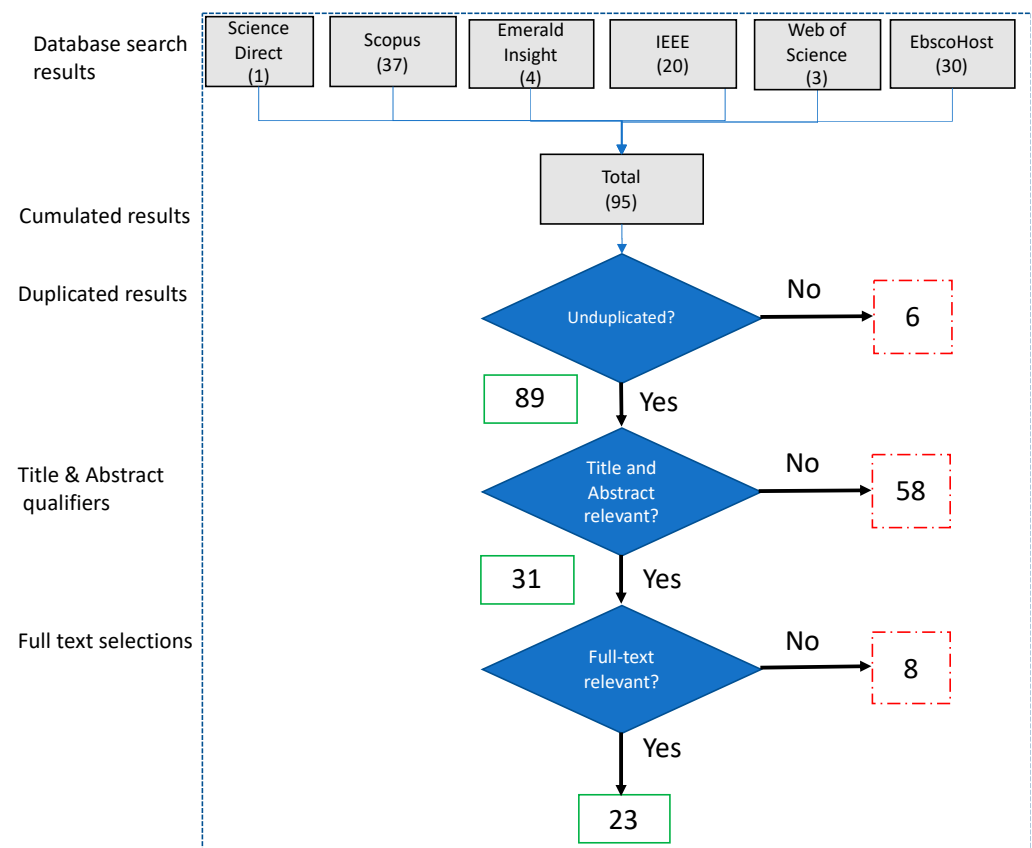


Figure 3. SLR filtering process.

The remaining 23 papers were subjected to thematic analysis using atlas.ti, discussed further in Section 4.5. The filtered publications were further categorised according to journal, year, and novelty. A summary of these papers is detailed in Table 3.

Table 3. SLR literature selection.

#	Author(s) and Year	Title	Year	Novelty
1	Djassemi [40]	A computer-based approach to material and process selection using sustainability and ecological criteria	2009	In a holistic computer-based approach, material and process selection is performed in accordance with sustainability and ecological criteria.
2	Naidu, et al. [41]	A methodology for evaluation and selection of nanoparticle manufacturing processes based on sustainability metrics	2008	An evaluation method that focuses on sustainability metrics ranging from economic, environmental, and sociological dimensions. Three nanoparticle manufacturing processes are evaluated.
3	Luque, et al. [42]	ADAPTS: An Intelligent Sustainable Conceptual Framework for Engineering Projects	2020	A description of the ADAPTS framework that includes the application, data, approach, tool, and sensing dimensions used to improve environmental sustainability of an olive oil manufacturing plant.
4	Jing, et al. [43]	Assessments on energy and greenhouse gas emissions of internal combustion engine automobiles and electric automobiles in the USA	2020	Integrated analysis of GHG emissions and energy in the industrial area of automobile engineering in the USA.
5	Helbig, et al. [44]	Benefits of resource strategy for sustainable materials research and development	2017	A framework proposed to reduce supply risk and enhance environmental sustainability taking into account basic research, technical development, application, and re-phase across a product life cycle
6	Hazen, et al. [45]	Big data and predictive analytics for supply chain sustainability: A theory-driven research agenda	2016	The paper proposes a research agenda for using big data and predictive analytics to improve supply chain sustainability by reviewing eight theories.

Table 3. Cont.

