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Digital Twins and Sustainability: A Comprehensive Review of Limitations and Opportunities

Master's thesis in Computer Science and Engineering

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Abstract

During the past few years there has been an increasing push to deliver sustainable products and improve production processes to meet the growing demand faced by various types of industries. There is a high importance placed on identifying and defining project, product, and policy goals but sustainability goals within these areas are difficult to define. Digital twins have shown to provide enhancement capabilities for industrial processes, task definitions, material handling, and an overall design of various products required in an expanding fast pace marketplace of today's world. Digital twins offer industries a virtual sandbox where they can model their manufacturing base, modify configurations in real-time bidirectionally between both digital and real world, and make predictions on improving sustainability. A systemic literature review was performed on an initial 230 studies which were later reduced to 32 studies following the guidelines by Kitchenham where metrics and indicators for defining sustainability goals were identified, coded, and themed using open coding standards. 499 codes and 12 themes (Performance, Environmental, Process, Quantity, Location, Distance, Temperature, Quality, Time, Financial, Human, and Other) were initially identified from the coded metrics and indicators. By addressing the research questions the codes and themes were reduced to 274 codes and 5 themes. The research themes consist of (1) identifying challenges in integrating metrics with digital twins, (2) Uncovering limitations specific to digital twins and sustainability, and (3) discussing the requirements engineering process on addressing limitations and validating the results. The findings from this study provide a guideline on which limitations and perimeters need to be set using digital twins in order to identify appropriate metrics and indicators for defining desirable sustainability goals for industries.

Keywords: Digital Twins, Real Twin, Sustainability, Metrics, Indicators, Industry, Manufacturing, Production, Systemic Literature Review.

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Simeon Petrov, Gothenburg, November 2023

Contents

List of Acronyms

AI	Artificial Intelligence
AMC	AMC Digital Library
CA	Cross Analysis
DT	Digital Twin
IEEE	IEEE Explore
IoT	Internet of Things
KPI	Key Value Indicator
QP	Quality Point
R2DFL	Real to Digital Twin Feedback Loop
RE	Requirements Engineering
RT	Real Twin
SG	Sustainability Goals
SLR	Systemic Literature Review
SD	ScienceDirect
SDG	Sustainable Development Goal
UN	United Nations

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1
Introduction

Due to how fast change has occurred with the way industries have had to upscale their output efficiently, long term goals for sustainability have not been the main focus moving forward. Instead a different type of goal has been focused on which is short term policy goals for projects as stated in Moldan et al. [1]. This has lead to a decrease in value for perusing the implementation of effective **Sustainability Goals (SG)** in manufacturing and other fields where setting sustainability goals can have a long lasting positive impact for industry developments. A refocus on sustainability would offer a long term ease in maintainability and a reduction in cost as mentioned by Franciosi et al. [2]. After sustainability goals have been realized, it would allow for the deployment of various applications (both new and old) to occur simultaneously. This can take place during the integration process without having to sacrifice neither quality nor productivity when adopting Industry 4.0 practices that encompass sustainability as the core value [3].

Industries often need a way to visualize and collect data at various levels from tasks, projects, and work settings for creating large scale abstractions or advanced digital models that can be examined and manipulated. This type of information allows them to plan for future events along with understanding how different operational tasks can be better optimized within their line of work or field of research. It is apparent that traditional simulations have become increasingly unfit to tackle objects and settings that are complex in nature. Meanwhile, researchers are raising awareness about the prospects of the **Digital Twin (DT)**, as this technology has the ability to provide and calculate concrete data from business intelligence information to planning and predictive data. Along with various operational metrics such as performance percentages of the numerous tasks and interactions that can occur in a **Real Twin (RT)** or a real life / real world equivalent. To demonstrate what this means, we can refer to the diagram in Figure 1.1 as a way to visualize the interaction process with a Real to Digital Twin Feedback Loop (R2DFL).

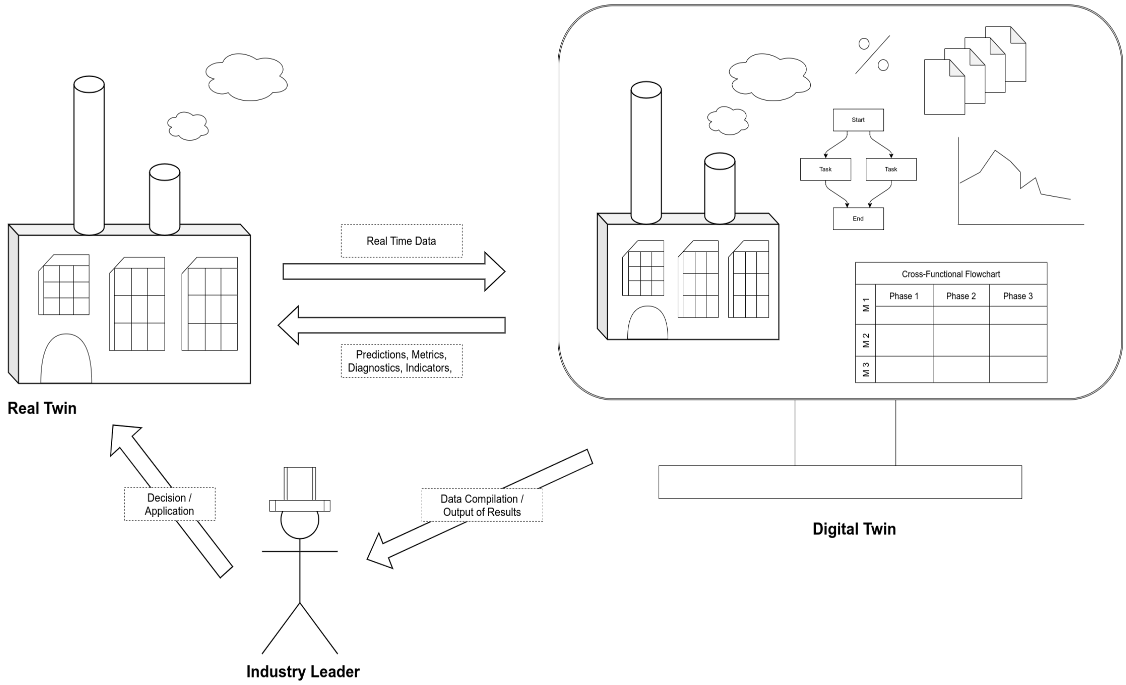

Figure 1.1: Real to Digital Twin Feedback Loop (R2DFL)

Until recently, simulations were favored over digital twins due to its small scale in both scope, resource utilization, and the ability to analyze single items or objects of interest [4]. Simulations allow for simulating real life objects, settings, or even environments that can provide researchers with an abundance of information in the form of models. From these models, data can be extracted in a one way direction, analyzed, and used for scientific predictions. A digital twin is able to provide an immersive virtual environment and allow for multiple models between multiple layers in the environment to be studied and interacted with at the same time unlike the capabilities of simulations [4].

digital twins use physical, virtual, interactive, and real-time data between one another to map all components in a product's life-cycle as described in He et al. [5]. A key advantage that digital twins have over simulations is that the real twin becomes immersed in a virtual (digital) environment encapsulated within the digital twin which allows for the ability to exchange data in both directions [6]. The virtual environment that digital twins produce can perform real-time large scale digital replications of real world items, objects, and tasks based on the current state of the real twin's environment in order to forecast different future outcomes depending on what parameters were set. In contrast, simulations are not ideal for real-time applications nor can they provide multiple levels of predictions. An example of this contrast can be depicted as a factory being the real twin subject where in a simulation a basic level of analysis is performed for a single prediction. Meanwhile a digital twins would output multiple different types of predictions based on real-time monitoring of the factory.

From these past few years digital twins was an underutilized technique in the industry, until around 2016-2017 when it managed to gain more traction and attention from both the academic community (e.g. China Association for Science and Intelligent Manufacturing) and businesses (e.g. Lockheed Martin) alike [1]. This was due to a growing interest in the wide array of benefits offered by digital twins, such as: a higher likelihood of first-time-right implementations, process improvement, and a lower demand on limited resources to name a few [7]. digital twins are considered by some to be a revolutionary push or a level above simulations similar to how the industrial revolution was the next level up for manufacturing [4], [7]. While this study will not focus too much on simulations, it is important to make a distinction between the two, and a case for much needed research into digital twins. Especially since digital twins become more widely used across different fields and industries such as manufacturing, farming, virtual and augmented reality, serious gaming, scientific predictions, and **Artificial Intelligence (AI)**. There are many more fields that can benefit from digital twins, where it is either difficult or time consuming to analyze or make predictions from large swaths of relevant tasks, where the use of simulations is simply not enough.

1.1 Problem Statement

Real-time data collection, concurrent data analysis, and large scale model replications are the main selling points for digital twins. Yet, when it comes to understanding, predicting, and mitigating potential issues of a digital twin through the use of metrics and indicators; it becomes very difficult to determine what sort of impact metrics and indicators have on sustainability for the real twin equivalent through the use of digital twins [8].

The traditional manufacturing methods for calculating and predicting sustainable processes and workflows have increasingly become too difficult to manage as it would require a significant investment into the amount of time, labor, and resources needed to maintain further continual growth. With rising demand for manufacturing and efficiency, many industries turn to digital modeling using the likes of simulations and more recently digital twins to solve their expanding presence on the market [9]. While digital twins can aid in finding solutions for sustainability problems experienced in manufacturing today, many industries have a difficult time determining which sustainability values and regulations are useful for defining effective sustainability goals for their projects.

To properly interpret and mitigate problems in a digital twins that arise in real twins, measurements in the form of metrics and indicators would need to be studied in order to understand what is working correctly and where sustainability and performance issues can be addressed. As there are no official frameworks or methods to which one can follow for identifying useful metrics, a literature review needs to be carried out to understand which types of measurements are reliable with digital twins. The reason for this is because many different studies use various types of metrics and indicators to describe their findings, but most of them can not be easily transferred over to be used in other studies, as many metrics are research specific or complex in their application. An example can be seen between the papers presented by Zamorski et al., where metrics are complex mathematical equations to measure mass, fidelity, and convergence of 3D models [10]. While in the paper by Ko et al., the metrics discussed are entirely different, consisting of temperature, CO2 emissions, and humidity for monitoring a vertical farming system [11]. There are a few limitations that metrics have in digital twins that stand out and need to be investigated which primarily affects the quality, accuracy, and effectiveness of collecting metrics from digital twins [12], [13].

1.2 Purpose of the Study

The purpose of this study is to perform a **Systemic Literature Review (SLR)** on the current usage of digital twins for sustainability. This will be done by following the guidelines that Kitchenham et al. [14] lays out for tertiary studies, e.g. review articles describing SLRs in software engineering. SLRs, which are referred to as secondary studies, are literature surveys with defined research questions, search process, data extraction and data presentation. Since this study reviews secondary studies, it is categorized as a tertiary literature review. By performing a SLR it will be possible to compile a list of key terms via thematic and open coding standards in order to cross reference thoughts and ideas between studies and identify strong indicators from metrics. These indicators can provide a base for designing a guideline that would be able to help industries identify sustainability goals for their real twins by using digital twins to track, collect, and suggest appropriate measurements.

2

Background

In this section I will describe the background information and afterwards review and synthesize information through literature between the relevant chosen sources. I also perform an in-depth cross analysis between sustainability values and goals along with indicators and metrics for the R2DFL. Furthermore, I will discuss how the potential of AI in industries can impact data analytics between sustainability and metrics. An insight into why accurate measurements for sustainability is needed to counter limitations found in real twins and bolster the opportunity for digital twins in industry, is presented below.

2.1 Digital Twins

Digital twins was a term that was first presented back in 1991 by David Gelernter but later became known publicly by Michael Grieves in 2002 and again in 2010 when NASA's John Vickers further popularized the term [6] [19]. Digital twins at the time was described as a virtual copy of an item, object, or product and it was an emerging new concept which could eliminate the need for manual data collection and paper based applications [19]. Since then, the concept of digital twins had matured to the point where it could be used to model how a physical product operated in a virtual space [6]; this provided a base for understanding product life-cycle management [19]. Digital twins have the ability to perform modeling, testing, apply optimizations, and a number of other specialized operation of a product in real-time as long as three properties (physical product, virtual space, and bi-directional data link) were met [19]. The simplified digital twin can be seen in Figure 2.1. With it's advancement since then, the digital twin of the past has evolved to include a multitude of capabilities that surpass traditional simulations and other traditional model analysis tools.

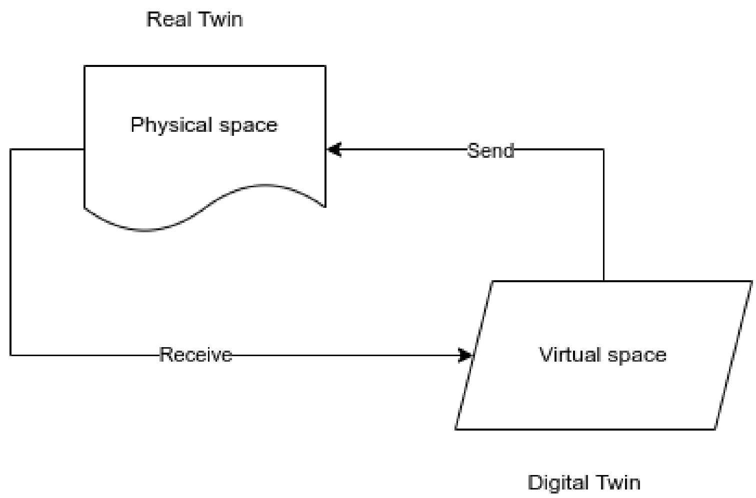

Figure 2.1: Simple Digital Twin Concept

2.2 Sustainability Requirements

Sustainability requirements are structured specifications derived from the different sustainability dimensions shown in Figure 2.2 which are used to help understand the level of abstraction needed for defining and implementing sustainable development practices [17], [41], [26]. These requirements include characteristics that embrace sustainability at their core such as efficiency, diversity, speed, durability, availability, functionality, and many other characteristics that form a sustainability requirement. **Requirements Engineering (RE)** in relation to sustainability requirements emphasizes that these characteristics must be assessed for sustainability in order to pass certain requirements e.g. do not exceed energy usage, do not reduce efficiency, do not limit functionality, do not shift but instead contain or limit problems, and other similar requirements that focus on enforcing sustainability [26], [27]. The behavior of systems and the behaviors of users can be affected by sustainability requirements as each requirement mandates certain thresholds and actions to be fulfilled which in turn directly influences their behaviors [26]. Venters et al., describes sustainable development in relation to sustainability requirement as a way of "achieving environmental, economic, and social welfare for present as well as future generations." [26]. A change in behavior, the design for sustainable development, and the outlook for future longevity of products projects and systems make sustainability requirements ideal for creating lasting sustainable goals.

2.3 Sustainability Goals

Sustainability requirements are often seen as building blocks for sustainability goals and makes sustainable development possible [17]. In 1987 the environmental and development branch of the **United Nations (UN)** World Commission created a development concept that contained a set of sustainability guidelines for various types of institutions to follow [17]. Ultimately these guidelines set the path for the creation of the **Sustainable Development Goal (SDG)** in a few variations. With SDGs becoming popular world wide, they are slowly and continually adapted into practice across various institutions and business from the financial sector to medical, industrial, and many more [20]. Unlike SDGs, sustainability goals are different in that they are aimed at being an achievable goal for smaller scale projects and tasks. A sustainability goal is based on a set of sustainability requirements (much like the ones that define SDGs) which are designed to prolong the use of a product, item, or object [17], [20].

2.4 Metrics and Indicators

Metrics and indicators are two distinguishable types of measurements. Metrics are a set of measurements that can provide information in the form of data about a task, process, object, or any other type of measurable entity [21]. Indicators are not the same as metrics primarily because they are more closely associated with signals to show the state of a situation and are not directly measurable by themselves [22]. On the other hand a group of indicators can provide measurable data when analyzed to reveal either a pattern of signals or various degrees of change occurring. Measurements in this study is described as a way to measure something in the traditional sense of the word and it is also used interchangeably to refer to both metrics and indicators as these therms are themselves are used to establish the measurement of something as well.

2.5 Related Work

The need for this research can be observed in a number of papers below:

Krafft et al., describes the impact and important role the VCIO model (values, criteria, indicators, and observables) has with AI and its usage in technical systems in relation to requirements for defining an ethical framework so that industries can easily adapt AI to their systems [16]. AI, while being sophisticated, can provide an immense technical contributions to how digital twins operate in identifying, sorting, and providing results from models with precise predictions. The VCIO model in combination with AI sets the stage for eliminating limitations by providing technical opportunities that were not previously possible. Retrieving appropriate sustainability requirements from a real twin as described by Carvalho et al. [17], can greatly improved the discovery of sustainability goals with the use of AI to systemically suggest strong indicators for metrics [8]. Through the VCIO model, a framework is laid out in the research paper which details how to put into operation and measure abstract data that is designed to predict transparent, accountable, and efficient goals from the model being studied [16].

Ketzler et al., describes how companies in the EU, with the help of the UN, can use digital twins to address limitations in city building by applying sustainable development goals for upcoming projects [8]. The paper along with the industries mentioned in it recognize that with the use of digital twins for city planning, along with goals for sustainability, can be coordinated through spatial data collected from real twins for planning, administration, and the development of future city life [8]. Findings of the paper show that there is a wide net of areas for developing sustainability where digital twins can be of value for defining goals with such areas of interest as urban management, earthquake predictions, and traffic simulations. When defining these goals using the VCIO framework as mentioned by Krafft et al. [16], the model can be used to enhance the process of selecting goals by limiting the amount of opportunities to just the ones that are useful for the case of city building [8].

Furthermore, Carvalho et al., describes sustainability as having three dimensions of impact which are of economic, social, and environmental natures [17] and are depicted in Figure 2.2. From these dimensions the environmental impact is discussed in regards to how sustainability requirements can be derived from digital twins and a real twin's product life-cycle. Sustainability requirements can then be translated into goals from addressing five main concerns (fidelity, energy control, complexity control, identification of environmentally and cost-efficient materials, and easy reproduction of new product designs) when applied to digital twins [17].

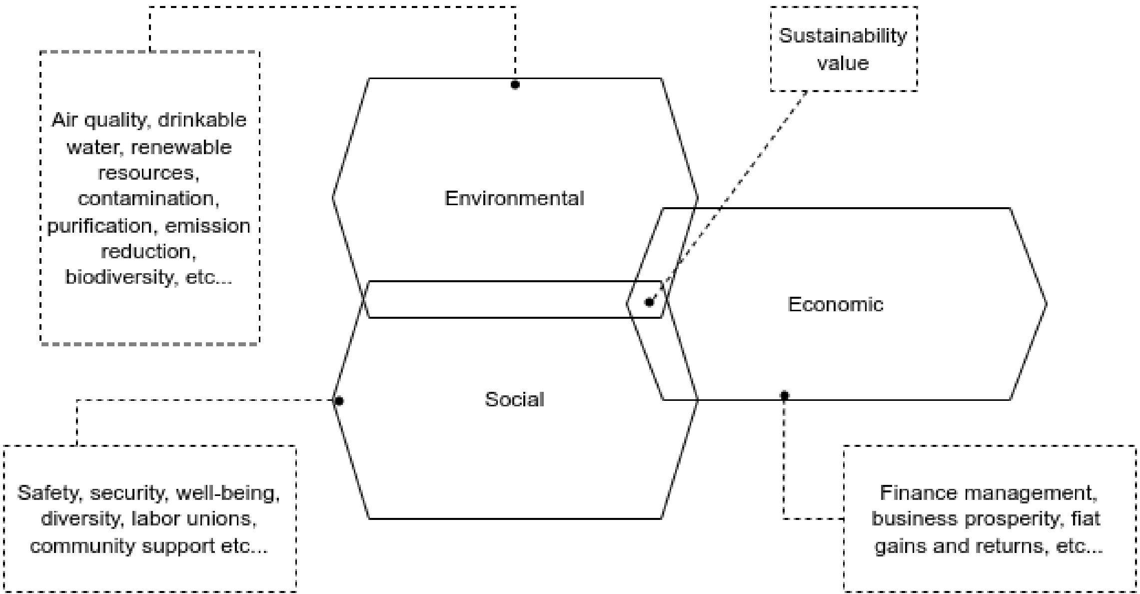

Figure 2.2: Sustainability Dimensions (Adapted from Chávez et al. [44])

To realize the value of sustainability goals, industries will need to have measurable data from which to derive or apply important indicators through the result of analyzing metrics. The paper by Moldan et al., brings up the process of defining indicators, as well as obtaining measurements via metrics where they are able to find the sustainability value indicators offer [1]. The problem faced afterwards is about interpreting and using indicators for further development in the R2DFL. Similar to the paper by Carvalho et al. [17], this paper also describes sustainability as having three pillars that are economic, social, and environmental in nature, from which it focuses on how indicators impact environmental sustainability. The paper recommends that in order to effectively interpret and use sustainability indicators, both activities and limits needs to be realized, so that the scope for sustainability is not too broad or too narrow [1]. Setting concrete activities and limits for defining indicators would allow for a more precise focus on optimizing workflows for the real twin.

The civil aviation sector in Dubai was examined by Al Sarrah et al., to identify important sustainability indicators that can be used in streamlining the aviation industry for meeting goals [25]. The data collection process involved utilizing qualitative data collection methods by performing literature reviews on the civil aviation sector and its industry along with interviewing passengers, aviation authorities, airport companies, and airliners. After compiling the data it showed that there were a number of similarities on the social, economic, and environmental indicators within and between the different stakeholders interviewed and literature reviewed. Yet, despite there being similarities on sustainability indicators, both stakeholders and the literature voice different views on which indicators are important for sustainability and thus which global goals (including sustainable development goals) are also important for sustainable development [25]. The findings from Al Sarrah et al., conclude that "there is a need for the stakeholders to use the indicators effectively in streamlining the aviation industry to meet global goals, such as sustainable development goals" [25] in all three dimensions of sustainability. This indicates that important and well thought out metrics and indicators do play a role in defining sustainability goals which can be enhanced with the use of digital twins. Deepu et al., argues that with the use of digital technologies from Industry 4.0 it can help bring smart solutions to businesses and industries that are in need of streamlining their workflows and processes via real-time data exchanges and performance enhancements [3].

3

Research Questions

While digital twins and metrics are very useful for understanding and predicting operations of real twins, we want to identify what their limitations are and propose how to manage them in the context of achieving sustainability goals. To do so, the operational domain, restrictions, constraints, and assumptions for digital twins must be understood. We believe that identifying, testing, and validating metrics against real-world data along with mapping tool effectiveness can help digital twins be more valuable in attaining sustainability goals. Therefore, this thesis aims to address the following research questions:

RQ1 – How can sustainability values and metrics be integrated in digital twins to achieve the sustainability goals of the physical twins (e.g. a factory)?