#	Author(s) and Year	Title	Year	Novelty
7	Tagliari, et al. [46]	Developing a specific structured procedure to assess sustainability performance in manufacturing processes	2020	A structured procedure to assess sustainability performance in manufacturing processes by taking into account the environmental, social, and economic dimensions of sustainability.
8	Dangelico, et al. [47]	Developing sustainable new products in the textile and upholstered furniture industries: Role of external integrative capabilities	2013	Proposes a new framework for understanding the role of external integrative capabilities in sustainable green product development.
9	Papoutsis and Sodhi [48]	Does disclosure in sustainability reports indicate actual sustainability performance?	2020	The research suggests that disclosure in sustainability reports can be a useful indicator of actual (realised) sustainability performance.
10	Ryberg, et al. [49]	Downscaling the planetary boundaries in absolute environmental sustainability assessments—A review	2020	The paper provides a comprehensive review of methods for downscaling planetary boundaries in absolute environmental sustainability assessments (AESA).
11	Singh, et al. [50]	Environmental impact assessment of different design schemes of an industrial ecosystem	2007	An LCA environmental assessment impact of industrial ecosystems.
12	Harland, et al. [51]	Environmental sustainability in the semiconductor industry	2008	A framework to address environmental sustainability challenges of the semiconductor industry is presented.
13	Seifi [24]	Governance and Socially Responsible Energy Consumption	2013	A discussion on the links between industrial engineering and environmental sustainability while using Bayes Theorem as a method of analysis to compare energy consumption.
14	Ben-Zvi-Assaraf, et al. [32]	Harnessing the Environmental Professional Expertise of Engineering Students-The Course: ‘Environmental Management Systems in the Industry’	2010	The study explores their perception of industrial–environmental issues.
15	Singh and Lou [52]	Hierarchical pareto optimisation for the sustainable development of industrial ecosystems	2006	The paper proposes a novel methodology for improving the sustainable development of industrial ecosystems (IEs) by using hierarchical Pareto optimisation.
16	Severo, et al. [53]	Impact of the COVID-19 pandemic on environmental awareness, sustainable consumption and social responsibility: Evidence from generations in Brazil and Portugal	2021	An analysis of the impact of COVID-19 on environmental awareness in relation to various generations.
17	Brezet, et al. [54]	LCA for ecodesign: the Dutch experience	1999	Evaluation of various LCA industrial eco-design case studies to extract limitations and opportunities.
18	Schröder, et al. [55]	Making the circular economy work for human development	2020	A novel hybrid framework for human development focused circular economy.
19	Thomas, et al. [56]	Research Issues in Sustainable Consumption: Toward an Analytical Framework for Materials and the Environment	2003	Central research questions are addressed within the context of industrial ecology.
20	Tseng, et al. [57]	Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: a data driven analysis	2021	Bibliometric analysis of sustainable industrial and operations engineering in relation to Industry 4.0.
21	Raffaeli, et al. [58]	Sustainable strategies: a continuously improving methodology	2021	An 11-step continuous improvement methodology for environmental and economic performance.
22	Phuong and Guidat [59]	Sustainable value stream mapping and technologies of Industry 4.0 in manufacturing process reconfiguration: A case study in an apparel company	2018	Sustainable value stream mapping (SVSM) is applied in an apparel company to identify sustainability issues.
23	Xiao, et al. [60]	Using modified Barabási and Albert model to study the complex logistic network in eco-industrial systems	2012	An eco-industrial system is improved upon.

4.5. Steps 7 to 8: Data Extraction and Synthesis of Core Findings

The 23 publications from the SLR filtering process were all subjected to a full-text reading by one researcher. During this process, a thematic analysis was conducted using the atlas.ti software platform. Five sets of themes were formulated for industrial engineering knowledge and environmental sustainability knowledge. These codes were based on strategy, theory, methods, and practices that belong to each knowledge domain. The codes were formalised before the analysis and linked with the three business execution levels on strategic (strategies), operational (theories), and tactical (methods and practices) levels [61]. This was used to create a cascading application stream of each knowledge component, starting with strategic vision (strategies) leading to a theory which is eventually deployed as methods and practices. A knowledge component is a topic or recursive element that is featured in the analysis. Each theme received a dedicated code using atlas.ti. To establish the overlap, the co-occurrences of the codes are presented in Table 4. The GR codes refer to the code densities using atlas.ti. The numerical values at each code intersection represent a code overlap. According to the PRISMA checklists detailed by Page, et al. [38], the study characteristics are featured in Table 3. Furthermore, the results were reviewed and critiqued by two researchers in this study to reduce the risk of bias in the analysis and the reporting thereof.

Table 4. Industrial engineering and environmental sustainability code co-occurrence table.

		Environmental Sustainability (ES) Codes			
		ES Method Gr = 24	ES Practices Gr = 94	ES Strategy Gr = 61	ES Theory Gr = 55
Industrial Engineering (IE) codes	IE Methods Gr = 24	2	0	1	0
	IE Practices Gr = 44	2	7	1	1
	IE Strategies Gr = 19	0	1	1	0
	IE Theory Gr = 41	0	3	2	5

As can be elucidated from the table, there is a weak relationship between the various subsets of industrial engineering (IE) knowledge and environmental sustainability (ES) codes identified by a zero entry during the analysis. The strongest relationship is between the various practices and theories with a code density overlap in seven instances.

To better contextualise the interaction of the codes above, a network diagram has been forward-engineered and is presented in Figure 4. The code relations between each paper and respective code show an intricate web between IE theory methods and practices linked with ES theory, strategies, and practices across the various literature sources.

This diagram demonstrates the intricate link between the themes and publications as part of the data extraction and synthesis. It also outlines the term associations between each code being associated or a part of one another to demonstrate hierarchy and cascading forms of application across the three business execution levels. The knowledge components (theme codes in atlas.ti version 24.1.1) feature in dedicated tables, with each theme discussed in the subsections that follow.