Motivation: *To understand and identify which areas containing issues need the focus of requirements engineering. By combining real-time monitoring, modeling tools, and telecommunications, digital twins can be used to optimize operations and improve sustainability performance. Integrating sustainability values and indicators into digital twins can benefit physical twins, such as factories, in meeting their sustainability goals.*

RQ2 – What are the limitations of digital twins and existing measurements in the context of addressing sustainability requirements?

Motivation: *While digital twins and existing metrics are useful instruments for addressing sustainability needs, their limits must be recognized while putting sustainability plans in place and using digital twins to inform decisions. Once the limitations have been identified, the scope of the tool can be defined. This includes identifying the operational domain and the limitations of the digital twin itself, such as data accuracy and completeness, scope, and complexity, any constraints or assumptions that may be necessary, etc...*

RQ3 – How can the requirements engineering process address this limitations and validate the digital twins for sustainability?

Motivation: *Mitigating these constraints and focusing on the long term might increase the usefulness of digital twins in reaching sustainability goals. To do so, it might be necessary to detail how to identify, test, and validate metrics against real-world data, and map the digital twin's effectiveness.*

4
Methods

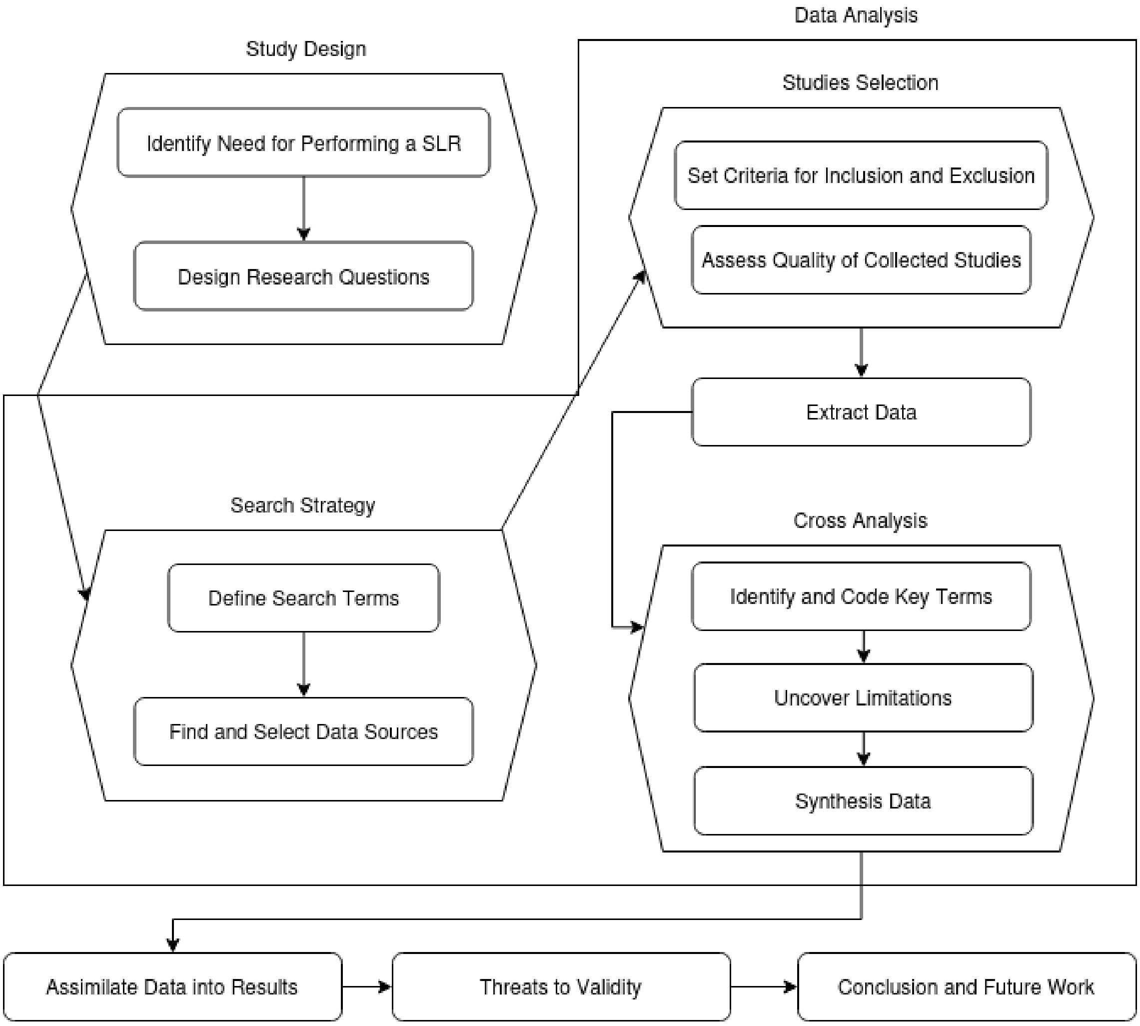

Figure 4.1: Review Protocol

This study follows a review protocol shown in Figure 4.1 above which outlines the different steps performed during this research. The review protocol closely follow the guidelines on conducting SLR by Kitchenham et al. [14]. There are five main phases to this study that include the study design, data analysis, results, threats to validity, and conclusion. Up until this point the study design has already been described in the previous sections above. The study design is followed by the data analysis phase and it contains the core of this systemic literature review. The data analysis phase is shaped by information gathered from existing literature that is then sorted, extracted, and cross analyzed. This process will allow for the identification of key metrics and indicators found in relation to sustainability goals to be documented and assimilated into results.

4.1 Search Strategy

Performing the search strategy involved identifying search terms that have a strong relation to the research topic and research questions. In order to define which terms were appropriate for the search I reviewed the context of the topic and research questions to assemble a list of terms that were used to identify relevant research literature. The search terms that were used are a combination of the following: “digital twins”, “sustainability”, “metrics”, “indicators”, “systemic literature review”, and “meta-analysis” as they were the most widely used terms in relation to this study.

Furthermore, because the focus of this study is partially about the retrieval and review of secondary studies for further analysis, the studies collected needed to be obtained from data sources that have a large archive of academic books, articles, and journals related to computer science, software engineering, and industrialization. The data sources that ended up being selected were: **AMC Digital Library (AMC)**, **IEEE Xplore (IEEE)**, and **ScienceDirect (SD)** (see Table 4.1 for the results). Springer Link and JSTORE were other potential data sources investigated initially, but the results returned from these sources were either empty, or did not relate to the thesis topic, research questions, or field of study for this thesis and thus were ignored.

When performing the search through the data sources I had to adjust the settings of the search filter to either show related results or limit which type of information was returned. In general the filters that were applied returned results that included only research papers, specifically conference proceedings and published journals. Books, magazines, and other literature was ignored due to the nature of the content found in those texts being either too large in scope or too irrelevant for this thesis. Since only three data sources were searched, each source will be described in detailed as to which search filters were applied. Also, it is worth mentioning that two of the data sources applied Boolean operators to search expressions or individual terms and they offered the option to change the Boolean operator from the default AND to OR or NOT. Boolean operators allow for the search function to sort based on the type of operator specified. For instance, AND is used to combine terms while OR can interchange terms and NOT excludes terms from both title and abstract.

The first source searched was AMC Digital Library where the search terms used for All Fields were *“digital twins” AND “sustainability” AND “metrics” AND “indicators” AND “systemic literature review” AND “meta-analysis”*. Custom search filters that were applied included searching only for *PDF files*, *Research Articles*, and limiting the publication date between *January 2018 and April 2023*. The reason that these dates were used is in relation to how far each data source could be search, IEEE Explore in particular had a max date rage for past research material set to the first month of 5 years ago, so that limit was applied to the *From* and *To* dates with April 2023 being the month and year when the data was retrieved. Along with that, the only default filter used was the sort order which was set to be ordered by *Relevance*. Applying the mentioned filters to the search terms resulted in the retrieval of *2,504* results from which a limit was applied based on the amount of results returned form the other data sources and a display of 50 results max page limit by AMC. This resulted in obtaining only the first *150* results which were all accessible for reviewing.

The second source that was searched was IEEE Explore and the search terms used were *"digital twins" AND "sustainability"* due to the fact that a combination with any of the other terms listed above returned no results. Further filters were applied to only search for *Conferences* and *Journals*. Default filters that accompanied the search query included the years of publications which were set between *2018* and *2023*. Another default filter that was used includes the sorting order of results which was set to return *Relevance*. With these filters applied *61* results were retrieved out of which only *54* were obtained for analysis due to access restrictions.

The third and final source was ScienceDirect. From this source, the search terms used were *"digital twins sustainability metrics indicators systemic literature review meta-analysis"*. Unlike the first and second data sources, ScienceDirect does not offer Boolean searching and treats each word as a single individual term resulting in either a single search for one word or multiple searches when multiple words are placed in the search. Search filters were applied to limit the publication results between *2018* and *2023* by year and a filter by Article type to include only *Reviewed articles* and *Research articles* was applied. The amount of results retrieved was *26*, from which all of the *26* results were able to be obtained for review.

Studies	**Obtained**
AMC Digital Library (AMC)	150
IEEE Explore (IEEE)	54
ScienceDirect (SD)	26
Total	230

Table 4.1: Studies Obtained from Data Sources

4.2 Studies Selection

The study selection consists of two phases that are designed to judge the collected studies. The first phase details the inclusion and exclusion criteria and the second phase handles the quality assessment of each included study.

4.2.1 Inclusion and Exclusion Criteria

The inclusion and exclusion criteria that this study follows is based on the guidelines presented by Kitchenham et al. [14]. Included studies are ones which are done as *meta-analyses*. Meta-analyses are studies which have studied and compiled their research based on other studies of the same or similar topic according to Hayes [15]. Table 4.2 shows the criteria selection process that was used for the inclusion and exclusion process. The inclusion and exclusion criteria was not just limited to Kitchenham's guidelines but also included an assessment of each studies' title and content (abstract, introduction, body, and conclusion). For assessing the studies by title and context, a modified set of terms that closely relate to the thesis's context were used and these terms are: "digital twins", "sustainability", "industry", "manufacturing", "production", "engineering", and "real time". Only English language studies were part of the inclusion criteria and every other language was excluded. In addition, grey studies or grey literature, which are ones that are included in a search but are not research related or are published outside the academic field are excluded [23]. Along with duplicate studies and studies which fail the quality assessment are also excluded.

Inclusion Criteria
A. Studies that provide full text
B. Studies that are written and published in English
C. Studies whose title and content focus on digital twins, sustainability, industry, and metrics or indicators
Exclusion Criteria
1. Studies that do not provide full text
2. Studies that are not written and published in English
3. Studies whose title and content do not focus on digital twins, sustainability, industry, and metrics or indicators
4. Duplicate studies
5. Grey studies

Table 4.2: Studies Criteria for Selection

4.2.2 Quality Assessment

The quality assessment procedures followed in this thesis is based on a quality checklist that follows the guidelines from Kitchenham et al. [14]. Each of the 61 total studies which have been sorted from the above inclusion and exclusion criteria are subjected to a quality assessment checklist and evaluated for sorting based on the number of quality points each study receives according to questions posed in the quality assessment checklist. There are a total of six quality assessment questions in the checklist (as shown in Table 4.3 below) that are assigned on a quality point scale between a No, Partially, and Yes answers worth 0, 0.5, and 1 points respectively.

#	**Questions**	**Quality Point (QP)**
Q1	Are the results clearly described?	No = 0, Partially = 0.5, Yes = 1
Q2	Is the content of the study well explained?	No = 0, Partially = 0.5, Yes = 1
Q3	Is the overall vision of the study obviously stated?	No = 0, Partially = 0.5, Yes = 1
Q4	Have evaluation techniques or procedures been described and have they been performed on any relatable projects, case studies, or data sets?	No = 0, Partially = 0.5, Yes = 1
Q5	Does the study focus on digital twins or sustainability?	No = 0, Partially = 0.5, Yes = 1
Q6	Are metrics or indicators elaborated upon?	No = 0, Partially = 0.5, Yes = 1

Table 4.3: Quality Checklist for Studies

In order to have a better understanding of how each question was assigned their respective points per study, A break down of the point assignment for each question is presented:

- *Q1*: No (QP=0), the results are either missing or not clearly described; Partially (0.5), the results exist but are not clearly described; Yes (1) the results are clearly described.

- *Q2*: No (QP=0), the content of the study is not clearly explained; Partially (0.5), the content of the study can be understood but lacks detail; Yes (1), the content of the study is understood.

- *Q3*: No (QP=0), the the vision of the study is either missing or not clearly stated; Partially (0.5), the The vision is stated but is confusing or does not cover everything; Yes (1), the vision is clearly stated.

- *Q4*: No (QP=0), the evaluation techniques and procedures have not been described or performed; Partially (0.5), the evaluation techniques and procedures have either been described or performed, but not both; Yes (1), the evaluation techniques and procedures have been clearly described and performed.

- *Q5*: No (QP=0), the study does not focus on neither digital twins nor sustainability; Partially (0.5), the study only focuses on digital twins or sustainability, but not both; Yes (1), the study focuses on both digital twins and sustainability.

- *Q6*: No (QP=0), metrics and indicators are not mentioned; Partially (0.5), metrics and indicators are mentioned but not elaborated on too well; Yes (1), metrics and indicators are elaborated upon clearly.

The questions presented in Table 4.3 are designed around the author's own criteria and formulation based on the guidelines in Kitchenham et al. [14] and own understanding of each question when assessing the secondary studies. The phrase *clearly described* in Q1 addresses the results of the secondary studies in relation to their contents on whether or not the results accurately reflect upon what was covered during the analysis phase of the studies. In Q2 the phrase *well explained* is meant to analyze and make sense of content described in each study and if that content is understood by the author. In Q3 the meaning behind *obviously stated* refers to the vision or goal that each study explains, whether or not it is stated and understood by the author. Q4 is meant to asses the description of evaluation procedures and if they have been used on other relatable data, while Q5 tries to find out if digital twins or sustainability were presented and discussed in the studies. Lastly Q6 uses the phrase *elaborated upon* to identify if metrics or indicators were described in extensive detail.

Reference	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Total QP**
[44]	1	1	1	0.5	1	1	5.5
[45]	1	1	1	0.5	0.5	1	5
[46]	1	1	1	0	0.5	1	4.5
[47]	0	1	1	0	0.5	1	3.5
[48]	1	1	1	1	0.5	0.5	5
[49]	0.5	1	1	1	0.5	0.5	4.5
[50]	1	1	1	0	0.5	0.5	4
[51]	0.5	1	1	0.5	0.5	0.5	4
[52]	1	1	0.5	1	1	0.5	5
[53]	1	1	1	1	0.5	5.5	5.5
[54]	1	1	1	1	0.5	1	5.5
[55]	0.5	1	1	0.5	0.5	1	4.5
[56]	0	0.5	1	0	0.5	1	3
[57]	1	1	1	1	0.5	0.5	5
[58]	1	1	1	1	1	1	6
[59]	1	1	1	1	1	0.5	5.5
[60]	1	1	1	0.5	1	0.5	5
[61]	1	1	1	0.5	1	0.5	5
[62]	1	1	1	0.5	0.5	0.5	4.5
[63]	1	1	1	1	0	0	4
[64]	1	1	1		1	1	6
[65]	1	1	1	1	0.5	0	4.5
[66]	1	1	1	1	0.5	1	5.5
[67]	0.5	1	1	0	0.5	0.5	3.5
[68]	0.5	1	0.5	0	1	0	3
[69]	1	1	1	0.5	1	0.5	5
[70]	1	1	1	1	0.5	1	5.5
[71]	1	1	1	1	1	0.5	5.5

Table 4.4: Part 1: Studies Rated by Quality Points

Reference	Q1	Q2	Q3	Q4	Q5	Q6	Total QP
[72]	1	1	1	0	0.5	0.5	4
[73]	0	1	1	0	0.5	1	3.5
[74]	0.5	1	1	1	1	0	4.5
[75]	1	1	1	0	0.5	0	3.5
[76]	1	1	1	0	1	0.5	4.5
[77]	0.5	1	1	0.5	1	0	4
[78]	1	1	1	0	0.5	0	3.5
[79]	1	1	1	1	1	0	5
[80]	1	1	1	1	1	1	6
[81]	1	1	1	1	0.5	1	5.5
[82]	1	1	0.5	0	0.5	0	3
[83]	1	1	1	0	1	0.5	4.5
[84]	0.5	1	1	0.5	1	1	5
[85]	1	1	1	1	0.5	0.5	5
[86]	1	1	1	0.5	0.5	0.5	4.5
[87]	1	1	1	1	1	1	6
[88]	1	1	1	1	0.5	0	4.5
[89]	1	1	1	1	1	1	6
[90]	1	1	1	1	1	0.5	5.5
[91]	0.5	1	1	0.5	0.5	1	4.5
[92]	1	1	1	0	1	0	4
[93]	1	1	1	0	1	0.5	4.5
[94]	1	1	1	0	0.5	0.5	4.5
[95]	1	1	1	0	1	0.5	4.5
[96]	1	1	1	1	1	0.5	5.5
[97]	1	1	1	1	1	1	6
[98]	1	1	1	1	0.5	0.5	5
[99]	0.5	1	1	0	0.5	0.5	3.5
[100]	1	1	1	1	1	1	6
[101]	1	1	1	1	0.5	1	5.5
[102]	1	1	1	1	0.5	1	5.5
[103]	1	1	1	1	1	1	6
[104]	1	1	1	1	0.5	1	5.5

Table 4.5: Part 2: Studies Rated by Quality Points

For the studies that managed to pass in both the Search Strategy and Studies Selection sections; those studies were assessed equally by the contents of their text. However, the quality assessment rating of the studies in Table 4.4 and Table 4.5 above was performed by *one person* (author of the thesis). Furthermore, to avoid bias among the studies collected for the quality assessment, each of the studies had already been sorted according to the sets of key words used and explained in the Search Strategy and Studies Selection sections. Also, there were a couple of steps involved when assessing the quality of each study:

1. Each of the studies' texts were read in full by the author.
2. Each of the studies was assigned a quality point for every question based on how well the studies met the criteria defined in Table 4.3's checklist.
3. Quality points for each of the individual studies was added together to reveal the final quality score.
4. Lastly, out of the 61 studies assessed only 32 passed the quality assessment.

Each study listed above had the possibility of receiving a maximum of 6 quality points in total. In order to exclude studies based on the quality point score, studies who's quality point was equal to or less than 75% (QP of 4.5 or less) of the total quality score were excluded. This process of elimination was done to ensure that a fair reliability check was performed on the quality assessment for each of the studies assessed. With less than a handful of studies having a minimum of a 50% (3 QP) rating and no studies below 50%, it was decided to adjust the reliability check to include only the top 25% (5-6 QP) of quality assessed studies. By setting a limit to excluding the lower 75% of studies, the amount of studies that passed the quality assessment was reduced to a manageable level for the time frame of this thesis. The studies in question are linked to the references: [44], [45], [48], [52], [53], [54], [57], [58], [59], [60], [61], [64], [66], [69], [70], [71], [79], [80], [81], [84], [85], [87], [89], [90], [96], [97], [98], [100], [101], [102], [103], and [104].

Table 4.6 displays how the studies were assessed based on the inclusion and exclusion criteria and the reliability check of the quality assessment:

	AMC	IEEE	SD	**All**
Excluded by grey & duplicate	4	3	6	13
Excluded by title	102	8	13	123
Excluded by content	31	2	0	33
Excluded by English language	0	0	0	0
Excluded by quality assessment	7	21	1	29
Included	6	20	6	32

Table 4.6: Studies Included and Excluded for Selection

AMC had a large number of studies excluded by title compared to IEEE and SD with title topics ranging from human computer interaction, technical medical theory, information communication technology, smart cities, software design, and other titles that did not match the selected keywords. Table 4.7 provides an overview of the average quality scores between studies correlated to their publication dates in order to find the mean (rounded) and standard deviation (rounded) of studies sorted by year. The correlation is made with the help of the dates listed in Appendix A which are mapped to the 32 studies that have passed the quality assessment. It can further be noted that there are no studies found for the year 2019 across all of the studies assessed.

	Year					
	2018	2019	2020	2021	2022	2023
Total number of studies	2	0	7	6	10	7
Mean of quality scores	5.25	0	5.36	5.67	5.4	5.5
Standard deviation of quality scores	0.25	0	0.35	0.37	0.37	0.38

Table 4.7: Average Quality Score (Mean and Standard Deviation) for Studies by Publication Date

4.3 Extraction of Data

In this study, the data extraction process for the SLR consisted of analyzing, identifying, and synthesizing key words, phrases, and important data which was obtained by applying open coding methods on the secondary studies. The studies that passed the quality assessment (also refereed to as the resulting studies) were listed with an ID and REF (reference) attached to them (Appendix A). Afterwards, the coding of data was recorded manually by writing down a unique ID for each study followed by a Code, Note, and a Quote with a Reference to said study (Appendix (B)). The code was extracted from the quote, while the note reflects the context or thought behind the quote from the study. The content of the quote and code that was derived and applied from the studies relates to metrics and indicators and were then sorted into themes (Appendix C) using the format of Theme and associated Codes for each individual theme. In deciding which terms were important to code and to help narrow down the scope of the coding process, two simple questions were asked:

1. Can the term be measurable as a metric?
2. Can the term be used to indicate a measurement or change?

4.4 Cross Analysis

The **Cross Analysis (CA)** phase consisted of three parts which are aimed at answering each of the research questions:

CA1. Identify measurable issues within literature related to digital twins and sustainable values that hinder the implementation of sustainability goals into the R2DFL (**RQ1**). By identifying the problematic issues it will be possible to present a list of initial requirements devised from analyzing the literature on what is needed to successfully achieve the sustainability goals desired for the R2DFL.

CA2. From existing literature along with the data from part 1, a compilation of metric limitations can be uncovered to show what the discrepancies are between the literature and RQ1 with requirements applied (**RQ2**). This would allow for weak indicators to be singled out, as well as the digital twin affects limiting sustainability advancement for the real twin.

CA3. By evaluating both the goals for sustainability from RQ1 and the limiting indicators derived from RQ2, it will be possible to parameterize a set of refined requirements that can act as a guideline to better address the concerns faced when uncovering sustainability goals through digital twins (**RQ3**). From the parametrization of requirements new opportunities would be available to further test, identify, and validate limitations between digital twins and real twins.

4.5 Open Coding

Due to how data is presented in secondary studies as usually being qualitative in nature, the open coding format by Khandkar et al. [18], was chosen. There are two main types of coding methods namely deductive and inductive coding. Deductive coding is when themes and codes are predefined. While the inductive coding method which is used in open coding requires a thorough examination of each source in order to build themes from codes. Open coding involves identifying descriptions in the text and assigning a code or key term to these descriptions. Afterwards, the code is linked to similar codes and categorized into themes across the study's literature. All of the results from the coding was recorded in Appendix B along with themes in Appendix C. Also, each of the studies coded are linked to Appendix A through the use of IDs.

5

Results

The findings from the quality assessed secondary studies are discussed within this chapter. The first section provides an overview of the initial results on the assimilation of data from the studies. The remaining sections discuss the findings in more detail in relation to the research questions and explaining the significance between codes from Appendix B and their relationship to the themes shown in Appendix C. This information then addresses the research questions by following the procedure outlined in the cross analysis of Section 4.4 above.