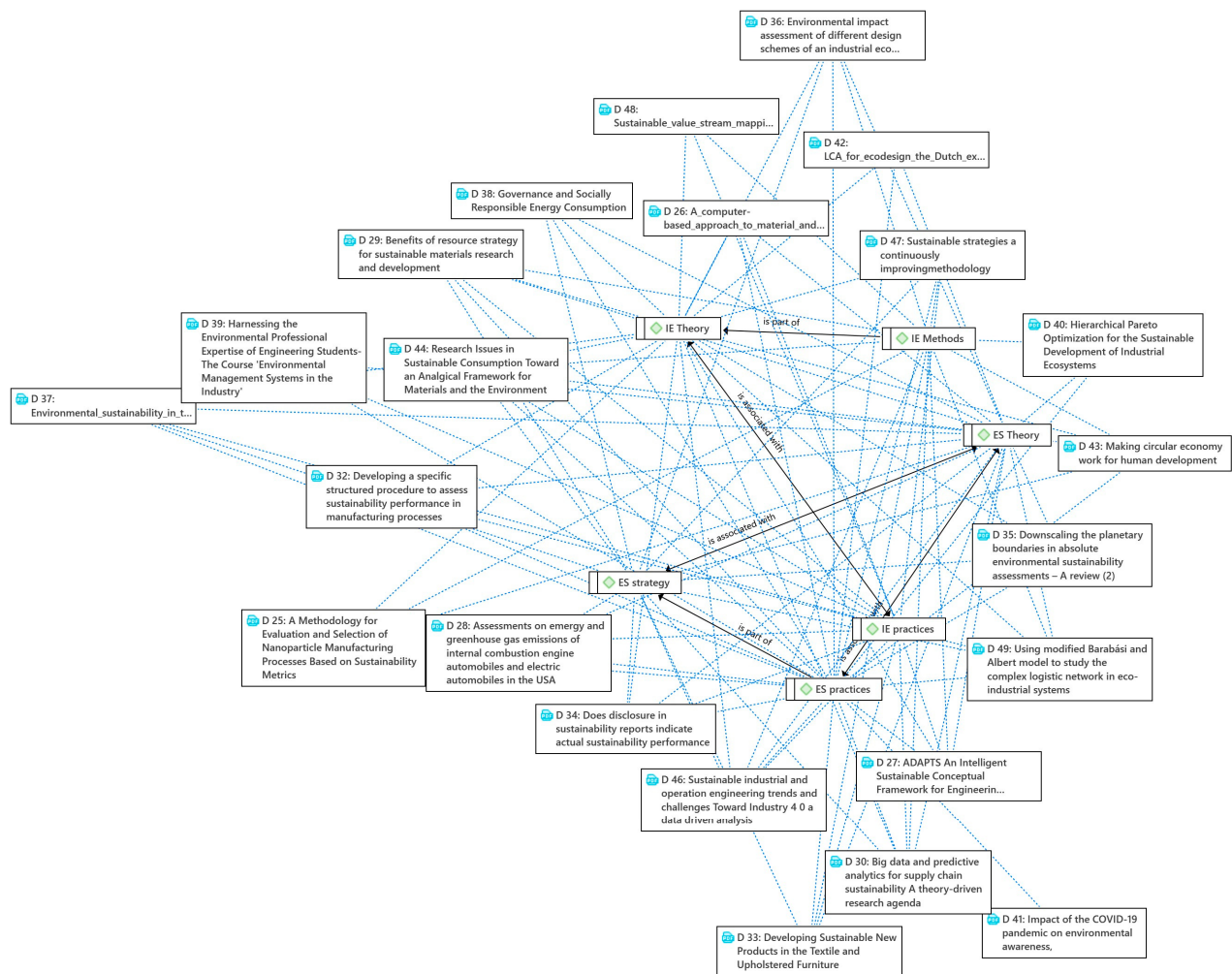


Figure 4. Network diagram for codes.

4.5.1. Strategy

Within IE knowledge, various strategies were revealed. These are further consolidated in Table 5. The numerical subscripts refer to the publications included in the thematic analysis, appearing in the order presented in Table 3. The succeeding tables will also contain these subscripts.

Table 5. Industrial engineering strategies.

IE Strategies	Paper References
Industry 4.0	[3,20]
Leapfrogging	[6]
Decision support systems and data analytics	[1,6]
Supply chain management (SCM)	[8]
Technology innovation	[6,8,18,19]
Risk mitigation	[5]
Product design	[8]
Resource consumption	[20]
Business strategy and profitability	[8,11,12]

Industrial engineers are believed to be able to pioneer the adoption of Industry 4.0 technologies. It can be argued that Industry 4.0 may support sustainable manufacturing by creating capabilities for product reuse, remanufacture, recycling, and reduction is a motivation for sustainable manufacturing [57]. Industry 4.0 technologies can create a smart manufacturing ecosystem paradigm since they create smart products and procedures that facilitate product reuse, remanufacturing, recycling, and reduction.

Technology leapfrogging is seen as the radical adoption of advanced technology where immediate prior technology has been absent [62]. For developing countries, this would allow companies to leapfrog foreign competitors [45]. Leapfrogging can be linked with a form of innovation and obtaining marketplace while being environmentally compliant. Hazen, et al. [45] believe that by leveraging big data and predictive analytics and applying this to resources and firm expertise, a marketplace advantage can be obtained. Furthermore, a decision support system becomes a crucial component when evaluating sustainability metrics, as explored by.

Unfortunately, environmentally focused efforts do not always yield financial gain for organisations [63]. It is therefore crucial that any simultaneous hunt for profit gains, technological innovation, and environmental performance is better understood. When promoting innovation, new product development, product differentiation, and increasing market appeal render a new solution that can disrupt a market.

Corporate sustainability has evolved as a business strategy initially perceived as abstract [51]. One such strategy can be used to improve supply chain operations. Dangelico, et al. [47] postulate that a collaborative supply chain aids in the development of green solutions. Risk mitigation strategies are also crucial to an organisation for the sustainable use of functionalized resources [44].

Industrial engineers pride themselves on efficacy. According to Galán-Martín, et al. [64] and as discussed by Tagliari, et al. [46], quantifying the sustainability level of a system or model is challenging considering various economic, environmental, and social aspects.

When reflecting on the ES domain, more sustainable principles are presented as strategic choices industries or organisations may employ. ES strategies are encapsulated in Table 6.

Various environmental sustainability strategies have been identified in the literature. While the IE strategies identified technology leapfrogging, Schröder, et al. [55] suggest lifestyle leapfrogging as an approach to avoiding fixed linear consumption patterns. This inherently configures circular systems and new business models that include sustainable consumption choices in developing countries. In relation to Industry 4.0, this helps to recover resources, reduce resource consumption, and increase resource allocation [57].

An emergent strategy was closely linked with supply chain management, more specifically, configuring closed-loop supply chains. Closed-loop supply chains could have negative employment outcomes for workers in low- and middle-income countries.

The most popular strategy obtained in this research was the circular economy (CE). The CE concerns itself with the conversion of goods at the end of their lifecycle into resources for others by creating closed loops that minimize waste and create industrial ecosystems [65]. Tseng, et al. [57] suggest that when applying this to a digital environment, increased utilization and resource efficiency are obtained through a redistributed application of used products. A digital environment is considered a method of applying emerging innovative technologies to recover usable material from used products and redistribute them in the production line [57]. CE practices and circular thinking can simultaneously promote human well-being and address environmental challenges [55]. This is a greater need in developing countries in the pursuit of job creation and improved health. The CE also aids in achieving several UN Sustainable Development Goals (SDGs).

Environmental considerations should be unbiased towards any point in a development cycle [51]. In contrast to popular opinion, Life cycle analysis (LCA) has proven to be contentious, inefficient, and expensive [56], and so efforts should be made to explore other

forms of evaluating environmental performance. In order to increase environmental reputation and develop green products, a product stewardship strategy can be employed [47].

Table 6. Environmental sustainability strategies.

ES Strategy	Paper Reference
Circular economy and sharing principles	[3,5,10,18,20]
Resource strategy, resource conservation (reduce, reuse, recycle)	[5,9,11]
Reducing carbon footprint, emissions, and energy (Reduce carbon)	[4,5,9,11]
Triple bottom line	[6]
Scientific knowledge creation	[6]
Environmental protection, management	[6,9,19]
The resource-based view	[6,8]
Low carbon impact, dematerialisation, decarbonisation and substitution (De-materialisation and carbonisation)	[8]
Green product and environmental innovation	[8]
Sustainable product development	[8]
Supplier evaluation	[9]
Reduce water consumption	[9]
Reduce energy consumption	[9,12]
Supply chain	[9,18,23]
Planetary Boundary	[10]
Eutrophication	[11]
Eco-effective symbiosis and an eco-industrial park	[11,19]
Clean production	[12]
LEED (Leadership in Energy and Environmental Design)	[12,18]
Sustainable resource management (SRM) and lifecycle thinking (LT)	[12]
Risk management	[13]
Energy labelling	[13]
Sustainable lifestyles	[18]
Global systems and engineered systems	[19]

The planetary boundary (PB) emerged as a strategy for achieving environmental sustainability as a conceptualized framework. PB provides a science-based analysis of the risk anthropogenic activities have in destabilizing the earth system at a planetary scale using nine boundaries for categorisation [66]. Being able to assess an activity relative to environmental boundaries perpetuates sustainability targets for said activity [49]. The nine boundaries possess safe operating spaces. According to Ryberg, et al. [49], an equal capita sharing of this space is advised across national, regional, and individual scales.

Large investments are needed in research and development [51]. Ryberg, et al. [49] suggest that R&D explores operational methods for sharing a safe operating space among humans and industrial units to maximise human welfare and capabilities.

What becomes rather apparent from these results is that any sustainability driven strategy must be symbiotic. Any strategic venture must have duality, trying to solve for a sustainability aspect alongside a profit, safety, cost saving, or productivity component.

The formulation of a sustainability driven strategy can vary. In one instance, Sen [67] believes that a symbiotic strategy can exist between sustainability development and differentiation. Another approach is to integrate a sustainability approach in its intended context, most considerably in a business context.

4.5.2. Theory

As the strategies now cascade into respective forms of theory, Table 7 provides the pertinent IE theory related to this research.

Table 7. Industrial engineering theory.

IE Theory	Paper Reference
Lean	[9,17,20–22]
Analytical models, algorithms, and machine learning	[1,3,6,7,11,18,20,23]
Multicriteria decision analysis	[1]
Facility planning	[2]
Value engineering and value creation	[3,5,6]
Simulations	[3,11,20]
Supply chain sustainability, reversed logistics, and closed-loop supply chains	[6,8,12,18,23]
Risk management	[13]
Game theory	[13]
Green engineering	[19]

Lean is an inherent industrial engineering philosophy that strives to reduce inefficiencies so as to improve organisational productivity [68]. By considering an inefficiency as high resource consumption or pollution, environmental sustainability improvements can be made by adopting Lean into an organisation. Lean manufacturing combined with Industry 4.0 can result in improved performance [57].

Various mathematical principles emerged in the analysis. The use of simulations, algorithms, machine learning, and decision analysis offer ways of modelling system behaviour and evaluating environmental performance metrics for optimal integration with production [41,42].

Configuring closed-loop supply chains with reverse logistic aspects can increase resource efficiency and create circular value chains. This ultimately leads to new value creation [47]. The various environmental sustainability theory is now presented in Table 8.

Industrial ecology is classified as a subset of ES theory despite being a transdisciplinary knowledge domain. Thomas, et al. [56] argue that industrial ecology strives to minimize costs and reduce environmental impacts. According to Munhofen, et al. [69], the components of industrial ecology are industrial metabolism, dematerialization, life cycle assessment, eco-design, and eco-industrial parks.

Tools for eco-design include the Lifecycle Expert Analysis of Design Strategies (LEADS) and an advanced methodology for environmental product development [54]. LEADS is a knowledge-based system for ranking DFE options using an environmental profile and assessment method [70].

Several social sciences theories in the form of agency, actor–network, social capital, and distributive justice theories. Actor–network theory systematically considers the infrastructure surrounding technological achievements with social relations as network effects. Agency Theory describes the relationship between entities that assigns tasks to one another [45]. This sophisticated network can be applied to supply chain management by explaining the interaction and flows of information, finance, and physical products [71,72].

As for distributive justice theories, utilitarianism, prioritarianism, sufficientarianism, egalitarianism, and libertarianism surfaced during the analysis. Building on the planetary boundaries framework, these justice theories can be used to define best practices using sharing principles that downscale according to seven dimensions [49]. Another social construct is that of coercive pressures and mimetic forces. According to Hazen, et al. [45], coercive pressures aid in the adoption of sustainable practices, while mimetic forces can result in organizations embodying sustainable traits from leading companies in their sector.

Resource dependence theory suggests that sharing principles are evident with organizations that lack resources and naturally develop relationships with other organizations [45,73].

Table 8. Environmental sustainability theory.

ES Theory	Paper Reference
Sustainable development and sustainability models	[1,7]
Environmental Management Systems	[1]
Building Information Modelling (BIM)	[3]
Life cycle analysis (LCA)	[3,8–10,19]
Cradle to cradle (C2C)	[3]
System boundary and planetary boundaries framework	[4,10]
Ecological engineering and modernization theory	[4,6]
Agency Theory (AT)	[6]
Environmental reform	[6]
Green manufacturing	[8]
Greenwashing	[9]
Institutional and distributive justice theory	[9,10]
Design for Environment (DFE) principles	[12]
Moore’s Law	[12]
Product and human ecology	[12,13]
Game theory	[13]
Cleaner and safer production	[14]
Industrial ecosystems and eco-industrial systems	[11,15,23]
LEADS (Lifecycle Expert Analysis of Design Strategies)	[17]
STRETCH	[17]
Circular humansphere	[18]
Industrial ecology	[19]

Risk analysis is complementary to the industrial engineering profession. It can be used to make strategic decisions. However, Seifi [24] argues that game theory is the most useful tool for strategic decisions considering risk management and analysis. Game theory is an economics and mathematical approach used for multi-actor decision making using game elements [74]. These strategic decisions can offer more effective decisions that concern environmental trade-offs.