5.1 Summary of Studies Processed

In Figure 5.1 it can be seen that the resulting studies are from four different types of sources. From a total of 32 studies, all 6 of studies from the AMC Digital Library were conferences (research articles). From ScienceDirect all 6 studies were journals (reviewed articles). The studies from IEEE Explore were unevenly split between 12 conferences and 8 journals.

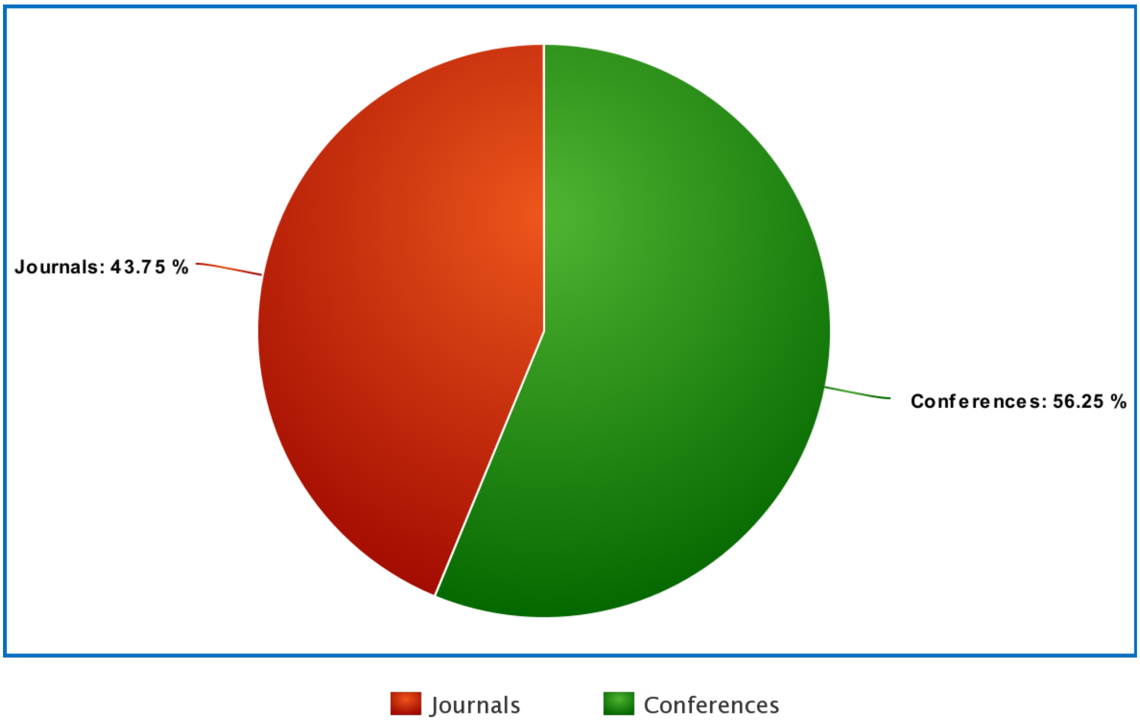

Figure 5.1: Resulting Studies by Type

Figure 5.2 provides an alternate perspective that sorts each of the studies by year and categorizes them by article type.

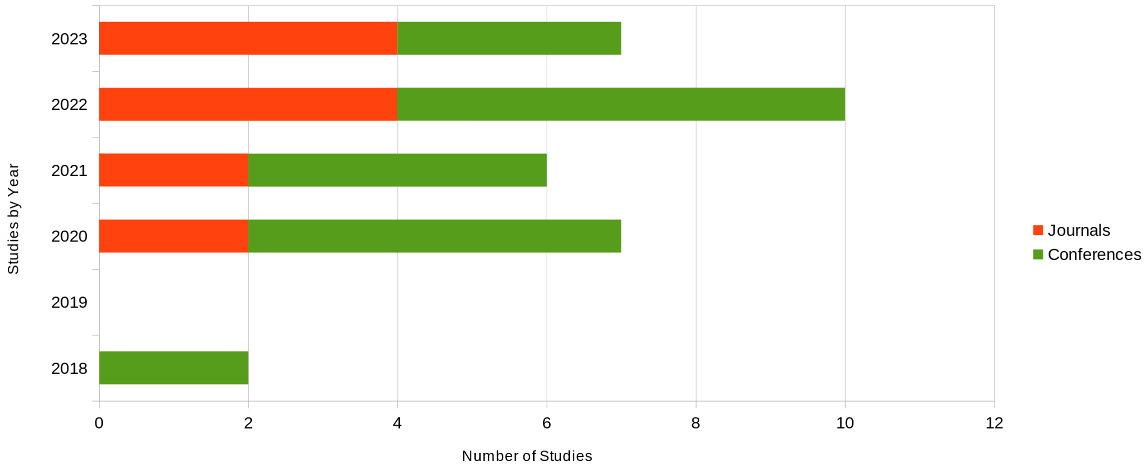

Figure 5.2: Resulting Studies by Year

Out of the 32 studies analyzed there was a total of 499 unique codes identified across all the studies combined in relation to metrics and indicator which are listed in Appendix B. These 499 codes were then categorized into 12 appropriate themes which are: *Performance, Environmental, Process, Quantity, Location, Distance, Temperature, Quality, Time, Financial, Human, and Other* metrics and indicators shown in Appendix C. Tables 5.1 and 5.2 showcase the number of unique codes identified per each individual study.

ID	Reference	Codes
01	[44]	36
02	[45]	22
03	[48]	14
04	[52]	16
05	[53]	10
06	[54]	6
07	[57]	17
08	[58]	27
09	[59]	39
10	[60]	34
11	[61]	12
12	[64]	6
13	[66]	15
14	[69]	31
15	[70]	23
16	[71]	18

Table 5.1: Part 1: Number of Codes per Study

ID	Reference	Codes
17	[79]	9
18	[80]	21
19	[81]	9
20	[84]	25
21	[85]	1
22	[87]	14
23	[89]	20
24	[90]	6
25	[96]	6
26	[97]	10
27	[98]	20
28	[100]	26
29	[101]	18
30	[102]	12
31	[103]	13
32	[104]	16

Table 5.2: Part 2: Number of Codes per Study

Figure 5.3 summarizes the frequency with which identified codes form the studies appear in relation to their theme. Each theme represents the type of metric and indicator the codes relate to. The unique codes per theme are identified as follows: 99 for Performance, 58 for Environmental, 13 for Process, 30 for Quantity, 14 for Location, 9 for Distance, 7 for Temperature, 88 for Quality, 54 for Time, 18 for Financial, 46 for Human, and 63 for Other.

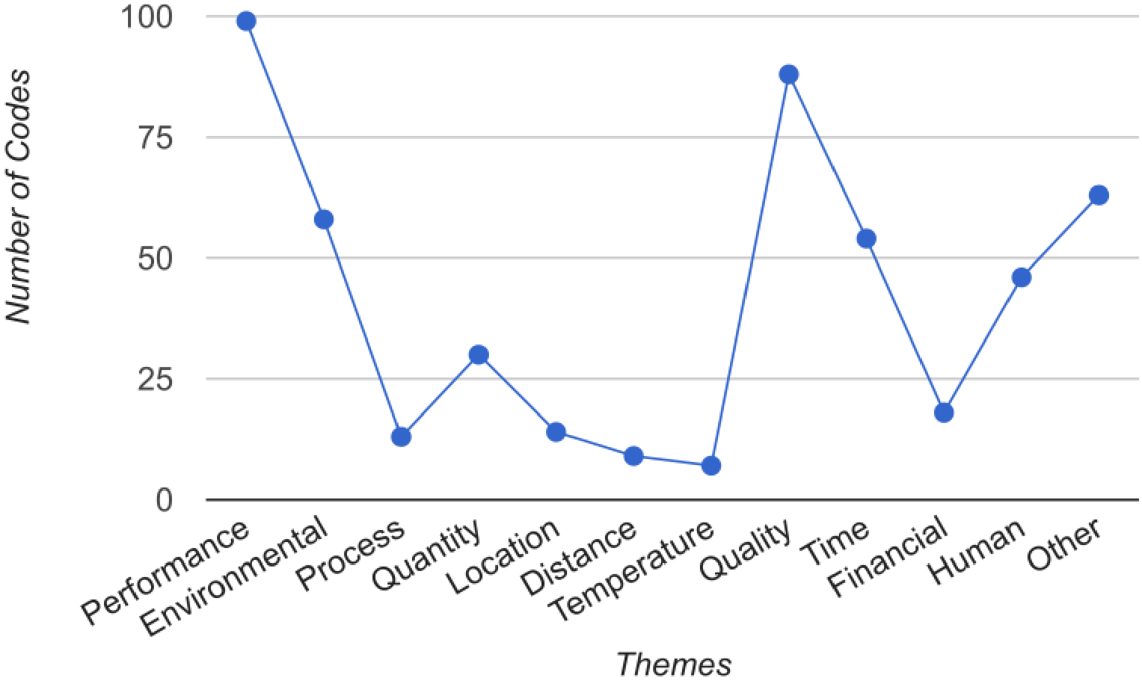

Figure 5.3: Number of Codes per Theme

Figure 5.4 briefly outlines which data sources were selected, the total number of studies obtained from each source, along with the process of including / excluding studies, and quality assessment. The resulting studies are then examined to (1) obtain primary studies and (2) perform coding in order to formulate themes. Primary studies were obtained by applying the snowballing method onto secondary studies as described by Kitchenham et al. [14] to uncover primary studies. Due to the design of this thesis described earlier in Chapter 4, only secondary studies were required and therefor primary studies were discarded and not used for this research.

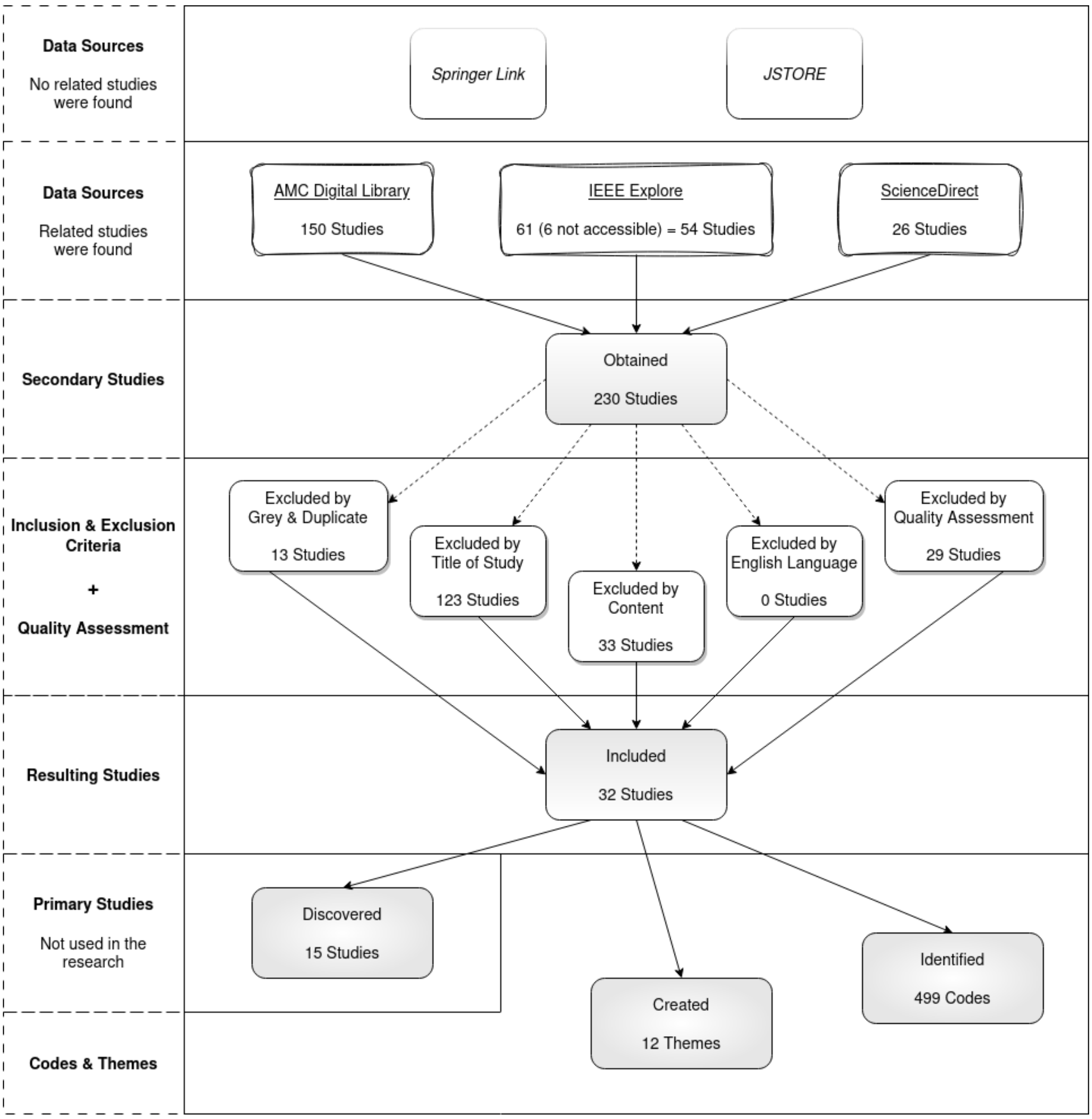

Figure 5.4: Outline of Data Process

5.2 RQ1 Findings

In regards to RQ1 it aims at achieving sustainability goals for the physical twins by understanding how sustainability values and metrics can be integrated in digital twins. CA1 has a direct relation to RQ1 through its identification of sustainability values and metrics from the literature that hinder their implementation for achieving sustainability goals. By listing the problematic values and metrics in detail a comparison can be made along with the statistical date to assess which values and metrics are important to achieve sustainability goals for the physical twins in the R2DFL.

In Chávez et al., the metrics and indicators are described as **Key Value Indicator (KPI)** and they looked at evaluating the parameters of five different categories: Production parameters (processing, availability, mean time to repair, setup time, and scrap processing time); Work procedure (type of work procedure (of product variants)); Material data (Material type, quantity of (respective) components, weight, amount of scrap, amount of rework, and cost); Energy data (amount of power consumed and (total) energy cost); and Material consumption (amount of material consumed) for economic, environmental, and social sustainability KPIs of which only environmental and economic KPIs were selected [44]. From the two KPI dimensions for sustainability there was an keen interest in assessing KPIs that would be useful in increasing throughput of a system's production capability. For the environmental KPIs the three main KPI categories looked at were emission, waste, and resource utilization while for economic KPIs the main KPI concerns were with cost, delivery, productivity, and quality [44]. It was discovered that eco-efficiency indicators found within environmental KPIs were not sufficient as a measuring method such as energy efficiency measures: amount of energy consumed and emission levels were unstable indicators when assessing production throughput as results vary between tests. Four different assemble station scenarios namely AS-IS, Base, Experimental 1, and Experimental 2 were design to test and evaluate the KPI indicators. By testing the four different scenarios it revealed that Experiments 1 and 2 using parallel assembly along with dynamic re-balancing ended up providing lower lead times, a higher throughput, increased efficiency, lower emissions, and a more even distribution of resources between production loads [44].

Ram et al., uncovered a number of indicators and metrics that contributed to the importance of actionable and non-actionable metrics within software development companies and their teams [45]. Actionable metrics included ones that related to git issues for software code in projects: a non-blocking files metric for problem identification, an alert system that indicated a need to address quality related issues, a critical issues ratio to determine how critical the issue was, and the well-defined issues Jira metric to understand which practices needed to be reviews to improve team collaboration on addressing issues. Non-actionable metrics on the other hand included: the experience level of employees, the time to perform tasks, mood of each employee, how the complexity of metrics affected team motivation levels, different type of estimation techniques for analyzing the workflow process, usefulness of of non-actionable metrics, accuracy, consistency, credibility, and reliability of the work performed and product quality. Based on the questionnaire results in Ram et al., non-actionable metrics were favored over actionable metrics as only 47% percent of employees agreed that metrics have to be actionable and 35% agree that only certain metrics need to be actionable as long as they are credible, accurate, consistent (top 3 out of 5 factors), and reliable [45]. The results also suggest that some actionable metrics are also practical to have such as the well-defined issues Jira metric [45].

From Mourão et al., a SLR was performed on the applicability of sustainability and green energy technologies onto the field of software engineering and its practices [48]. The research investigates the amount of evidence, research methods used, contribution types, domains and areas where sustainability was applied, as well as the distribution of use between academia and industry. The evidence identified in this study showed that metrics were a minority contribution type among all the literature analyzed making indicators the core type fo contribution identified for the purpose of this thesis. The results in Mourão et al., suggest that the contribution type is an import factor as only three contribution types were favored and the remaining 6 received little to no attention from the community to address product quality [48]. the balance dynamic for energy sustainability between studies examined shows that energy consumption and energy savings were of interest to the researchers but spreading energy awareness was not nearly as desired in comparison. The results further present a high interest in requirements related to sustainability and software design. There are suggestions aimed at improving and refocusing efforts to increase interest in sustainability practices from industry and academia for the indicators in awareness, types of input, contribution effort, focus on evaluation experience vs the existing solution based studies, and scenario differences [48].

Lv et al., describes the implementation of DTs for smart city management through the use of multi-GPU powered Bayesian algorithms for advanced data model processing using big data mining techniques and neural networks to generate optimized structures during the city building process [52]. Despite the complexity of this study, data visualization provides researchers with the ability to see operational mechanics applied in real time for object observation to assess the completeness of the mathematical equations applied. The metrics and indicators found in this study correspond primarily to the themes of performance and quality with key metrics being: render times, distribution density, amount of data, amount of storage space, performance of the algorithm, and other. In the study Lv et al., points out a couple of problems faced by the implementation of the DT setup, namely that there is not enough time to analyze the distribution density of the data points generated by the DT and the degree of information integration is incomplete in terms of heterogeneity, large data volumes, high complexity, and scarce labeled data [52].

The study by Pan et al., goes over the crime rates and safety concerns for smart cities using DTs to dynamically sense crimes and provide dynamic decision-making for crime detection and reduction [53]. Specifically the study is aimed at the law enforcement industry and aims to provide advanced solutions in terms of cameras that are able to be used in crime detection and predictions by identifying people and vehicles and predicting their path of escape in the case a crime were to occur. Crime detection relies on license plate reading technology along with their placement throughout the city, and a short term algorithm designed to identify and predict a targets next moves [53]. Metrics and indicators identified in this study focus on the rate of change of situations; camera placement and coverage; direction, time, and location where the crime was committed; and a couple of other indicators. The study pointed out that there was issues related to the level of camera coverage due to there being a limited amount of cameras to place around the city with placement needing to be dynamic to tackle the rate of change in a fast pace decision making environment that law enforcement has to deal with [53].

Bibri et al., describes the state of urban analytics for sustainability with smart cities via data mining and data mining frameworks [54]. The study presents smart sustainable cities, big data analytics, and the concept of data mining along with its process as way forward for addressing urban sustainability problems with smart cities. Data mining is a useful process which allows for the researcher to view the different type of data and apply specific types of analytics methods in an effort to understand what changes need to be made. Even with appropriate analytics methods there are problems that can affect the quality of data changed. For instance Bibri et al., makes a number of distinctions and comparisons to highlight areas of improvement relating to the amount of data processed with large data sets being difficult to process and taking up time to perform [54]. The amount of tasks is also another issue that can affect the data processing and analysis phase as researchers point out that fewer tasks are better and more effective. Also, the level of dataset diversity can be a problem if not enough data has been collected for analysis [54]. There are further indicators to consider when performing urban analytics which are whether the costs on studying the data outweigh the effort it takes to obtain that data, plus what the data strengths are compared to their weaknesses during the whole analysis [54].

The study by Mendula et al., analyzes ways to improve sustainability of urban activities in smart cities by monitoring vehicles and their transit routes and replicating their activity using digital twins in order to optimize operative actions and predict better alternatives using predictive schemes [57]. A remote data monitoring system was put in place along with GPS sensors attached to vehicles to analyze traffic patterns within a metropolitan region of a city. The data analyzed looked at the amount of traffic generated during March 2020 in Italy along with start and end time of each vehicle's trip, their latitude and longitude, average speed, total speed, date of trip, lag order calculated on the network, degree of difference between vehicles, and size of moving average (mass of each vehicle) [57]. Problematic metrics and indicators identified affect the performance and quality of data collected, these include: the signal delay of receiving data on time, the meaningfulness of the data to determine how useful the information collected is for application, as well as the similarity of results as identical results tend to be difficult to differentiate later for method application to the real twin [57].

Grassland pastures and farmland management using digital twins was examined by Purcell et al., with an aim of optimizing the performance and efficiency of managing livestock along with the farmland's resources for sustainable farming [58]. Agriculture has an ever growing problem with the rate of demand for food production and other resources that need a smart solution for addressing change in the market. The concept of digital twins was introduced for integration along with testing more advanced technologies (e.g. grasshopper) to streamline the process of farming and applying/modifying algorithms geared towards simplifying resource distribution problems [58]. There were a variety of different metrics and indicators identified in this study with the majority of them describing farming measurements such as: herbage mass, forage availability, dry matter, grass height, weight of herbage mass, measurement location, date, time, and temperature among others. Metrics and indicators that were difficult to manage consisted of the implementation costs needed for building the improved infrastructure suggested by the digital twin. The digital twin model accuracy is another metric that can be negatively affected as the study only had examples of manual data instead of automated data for increased accuracy and the feedback rate from the current study was also not automated which would have benefited from reduced overhead in the time it took to report change [58].

Research done by Wang et al., on advanced driver assistance systems distinguishes the differences between the cyber (cloud) world and the physical (real) world then links them together in order to establish a communication channel from the digital twin to the real twin that provides an advanced cyber assisted framework to the driver [59]. The driving assistant in this study had a focus on assisting with driving through traffic and merging lanes both on normal roads and on highways. From the physical world the researchers were able to track vehicle movement and observe different metrics and indicators around the driver such as the driver's gaze, fuel consumption, vehicle speed, traffic light signal, maneuverability, road type, and other qualities needed by a digital twin. Once this data is connected to the cyber world, the researchers were able to relay the information to a digital twin for advanced modeling and analysis with resulting predictions on what to change for improving environmental sustainability. Connected vehicles are equipped with a hotspot, sensors, and other technologies used in collecting and relaying data for evaluations and predictions. Some of the metrics and indicators used with the cyber world include: the wireless connection strength between the real and cyber world, pre-processed data, actuation guidance, system performance, communication accessibility, communication delay, packet loss, and others. Metrics and indicators that posed problems or could be improved were the communication delay between systems and packet loss on the network, along with system performance and position synchronization of the vehicles in a mixed traffic scenario as extra modules would have to be installed and tested [59].

In the study by Lam et al., the management of cold chains and their risk factors were analyzed and simulated using digital twins to determine the best approach for handling perishable goods over a span of time from production to use [60]. Lam et al., designs a risk analysis model using the help of digital twins that examines the four risk stages of a cold chain lifecycle by simulating risk identification (e.g. of a vaccine manufacturer), risk assessment (e.g. of a distribution center), risk response (e.g. of a regional warehouse), and risk monitoring and control (e.g. of a vaccination center) [60]. Data for the risk analysis is taken from real world centers of storage and distribution which are then communicated over to the digital twin for a full simulation. The study provides a variety of metrics and indicators to help evaluate the risk analysis process, namely ones related to temperature, quality, safety levels, humidity, storage space, and security of the product being transported. The risks identified using the digital twins outlines that weather, network, storage, and security related metrics and indicators can be concerns when managing cold storage products but there is no single metric or indicator that is problematic in this study.

Maksimović examines the potential of using digital twins to improve sustainability efforts in terms of the 17 SDG implementations brought forth by the United Nations and their 2030 initiative for sustainable development [61]. Digital twin application domains are diverse covering domains such as manufacturing, aerospace, vessels, agriculture, automobiles, and others. Out of the 10 application domains only industrial applications, the energy sector, healthcare, and smart city were selected by Maksimović as they are the ones that can benefit from digital twins the most due to low risk level and fast time to market after implementing digital twins [61]. With the difference between physical and digital twins, AI and machine Learning were incorporated to the digital twin process for asset management between both cyber and physical worlds [61]. Between the four domain applications the metrics and indicators uncovered were: risk level, cost waste, efficiency, and time to market for various products and processes. On the other hand there were potential challenges to the study for digital twins to achieve SDGs. These challenges included metrics such as effort to repair fault, fault repair time, cost of the fault, cost of processing, cost of maintenance, the amount of resources needed, and the complexity of the systems. Furthermore AI and machine learning were found to have increased the contribution to sustainability in the development of identifying SDGs [61].

Broo designs a framework for sustainable cyber-physical systems with the help of data science techniques by using digital twins as an application method for model generation and predicting changes in infrastructure projects [64]. A case study was performed by Broo to determine how digital twins can be applied to cyber-physical systems and increase the quality of life for citizens in smart cities along with a supported environmental effort that boosts sustainability. In the case study a systems architecture is outlined which details four layers: goals, shakeholders, smart infrastructure, and services with smart infrastructure making use of digital twins/entities, KPIs, and an interoperable data layer for communication between different digital twins [64]. Indicators from the study included the level of collaboration between stakeholders on different projects along with purpose applicability of a task in the project and different levels of component compatibility. Indicators that posed problems included: level of interest in data, value of stakeholders, value of domain, value of disciplines as the data may not be in the favor of either party. The applicability of the purpose is another issue when a weak purpose can't be defined which becomes a short term solution instead of a long term one [64].

Artificial intelligence in Siddiqui et al., helps to enhance digital twins and their operations in automation tasks using predictive maintenance in industrial settings [66]. The study combines predictive maintenance algorithms that follow the process of acquiring data, feeding that data into a digital twin model where data is collected, trained, validated, and tested before modeling a structure, afterwards in the process continues with identifying indicators that change conditions of the data, abnormality detection, and finally applying the predictive maintenance application to the real twin. A case study was performed to validate the methodology presented by Siddiqui et al., in which an industrial automation system's behavior was modeled through an artificial neural network to collect and analyze dynamic, sequential, and time series data. The study identified five different types of hyperparameters for the neural network relating to the total layer, hidden layer, number of neurons, number of input delays, and number of feedback delays that affect its performance of the model. Other metrics and indicators include network efficiency of the neural network as the network might underfit or overfit data to cause lag; performance metrics used to evaluate the trained network: mean square error, mean absolute error, sum square error, standard deviation; real data availability, overall neural network performance; and performance accuracy from using real data [66]. The hidden layer and network efficiency are presented as a problematic metrics in the study due to the challenge of overfitting and undefitting parameters affecting the network [66].

Sustainable control systems for engineers that are context aware in address the challenges of industry 4.0 were researched by Diaz et al., via a systemic literature review [69]. Context aware systems as described by the study are designed to sense context rich information, process that data, and present contextual information requested by the application or system via a four stage life-cycle: accusation, modeling, reasoning, and dissemination. The study takes a further dive into key context aware system methodologies presented in other studies and the societal challenges affecting its application in: digital society, food, health and well-being, smart resource management, urban planning, mobility dynamics, logistics. energy demand, delivery, and society. A number of metrics and indicators were derived from Diaz et al., such as: computational cost, instrumentation failure, carbon footprint, throughput, context awareness, density of materials, and others [69]. Out of the numerous measurements there were metrics and indicators that lowered the research quality, namely: instrumentation failure as this indicator prevent further progress in the decision making process for creating the context map used in the study, computational cost due to the time and amount of resources needed for performing the real time computations could be high if the equation is complex, along with industry flexibility and the level of data integration since the output of the model depends on how well data and structures are integrated data in the process and if the industry is flexible enough to accommodate changes for context aware systems [69].

Liao et al., researched the applicability of a digital twin approach for modeling an accurate vehicular ramp merging system on various road types and conditions when performed around other vehicles [70]. The ramp merging system was designed to apply three separate algorithms for position synchronization and geo-fencing, determinate merging behavior and sequences based on different scenarios, and algorithm for tracking the speed needed for adjustment when merging [70]. The implementation focuses on a cloud networked solution that utilizes digital twins for real time maneuver determination when performing different merging scenarios while at the same time adjusting for speed, trajectory, and lane detection in its execution. The ramp merging system makes use of a few metrics in its calculations for merging relating to speed, fuel consumption, distance, direction, and communication measurements. Communication delay was as problematic metric as the vehicles equipped with the system needed to reply to network events in real time [70].

Ontology-based digital twin integration into product lifecycle management for the lifecycle of product systems was examined by Ren et al., via a case study where an industrial application was performed [71]. In product lifecycle management there are three phases of the lifecycle that were modeled using digital twins to evolve the beginning, middle and end of life phases of a product where the beginning phase manages customer demands and design specification, the middle phase examines product information and user habits, and the end phase deals with product status and dismantling information [71]. After the product lifecycle management model was evolving by implementing complex features, a shared knowledge plane was designed to manage, monitor, and process various data from mining, security, quality and activity characteristics to share between an agent that sends information to the physical product and the digital twin. From the enhanced ontological model there were a number of metrics and indicators used to to measure different variables in the case study which included different types of usage such as frequency of use and usage conditions, size and change of platforms, product quality, customer needs, defect rate, and others. While there are metrics discovered, none of the metrics or indicators provide any negative effects or undesired mechanics within the literature.

In the literature by Bentley et al., housing accommodations were examined using machine learning which analyzed external synthetic energy usage data to improve the sustainability of the housing accommodations [79]. Due to the lack of real world data available, an agent-based synthetic data generator algorithm was designed to train the machine learning model via three phases: the initialization phase creates the required data needed to run the model such as guests and buildings; the run phase performs calculations and matches guests to buildings for their accommodations; and the output phase collects and presents data about energy usage per apartment, guest, billing per month, and so on for the machine learning model to learn and train itself to determine where energy can be reduced for sustainability. Different calculations are then performed to determine various types of metrics and indicators for energy, costs, temperatures, size, and other units needed for sustainable accommodations. A case study on a 4 year scale was performed to conduct experiments using two machine learning algorithms, one being a linear regression and another being a multi-layer perceptron regressor algorithm. The use of these algorithms resulted in calculations for various variables and data points between daily and monthly energy usages, meter readings, and guest energy usage metrics to show that years three and four were the most sustainable in terms of energy usage. Bentley et al., makes a comparison between the two machine learning algorithms used and as a metric described the linear regression algorithm's accuracy as being consistently lower than the multi-layer perceptron regressor algorithm used for machine learning [79], which ultimately means that the linear regression accuracy metric is not ideal when evaluating for sustainability in the study.

VvanKol et al., evaluates the adaptability of mechatronic applications for the bulk handling industry by testing various types of adaptability designs and technologies from e.g. robotics to big data to cyber-physical systems using industry 4.0 practices [80]. The bulk handling industry is composed of heavy machinery that is primarily energy inefficient, limited in performance, pollutant, but is able to handle bulk quantities of materials. Many of the tools offered by industry 4.0 practices are difficult to implement for advancing the bulk handling industry therefore VvanKol et al., opts to investigate the adaptability of mechatronic designs into bulk handling systems. Adaptability can be either manual or automatic ranging from discrete to continuous in terms of application categories where performing geometric modifications are discrete while operations closer to system control are continuous. Well defined KPIs are needed for implementing adaptability into bulk handling systems which the study lists performance metrics and indicators as being the primary focus with implementation. A whole list of KPIs were presented in the study with each KPI belonging to an adaptability category such as vibration and fluidization. A example is provided with an excavator to showcase which, how, and where measurements can be improved as the level of maturity for the sensors used is either missing or not ideal for the bulk handling industry and continue to negatively affect equipment performance, energy consumption, and environmental pollution [80].

Machine learning powered lifetime-learning models were designed for digital twins as described by Yang et al., using a proposed module based framework that allows existing implementations of digital twins used in time sensitive and other industries to become self adaptive to old and new data alike in a changing environment [81]. The framework starts off with a pool of data that becomes evaluated as two modules where module B checks for similar data to merge with the existing model or if no data is similar, than module A creates new data points to merge with the model, afterwards the model is tested and implemented via module C of the framework. A case study was then performed to evaluate the model and framework's performance using data that had both passed and failed results which were collected during the years 2001 and 2016 and presented as distribution graphs. Four types of machine learning algorithms where applied to the collected data: Decision Trees, Naive Bays, Decision Trees with CostMatrix, and Naive Bays with CostMatrix which tested the performance of the four predictive models to generate distribution graphs and their shifts between model data. Evaluation of and analysis performed by the lifetime-learning model takes into account performance, environmental, and other metrics and indicators such as: model performance, model robustness, system changes, and distribution shifts. During the case study it was discovered by Yang et al., that the indicators sensor quality and sensor reliability from 2001 displayed higher performance in the model compared to 2016 when newer sensors were used. Furthermore, the study concluded that it was difficult to interpret differences in distribution shifts but no metrics or indicators were found to have affected the outcome of the results [81].

A review was performed by Malik et al., on how smart manufacturing and artificial intelligence affects digital twins in regards to sustainable productivity for real-world uses and industrial applications [84]. The content of the study described the need for automated manufacturing for machinery with sensor readings to meet customer demands by applying big data along with digital twins to all stages of the product life cycle to deliver sustainable long lasting products. To improve the current process with knowing that automation is needed moving forward, AI was chosen to be integrated with digital twins as it showed potential to handle complex problems and apply smart monitoring and predictive maintenance to automated tasks. Algorithms used by AI for digital twins are primarily designed for supervised learning followed by unsupervised learning and reinforced learning; where each type of learning algorithm requires large amounts of data that is either sorted, unsorted, or both to create an intelligent system governed by rules. these rules allow for checks to be applied and enable relearning of previous behaviors in the digital twin which are then transferred over to the physical twin for continuous corrective learning within each product. The study provides a large number of metrics and indicators relating to performance, quality, and other characteristics that make up a sustainable industrial process and product. The study however notes that the installation cost of systems will increase do to external sensor mountings, while the indicators market demand, market flexibility, capital, and labor hours can all have a negative impact due to the rate of change by the market and customer demands [84].

Lombardo et al., investigates whether or not it is possible to link multiple digital twins together to form a social network of digital twin and exchange data between them [85]. Sociality-as-a-Service as described by Lombardo et al., is a layered network protocol consisting of mapped IP-subnets connected to a virtual application network that is able to relay data from one or multiple digital twins to other digital twins connected on the same subnet. The study performs research into previous networks that have designed networked digital twins and have fund that unlike the subnet approach, previous works have used nodes that needed to be constantly updated to keep the network informed of changes. Also unlike the node networked digital twin setup, Sociality-as-a-Service as designed in the study uses a low latency technology referred to as the digital twin network which when connected to the other layer in the social network via proxy, communication of data is delivered very rapidly between digital twins and the various layers in the overall network. Lombardo et al., concludes that the study was successfully able to share data from multiple digital twins to a real world object and back, but notes that the setup designed can be easily manipulated.

The architecture and life-cycle of intelligent manufacturing systems was evaluated by Li et al., in order to determine how to evolve the architecture and make it more sustainable with the help of digital twins [87]. Since digital twin are able to model the architecture, it acts as a driving force for evolving the architecture through three layers of transformation where the physical object layer scans and replicates the existing design of the system; the second layer transcodes the physical data into a virtual model and appraises the object's quality; while the third layer applies the needed changes from analyzing the and testing different variables in the virtual layer. The output of the data is then evaluated for sustainability via a three phase sustainability model transitioned into an indicator system which examines social effects (on employees and users) and environmental effects as indicators. Social and environmental effects are then weighed and calculated into indicator value and importance degree which are passed into a two-stage evidence systems that performs a weighed sum combination process to determine the exact mass of the indicators provided for a calculated sustainable result when setting implementation priorities [87]. Through the use of digital twins metrics such as object quality, model integration complexity, and large area are tested in virtual models for intelligent manufacturing integration and indicator analysis. From the study Li et al., notes that the metrics error rate and level of accuracy pose a problem to the assessment of indicators as the gap between the data is large and prone to errors.

In the study by Wang et al., a digital twin powered architecture designed to manage block-chain **Internet of Things (IoT)** devices was investigated, designed and tested in an experiment to determine energy sustainability, data fidelity, and other factors that improve their adoption and application [89]. The IoT system model was designed around increased information flow with minimum cost to environmental factors thus making it more sustainable by using digital twins to sort and distribute information in an energy efficient way. Operation of the system includes the participation of physical and virtual spaces for agents to perform data collection and management of information obtained from the real world, the system also has services that are delegated and managed by agents whom relay data to and from digital twins, settings and changes, along with other information between digital and service oriented spaces. A fault-tolerant approach has been taken by Wang et al., with the introduction of block-chain technologies for IoT devices (sensing of data) and agents (collection and management of data) which provides and task loader and executioner method of managing how data is is prioritized, stored, and used in the process. With block chain technology everything is recorded and stored fro further examination or re-evaluation at a later date making it a very attractive for use with digital twins and its information modeling capabilities for streamlined sustainable scenarios. Regarding sustainability, energy usage with IoT devices relies on complex digital models that sense, calculate, and delegates the division of energy supply into multiple parts which allows for a determination within a range or power usage to adjust for energy depletion and energy recharge cycles within IoT power sources. An experiment was performed to test the blockchain based system design using different preset sensing strategies, parameters, and energy consumption rates to show that based on a number of devices their energy debt, and energy consumption, different levels of sustainability can be achieved. Ultimately the model chosen to represent the architecture for blockchain based IoT devices was based on measurements of weighed data fidelity, weighed reveal delay, and max-weight-delay which provided a maximum performance and sustainability. The study does mention that the amount of energy impacts the energy supply to IoT devices and can affect sustainability which needs to be regulated [89].

Fritzson et al., provides an overview of the Modelica modeling language and the OpenModelica environment for building digital twins and managing virtual models as well as monitoring energy resources and promoting a sustainable society [90]. The Modelica language is able to model cyber physical systems (e.g. temperature system) and their behavior through object-oriented code, concepts, and mathematical equations which provide for code reuse and integration with via various libraries. furthermore, the Modelica language can model continuous and discrete time based events and scenarios for a complete mechanized model view of the cyber physical system [90]. On the other hand, the OpenModelica environment provides modeling, simulation, and a development environment where industrial designs can be tested in conjunction with the Modelica language. OpenModelica is also able to efficiently compile model code generations in C, C++ Java, C# and other programming languages to allow for models to be transformed and executed in real time [90]. 3D visualization of compiled models listing their variables and metrics is another feature offered by the OpenModelica development environment where engineers can inspect models, real time events, time based interactions, and code efficiency within a digital twin. Lastly the Functional Mockup Interface standard was used to apply interoperability between different modeling and code generation tools into the OpenModelica development environment, this allowed for conversion and readjustment of external models to be compatible with the existing tools described in the study.

Resources and product cascading in the recycling and mining industries have become difficult to manage and a sustainable solution is needed to filter and sort materials in an intelligent way [96]. Pehlken et al., describes this type of resource management as urban mining and aims to apply digital twins to the process of sustainably managing these resources. Cascading of products/materials has lead to recycling and reuse of materials for reintegrating resources than can still be used again. Yet, there are problems as more and more products are added to the cascading effect leading to a lack of understanding of which types of products are being cascaded as this can determine how in terms of categorizing products for efficient reuse, how to diversify production, and where to setup distribution locations [96]. A case study was performed where a web based platform used digital twins to scan, plan, and model potential sustainable outcomes where different automobile parts were cascaded via sorting by type, age, and quality. Results form the case study lead to reduced carbon emissions due to sorting usable parts for reuse vs non usable parts and increase in quality products for recycling.

Assembly lines at factories, companies, and workshops are the heart for building products ready to ship from the manufacturing industry, yet as the scale of production increases and the quantity of products and their parts require faster assembly and greater care which means that a new take on product assembly is needed [97]. In the study by Assad et al., web-based digital twins are explored to promote intelligent and sustainable assembly line operation. By creating a web-based architecture that can interact with assembly lines, integrate with digital twins on a server, store and categorize product data, and provide a 3D modeling interface for to the operator for product inspections; the operator can determine based on output from the digital twins whether or not the default action provided by the digital twins will be sufficient or if another step is needed in the process. In order for the assemble line to be sustainable, digital twins were adjusted to focus on reducing energy consumption and ensuring smooth operations by monitoring indicators such as clamp time, weld time, release time, cycle time, and weld current for product assembly. Assad et al., further performed a case study in which a battery welding station was integrated to the web based digital twin where the web-based system read the energy output from the welding station, sent this data to the digital twin for a mathematical evaluation, and wrote back new instructions to the assembly line's programmable logic controller to instruct the welding station to apply welds in moderation, thus reducing the overall energy consumption.

In Zahraee et al., an investigation was performed on the resilience of the biomass supply chain industry for agricultural products against the COVID-19 outbreak in comparison to compliance, policies, technologies, and sustainability that existed around that time [98]. Specifically the effects fo COVID-19 were explored and the implications of existing sustainability practices, policies, technologies, etc..., were explored and what changes they brought for the biomass industry and agricultural products. The process from which an agricultural product is harvested, stores, converted to an final product and sent to the store shelves or other places can be affected by COVID-19 throughout all stages from number of workers to skilled employees and delays in transportation. To understand how to minimize the effects Zahraee et al., performed a literature review where effects of COVID-19 on supply chain and logistics were analyzed, how those effects affected biomass renewable energy, and what sort of approach can be taken in the future to counter uncertainties, meet demand, and comply with sustainability regulations [98]. Impacts to sustainability on economic, environmental, and social effects were studied with the most affected being the energy sector which resulted in lost revenue, high energy costs, low amount of investment, low energy demand, and a loss of skilled/regular workers. The study concludes and recommends that in order to counter the damage caused by COVID-19, it was proposed that a renewable biomass system needed to be created and new incentives put forth for recruiting and retain skilled workers, reducing energy usage, expanding energy access, diversifying supply-chains, and support the transportation sector [98].

Industrial product-services systems are a mix of product and services targeted at meeting customer needs through product design, delivery of services, scientific innovations, and applied engineering practices [100]. In the study Brissaud et al., investigates the challenges and opportunities available for integrating product-services systems designs into industry and for use with industrial applications by researching its design specifications in: conceptual and detailed deign, value co-creations, business models along with their servitizations and services, sustainability, risks and uncertainties, and digitalization. With new technologies accompanying product-services systems designs for industrial use, opportunities for smarter technologies such as cloud computing, IoT, 3D visualizations, data analytics, digital twins, and distributed ledgers all used to connecting physical products to digital systems which arise in providing implementation/integration methods that are sustainable in industrial settings [100]. There are a couple of recommendations made for improving the design of product-services systems for industry to produce better business value and value creation in product outcomes, product performance, product usage, process efficiency, price, and a number of positive environmental impacts by incorporating smart digital technologies mentioned earlier all while increasing the number of services and functionalities due to growing customer and market demands. To meet the ever growing demands in industry, a social and sustainable value-driven circular life cycle framework was deigned to integrate products and services into the industrial process using a four layer design which aims to manage the dynamics of supply and demand and handle resource constraints of each through: business models, organizational maturity, value creation, and enabling capabilities. In regards to metrics and indicators Brissaud et al., describes a number of them in the study relating to products, services, and their importance within industry, but the use of contracts have hindered progress towards sustainability which are described to have caused low quality output, high costs, and downtime in industries similarly to what has been uncovered in Moldan et al., [100], [1].

Enhancing the interplay relationship between digital twins and the industrial internet was studied by Cheng et al., who investigated existing ways of communication between digital twins, value chains, manufacturing/production facilities and their equipment, along products/services within industry [101]. Cheng et al., establishes a three level framework for the interplay between digital twins and industry to efficiently communicate with one another: product lifecycle level, inter-enterprise level, and the intra-enterprise level; for each of these levels the use of digital twins was examined to determine which areas they were operational in and by how much progress was needed in other areas to support or implement digital twins for enhancing the communication between industrial applications within the three level framework. As the levels establish a framework for communication, the connection between the two enterprise levels and product lifecycle level is made through an industrial internet platform that shares knowledge from uploaded data. Data uploaded to the industrial internet platform contains information on the process and metrics and indicators used such as: product quality, energy optimization, materials, processing capability, cost, design effectivity, and production capability used by the different services, equipment, and advanced technologies e.g. digital twins for creating sustainable products to market. In a case study both of the virtual and physical product underwent a four stage lifecycle process using digital twins and the manufacturing base where the product (steam turbine) is designed, manufactured, serviced, and eventually recycled based on the various parameters, metrics and indicators provided during the inter- and intra- enterprise levels. The two enterprise levels are composed of five different layers that handle interacting with web based services, access control and business management related roles, system modeling and design, digital twin data and integration, and finally different value streams from manufacturing to product delivery phases.

Destouet et al., performs a literary survey to understand how introducing industry 5.0 aspects (e.g. sustainability, human considerations, and resilience) can be used to support flexible job scheduling problem [102]. The job scheduling problem is characterized in for several criteria and there are two types of schedules, one being static/deterministic scheduling for expected events (e.g. working hours) and the other being dynamic/stochastic scheduling for unexpected events (e.g.break down of machinery). Challenges presented in industry 5.0 go beyond what technologies in industry 4.0 can help resolve and require a more a more integrated environment that includes both a resilient and human approach to tackle time-based, cost-based, job number-based, revenue-based, environmental-based, ergonomic-based, and composed objective based scheduling objectives for sustainability. The study also describes job-shop scheduling problems and focuses on the flexible job-shop scheduling problem as a base for incorporating human and environmental factor for developing a sustainable scheduling method that is pro-active in pre-scheduling tasks and optimizing processing time for each task. The human factor in the flexible job-shop scheduling problem is described as a dual resource-constraint containing two entities with one being the human worker while the other is the machinery operated by one or more human worker. Metrics related to the human factor consist of skills, cost, learning rate, ergonomic risks, rest, and age which contribute to the complexity of performing various operations on a set schedule and are hard to evaluate in digital models for improving sustainability. The environmental factor on the other hand focus on metrics such as energy consumption, carbon emission, noise emission, and to some degree recycling of resources which have a direct affect on green energy and sustainable manufacturing. When both human and environmental factors are taken into account, Destouet et al., points out that they are mutually exclusive in supporting the job scheduling problem as it is stated that workers wellbeing will need to be taken into account due to its ability to improve the production process and at the same time energy consumption and other environmental factors can be optimized by workers utilizing hybrid methods/technologies for sustainable task scheduling [102].