One could also argue that systems will naturally reach a more sustainable state. Moore’s law can also be associated with sustainability. The exponential advancement of technologies also results in energy efficiency gains and performance indirectly impacts environmental performance [51].

4.5.3. Methods and Practices

The methods and practices theme has omitted tables since the results became more fragmented. Due to these low code densities, they are clustered into various discussions. Methods and practices are blended in this subsection with methods more theory-specific and practices represented with more of a practical backing.

Quantitative methods in the form of linear regression, algorithms, simulations, Bayesian and neural networks, multi-objective optimization, structural models, and decision support systems were prevalent as industrial engineering methods [41,42,50].

An Ishikawa (fishbone) diagram also emerged as a common industrial engineering tool used for primary and secondary cause identification and can be applied to any context, even for environmental concerns [58].

A green supply chain can be achieved by managing supply chain functions, vertical integration, outsourcing, and sourcing [45,60]. Careful supplier selection and development aid in reducing the carbon footprint of an organisation as well.

In order to obtain increased efficiencies, resource and energy efficiency during industrial upscaling must be systematically applied during a transformation [44,47]. Furthermore, determining bottlenecks or benefits aids in generating cost savings that can be used to invest in new (cleaner) technologies [46], renewable energy, or waste heat recovery technologies [44].

These are to be integrated within existing systems to promote product innovation and the re-engineering of products, processes, and technological systems [42,45,56]. These all warrant external and internal integrative, technological, and marketing-related capabilities [47]. Embodying these capabilities absorbs critical knowledge and resources using collaborative networks.

A business culture with shared goals, expectations, systems, values, and efforts helps differentiate customer value. It also strives to obtain the highest quality and minimum or reduced costs [40,42]. To effectively sustain this, training programs and creating incentives are key [45,47]. Furthermore, environmental ethics should be integrated into business culture [51].

Sustainable manufacturing and net zero emissions are attracting more research interest [57,58]. This can also seek out continued environmental improvement that abides by process and safety metrics that are continuously monitored [40]. Material to eco/sustainability is also reduced since the degree to which a material consumes energy and releases emissions is modified [40].

When considering the environmental sustainability aspects, one area of overlap with industrial engineering is the adoption of ISO standards [45], more specifically, the ISO 9000 and 14000 series [32,48,50,54]. Both are among the most widely known standards that are implemented across the globe. ISO 9000 focuses on quality concerns, while ISO 14000 addresses environmental management issues [75]. This can also be used as a model for corporate sustainability [32].

Life cycle analysis is one of the most prominent method of assessing the environmental impacts of products and services [40,47]. This procedure of evaluating and analysing environmental impacts uses an extensive set of input and output data on material and energy at different production stages [50]. However, Brezet, et al. [54] stresses that LCA lacks standardization and is not yet appropriate for computing environmental effects or performing external comparisons. It can, however, be effective in validating green design options amidst poor energy mixes. Adaptions include the ReCiPe method. The lifecycle thinking analysis methodology aids in the eco-design phase in organizations. Traditional environmental methods such as carbon footprinting, reducing pollution, and the 3Rs and smart waste management are also featured in the analysis [43,51,55,57].

Environmental policies and legislature reinforce governance and a commitment towards actionable forms of practice for environmental sustainability. The Organisation for Economic Co-operation and Development (OECD) Environment Directorate reports on policy initiatives that promote more sustainable consumption patterns [56]. More examples of policies or schemes include the IPCC, Eco-Management and Audit Scheme (EMAS), Kyoto Protocol, Montreal Protocol, GRI, and Rio Declaration [32]. Environmental policy and taxes require strict environmental auditing for compliancy. There are also public environmental policies that can be used in green operation or to facilitate a green product design [47].

Sustainability and eco-auditing are more actively being applied in industries [40]. Environmental accounting, or green accounting, is a tool to assist with environmental and operational costs that concern natural resources [76]. This specialised accounting system

can also make considerations for materials, CO₂ emissions, and other budgets, permitting prescribed volumes of respective inputs without penalty [49,56]. This can even stem so far as to enable carbon trading and the selling of surplus carbon quotas between organizations in the same industry [47].

A novel method to measure environmental performance is to evaluate emergy. Emergy is defined as the availability of energy (exergy) directly or indirectly related to the transformation of a product or service [43,77]. It can also be associated with the indirect and direct energy consumption. This is further researched by focusing on emergy transformity and analysis along with the emergy society database [43,52].

As a means of evaluating performance, various performance metrics and evaluation methods are situated in the literature. The RobecoSAM's corporate sustainability assessment analysis, material circularity indicator (MCI), sustainability metrics, work environment index, Sector Competition Index (SCI), and end-of-life recycling rate [41,44,48,55]. The Kinder–Lydenberg–Domini (KLD) index and Global Reporting Initiative (GRI) are also used for ESG reporting purposes [48]. Evaluation methods include the Life Cycle Impact, the AICHe total cost, and absolute environmental sustainability assessments (AESAs) [49,50].

Resource consumption forms the crux of any environmental improvement initiative. The exact acquisition of raw materials and technical know-how helps build a more reputable environmental profile [40,47]. Eco-design practices can also be used to reduce material consumption. This can also be used to increase environmental awareness, leadership, and literacy [51,53]. Eco-labels can be used to inform consumers of the environmental effects of their consumption and encourage producers to increase environmental standards using the information they provide [78]. It is therefore apparent that this would transform organizations, supply chains, and consumers' mindsets and increase eco-efficiency [32,55].

4.5.4. Circle Packing Knowledge Components

To further the findings yielded from the thematic analysis, a circle packing diagram is used in conjunction with the body of knowledge categorisation by the Institute of Industrial and Systems Engineering (IISE). The IISE Body of Knowledge identifies knowledge areas that apply to the field of industrial engineering, as illustrated in Figure 5.

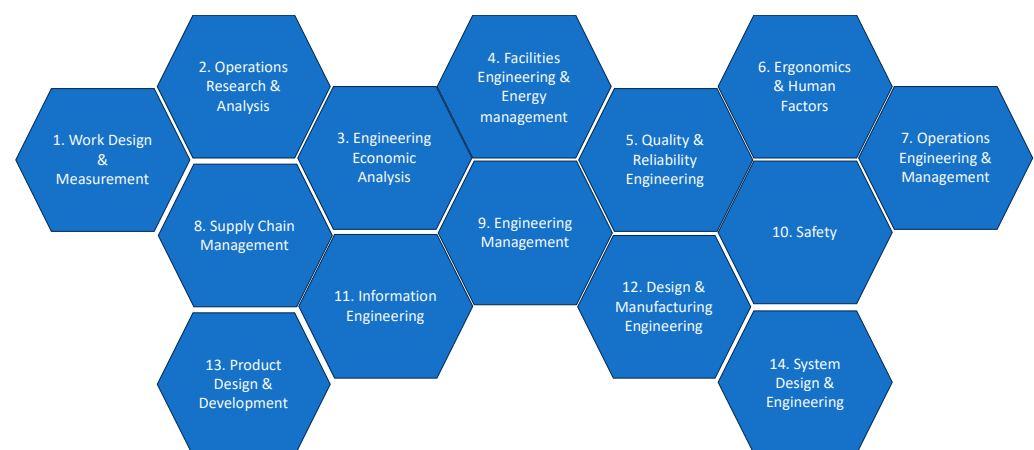


Figure 5. IISE Body of Knowledge, redrawn from (IISE) [23].

The shortcoming of this taxonomy model is that it does not speak to environmental sustainability. It does, however, present the core value of the industrial engineering profession, and so it becomes a cohesive way of structuring the findings. Using circle packing, a hierarchical structure is formed by linking each IE or ES strategy, theory, method, and practice that links with these body of knowledge areas. Figure 6 contains the legend (segmented for enhanced legibility), while Figure 7 presents the circle packing diagram that consolidates the findings from this research.

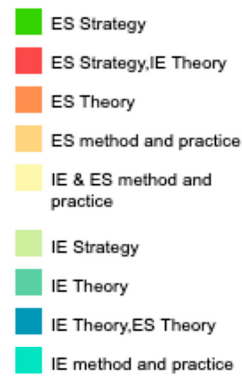


Figure 6. Legend for circle packing diagram.

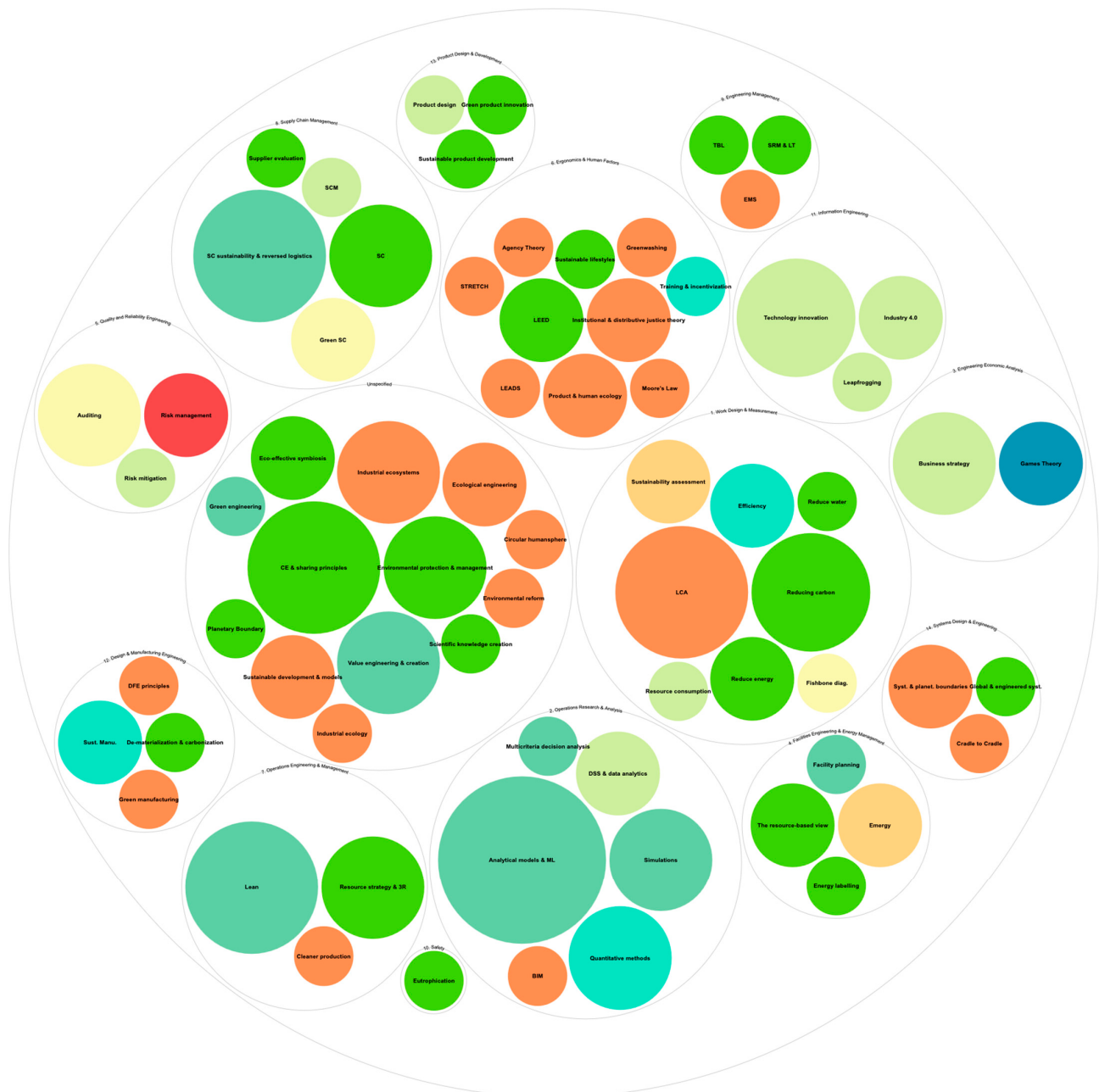


Figure 7. Circle packing diagram containing IE and ES knowledge components clustered according to the IISE body of knowledge areas.