Low carbon technologies can have a massive impact on transforming regular cities into sustainable cities for a long term outlook [103]. Shang et al., points out in the study that technologies used by sustainable urban development initiatives provide the ability to control and reduce temperature, limit CO2 output, and minimize energy consumption. The study analyzes urban development in cities across the world and why urbanization has caused higher demand in energy usage and environmental pollution along with what type of low carbon sustainability initiatives and sustainable development goals different countries were looking to apply and achieve in their cities moving forward. Application of low carbon technologies such as non-fossil fuel energy has shown to lower CO2 and energy emissions through technologies wind, solar, and nuclear energy devices compared to fossil energy which include coal, crude oil, and natural gas [103]. The change from fossil to non-fossil energy sources affects the type of materials that need to be used along with building performance, implementation accuracy, construction efficiency, waste reduction, and environmental impact to low carbon cities. Furthermore, as governments were looking into the potentials of enacting low carbon policies from evaluating energy models and energy consumption, it was discovered that energy policies alone are not suited to guarantee low carbon emissions and instead a better approach would be to combine energy policies with current climate for maximum impact on carbon reduction [103]. The study concludes that for low carbon cities to become a reality four concrete steps need to be taken: (1) increase new and existing types of energy and control their proportions, (2) minimize the use of coal base energy and promote non-fossil alternatives, (3) research and development into low carbon city technology needs to be prioritized, and (4) accelerate green initiatives for low carbon city building [103].

Papacharalampopoulos et al., performs a case study on an additive manufacturing process of a laser-powder bed fusion system where the design and performance of a digital twin powered manufacturing system framework is tested to determine how best to incorporate resilience and agility in manufacturing [104]. Implementing resilience and agility through the help of digital twins in manufacturing has the ability to to increase adaptability and provide real-time optimizations within the manufacturing process. The digital twin framework that was designed by Papacharalampopoulos et al., consists of real twin, dummy data generator, and digital twin where the digital twin performs a model generation, a quality assessment of that model, along with a what-if scenario test that evaluates error recognition and KPIs in a closed-loop design. In the case study the framework tests and tries to improve the temperature-tracking control process used by the laser-powder bed fusion system by making use of two artificial neural networks, that (1) evaluate important KPIs, laser power, and scan speed and (2) validate that machine and process perimeters are accurate. Furthermore, real-time predictions were tested using the artificial neural networks to cross-validate data for determining which perimeters to set by predicting the optimal temperature from multi-node trial and error training of the model which has increased the learning rate of the artificial neural network and ultimately reduced overfitting and underfitting of the model leading to more agile and resilient results for the real world twin.

The literature above does discuss values and metrics related to sustainability concerns. Regarding CA1 there were a number of measurable issues found throughout the literature that hinder the implementation of sustainability goals. In Chávez et al., the metrics and indicators that were listed as undesirable were the amount of energy consumed, level of productivity, and emission level [44]. From Ram et al., metrics that are actionable were less favored in the literature which included non-blocking files, critical issues ratio, and quality-alert with an exception made for the well-defined issues jira metric [45]. The literature by Mourão et el., showed that energy awareness was not a favorable indicator for promoting sustainability as little interest was shown [48]. Lv et al., described the metrics and indicators rendering time, completeness, degree of information integration, distribution density, amount of data, and reasoning complexity as problems in the way of implementing digital twins for to drive sustainability [52]. In Pan et al., the the metric level of camera coverage had an undesirable affect on the metric change rate over time which affected affected the applicability from digital twin to real twin [53]. The literature by Bibri et al., shows that the amount of data, amount of tasks, and level of dataset diversity are metrics that slow down processing and analysis of data and affect accuracy in the digital twin [54]. Mendula et al., identifies signal delay, data meaningfulness, and result similarity as indicators and metrics that negatively affect information accuracy for achieving the set goals in the study [57]. Purcell et al., depicts model accuracy and feedback rate as undesired metrics that affect performance and accuracy for sustainable farming [58]. Wang et al., describes the metrics communication delay, packet loss, system performance, and position synchronization as unreliable due to the added cost and resources needed optimizing the digital twin [59]. In Maksimović et al., the metrics and indicators effort to repair fault, fault repair time, cost of the fault, cost of processing, cost of maintenance, amount of resources, and system complexity represent increasing problems when maximizing the potential of digital twins for improving sustainability related to sustainable development goals [61]. Broo lists level of interest in data, value of stakeholders, value of domain, value of disciplines, and purpose applicability as metrics and indicators which limit the quality of life and environmental effort in future smart and sustainable cities [64]. From Siddiqui et al., the metrics and indicators hidden layer and network efficiency are described to cause overfitting and underfitting in the digital twin model [66]. Diaz et al., points to instrumentation failure, industry flexibility, and level of data integration as causes for reduced reducing research quality in sustainable society such as logistics, urban planning, and healthcare [69]. Liao et al., on the other hand only listed communication delay as a metric that causes problems for sustainable systems, environments, and with digital twin when it is used in real-time scenarios [70]. Bentley et al., VvanKol et al., and Wang et al., also present one metric each: linear regression accuracy as a measurable algorithm has shown to present low accuracy in tests compared to other algorithms [79], level of maturity was proven to be low for sustainable bulk handling [80], and the amount of energy in low yield has reduced performance in energy sustainable IoT devices [89]. Malik et al., described installation cost, market demand, market flexibility, capital, and labor hours were negative for sustaining in practice due to high demand in the market [84]. Error rate and level of accuracy were listed by Li et al., as metrics that are difficult to assess indicators with due to large gaps in data [87]. The daily usage charge and contract availability were indicators that Brissaud et al., that have resulted in reduced sustainability for industries [100].

Out of 499 metrics and indicators a total of 56 problematic metrics and indicators were identified which cause problems when implementing sustainability goals for industries. This reduced the overall important metrics and indicators to 434. The 56 metrics and indicators removed cannot be integrated in a digital twin due to their characteristics which have caused reduced sustainability within the industry. Table 5.3 below lists the problematic measurements explained above.

amount of energy consumed	level of productivity	emission level
non-blocking files	critical issues ratio	quality-alert
energy awareness	rendering time	completeness
degree of information integration	distribution density	reasoning complexity
level of camera coverage	change rate over time	amount of data
amount of tasks	level of dataset diversity	signal delay
data meaningfulness	result similarity	model accuracy
feedback rate	communication delay	packet loss
system performance	position synchronization	effort to repair fault
fault repair time	cost of the fault	cost of processing
cost of maintenance	amount of resources	system complexity
level of interest in data	value of stakeholders	value of domain
value of disciplines	purpose applicability	hidden layer
network efficiency	instrumentation failure	industry flexibility
level of data integration	communication delay	linear regression accuracy
maturity	amount of energy	installation cost
market demand	market flexibility	capital
labor hours	error rate	level of accuracy
daily usage charge	contract availability	

Table 5.3: RQ1: Problematic Metrics and Indicators

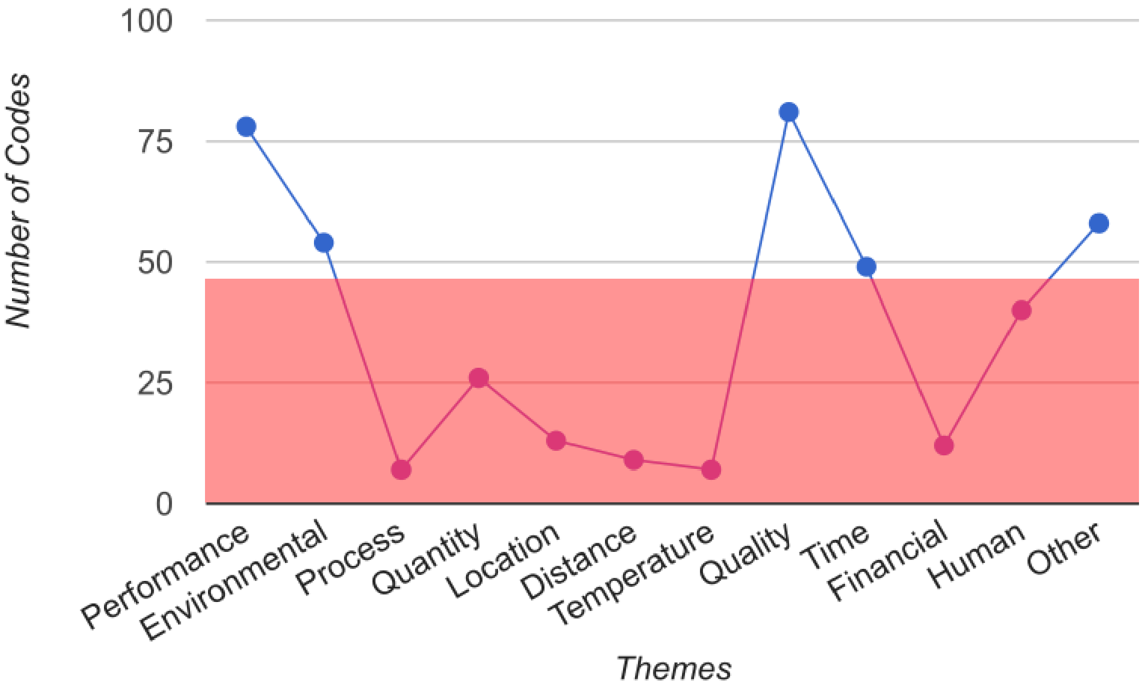

Figure 5.5: Number of Codes per Theme Update 1

The physical twin's (e.g., a factory) overall sustainability according to the literature is primarily measured using performance (e.g. throughput, model robustness, scalability), environmental (e.g. amount of power consumed, energy optimization, environmental pollution), quality (e.g. reliability, consistency, usage conditions), time (e.g. availability, elapse time, time to market), and a number of other metrics and indicators (.e.g. grass height, storage space control, mean square error). Figure 5.5 displays an updated graph showing the changes made from Figure 5.3 to reflect on the removed measurements with: 78 for Performance, 54 for Environmental, 7 for Process, 26 for Quantity, 13 for Location, 9 for Distance, 7 for Temperature, 81 for Quality, 49 for Time, 12 for Financial, 40 for Human, and 58 for Other. Measurement categories around the 50 point mark and higher were selected for measuring sustainability as the metrics and indicators within these categories were the most talked about in the literature.

The tools needed for integrating sustainability values and metrics for achieving sustainability goals as described in the literature is by applying big data [52], [54], [80], [84], AI [61], [84], machine learning [61], [79], [81], neural networks [52], [66], [104], and in some cases a combined approach using contracts [100] is needed as these tools will provide the most accurate methods for uncovering which metrics and indicators to use and convey the desired values needed in forming sustainability goals during the integration process. Requirements engineering practices could further help with the integration of sustainability goals within the digital twin to ensure that performance, environmental, quality, time, and other metrics and indicators are suitable and offer sustainability values. By eliciting functional and non-functional requirements for the physical twin, digital twins could be used to optimize operations and comply with the expected sustainability goals imposed by big data, AI, machine learning, neural networks, and contracts.

5.3 RQ2 Findings

RQ2 is designed to present the limitations of digital twins in the context of suitable metrics for sustainability requirements including the current metrics and indicators found in digital twins. CA2 provides a compilation of metric limitations used in addressing RQ2 by direct comparison in order to single out the limitations and differences found in digital twins verses the the findings from RQ1 and discard metric limitations and weak indicators by applying sustainability requirements. When further comparing the differences and similarities between the data of RQ2 to RQ1, we will have a more advanced understanding on which limitations already exist verses which limitations have been found from the literature.

While digital twins, together with appropriate requirements engineering practices and existing metrics, can be useful for addressing sustainability needs of physical twins (e.g., a factory), the academic literature discusses a number of challenges that exist in state-of-practice digital twins such as latency, design quality, effectiveness, and resource usage to name a few (more are presented later on in this section). On the one hand, current limitations/challenges of digital twins consist of (1) complexity of production capability, digital twin modeling, and complexity of materials that need to be translated into the digital world [12], [28], [30], [32]. Another challenge is with (2) production capability due to human behavior, product diversity, cost to produce, production capacity, and lack of production data [28], [33], [34]. (3) Time is another limitation that can cause a shift or de-synchronization to occur in time critical system such as differences in production speed between workers (some working faster than others), time differences between information delivery between real and digital twin, and time can affect the development time of products, services, and programs [28], [31], [32], [33]. (4) Reliability of digital twins and their prediction capabilities [28], [30], also (5) accuracy of initial data, accuracy of model, and accuracy of real twin devices can all further affect digital twin reliability [28], [31], [33], [34]. The way (6) security is implemented between real and digital twin [3], [8], [12], [17], [32] along with (7) ethical issues with the use of digital twins to replicate humans from the physical world into the virtual world [29].

Other challenges are (8) implementation and integration which have plagued digital twins due to the complex nature of setting up the correct environment for accurate synchronization along with the advanced tools needed to link data sources together [3], [8], [19], this had lead to problems with (9) management of digital twins along with the data that is processed at high volumes which has increased the workload and complexity of sorting data. (10) Information digitization has been increasingly difficult to convert from real twin to digital twin and vice versa since demand and complexity for data digitization is rapidly increasing [3], [12], [17]. (11) Production efficiency and (12) reducing the carbon footprint have a direct correlation to one another because they both affect sustainability in terms of performance and environmental pollution as more advanced technologies are introduced into the product manufacturing process [5].

The (13) maintenance of machinery is another limitation as it relies on humans to maintain and repair equipment which can be unpredictable to calculate when the repair will be complete and how it will be done [7], [12], to add on to this, the (14) cost repairs along with the cost to implement digital twins into a test or production environment is usually high verses the resulting value of digital twins [12], [19]. There is major challenge regarding (15) lack of oversight, regulations, and standards that have not been addressed by any official oversight body to check whether or not safety, ethical, or other standards are in place and monitored [12]. (16) Network speed and (17) processing power were two other limitations mentioned because digital twins have no control on how fast the network linking to the real twin is nor does it have much control over how much processing power is needed as the processor is limited to its maximum frequency of operation [19].

Moreover, the mentioned challenges related to complexity, information digitization as well as the lack of oversight, regulations, and standards coupled with ethical issues make it very difficult to determine if the digital twin will represent the real twin accurately. Furthermore, there are a few other challenges from above namely cost, maintenance, production efficiency, network speed, processing power, and carbon footprint which have a greater impact on sustainability goals. All of these constraining factors taken together lead to state-of-practice digital twin practices unfit for ensuring the sustainability goals of the physical twin.

On the other hand, current metrics and indicators of state-of-practice digital twins from the existing literature such as accuracy [35], [37], latency [35], performance [3], [12], [17], [36], [37], [28], design quality [17], [36], synchronization [36], optimization [17], [36], [28], system quality [36], effectiveness [36], [28], resource usage [5], production cost [12], operation time [12], number of risks [12], and scalability [13] have helped to minimize uncertainty when formulating sustainability goals.

Based on the UN's 2023 progress report on sustainable development goal implementation there are 17 total SDGs listed: SDG #1 Eradicate extreme poverty and implement social protection systems; SDG #2 Achieve food security and end malnutrition; SDG #3 Increase skilled birth attendance, end preventable deaths, end malaria epidemic, and increase vaccine coverage; SDG #4 Ensure primary education completion; SDG #5 Eliminate child marriage and increase women in political positions; SDG #6 Universal safe drinking water and universal safe sanitation and hygiene; SDG #7 Universal access to electricity and improve energy efficiency; SDG #8 Sustainable economic growth and achieve full employment; SDG #9 Sustainable and inclusive industrialization, increase research and development spending, and increase access to mobile networks; SDG #10 Reduce inequality within countries; SDG #11 Ensure safe and affordable housing; SDG #12 Reduce domestic material consumption and remove fossil fuel subsidies; SDG #13 Reduce global greenhouse gas emissions; SDG #14 Ensure sustainable fish stocks and conserve marine key biodiversity areas; SDG #15 Conserve terrestrial key biodiversity areas, conserve mountain key biodiversity areas, and prevent extinction of species; SDG #16 Reduce homicide rates, reduce unsentenced detainees, and increase national human rights institutions; SDG #17 Implement all development assistance commitments, increase internet use, and enhance statistical capacity [38]. Out of these, SDGs numbered 3, 6, 7, 8, 9, 12, 13, 14, and 15 are applicable to the research done in this thesis as they along with the literature target (relate to and help define) sustainability with industries, manufacturing, production, and industry 4.0 [17], [39], [40], [42].

Even though challenges and metrics from state-of-practice digital twins have been uncovered, sustainability goals further need to be parameterized by existing sustainability requirements. Literature on sustainability and its requirements suggest that industries that want to achieve sustainability goals and make use of industry 4.0 practices (e.g. digital twins) will require an analysis of massive data, implementation of on-demand production and customization capabilities, and dynamic configuration processes [17], [39]. In order for there to be a successful definition of what sustainability goals consist of, existing sustainability requirements need to be listed. The literature describes adopting resource efficiency (regulating water, energy, waste) [17], [20], [39], [40], reducing environmental impact [17], [20], [39], [40], reduce cost [17], [20], [39], [40], reduce pollution and CO2 [17], [20], [39], [40], recycling [20], [39]; effectivity [17], [20], [39], management of renewable and non-renewable resources [17], [20], [39], [40], apply energy-saving and energy-reduction practices [17], [20], [39], optimization of products, life cycles, and technologies [17], [20], [40], improved performance [17], [20], [40], and energy reduction and regulation [17], [20], [40]. A number of important sustainability characteristics are also relevant in defining sustainability goals which include: security, satisfaction, freedom from risk, functional suitability, compatibility, reliability, effectiveness, maintainability, and performance efficiency [17], [20], [41].

By comparing and differentiating data from Sections 5.2 (performance, environmental, quality, time, and other metrics/indicators) as well as sustainability requirements to the challenges faced and metrics found in state-of-practice digital twins it will be possible to fully answer RQ2. From the remaining measurements, metrics and indicators found in the themes of performance, quality and time can be further eliminated which are shown in Table 5.4 below.

production downtime	implementation accuracy	level of integration
product assembly efficiency	production efficiency	construction efficiency
processing efficiency	processing capability	complexity
model integration complexity	reliability	sensor reliability
result reliability	data accuracy	system integration
production time	mean time to repair	setup time
delivery time	lead time	design period
time of crime	time of trip	date of trip
start time	end time	vehicle travel time
discrete time	available time	date
state of pasture	time to file report	time to market
time of day	activation time	time slots
reveal delay	generation time	collection time
continuous-time	discrete-time	clocked discrete-time
years to change energy sector	time to normalize energy demand	time to market

Table 5.4: RQ2: Problematic Metrics and Indicators

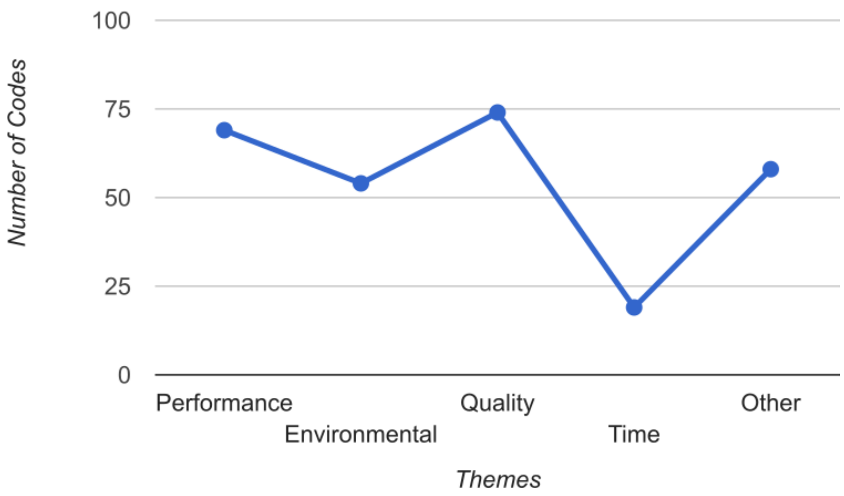

Figure 5.6: Number of Codes per Theme Update 2

A revised list of issues and changes is shown in Figure 5.6 which displays an updated graph showing the changes made from Figure 5.5 to reflect on the removed measurements with: 69 for Performance, 54 for Environmental, 74 for Quality, 20 for Time, and 58 for Other which resulted in a total of 274 codes (see Appendix D for a full list). Themes labeled Process Quantity, Location, Distance, Temperature, Financial, and Human were discarded from the parametrization made previously in Figure 5.5.

5.4 RQ3 Findings

RQ3 concerns the validation of digital twins for sustainability via the process of requirements engineering. CA3 is used to address RQ3 with the evaluation of the goals for sustainability from RQ1 and the limiting indicators derived from RQ2 in order to parameterize a set of refined requirements that can act as a guideline to better address the concerns faced with sustainability goals via digital twins. The new guideline formed will provide capabilities to industries to test, identify, and validate which metrics and indicators are appropriate for specific tasks.

Requirements engineering practices can help mitigate measurable constraints and help developers focus on the long term usage of digital twins for reaching sustainability goals. As a result along with the discussion in Sections 5.2 and 5.3, requirements engineering could further promote the integration of relevant requirements within digital twins. To do so, it would be necessary to detail how to identify, test, and validate metrics against real-world data. In multiple instances the literature exemplifies and recommends that either single or multiple frameworks, architectures, or diagrams of the platform which details specific steps for identifying and testing different aspects of the study would need to be created as a verification guideline [44], [53], [54], [59], [60], [64], [66], [69], [70], [71], [80], [81], [85], [87], [89], [90], [97], [98], [100], [101], [102], [103], [104]. Either the same or similar approach can be taken to identify test and validate metrics against real-world data. Other methods to identify, test, and validate metrics and indicators would be to apply specific requirements engineering practices that allow for brainstorming and narrowing down the list of potential metrics where the methods for functional requirements could include user stories, event/function lists, and task descriptions [43]. While non-functional methods would include the MoSCoW prioritization technique to prioritize between which metrics must, should, could, and wont be useful for achieving sustainability goals [43]. Moreover, to map the digital twin's effectiveness, a comparison of data to similar studies, previous data, or real world scenarios is suggested by the majority of the studies [44], [48], [52], [53], [58], [59], [64], [70], [71], [79], [80], [81], [85], [87], [89], [90], [96], [97], [98], [102], [104].