The density (size) of each circle is a product of the code densities from the thematic analysis and is also associated with the authors identified in the literature review. The hierarchy is structured to align each knowledge component with the IISE Body of Knowledge areas. The current representation also hides knowledge components that overlapped text over each other which are later expanded. Unfortunately, some of the knowledge components did not conform to any of the body of knowledge areas, and so, an “unspecified” field has been created.

As illustrated in the diagram, the majority of these are associated with the ES theory, followed by an ES strategy. The diagram shows a healthy balance between the various knowledge component types within the IISE Body of Knowledge areas. Although holistic, it is possible to stratify the results and delve deeper into the knowledge areas and provide enhanced legibility. This stratification divides the 14 knowledge areas and unspecified fields into three parts containing five knowledge areas, respectively. The first five knowledge areas are presented in Figure 8.



Figure 8. Circle packing diagram containing first five knowledge areas.

The results showcase at least one of every knowledge type from the IE or ES. However, there are limited methods and practices for the first five knowledge areas. The engineering economic analysis knowledge area is the least represented with only IE knowledge components. This shortcoming reveals a lack of ES economic knowledge components reported in the literature. Figure 9 continues the presentation of the knowledge areas by showing knowledge areas 6 to 10.



Figure 9. Circle packing diagram containing knowledge areas six to ten.

With the IISE taxonomy classifications, ES strategies are dominant in knowledge areas six to ten, most noticeably with regard to ergonomics and human factors. A text overlap in engineering management hid the triple bottom line and sustainable resource management and lifecycle thinking. It is also evident that the IISE Safety Knowledge area is neglected in the literature. Figure 10 presents the remaining knowledge areas alongside an unspecified category which did not conform to the IISE classifications.

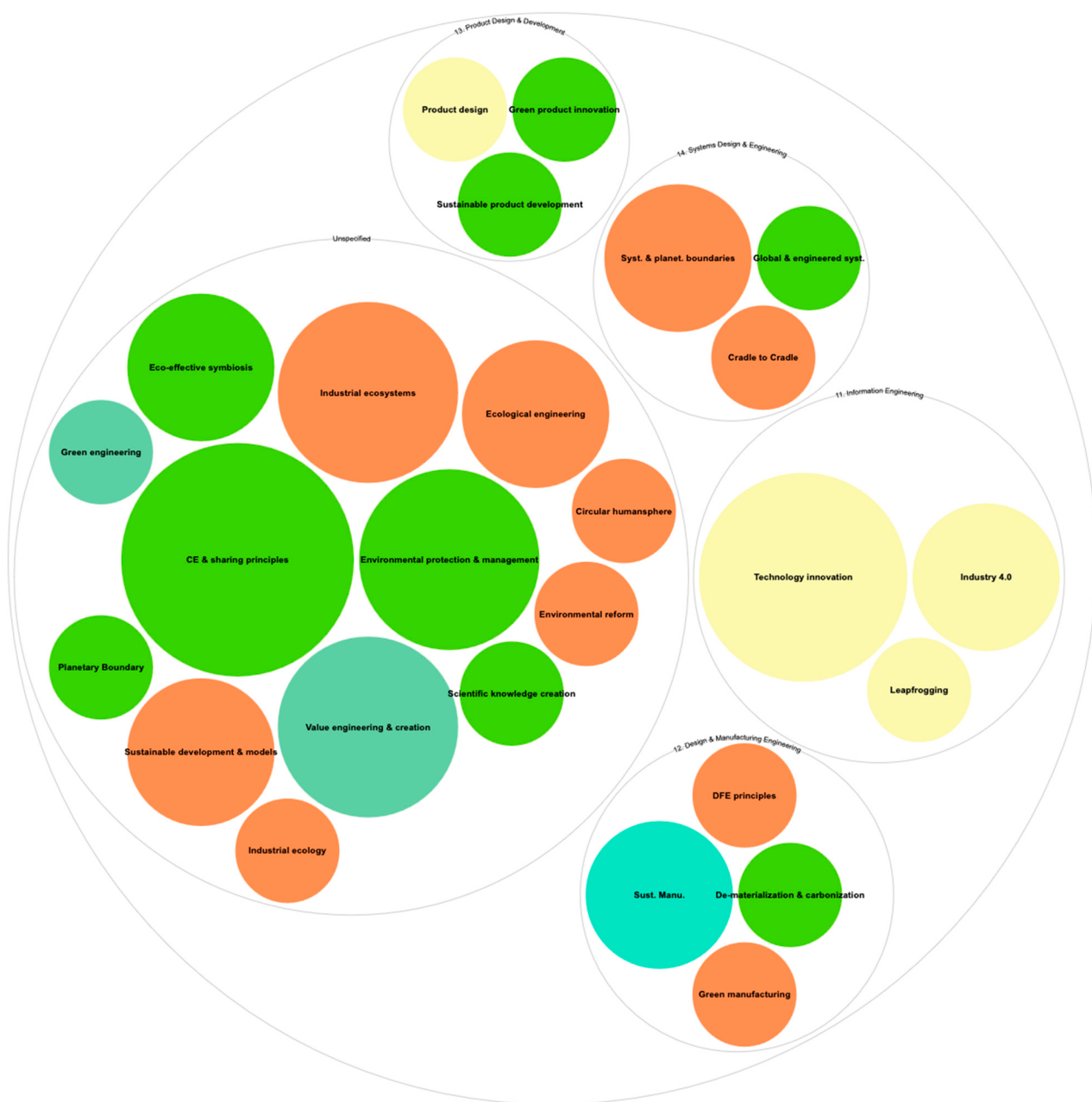


Figure 10. Circle packing diagram with the remaining knowledge areas and unspecified area.

Figure 10 tells us that the only IE strategic knowledge components linked with information engineering, the most imbalanced IISE knowledge area. For the design and manufacturing engineering knowledge area, a low carbon impact, dematerialization, decarbonization, and substitution overlapped with the sustainable manufacturing knowledge component. These results from the circle packing illustrations are further discussed in Section 5.

5. Discussion of Results

The realms of industrial engineering and environmental sustainability share innate links, some of which are dissociated and others that are synergetic. Only three knowledge components overlapped, namely green supply chain management, the circular economy, and technology management. There exist opportunities to use concepts such as Lean and Green and the transdisciplinary nature of industrial ecology to further environmental

improvements. Most of the results were siloed or fragmented, as was the case for most environmental sustainability knowledge components.

Lean is inherently associated with industrial engineering knowledge. The idea of green or environmentally conscious manufacturing with Lean can aid in more sustainable new products and increased sustainability performance [47,48]. A modified version of Lean is that of Lean and Green, which is a hybrid philosophy that strives to seek out simultaneous productivity improvements and environmental performance [34,79].

The idea of a green supply chain embodies traditional operations management and supply chain concepts from industrial engineering. Moreover, this has been identified and adopted under environmental sustainability aspects that incorporate amongst others reverse logistics and circular thinking. Supplier selection practices and material acquisition methods can be applied to have a more reliable, environmentally considerate and robust supply chain.

The circular economy is a sound means of reducing material consumption and waste. The industrial engineering discipline can further contribute towards more robust conceptualisation and implementation of circular thinking using the systems thinking instincts it has. More complex modelling approaches can be used to develop quantitative results on sustainability performance measures.

LCA is still a contentious matter that has polarised opinions. Some authors believe that with life cycle thinking, resource consumption and carbon footprints are systematically reduced, while others believe that it is not standardised enough. Nonetheless, there exist traits and characteristics of LCA that can be used to primarily facilitate environmental gains.

Technology development, integration, and readiness characteristics were uncovered in the research. Technology innovation and Industry 4.0 are becoming increasingly intertwined with environmental sustainability endeavours. Industry 5.0 is a newly coined term that remedies a shortfall of Industry 4.0, being distracted from social fairness (social sustainability) and sustainability and more focused on increasing production efficiency and flexibility [80]. It is therefore apparent that Industry 5.0 may be the more favourable term to use when discussing environmental considerations. The term Industry 5.0 was not associated with any of the literature obtained during the SLR, and so more practical methods to carry out environmental sustainability can be linked with strategies, theory, methods, and practices going forward.

The Quadruple Helix Model was originally developed by Carayannis and Campbell [81] towards conceptualising four components of an innovation system: academia, industry, government, and society. The results from this study have direct implications for the applications it can have in engineering education, industry implementation, and policy making. For governments, the formulation of policies and measuring conformance in local contexts can be inspired by some of the results obtained. ISO standards and reporting standards can be enforced in more industries. Furthermore, the adoption of new policies can be inspired using environmental sustainability aspects but carried out using change management theory from industrial engineering.

The circle diagram presents the various knowledge components as features within the distinct body of knowledge categories. It proposes that environmental sustainability is far reaching, with 13 knowledge components unspecific to the categories. The safety category is the least populated area, hinting that research in this field is explored in more detail and documented in the literature more evidently.

6. Conclusions, Limitations and Future Research

This study provides a state-of-the-art exploration of how the knowledge of the industrial engineering profession may appeal to environmental sustainability. This research establishes symbiotic relationships between aspects of IE knowledge that achieve environmental sustainability through strategies, theory, methods, and practices discussed. Although currently stratified, these results can be pieced together to form innovative solutions that harness industrial engineering knowledge primarily. It is argued that industrial

engineering can be seen as transdisciplinary or can at least promote or cultivate new forms of transdisciplinary knowledge areas that can appeal to broader contexts. The findings from this research can be enhanced by more explicit strategic, tactical, and operational approaches that can be informed by the strategies, theories, and methods and practices filtered in this study. Using implementation science, this can be transcended into more of a transdisciplinary problem-solving paradigm using industrial engineering. These results can inform policies concerning the triple bottom line and ESG reporting.

A paradigm shift is needed as a core steppingstone to blend concepts from these two subsets of knowledge between respective multidisciplinary, interdisciplinary, and transdisciplinary domains. The exact assortment of these concepts is yet to be established. Future research can develop frameworks or conceptual models that help with the adoption of various forms of knowledge or practically involve subject matter experts with industrial engineering or environmental sustainability experience. This can be used to create contextualised solutions to problems that can be solved via this hybrid combination.

According to Dangelico, et al. [47], organizations do not possess the necessary environmental knowledge and competencies to develop green products. Therefore, the eco-design process combined with industrial engineering process thinking can offer new methodologies or approaches for green product design. This can transcend DFE principles, cradle to cradle, life cycle analysis, and eco-design into more robust methods applied in industries.

A drawback from this study is that the findings are unspecific to a particular industry, and perhaps more importantly, not contextualised to any region or country. Researchers and practitioners can further this study by modifying these results for applicability in its area of application.

Technology management, industrial ecology, and green supply chain management were considered to overlap between industrial engineering and environmental sustainability knowledge in this study. Industrial ecology was the only form of transdisciplinary knowledge that featured in the results. Lean and Green could also be a hybrid philosophy that can be included. It is therefore of particular interest to consider the vast array of industrial engineering principles that can be modified as singular or collective forms of theory or strategies. This would then dictate the relevant methods and practices that can be used to practically implement solutions from these hybrid concepts or ways of thinking.

Furthermore, the articulation of the circle packing diagram representation argues that environmental sustainability can be intrinsic to the industrial engineering body of knowledge. While this shows a symbiotic relationship through the high degree of interconnected concepts, there is an evident gap in knowledge components accentuated by the unspecified field. Future research could explore a new class or categorisation that formalises the environmental sustainability paradigm with the industrial engineering body of knowledge.

This research provides a novel overview by finding the nexus between industrial engineering and environmental sustainability using results from the SLR, thematic analysis, and circle packing aligned with the IISE Body of Knowledge. It is the first research of its kind to explore the relationship between industrial engineering and environmental sustainability knowledge. The circle packing diagram can be analogised with spores which grow and spread similarly to how knowledge finds itself as seeds initially (infancy), diversifying and growing (spore development) and cross-pollinating to sustain itself (dissemination and preservation). These results can be used to create new transdisciplinary knowledge that can aid in addressing environmental challenges using the knowledge components obtained.

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