5.5 Recommended Guideline

Sections 5.2, 5.3, and 5.4 provided an important analysis of the literature which reduced the number of measurements uncovered by answering both RQ1 and RQ2. As a result Figure 5.6 was the outcome with relevant themes ordered from the highest to lowest number of metrics and indicators being Quality, Performance, Environmental, Other, and Time. A full list of indicators that industries can look through and follow for determining which metrics to use for defining sustainability goals are compiled from RQ1, RQ2, and presented in Appendix D as codes beside the matching theme. Based on the identification process outlined in RQ1 and RQ2 along with the indicators identified in Appendix D, a recommended guideline for industries to follow is described below:

1. Determine what the objective is from the real world task or project in question.

2. Deploy digital twin technology to scan the working environment and design a model for digital manipulation.

3. Specify the themes listed in Section 5.2 as perimeters for the digital twin.

4. Consider the deployment of tools and technologies discussed in Section 5.2 to help with further parametrization and model prediction accuracy.

5. Decide which sustainability perimeters to apply for finding the needed metrics from Section 5.3.

6. Compare the chosen perimeters from Section 5.3 to Appendix D and select the closest matching indicators.

7. Once the indicators have been selected, the sustainability goal along with the metrics to define it will be understood and can be validated using the methods presented in Section 5.4 and through the digital twin.

6
Threats to Validity

This study has been worked on by one person (the author) and therefor limitations and mistakes can be present due to the range, scope, and depth of content collected and reviewed in this SLR. The two types of threat levels affecting limitations to keep in mind are threats to internal and external validity.

Internal validity threats might include selection bias on the papers chosen to be reviewed through key terms used in search queries. Selection bias is a threat for determining what literature to select for review because the terms used might not be the same ones used by someone else to select the appropriate literature. The questions from Table 4.3 and the quality assessment that followed were designed solely by the author of this thesis and therefor presents a selection and personal bias on how the questions are understood and answered during quality assessment as well as the assignment of quality points. Another threat might include detection bias as it could turn out that not all terms are appropriately identified, coded, or linked between different statements, meanings, and codes.

As for external validity threats, these can affect the choice of databases used, where one database might have more papers leaning towards one bias and another database being the opposite. E.g. Springer Link might have more papers on digital twins v.s. JSTOR which might have more papers on sustainability. This was difficult to mitigate but the sources that were chosen were selected based on their reputation with academia and computer science and software engineering collections. Another threat that can occur is generalizability of terms and history where the scope on the terms used are too general in their focus throughout the study, or a general representation of historic events are talked about but do not provide anything concrete or meaningful information to the maturity of the study.

Delimitations of this study might exclude literature that is not relevant to the the research questions. For instance, if there is a research paper that talks about digital twins and farming but does not mention anything about using metrics, indicators, or sustainability, then it will not be taken into consideration for this study. Similarly, after passing the search terms and collecting literature based on those search terms, and if the literature does not contain any relevant information, then this group of papers will also be discarded.

7
Conclusion

7.1 Conclusion

This study aims to provide a guideline for industry leaders that simplifies the identification process of understanding which measurements are needed for setting and implementing appropriate sustainability goals in current and future projects. With this level of understanding there is a potential to advance the use of digital twins in fields such as industrialization, data mining, and data driven development. The scientific contribution from this study would allow for further development and refinement to research fields related or involved with digital twins. Researchers could for instance have the ability to incorporate the use of other technologies, such as AI or machine learning in digital twins and parameterize their research via the guideline this study produces, for more accurate and precise data modeling.

7.2 Future Work

Since this study performs a systemic literature review using secondary studies as the main data source, there is a potential for improvements to be made in the future. Future work could involve performing some of the ideas listed below:

Idea A) A longitudinal study focusing on the changes in, and the evolution of, sustainability related practices/requirements over time within the literature or through a company. This type of study would require to keep track of subjects (humans or artifacts, e.g., requirements specifications) between data collection waves.

Idea B) An intervention in a company and an action research study focused on the social impact of sustainability goals. This type of study could focus on how the introduction of requirements engineering methods elicit sustainability-related requirements and what their affects bring to the context of the real twin and digital twins.

Idea C) An experiment study that would use digital twins to validate the findings in this study by applying the knowledge discussed to a real world scenario. In the study's experiment, tools and technologies could be setup tested by interacting with the digital twin in real time (e.g. AI powered digital twin processing) in an experiment group verses a comparison with a control group where no tools are used.

Idea D) A mixed study approach that combines a case study with a systemic literature review or action research where a more detailed analysis between two different study techniques can be applied. A theoretical understanding of digital twins sustainability goals and measurements can be compared to a case study to uncover limitations that could not be found with just a single research method. Knowledge between the two types of studies can be compared and integrated to discuss multiple approaches, frameworks, theories, challenges, and distinguish discrepancies as a whole.

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A

Appendix 1

A.1 Secondary Studies

ID	REF	Secondary Study	Year
01	[44]	Achieving Sustainable Manufacturing By Embedding Sustainability KPIs In Digital Twins	2022
02	[45]	Actionable Software Metrics: An Industrial Perspective	2020
03	[48]	Green and Sustainable Software Engineering - a Systematic Mapping Study	2018
04	[52]	Smart City Construction and Management by Digital Twins and BIM Big Data in COVID-19 Scenario	2020
05	[53]	Smart City Digital Twins for Public Safety: A Deep Learning and Simulation Based Method for Dynamic Sensing and Decision-Making	2020
06	[54]	The Big Data Deluge for Transforming the Knowledge of Smart Sustainable Cities: A Data Mining Framework for Urban Analytics	2018
07	[57]	A Data-Driven Digital Twin for Urban Activity Monitoring	2022
08	[58]	A Digital Twin for Grassland Management	2022
09	[59]	A Digital Twin Paradigm Vehicle-to-Cloud Based Advanced Driver Assistance Systems	2020
10	[60]	A Digital Twins Model for Analyzing and Simulating Cold Chain Risks	2023
11	[61]	A faster path to sustainability the use of Digital Twins	2023
12	[64]	A Framework for Using Data as an Engineering Tool for Sustainable Cyber-Physical Systems	2021
13	[66]	Artificial Intelligence Enabled Digital Twin For Predictive Maintenance in Industrial Automation System A Novel Framework and Case Study	2023
14	[69]	Context Aware Control Systems: An Engineering Applications Perspective	2020

Table A.1: Secondary Studies Part 1

ID	REF	Secondary Study	Year
15	[70]	Cooperative Ramp Merging Design and Field Implementation A Digital Twin Approach Based on Vehicle-to-Cloud Communication	2022
16	[71]	Data Evolution Governance for Ontology-Based Digital Twin Product Lifecycle Management	2023
17	[79]	Generating Synthetic Energy Usage Data to Enable Machine Learning for Sustainable Accommodation	2021
18	[80]	Introducing adaptive mechatronic designs in bulk handling industry	2021
19	[81]	Lifetime Learning-enabled Modelling Framework for Digital Twin	2022
20	[84]	Smart Manufacturing with Artificial Intelligence and Digital Twin A Brief Review	2022
21	[85]	Sociality-as-a-Service: A new platform for networked Digital Twins	2022
22	[87]	Sustainability Assessment of Intelligent Manufacturing Supported by Digital Twin	2020
23	[89]	Sustainable Blockchain-Based Digital Twin Management Architecture for IoT Devices	2023
24	[90]	The Openmodelica Environment for Building Digital Twins of Sustainable Cyber-Physical Systems	2021
25	[96]	Urban Mining: Applying Digital Twins for Sustainable Product Cascade Use	2020
26	[97]	Utilising Web-based Digital Twin to Promote Assembly Line Sustainability	2021
27	[98]	Agricultural biomass supply chain resilience: COVID-19 outbreak vs. sustainability compliance, technological change, uncertainties, and policies	2022
28	[100]	Designing value-driven solutions: The evolution of industrial product- service systems	2022
29	[101]	DT-II:Digital twin enhanced Industrial Internet reference framework towards smart manufacturing	2022
30	[102]	Flexible job shop scheduling problem under Industry 5.0: A survey on human reintegration, environmental consideration and resilience improvement	2023
31	[103]	Low carbon technology for carbon neutrality in sustainable cities: A survey	2023
32	[104]	Manufacturing resilience and agility through processes digital twin: design and testing applied in the LPBF case	2021

Table A.2: Secondary Studies Part 2

B

Appendix 2

B.1 Coding of Secondary Studies

ID	Code	Note	Quote & Reference
01	processing time, availability, mean time to repair, setup time, scrap processing time	production parameters	“Table 1: Data categories and parameters of interest for the study” [44]
01	type of work procedure	work procedure	“Table 1: Data categories and parameters of interest for the study” [44]
01	material type, quantity of components, weight, amount of scrap, amount of rework, cost	material data	“Table 1: Data categories and parameters of interest for the study” [44]
01	amount of power consumed, energy cost	energy data	“Table 1: Data categories and parameters of interest for the study” [44]
01	amount of material consumed	material consumption	“Table 1: Data categories and parameters of interest for the study” [44]
01	throughput	environmental impact	“These three parameters were varied because it was of interest to evaluate if the throughput could be increased simultaneously as the KPIs for the environmental impact could be kept at a minimum.” [44]
01	sustainability performance	insufficient measuring method	“eco-efficiency indicators alone may not be sufficient for measuring sustainability performance” [44]

Table B.1: Coding of Secondary Studies Part 1

ID	Code	Note	Quote & Reference
01	amount of energy consumed, level of productivity, emission level	unstable indicator	"energy efficiency measures that assess energy consumption levels can either increase productivity and hence emission levels, or reverse, reduce emission levels while also reducing productivity" [44]
01	process complexity	combine method and indicators for improved sustainability	"To overcome difficulties with the decision-making process, current research proposes the use of DES methods in combination with integrated performance indicators to conduct virtual experimentation and analyze complex process flows to improve the sustainability of manufacturing" [44]
01	emission level, amount of waste, amount of resources utilized	environmental KPIs for DES	"Figure 4: Selected KPIs to use in the simulation model (Annepavar and Gopalakrishnan 2021)." [44]
01	cost, delivery time, productivity, quality	economic KPIs for DES	"Figure 4: Selected KPIs to use in the simulation model (Annepavar and Gopalakrishnan 2021)." [44]
01	amount of resources utilized	AS-IS equal high utilization rates bottlenecks	"The Base scenario still yields better results and performance regarding resource utilization." [44]
01	amount of resources utilized, number of bottlenecks, utilization rate, throughput	Base equal high utilization rates bottlenecks	"Even though the Base scenario provides better results compared to AS-IS, it still has an imbalance in terms of resource utilization. This affects the sustainability KPIs negatively by increasing the number of bottlenecks and the utilization rates of the resources as well as the throughput of the system." [44]
01	throughput per hour	parallel assembly station re-balanced (1) and dynamically re-balanced (2)	"experiments 1 and 2 provide much higher throughput and throughput per hour compared to the Base scenario" [44]
01	lead time	parallel assembly station re-balanced (1) and dynamically re-balanced (2)	"Lead time is also lower for these two experimental scenarios compared to the Base scenario." [44]

Table B.2: Coding of Secondary Studies Part 2

ID	Code	Note	Quote & Reference
01	efficiency, throughput per hour	dynamically re-balanced station (2) is more efficient	“Experiment 2 yields an even better result throughput per hour due to the additional station, which is used more efficiently by both product variants” [44]
01	utilization rate, capacity	even distribution of resources	“evens out station utilization and the capacity needs of the other stations. Compared to experiment 1, experiment 2’s flexible additional supporting station avoids experiment 1’s bottlenecks” [44]
01	amount of material, energy emission per part	lower emissions and less material	“Regarding the environmental impact, it can be seen that experiment 2 has a lower amount of total material and energy emissions per part when compared to the base and experiment 1 scenario.” [44]
01	amount of waste, throughput, lead time, material efficiency, energy efficiency	production loads evenly distributed	“This scenario shows that it could be possible to decrease waste and non-value-adding activities. Thereby, this scenario can contribute to higher throughput, decreased lead times, and improved material and energy efficiencies.” [44]
02	non-blocking files, quality-alert	metric for problem identification	“the team used the ‘non-blocking files’ metric to identify problems that were blocking certain development tasks,” ... “The Solution provides a quality-alert feature, where once a metric crosses a user-defined threshold, indicating violation of a quality goal defined by the UC Quality Engineers (QEs), it triggers an alert. The alert is accompanied by a recommendation to correct the situation,” [45]
02	critical issues ratio	critical issue ratio metric converted to development task	“the PM accepted the alert generated by the metric ‘critical issues ratio’, which tracks completed development tasks with critical severity issues, and converted it into a development task that called for review and update of the team’s validation process.” [45]
02	non-blocking files, critical issues ratio	acting on metrics requires knowledge and contribution	“In case of the ‘non-blocking file’ metric, the UC team was familiar with the metric and knew it to be reliable. In case of the ‘critical issues ratio’ metric, again the familiarity of the metric and PM’s close scrutiny of the generated alert played an important role.” [45]

Table B.3: Coding of Secondary Studies Part 3

ID	Code	Note	Quote & Reference
02	well-defined issues jira	enforcing practice increases compliance	"Using the 'well-defined issues jira' metric, the UC Champion learned that the developers were not always following the practice of maintaining the 'Definition of Done' (DoD)" ... "The metric enabled the UC Champion to take the decision of reinforcing the practice of maintaining DoD across the team. Soon thereafter, the metric's value started increasing, reflecting improvement in the practice of maintaining the DoD fields" [45]
02	mood	metrics motivate workers	"Metrics act as an objective benchmark for everyone, regardless of their extent of involvement in a project." [45]
02	complexity	desired metrics are balanced and reliable	"CC3 practitioners prefer high-level and simple metrics." [45]
02	estimated ticket density, spent density, effort spent, effort estimated	effort estimation improvement	"The UC team used metrics like 'estimated ticket density' and 'spent density' to track original effort estimated" ... "As a result, the team identified gaps between their effort spent and effort estimated" [45]
02	experience level, time	overcoming obstacles	"POs and SMs identified a process bottleneck, where the development tickets would stay in the 'merge request' phase of their development process longer than necessary" ... "cause was attributed to experienced developers having inadequate time and resources " ... "This was resolved by granting the medium-experienced developers the rights to perform merges." [45]
02	product quality, process effectivity	process metrics improve team performance	"ensure software product quality, and improve and sustain the effectiveness of the development team" ... "CC4 wants to enable even the POs with mid-level experience to make quick team-oriented decisions" ... "They find that process metrics (metrics measuring development process) allow them to do that" [45]
02	practical metric, decision-making metric, data quality	characteristics of good actionable metrics	"participants agree that an actionable metric should be practical (94%) (Q1), inform decision-making (76%) (Q2), and exhibit high data quality (76%) (Q5)" [45]

Table B.4: Coding of Secondary Studies Part 4

ID	Code	Note	Quote & Reference
02	usefulness	non-action is useful for metrics	"participants believe that even a non-actionable metric can be useful (69%) (Q10)." [45]
02	accuracy, consistency, credibility	actionable metrics quality requirements	"There is unanimous agreement among the participants that an actionable metric must be accurate (100%) (Q11), consistent (100%) (Q12), and credible (100%) (Q14)." [45]
02	reliability	decision-making wryness	"Ideally, a metrics program should facilitate data-driven decision-making. However, practitioners are wary of relying on metrics for decision-making, unless they are reliable." [45]
03	contribution type	contribution types lean more towards approach, framework, and model	"We can observe from the presented data that the researchers have concentrated considerably more on the exploration of approaches, frameworks and models. This may indicate that researchers expect these three contribution types would promote gains in energy efficiency and, consequently, to obtain more sustainable software products." [48]
03	product quality	contribution types are low	"the other 6 contribution types need to receive more attention by the researcher community. Such research could improve the understanding of how sustainability could affect the software development process without impact the quality of delivered products." [48]
03	amount of energy consumed, amount of energy saved	desire to improve efficiency	"56% of the primary studies proposed means to achieve the energy efficiency of the software in terms of consumption and energy savings. " [48]
03	energy awareness	desire to spread and understand energy awareness	"Finally, 19% seek to understand energy awareness, that is, how sustainability has been currently addressed in software development process in practice through the perceptions and attitudes of SE professionals." [48]
03	sustainability requirements, software design	high interest in sustainability requirements and software design	"the most investigated phase is requirements, with a total of 18 studies. Next, software design, with 16 studies." [48]

Table B.5: Coding of Secondary Studies Part 5

ID	Code	Note	Quote & Reference
03	sustainability effort	not enough effort on testing, maintenance, and construction of software	“However, we can observe a gap in the next phases of the SDLC, especially in the maintenance one. Future research should focus on achieving sustainability in the construction, testing and maintenance phases of the software.” [48]
03	scenario difference	too many scenarios are simulations are theoretical vs applied	“study presents a perspective that observes the academic (simulated) and industrial (real) scenarios used by the research.” [48]
03	contribution	professional contribution is missing from studies	“The results presented by [2, 11, 12, 17] show that the Green domain needs contributions from industry professionals.” [48]
03	evaluation, experience	more focus needed in evaluating and having experience	“Such numbers point out to the need for evaluation and experience studies, since most of the primary studies bring solution proposals.” [48]
03	awareness	increased awareness for sustainability research	“possible to observe that there is a predominance of solution proposals in the majority of the primary studies analyzed” ... “This ratifies that the Green SE field have increased in attention by the research community.” [48]
03	type of input	focus to tackle sustainability within industries	“Most researches have industry input (56%). The academy distribution is comparatively smaller (5%).” [48]
04	visualization quality	data visualization	“If the path and the direction of the camera are set, the animation can be completed, which truly realizes the three-dimensional design of the architect’s brain – three-dimensional architectural information model – real architecture. Architectural visualization allows the architect to virtually build his own design works in advance, and timely correct unforeseen errors in advance.” [52]
04	completeness	object being observed needs to be near complete	“Smart cities also require a relatively complete urban infrastructure, especially a complete design of urban network infrastructure and the ability to carry BD.” [52]
04	programmability, compatibility, extensibility, difficulty of operation	modeling program needs to accommodate multiple operations	“The advantages of Unity 3D for BIM design are programmability, compatibility, extensibility, and easy operation.” [52]

Table B.6: Coding of Secondary Studies Part 6

ID	Code	Note	Quote & Reference
04	communication cost, probability of secondary errors	communicate to reduce errors	"the construction staff can interact with the designers in the same model via the internet platform developed by Unity 3D, reducing the communication cost and the probability of secondary errors while solving the problems during the construction." [52]
04	rendering time	rendering time reduced	"Using Unity 3D to display the schemes not only saves a lot of rendering time but also provides interaction." [52]
04	amount of storage space	algorithm to reduce space	"Data of smart cities usually occupy a large storage space. Thus, a batch processing algorithm is designed to calculate the approximate set of the compositive rough set." [52]
04	consistency of situation	information library from model	"In the meantime, it employs the digital technology to provide this model with a complete information library for the building project consistent with the actual situation." [52]
04	degree of information integration	improved information access and exchange from model	"Rich in building engineering information, this 3D model can significantly improve the degree of information integration, thereby providing a platform for engineering information exchange and sharing for the stakeholders of the building engineering project." [52]
04	distribution density	algorithm for estimating unknown from sample data	"Suppose that the joint probability distribution density of random variables x and θ is p(x, θ); in that case. their edge densities are p(x) and p(θ), respectively. If x is the observation vector and θ is the unknown parameter vector, the estimation of the unknown parameter vector will be obtained through the observation vector." [52]
04	amount of data	data management	"A GPU based algorithm is proposed for parallel computing approximate sets to deal with massive and high-dimensional data." [52]

Table B.7: Coding of Secondary Studies Part 7

ID	Code	Note	Quote & Reference
04	performance of algorithm	algorithm improving performance	"Compared with the approximate set calculation algorithm based on GPU, the performance of the approximate set calculation algorithm based on Multi GPU has reached a higher level" [52]
04	reasoning complexity	algorithm to reduce complexity	"This operation can transform the label estimation problem into the maximum possible interpretation problem in the Bayesian network for solution, and the joint tree reasoning algorithm is used to reduce the reasoning complexity. The simulation results show that the proposed MLBN algorithm can effectively improve the performance of multi label classification." [52]
05	location of crime, time of crime	action analysis and data resampling	"The location and time of historical crime records are the most frequently used features. Researchers have used different geographical and temporal intervals to group the crime records before using them as training data." [53]
05	prediction accuracy	evaluating metrics and samples improves accuracy	"Dependent on the differences in resampling, model structure, and evaluation metrics, prior deep learning crime predictions have accuracies between around 50% and 90%, which provides a satisfying foundation for applying the crime prediction to crime sensor placement." [53]
05	level of camera coverage	multiple placements vs dynamic placement	"Most of the relevant studies attempt to enhance the coverage of multiple cameras in a small area" ... "Very few studies are about city-wide dynamic placement of camera sensors." [53]
05	change rate over time	rate of change	"The shortcoming of prior studies is that they ignore that urban crime is constantly changing spatiotemporally, especially over a short time frame (e.g., weeks), and do not make full use of the flexibility of crime sensors placement and crime prediction to capture this dynamic change" [53]

Table B.8: Coding of Secondary Studies Part 8

ID	Code	Note	Quote & Reference
05	decision making capacity	dynamic solutions are more effective but harder to operate	"dynamic placement of crime sensors is a more complex task, which requires the capacity for dynamic-decision making" [53]
05	location of crime, direction of crime, LPR placement effectivity, record update rate	increase resources based on prediction	"detecting a crime vehicle can be obtained for a single LPR placement (i.e., location and direction of the LPR). The placement of multiple LPRs can be derived based on the ranking of the probabilities. The crime records are updated continuously every time before predicting the crimes in the next time frame" [53]
05	difficulty rate	resample or train model for improved performance	"Resampling was conducted to aggregate data spatiotemporally and lower the difficulty of prediction." [53]
05	direction of crime	trajectory calculation	"The trajectory of these random walkers is recorded, based on which the number of captured random walkers in both directions can be calculated for each road segment." [53]
06	amount of data	hard to process large volumes of data	"However, merely keeping up with data flood, and storing the bits that might be useful, is challenging enough, not to mention analyzing datasets to spot patterns and extract useful knowledge." [54]
06	amount of tasks	fewer tasks are more effective	"Although there are a large number and variety of specific data mining algorithms" ... "to perform different data analysis tasks, there are only a small amount of fundamentally different kinds of tasks these algorithms perform." [54]
06	analytics methods	diagnostics for sustainability problems	"The data mining tasks relate to different analytics methods, including descriptive (what happened?), diagnostic (why did it happen?), predictive (what will happen?), and prescriptive (what should be done?) used to solve different decision–making problems related to urban sustainability" [54]
06	data strengths vs weaknesses	problem definition	"matching the problem with the data, a process that involves understanding the strengths and weaknesses of the available data." [54]

Table B.9: Coding of Secondary Studies Part 9

ID	Code	Note	Quote & Reference
06	level of dataset diversity	diverse data is important	“Prior to this, it is important to ensure that the diverse kinds of datasets pertaining to the areas associated with urban sustainability are open for use by the city constituents with respect to data–driven applications in relation to operations, functions, services, designs, strategies, and policies.” [54]
06	data costs vs benefits	cost to effort balance	“A critical part of the data understanding stage in the context of smart sustainable cities is estimating the costs and benefits of data sources and data repositories, and deciding whether further effort is merited.” [54]
07	trip distance	track numerical indicator	“Trip and device identifier: numerical identifier of the trip and of the on-board device, respectively.” [57]
07	time of trip, date of trip	trip length	“Start/End date/time: time/date when this trip was initiated i.e., corresponding to the time/date the vehicle engine is turned on/off.” [57]
07	start time, end time, latitude, longitude	gps position	“Start/End latitude/longitude: GPS coordinates denoting the place when this trip initiated/terminated.” [57]
07	average speed of trip	trip velocity	“Average velocity: average speed in km/h of the trip.” [57]
07	vehicle travel time, vehicle distance	distance traveled	“In general, an intermediate data point is generated whenever a vehicle has traversed 1km or 60seconds have passed since the last data generation.” [57]
07	data meaningfulness	lack of data	“The system currently tracks data at a road-arch granularity, a constituent of the street, which is currently not considered as a basis for the forecasting techniques due to the lack of meaningful data for the whole area of interest.” [57]
07	result similarity	model training from previous data	“The algorithms have been trained with and without weekend days, obtaining similar results in both scenarios.” [57]

Table B.10: Coding of Secondary Studies Part 10

ID	Code	Note	Quote & Reference
07	lag order, degree of difference, size of moving average	lag, raw observation, size	"• p: The number of lag observations included in the model, also called the lag order. • d: The number of times that the raw observations are differenced, also called the degree of differencing. • q: The size of the moving average window, also called the order of moving average." [57]
07	discrete time, signal delay	time for delay comparison	"Autocorrelation is commonly used in discrete time series to compare a signal with a delayed copy of itself." [57]
08	implementation cost	costly to setup DTs	"primarily conducted at lab scale" ... "DTs often utilize experimental technology stacks (e.g., sensor networks and data-driven models) [12], which can be impractical and costly for general implementation and wide-scale adoption." [58]
08	herbage mass, forage availability	availability calculation for pasture	"Herbage Mass (HM) is a measure of forage availability on a given pasture at a given time." [58]
08	herbage mass availability, dry matter, amount of forage	forage remaining after calculation	"The available HM is dependent on the Dry Matter (DM) of the forage, which is the forage after it has been dried and is calculated for a given area." [58]
08	available time, number of resources	calculation for managing resource availability	"Manual assessment is often required to approximate the HM, commonly requiring in situ destructive sampling and is dependant on the available time resources of the farmer [15]." [58]
08	weight of herbage mass, amount of fresh grass, height of dry matter, size of dry matter	calculation for HM	"• HM is herbage mass in kg of DM/ha • g is the fresh grass (before drying) in g/1000 • m is the percentage of DM from the collected fresh grass sample • The square of size 50 $\times$ 50cm is multiplied by 10000, equivalent to one hectare." [58]
08	number of livestock, amount of sampling	labor intensive process	"Although HM provides a key metric by which to assess the optimal number of livestock a pasture can carry, it sufferers from labour intensive manual testing, where the resolution of data is directly proportional to the amount of sampling done." [58]

Table B.11: Coding of Secondary Studies Part 11

ID	Code	Note	Quote & Reference
08	available grass cover, total grass cover	tool for managing average approximation	“The ”Grasshopper” is a commercially available tool that allows semi-automatic measurement of available and total grass cover of a pasture [16].” [58]
08	amount of compression, measurement location, date, time, temperature of measurement spot	data recording	“Each measurement taken (i.e. each drop) is recorded with an ID, the measured compression of (i.e., grass height), latitude and longitude of the measurement location, date and time, temperature (in °C) at the spot of measurement, as well as additional meta-data.” [58]
08	grass height	grass height calculation	“RPM tools provide a method to assess HM based on compressed grass height measurements” [58]
08	grass height, dry matter, herbage mass	future forecasting via DT	“the purposed DT contains a virtual model of the pasture in question, making use of the grass height and dry matter measurements, as well as the calculated HM to forecast the future state of a pastures.” [58]
08	feedback rate	faster feedback	“automatic data assimilation between physical and virtual instance should remove overhead and allow for timely feedback.” [58]
08	model accuracy	capture of data	“A benefit of the DT is its ability to gather and store data over an entities entire life cycle, as part of the design process entity interaction and data must be captured and modelled accurately to ensure correct operation of the system.” [58]
08	state of pasture	dynamic data for state	“Dynamic data: Data that describes the state of a pasture at a given time (e.g. dry matter, plant height)” [58]
08	size of pasture, grass type	static data for properties	“Static data: Data that describes static/permanent properties of a pasture (e.g. size, grass type)” [58]

Table B.12: Coding of Secondary Studies Part 12

ID	Code	Note	Quote & Reference
09	connection strength	communication module links both layers	"Additionally, the communication module plays a crucial role in this system framework as a nexus to tightly connect two layers together." [59]
09	vehicle speed, driver's gaze, traffic light status	sensor measurements	"The sensors may detect the dynamic states of physical entities, changes in operating process, or event occurrences, such as vehicle speed, driver's gaze, and traffic light status, and aggregate the measurements under different resolutions." [59]
09	actuation guidance	processed data form cyber later sent to physical layer	"On the other hand, the processed results from the cyber world are received (again via the communication module) and serve as the actuation guidance for the entities or processes in the physical world." [59]
09	maneuver safety, maneuver mobility, maneuver environmental sustainability	post-processed guidance for taking action	"The actuation guidance sent from the cyber world will advise the automatic controller or human driver of connected vehicles to conduct cooperative/intelligent maneuvers, and in turn benefits transportation systems with respect to safety, mobility, and/or environment sustainability." [59]
09	sensed data, fused data	discovered data is managed	"sensed data from the physical world are cleaned (such as outlier detection and removal, missing data imputation) and fused (including time synchronization)." [59]
09	pre-processed data	after processing data is applied	"Then, the pre-processed data may be stored in the database (e.g., for digital traceability) or be sent to the data mining & knowledge discovery module for further exploration with advanced computational techniques (such as machine learning)." [59]
09	system performance	resulting application from predictive analysis	"The cogitative actions are transmitted (via the communication module) back to the actuators in the physical world to improve the overall system performance." [59]

Table B.13: Coding of Secondary Studies Part 13

ID	Code	Note	Quote & Reference
09	advisory speed	communication system to improve delivery speeds	"ADAS based on V2C communication is developed within the digital twin framework, which aims to provide the advisory speed information to the drivers of equipped vehicles." [59]
09	communication accessibility	physical world modules	"1) Cellular hotspot: This module provides cellular access to the DVI device, and therefore enables V2C communication in this digital twin model." [59]
09	latitude, longitude, speed of information	physical world modules	"2) GNSS: This module is equipped on the vehicle to measure its real-time raw position (latitude and longitude) and speed information" [59]
09	current speed, advisory speed, latitude, longitude	physical world modules	"3) DVI device: This module shows the advisory information (via V2C communication) to the driver" ... " may include current speed (the left number), advisory speed (the right number) and some other additional messages (e.g., verbal guidance, latitude and longitude, IP address)." [59]
09	vehicle speed, system performance	physical world modules	"4) Driver: The driver of the equipped vehicle adjusts the vehicle speed according to the DVI by pressing the accelerate/brake pedal." ... " to predict the tracking errors and compensate for the guidance in real time to improve system performance." [59]
09	road type, road length, direction, speed limit, merging zone, influence zone, position synchronization, geo-fencing	cyber world modules	"1) Map matching: For the map matching module, a pre-built map of the testing field is available on the cloud server, with information such as the road type, road length, road ID and direction, road speed limit, merging zone, and influence zone. The main functions of the map matching module are position synchronization and geo-fencing." [59]
09	advisory speed	cyber world modules	"2) Motion planning and control: This module generates the raw advisory speed of the ego vehicle." [59]

Table B.14: Coding of Secondary Studies Part 14

ID	Code	Note	Quote & Reference
09	speed tracking error, advisory speed	cyber world modules	"3) Human behavior model: This module predicts the speed tracking error generated by the driver, and compensates for the raw advisory speed in real time." [59]
09	human behavior, vehicle speed	cyber world modules	"4) Digital twin visualization: This module demonstrates the digital replica of vehicles in the cyber world. It receives advisory speed from the human behavior model, and also the position and vehicle speed from the map matching module." [59]
09	vehicle speed, vehicle acceleration, energy consumption, vehicle emission	cyber world modules modules	5) Performance evaluation: The performance evaluation module analyzes the data in real time. The speed, acceleration, energy consumption, criteria pollutant emissions" [59]
09	current speed, lane distance, longitudinal speed	estimated time to merge calculation	"Based on the current speed and the distance to merge, an estimated time to merge value can be calculated by the motion planner on the cloud server [18]." [59]
09	distance trajectory, packet loss, seconds	packet loss during test	"Note that, the packet losses of V2C communication can be seen when the distance trajectory is flat within a short period (the distance value is not updated), such as 11-12 second for the mainline vehicle 1, 12-14 second and 23-24 second for the ramp vehicle." [59]
09	fuel consumption, vehicle emission	drastic changes in speed affect sustainability	"the ramp vehicle is shown to consume more fuel and produce more pollutant emissions than the two mainline vehicles due to its drastic speed changes. Mainline vehicle 1 and 2 are shown to consume similar amount of fuel and" [59]
09	communication delay, milliseconds	communication delay in packets	"The average of the communication delay is 88 ms, and the maximum is 854 ms." [59]
10	product temperature, product quality, product safety level	temperature sensitive	"Cold chain management is a process of controlling the temperature of perishable goods from the point of origin through the distribution chain to the point of consumption, and the most important requirement is to maintain them at a good quality and safety level [3]." [60]

Table B.15: Coding of Secondary Studies Part 15

ID	Code	Note	Quote & Reference
10	time to file report	time sensitive	"Considering the strict quality requirements for pharmaceuticals and life science products, any incidence or disruption should be reported in a timely manner, so that the corresponding parties can take immediate action to mitigate risks." [60]
10	interfacing quality	tools for monitoring collected data	"In order to establish a digital replica of the physical cold chain logistics, IoT technology is deployed to achieve effective data acquisition regarding environmental conditions and shipment movements, which are also connected to existing logistics information systems via data interfaces and pipelines." [60]
10	type of vaccine, handling of vaccine, dilution of vaccine, operation flow, pre-cooling technology, quality of packaging materials, packaging requirements	cold chain indicators for processing and packaging	"1) Processing and packaging" ... "Type of vaccine" ... "Handling of vaccine" ... "Dilution of vaccine" ... "Operation flow" ... "Pre-cooling technology" ... "Quality of packaging materials" ... "Packaging requirements" [60]
10	data processing error, manual operation error, communication error, technical problem, data leakage	cold chain indicators for logistics	"2) Logistics information processing" ... "Data processing error" ... "Manual operation error" ... "Communication error" ... "Technical problem – data leakage" [60]

Table B.16: Coding of Secondary Studies Part 16

ID	Code	Note	Quote & Reference
10	sanitary conditions of storage area, temperature and humidity control, storage space control, security control, inbound / outbound operations	cold chain indicators for warehousing	"3) Warehousing" ... "Sanitary conditions of storage area" ... "Temperature and humidity control" ... "Storage space control" ... "Security control" ... "Inbound/outbound operations" [60]
10	equipment sanitation, pre-cooling equipment failure, temperature and humidity control, loading and unloading operations, cargo monitoring, extreme weather, security control, traffic congestion, transportation equipment malfunction	cold chain indicators for transportation and distribution	"4) Transportation and distribution" ... "Equipment sanitation" ... "Pre-cooling equipment failure" ... "Temperature and humidity control" ... "Loading and unloading operations" ... "Cargo monitoring" ... "Extreme weather:" ... "Security control" ... "Traffic congestion" ... "Transportation equipment malfunction" [60]
10	risk level	transportation and distribution are high risk	"If the vaccine cold chain risk level rises to 100%, 21% is found to be in the high risk level for the processing and packaging category, 34% for logistics information processing, 28% for warehousing and 46% for transportation and distribution." [60]
10	processing error, inbound / outbound operations, temperature, humidity, posterior probability	risk factor areas to improve	"Among all the elements, the data processing error (LIP1), inbound/outbound operations (WD5) and temperature and humidity control (TD3) had a larger posterior probability." [60]

Table B.17: Coding of Secondary Studies Part 17

ID	Code	Note	Quote & Reference
11	time to market, risk level	fast delivery and low risk	"The usage of DTs in numerous domains is explained by the accelerated time to market and decreased risk [10]." [61]
11	cost, waste, efficiency	factory DT improvements	"In addition, the pharmaceutical industry is using factory DTs to find process improvements that will increase efficiency, reduce costs and waste." [61]
11	fault repair time, fault cost, effort to repair fault	reduced faults	"With the help of DT technology, any asset can be cost-free evaluated in a range of test conditions, including damaging ones, hence enabling faults' fixing more quickly, cheaply, and easily." [61]
11	amount of resources, cost of processing, cost of maintenance	reduced usage and spending	"As a result, fewer resources are being used and the entire cost of processing and maintenance is much reduced." [61]
11	system complexity	complex systems limit DTs	"Also, it is commonly known that complex systems, particularly ones that include societal components, represent a problem when trying to simulate interdependencies and emergent features." [61]
12	level of collaboration	stakeholders have different skills	"Even though in the different phases (design, construct, integrate, operate, maintain) of these projects several stakeholders are working collaboratively, there are rare occasions where they all come together." [64]
12	level of interest in data, value of stakeholders, value of domains, value of disciplines	not all components are compatible with one another	"However, different data are of interest and value for different stakeholders, domains, disciplines at different phases of the systems' life cycle." [64]
12	purpose applicability	difficulty in define purpose leads to short term solutions	"it is very difficult to create an overarching purpose, which is common for all of the stakeholders, and even includes future generations." [64]
13	total layer, hidden layer, number of neurons, number of input delays, number of feedback delays	hyperparameters for neural network predictions	"• Number of total layers • Number of hidden layers • Number of neurons • Number of input delays • Number of feedback delays" [66]

Table B.18: Coding of Secondary Studies Part 18

ID	Code	Note	Quote & Reference
13	hidden layer, network efficiency	underfitting & overfitting affecting efficiency	"Selection of a hidden layer in a neural network is a challenging task because the network might overfit or underfit data which can affect the efficiency of the network badly [17]." [66]
13	mean square error, sum square error, mean absolute error	performance matrices of network	" • Mean square error (MSE) • Mean absolute error • Sum square error" [66]
13	mean square error, mean absolute error, standard deviation	condition indicators for system health analysis	"Condition indicators are important because they help to identify the difference between healthy and faulty data." ... " • MSE • Mean absolute error • Standard deviation" [66]
13	threshold level, threshold	anomaly detection threshold	"If the performance of the physical system exceeds the threshold, that should be taken as an alert." [66]
13	availability of real data, network performance	effects on neural network performance	"If the real output from the system is available for training, series parallel architecture can be used for training because real data will be used instead of estimated output from the network for training which can improve the network performance [24]." [66]
13	performance accuracy	using real data improves accuracy	"The performance of the Digital Twin against the real operation of the physical system was highly accurate because real data were used for training." [66]
14	context acquisition, processing, acting	context aware CPS system	"i) context acquisition (using sensors for collecting low-level contextual information); ii) processing (applying reasoning methods for obtaining high-level contextual information); iii) acting (automatic execution of services and actions after context detection) [32]." [69]
14	objective	context grading map	"Phase 1: For each objective (e.g. safety, maintenance, nominal, high throughput operations) a context map is calculated." [69]
14	visual feedback	feedback grading scale for metric types	"Phase 2: Once these maps are available, the process is evaluated online with visual feedback information." [69]

Table B.19: Coding of Secondary Studies Part 19

ID	Code	Note	Quote & Reference
14	instrumentation failure	action taken based on failure	“: if an instrumentation failure is present, the green bullet is no longer achievable, and the context map to be further used for decision-making process should be the one for safety or for maintenance operation conditions.” [69]
14	computational cost	computed settings for fast systems	“These controller settings are apriori computed based on various predefined contexts - this reduces significantly the real time computational costs making it a viable solution for fast acting systems [37].” [69]
14	simplicity of model	model simplicity reduces costs	“Alternatively, if simple models are used instead, the effort shifts towards the design of the controller and optimization cost functions.” [69]
14	carbon footprint, water footprint, number of jobs, total cost	food sustainability	“This approach allows the simultaneous consideration of all three dimensions of sustainability including carbon footprint, water footprint, number of jobs created and the total cost of the supply chain design.” [69]
14	context awareness, industry flexibility	result of increased efficiency and productivity	“Aiming efficiency and productivity increase in manufacturing industry, several works imply context awareness, especially in flexible manufacturing systems, such as pharma industry [84].” [69]
14	fuel consumption, vehicle emission	fuel consumption	“The analyzed safety and ADAS oriented models are linked also to the objective of fuel consumption efficiency in vehicles, as many context properties are found to have significant effect on emissions.” [69]
14	temperature, humidity, light level, number of satellites, soil type, gas level, time of day, classification accuracy	classification techniques	“Therefore, are used inputs such as temperature, humidity and light, number of satellites (from GPS), soil type (from inertial measurement unit (IMU)), gas level and time (day/night). The obtained classification accuracy was 87.5%.” [69]

Table B.20: Coding of Secondary Studies Part 20

ID	Code	Note	Quote & Reference
14	throughput, level of data integration	better output when integrated through the use of AI	"Multi-agent artificial intelligence algorithms applied to wind farm throughput optimization seems to be better positioned when data and structural features are integrated [134]." [69]
14	energy reduction, energy efficiency, energy productivity	adaptive technologies improve sustainability	"As energy consumption is also an issue in industry, adaptive plants have proved to achieve a reduction in energy, but also a greater efficiency and productivity of the processes." [69]
14	density of material, contamination level	changes in climate	"Climate change effects can be assessed by detecting changes in the density of the water/ice/silage/etc and measure contamination to determine affected area." [69]
15	node coordinates, associated links, directed path, vehicle position	algorithm for map matching	"Coordinates of nodes (Ai) and associated links (li) along the directed path or network, subject vehicle's position (P), shown as Fig. III-B." [70]
15	distances to merging-point, current speed, advisory speed, speed limit, elapse time	algorithm for vehicle ram merging	"1. Distances to Merging-point (D2M) and 2. Current Speeds (v ci) of the three vehicles. 3. Advisory Speed (v ai). 4. Speed Limit (L). 5. Elapsed Time (t)." [70]
15	longitudinal position, vehicle speed, activation time	initial state of vehicle	"Specifically, the initial states of the vehicles are defined as what the longitudinal positions and speeds are when the vehicles first activate the motion controller at time t0 ." [70]
15	latitude, longitude, altitude	module to measure vehicle position	"GNSS: This module is equipped on the vehicle to measure its real-time raw position (latitude, longitude and altitude) and speed information" [70]
15	current speed, advisory speed, speed limit, latitude, longitude	module to advise and measure vehicle speed	"As shown in IV-B, the information displayed on the HMI include current speed (the left number), advisory speed (the right number), speed limit, and some other additional messages (e.g., latitude and longitude, IP address)." [70]

Table B.21: Coding of Secondary Studies Part 21

ID	Code	Note	Quote & Reference
15	update frequency, speed, distance trajectory, fuel consumption, vehicle emission	performance evaluation parameters	“With a certain update frequency, this module evaluates the speed and distance trajectories, as well as the fuel consumption and pollutant emissions of all connected vehicles.” [70]
15	distance between vehicles, constant speed	distance to merge	“During 0 – 8 seconds in V-B, RV accelerates to close its gap with the string on the mainline, and MV1 and MV2 keep a relative constant speed.” [70]
15	speed variance	reduced speed reduces accidents	“Since the accidence rates increase with increased speed variance for all classes of roads [30], a safe merging environment can be created by reducing the speed variance.” ... “The results show a reduction of 67.41% in terms of average speed variance, proving that the cooperative merging approach is safer than the baseline scenario.” [70]
15	fuel consumption, vehicle emission	reduced emissions	“A reduction up to 31.21% in pollutant emissions and a reduction of 7.45% in fuel consumption can be obtained after implementing the proposed model comparing to the baseline, respectively.” [70]
15	communication delay	communication	“Since the target vehicle is designed to reply immediately, when the ego vehicle receives the reply message and at time t2 , the communication delay is calculated as t2-t1 .” [70]
16	product quality, customer satisfaction	product design	“Through product serialization data management, under the presumption of ensuring the basic universal functions of the product, the manufacturer can develop variant products, improve quality, and increase customer satisfaction in response to market trends and specific consumer needs.” [71]
16	bill of material, process time	DT model allows for quick assessment	“The model includes the appearance of a “3-D design model” and the kernel of “product manufacturing information + bill of material (BOM),” which allows for reasonable production process planning.” [71]

Table B.22: Coding of Secondary Studies Part 22

ID	Code	Note	Quote & Reference
16	customer needs	domain knowledge	"the data generated by the data twin is more useful for enterprises to investigate the overall customer needs." [71]
16	procurement data management level, price, delivery, quality	supply chain management	"The procurement data management level will directly impact enterprise performance. There are the following three fundamental procurement objectives: price, delivery, and quality." [71]
16	stock safety, amount of money, procurement risk	DT utilization	"The manufacturer can deal with the disturbance of external factors in a reasonable manner, reduce the safety stock, save money, and reduce the procurement risk." [71]
16	defect rate	DT utilization	"By accessing quality data, such as tool wear, geometric measurements, and machining parameters, the digital twin can define acceptable ranges for key quality indicators, provide intelligent quality control, and reduce defect rates." [71]
16	data growth, frequency of use, usage conditions, equipment use	operational status	"This type of data consists primarily of time-series data, which are generated on a periodic or quasiperiodic basis and grow rapidly. Usage data include information, such as the frequency, conditions, and methods of equipment use." [71]
16	platform size, platform change	adjustability	"When the overall size of the platform changes, the size of each component must be adjusted proportionally to ensure the platform's normal operation." [71]
17	energy usage	sustainable housing	"Currently, because of the reasons listed in the introduction, it is not able to predict a fair energy usage policy for the apartments." [79]
17	average temperature, EPC rating, floor area, average number of guests, average energy usage	sustainable housing	"The features presented for learning were: average temperature (temperature), number of rooms, EPC rating (EPC), floor area, community heating (community), occupancy, average number of guests per day (num guests), average guest energy usage profile (guest profile)" [79]

Table B.23: Coding of Secondary Studies Part 23

ID	Code	Note	Quote & Reference
17	linear regression accuracy, energy consumption	linear regression and MLP	"The results are shown in Fig. 4. The results confirm that there is a nonlinear correlation between input variables and energy usage in the apartments as the accuracy for Linear Regression is consistently lower (0.09-0.52) compared to accuracy for MLP Regressor (0.51-0.91)." [79]
17	temperature, EPC rating	top features for sustainable housing	"the top three features found by both ML methods are: temperature, EPC and guest profile, showing that they successfully identify the key factors in the model" [79]
18	equipment performance, energy consumption, environmental pollution	prediction	"The bulk handling industry faces many challenges on the way to "smartness", including varying operational conditions and design restrictions that result not only in a deviation from the nominal equipment performance but also cause unnecessary extreme energy consumption and environmental pollution." [80]
18	adaptability	scale between discrete and continuous	"The adaptability can be explored for a single operational condition or as a compilation of multiple properties." [80]
18	material shape, material size	geometric properties of materials	"An improvement of the performance may result from a change of shape or size." [80]
18	adaptability score, feasibility, continuousness	adaptation grading	"Next, score values in a column are summed to determine the total score of each adaptive solution, in terms of feasibility and continuousness." [80]
18	geometry modification, fluidization, vibration, deformable structure, system control	adaptability grading categories	"Table 2. Adaptability evaluation matrix: determining feasibility and continuousness of available adaptive solutions" [80]
18	level of maturity	some sensors not used	"Therefore, sensor-based measurement systems should be further investigated to reach a sufficient level of maturity for implementation in industrial applications." [80]

Table B.24: Coding of Secondary Studies Part 24

ID	Code	Note	Quote & Reference
18	process efficiency, payload volume, payload density	Example of implementation strategy	“a dragline excavator is equipped with an integrated sensor-control system with optical sensors to enhance the process efficiency as well as obtaining value information about the performance, such as the payload volume and density.” [80]
18	dig performance, blast performance, bucket size selection, production downtime	Example of implementation strategy	“the digging area provided 1) a reliable assessment of dig and blast performance, 2) an improved bucket size selection, and 3) decreased production downtime” [80]
18	cable strength	Example of implementation strategy	“However, if the configuration of the operating ropes/cables are unknown or the related sensor system has high uncertainties or faults,” [80]
19	model performance, model robustness	living model	“In case that the performance of the living model starts to deteriorate, the framework will start model transfer by applying the corresponding techniques in order to enhance the performance and maintain the robustness of the living models.” [81]
19	performance quality, system changes, wheel material change, environment change	performance deterioration	“It is highly possible that the performance deterioration is contributed: by (1) WILD system changes, (2) wheel materials changes, and/or (3) operational environments’ changes.” [81]
19	sensor quality, sensor reliability	decrease performance due to more accurate sensors	“Then, the only difference is due to the fact that the WILD sensor quality and reliability have been improved.” [81]
19	distribution shift	linear search method	“We applied a simple and straightforward method, the linear search, to explore the shift relationship between two datasets With the linear relationship, we transformed the 2016 data back to the 2001 data to minimize the distribution shift.” [81]
20	financial, social, governance, productivity	manufacturing	“Financial, environmental, social, and governance factors are important indicators that can be used in understanding productivity in manufacturing” [84]

Table B.25: Coding of Secondary Studies Part 25

ID	Code	Note	Quote & Reference
20	water use, waste generation, quality of life	manufacturing	"This includes factors such as water use and waste generation in production processes, along with company policies that affect employees' quality of life." [84]
20	productivity, availability, financial quality, environmental footprint	manufacturing	"The research shows that embracing the trilemma of productivity, availability, and quality (proclaimed as financial) toward sustainable, resilient manufacturing companies can improve their environmental footprint." [84]
20	market demand, market flexibility, capital, labor hours	general developments	"This includes volatile markets demanding more flexibility in using resources like capital expenditure or labor hours." [84]
20	adaptability	integrating AI	"Utilizing AI at this level improves the adaptability of digital twins, which can dynamically change the boundary conditions at the factory floor level" [84]
20	scalability, accuracy	integrating AI	"A lightweight model equipped with these types of software could be used during rapid scaling up periods. This way, fast insights can be gained without sacrificing accuracy." [84]
20	installation cost	sensor cost	"Nevertheless, this increases the installation cost because there must be an external source for each type of sensor attached on top of the machinery." [84]
20	number of features, component variation, data points, mean value	component analysis vs clustering	"Principal component analysis helps to reduce the number of features while preserving variation, whereas clustering reduces data points by summarizing several points into their expected or mean values (in the case of k-means)." [84]
20	mood	production planning and control	"These models allow forecasting what someone might do based solely on their current state/mood without any input about personal preferences." [84]
20	product quality, product assembly efficiency	quality control	"Various computer vision models have been used [26] to address quality issues and efficiency in the assembly of products." [84]
21	type of input protocol	connection management	"In particular, it will provide a setup regarding the following parameters: type of input protocol, normalization of output data, connection policies (privacy, security, authentication protocols, etc." [85]

Table B.26: Coding of Secondary Studies Part 26

ID	Code	Note	Quote & Reference
21	latency	low latency between DT and real world	“In these application scenarios, a DT Network (DTN) uses advanced networking technologies to support low latency interactions between DTs as well as, of course between the physical objects and their digital counterparts.” [85]
21	layer	layered network protocols	“Such approach moves the focus from application layer logic to network layer mechanism.” [85]
22	model integration complexity	application layer	“In the proposed MCDM method, trapezoidal fuzzy number (TFN) is introduced into AHP for the determination of indicator value, which is abbreviated as TFN-AHP; the indicator importance degree is determined by the integration of complex networks modeling and PROMETHEE II” [87]
22	evidence combination taking indicator value, indicator importance degree	indicator system	“According to the two-tier indicator system of SAoIM, the sustainability of intelligent manufacturing projects is assessed by two-stage evidence combination taking indicator value (phase 1) and indicator importance degree (phase 2) as input data.” [87]
22	environmental effects, social effects	ecological environment, human health, social effects on users and employees	“The influence factors of SAoIM mainly include general environmental effect, social effect on employees and social effect on users based on the summary of the existing research.” [87]
22	object quality	comparison scale from 1-9 for TFN	“TABLE 2. The transformations from traditional nine-level comparison scale to modified nine-level comparison scale by TFN.” [87]
22	consistency	consistency test	“Then consistency test is carried out. E (1,1) , E (1,2) , E (1,3) and E (1,4) are mapped into real number matrices DV (1,1) , DV (1,2) , DV (1,3) and DV (1,4) .” [87]
22	result reliability	model comparison	“The most common means of assessing the reliability of the result is to compare it with other similar models.” [87]
22	design quality, large area	model ranking alternative indicators	“while alt. 8 and alt. 7 are the top two alternatives and alt. 1 and alt. 5 are the last two alternatives.” [87]

Table B.27: Coding of Secondary Studies Part 27

ID	Code	Note	Quote & Reference
22	entropy method, indicator importance	indicator importance degrees	"It can be seen from Table 26 and Fig. 5 that in the process of calculating the indicator importance degree by entropy method, the importance degrees of all indicators are relatively average." [87]
22	error rate, level of accuracy	indicator values	"The error of accurate scoring method is large, which cannot truly reflect the judgment intention of the expert group." [87]
23	number of data logs, time slots	data collection function	"total number of data logs generated from the sensing tasks of device n in T time slots" [89]
23	energy supply over time, number of devices	recharge rate	"the time horizon with stable energy supply is divided into multiple stages 1, 2, ..., K with T time slots." ... "the energy replenishment at the beginning of any stage constantly supports the basic functionalities of all physical devices" [89]
23	number of devices	amount of devices	"We extend traditional DT cases to industrial DT platforms with a large-scale deployment of IoT devices (i.e., a large N) and study the data sensing policy of devices in the system." [89]
23	energy debt, energy consumption	energy supply rate to number of devices	"the maximum energy debt with respect to the energy consumption process of devices can be depicted by" [89]
23	amount of energy	loss of energy leads to operation problems	"It can be easily found that if Q is greater than B, the system will encounter energy depletion, which may cause severe operation problems, and devices would not be able to work correctly and provide the expected sensing data for DT services." [89]
23	amount of energy, data accuracy	information loss reduction	"With Theorem 1, we know that the energy supply of the system significantly impacts the data fidelity of DT models." [89]
23	reveal delay, generation time	generation time to current time	"The reveal delay of a time slot is characterized by the time spanning from the generation time of the most recent collected log to this time slot at any agent." [89]
23	weighted-sum, throughput constraints, number of sensing tasks, collection time	P2 optimization aims	"In P2, the optimization goal (28a) aims to minimize the weighted-sum reveal delay of all devices in a stage, and (28b) shows the collection throughput constraints for all devices, where the expected collection times should be greater than the expected number of sensing tasks in any stage." [89]

Table B.28: Coding of Secondary Studies Part 28

ID	Code	Note	Quote & Reference
23	packet latency, update frequency	data transfer	"However, with a fixed arrival delay, the AoI of a data packet in their formulation is completely determined by the information collecting strategy of the agent, which cannot reflect the fundamental updating frequency of information source, i.e., the data generation process of sensing tasks." [89]
23	reveal delay, max-weight-delay, performance acceptability	offset reveal delay	"To minimize the expected reveal delay with the requirement on the times of data collections" ... "we leverage the max-weight-delay (MWD) policy to solve P2, and the performance should satisfy Lemmas 1 and 2." [89]
23	energy supply, data fidelity	energy sustainability	"In time slot t = 0, according to the popularity profiles and the energy policy of the system from the request chain, the sensing policies of devices are set to improve the weighted data fidelity while guaranteeing the sustainable energy supply." [89]
24	continuous-time, discrete-time	model calculation	"Modeling in Modelica of both continuous-time and discrete-time aspects of systems is possible in an integrated way." [90]
24	clocked discrete-time, precision, performance	modeling and simulation	"From Modelica language version 3.3 and later modeling using clocked discrete-time constructs is also supported for increased modeling precision and simulation performance." [90]
24	code efficiency	model code	"Models are compiled to efficient C or C++ code." [90]
25	number of material captured, amount of energy captured	quantity and quality	"The product cascade methodology requires capturing flows of materials and energy along the entire PLC from cradle to cradle." [96]
25	carbon emission, material quality	case study	"Extending the life cycle of individual parts of a car (up to a certain point in time) can help reduce CO2 emissions, since repairing vehicles with parts that are still intact or repaired spare parts saves considerable resources (e.g. steel, aluminum, critical raw materials, etc.)." [96]

Table B.29: Coding of Secondary Studies Part 29

ID	Code	Note	Quote & Reference
25	energy payback time, life-cycle performance	energy efficiency	"Wind turbines are known for their short energy payback time and good life cycle performance since they generate energy from wind as renewable energy source." [96]
26	process performance, productivity, sustainability	process evaluation	"In general, process performance is evaluated based on its productivity (e.g. optimal cycle time) and sustainability (i.e. low energy consumption) [20]." [97]
26	sustainability performance, energy consumption, productivity	sustainability evaluation	"Thus, with the implemented architecture, the station sustainability performance in terms of energy consumption and productivity (i.e. cycle time) is evaluated." [97]
26	weld current, cycle time	base metrics	"The parameters (X) are considered to be influencing energy consumption for this case study are the welding current (WC) and the cycle time (CT)." [97]
26	clamp time, weld time, release time	cycle time metrics	"Cycle time includes the clamping time, welding time and release time." [97]
27	energy usage, years to change energy sector	high energy demands	"The energy sector will be shaped by this unexpected situation and the stimulus packages applied by the governments for the next years, significantly affecting the energy industry at large, clean energy, and energy security transitions." [98]
27	amount of revenue	high cost strain and revenue loss	"The financial impact is felt in the biomass energy industry across the value chains, in which most of the energy companies lost considerable revenues." [98]
27	amount of investment, time to normalize energy demand	insecure energy and low investment	"The COVID-19 crisis along the biomass energy sector will significantly affect the investment, raising concerns about energy security due to the necessity of investment even if it takes a long time for the global energy demand to return to the trajectory before the crisis." [98]
27	manufacturing capacity	exploration of manufacturing capacity	"Hence, different mechanisms and options should be explored to improve the manufacturing industries' capacity." [98]

Table B.30: Coding of Secondary Studies Part 30

ID	Code	Note	Quote & Reference
27	energy, capacity, amount of skilled workers, amount of capital, amount of research	renewable energy limitations	"1) immature renewable energy supply chains, 2) ambiguity in the actual capacity of renewable energy, 3) the absence of skilled workforce and capital, and 4) the deficiency of the research & development (R&D) projects." [98]
27	tax rates, worker performance	measured to boost manufacturing	"Such options might involve tax deduction and grants for investments in R&D projects, performance-based financial awards from different financial resources without the need for any repayment." [98]
27	income tax	more measures to boost manufacturing	"Similarly, some other measures could also be taken into account, for instance, lowering the income tax for selling power generated by renewable energy technologies locally produced, giving financial subsidies to power produced with locally-made renewable energy technologies, etc." [98]
27	job safety, job security	waste management	"Solutions based on technology, including the automated processes of waste valorization (e.g., gasification, pyrolysis, and hydrothermal carbonization), promise to provide by-products of high quality while ensuring that the staff involved have maximum safety and job security." [98]
27	carbon emission	emission reduction	"Global CO2 emission is expected to reduce in 2020 significantly, but ongoing efforts and commitment are needed towards a sustainable energy pathway." [98]
27	global temperature	temperature	"It is imperative to be ambitious and strategic and act decisively to make the shift structurally required to fulfill the agenda for sustainable development in 2030 and preserve 1.5 °C degrees of global warming." [98]
27	cost increase, job creation	price and amount of jobs	"Public finances alone would not accept the burden significantly as costs increase and technologies continue to develop. Notably, there will be a fast job creation due to stimulus investments." [98]

Table B.31: Coding of Secondary Studies Part 31

ID	Code	Note	Quote & Reference
27	worker skills	retain skilled workers	"The programs could also support the retention of fossil-fuel workers with reoriented skills for the energy transition." [98]
28	number of services, number of functionalities, customer demand	product-service system improvements	"The easiest one with immediate results was to create new services and functionalities leaning on the actual product to meet the increasing customer demands." [100]
28	system integration, product value	product-service system improvements	"The second one was to develop new adapted solutions that integrate products and services in a new system that offers more value to the customer." [100]
28	product outcome, product performance, product usage, product experience	product design	"Users at both B2B (Business to Business) and B2C (Business to Customer) levels need outcomes, performances, utility of using the products and a good experience in terms of sustainability (economic, environmental, and social)." [100]
28	functionality, availability, result delivery	IPS2 characteristics	"IPS2 can be characterized by a spectrum of the degree of the provider's commitment to the customer: function-, availability-, and result-oriented businesses [125]." [100]
28	daily usage charge, contract availability, performance level	performance penalties	"For instance, Hitachi Rail has moved towards contracts for, e.g., 20+ years where Hitachi Rail manufactures and owns trains and the operators pay a daily usage charge [226]: these contracts are based on availability with associated possible penalties (in case the performance is not reached)." [100]
28	process efficiency, product value	product integration incentives	"Integrating products and services with IPS2 by design can be regarded also as attempts to increase efficiency (and thereby value)." [100]
28	environmental impact	reduce physical transport	"for instance, an IPS2 including services effectively using information from machine-to-machine communication networks reduced the need for physical transports and thereby the environmental impacts [92]." [100]

Table B.32: Coding of Secondary Studies Part 32

ID	Code	Note	Quote & Reference
28	uptime, price, fuel efficiency, plant optimization, location tracking	scania product-service systems portfolio	“1) fleet management including uptime guarantee with a fixed price called Fleet Care, 2) tailor-made partnership aiming to maximise the fuel efficiency of the fleet called Ecolution, 3) plant optimization giving consultancy service to sites for construction or mining that involve transport by trucks, and 4) a position-based service for automatic vehicle adjustment” [100]
28	uptime, output	customer value	“The service-based solutions (C1) at Siemens Energy providing higher customer value such as uptime, improved output, and hassle-free operation were initiated in the 1980s.” [100]
28	quality, cost, downtime	contract maintenance	“Such upkeep contracts are often based on corrective maintenance using prior experience, resulting in lower quality, higher cost and longer asset downtime for maintenance.” [100]
29	user satisfaction	DT user enhancement	“With regard to the service phase, DT-II enables to enhance users’ satisfaction.” [101]
29	production efficiency	real-time schedule interactivity	“While conducting formal mass production, real-time scheduling can be implemented based on the interactive iterations among physical shop-floor, virtual shop-floor in production service systems, so as to improve production efficiency.” [101]
29	product quality, energy optimization	DT factory achievements	“In addition, product quality control and energy optimization in a factory can also be achieved under the circumstance of DT-II.” [101]
29	materials, processing capability, cost, design effectivity, production capability	design phase capabilities	“In product design phase, considering the feasibility of subsequent manufacturing, including material, processing capability, cost, etc., quick and effective design can be carried out based on the production capability of upstream and downstream enterprises.” [101]
29	time to market, level of experience	implementation mechanism in product lifecycle level	“taking account of the data of product function definition, market requirement, user review, time to market, performance requirement and the designers’ own experience.” [101]

Table B.33: Coding of Secondary Studies Part 33

ID	Code	Note	Quote & Reference
29	performance, evaluation	evaluation of product performance	"The performance of the product prototype is further evaluated in this process." [101]
29	product health, user experience	habits and experience with product	"This part is mainly to obtain a variety of product states and users' usage habits to achieve product health maintenance, function upgrade, operating guidance, thus providing users with a good experience." [101]
29	design period, design quality	turbine design	"The DT-II can be used in steam turbine design to shorten design period and improve design quality, because it embraces the data from the steam turbine lifecycle, which can be transformed into knowledge to enhance the design of next-generation steam turbine." [101]
29	equipment failure	design durability	"The information with regard to equipment failure and maintenance, for example, abnormal vibration and oil system trouble, is essential for finding the design weaknesses and optimizing material choice, parameter determination and structure design." [101]
29	production time, production costs, production efficiency	time to market	"so as to shorten production preparation time and production period, reduce production cost, improve production efficiency and steam turbine processing quality." [101]
30	skills, cost, learning rate, ergonomic risks, rest, age	human factors	"The papers considering the human factor are mentioned by the following metrics: Skills (Sk), Cost (Co), Learning rate (Lr), Ergonomic risks (Er), Rest (Re) and Age (Ag)." [102]
30	energy consumption, carbon emission, noise emission	environmental factors	"Papers taking into account the environmental factor are specified in the "Environmental factor" column by the following parameters: Energy consumption (Ec), Carbon emission (Ce), Noise emission (Ne), or Recycling (Re)." [102]
31	carbon	carbon	"CO2 is a vital medium for carbon cycling worldwide." [103]
31	carbon monoxide	carbon monoxide	"The results suggested an 80% reduction in Carbon Monoxide (CO) by 2050." [103]

Table B.34: Coding of Secondary Studies Part 34

ID	Code	Note	Quote & Reference
31	energy consumption	energy model for schools	"Lizana, Serrano-Jimenez, Ortiz, Becerra and Chacartegui (2018) provided a new energy model to assess school buildings' actual energy properties and potential energy consumption, minimizing input information acquisition." [103]
31	building performance, implementation accuracy	low carbon building design	"Innovatively, they used a coherent set of hypotheses and routines about the school's boundary conditions, derived from its modular base, typical architectural appearance, and space use, and an iterative demarcation operation of the model based on actual building performance. Finally, high accuracy was achieved." [103]
31	energy consumption, environmental pollution	LCE transition	"The empirical results showed that with limited per capita environment resources, China's carbon transaction mechanism was positively correlative to the transition to an LCE." [103]
31	carbon price	climate tax	"Carbon pricing, in the form of taxes or emissions trading schemes, is often seen as the primary or only necessary climate policy tool that will see diffusion and marketizing" [103]
31	power generation	renewable energy promotion	"Moreover, they could expand renewable energy generation, optimize power generation processes, strengthen monitoring and supervision, and promote generation rights and carbon emissions trading." [103]
31	construction efficiency, waste reduction, environmental impact	building material quality	"improving the construction efficiency and reducing waste and environmental impact over the life of the building." [103]
31	processing efficiency, energy consumption	carbon policy outcome	"Doing so could significantly reduce the number of empty knives, improve processing efficiency, and reduce energy consumption." [103]
31	temperature	climate control	"Based on the above review, it is critical to control climate change to contain global warming (within $2 \circ$C and $1.5 \circ$C)." [103]

Table B.35: Coding of Secondary Studies Part 35

ID	Code	Note	Quote & Reference
32	process quality	implementation challenges	"(c) a Quality assessment monitoring, able to aggregated characteristics from machine learning and control output," [104]
32	productivity	implementation challenges	"(d) running a set of what-if-scenarios boosting productivity" [104]
32	level of integration	implementation challenges	"(e) the control generation which will generate the signals that will drive the machine actuators. It is noted that the control is able to integrate various criteria, such as KPIs tracking" [104]
32	model usability	implementation challenges	"Uncertainties could be integrated [10] also extending the usability of the models." [104]
32	laser power, scan speed, melt-pool length	process perimeters	"laser power and the scan speed and the targeting KPIs are considered to be the peak temperature and the melt-pool lateral dimension (length)" [104]
32	temperature, melt-pool length	ANN characteristics	"The process parameters of the design space are imported as inputs to the DT-FR then KPIs (temperature or melt-pool length) are predicted, as shown in Fig. 5." [104]
32	simulation time	DT inverse design	"This issue can be resolved with more time-consuming simulations resulting to a considerable dataset." [104]
32	number of layers, number of hidden nodes, number of epochs, learning rate	real-time prediction	"After some trials with respect to the number of layers, the hidden nodes, the number of epochs and the learning rate, the resulted training parameters are shown in Table 1." [104]
32	R-squared, accuracy, testing performance	real-time prediction	"Therefore, the metric R-squared (R2 – Accuracy (%)) is adopted from regression analysis to compare the testing performance." [104]

Table B.36: Coding of Secondary Studies Part 36

C

Appendix 3

C.1 Themes of Secondary Studies

Theme	Codes
Performance	performance, throughput, sustainability performance, number of bottlenecks, utilization rate, throughput per hour, efficiency, capacity, material efficiency, energy efficiency, process effectivity, accuracy, consistency, degree of information integration, performance of algorithm, lag order, degree of difference, size of moving average, current speed, advisory speed, speed limit, average speed of trip, data meaningfulness, result similarity, model accuracy, feedback rate, vehicle speed, maneuver mobility, system performance, communication accessibility, speed of information, speed tracking error, vehicle acceleration, packet loss, communication delay, data processing error, manual operation error, communication error, technical problem, system complexity, total layer, hidden layer, number of neurons, number of input delays, number of feedback delays, network efficiency, threshold level, threshold, availability of real data, network performance, performance accuracy, computational cost, level of data integration, associated links, update frequency, defect rate, platform size, platform change, equipment performance, process efficiency, payload volume, payload density, dig performance, blast performance, production downtime, model performance, model robustness, scalability, product assembly efficiency, weighted-sum, throughput constraints, packet latency, update frequency, max-weight-delay, performance acceptability, code efficiency, life-cycle performance, process performance, manufacturing capacity, product performance, functionality, performance level, plant optimization, production efficiency, processing capability, design effectivity, production capability, building performance, implementation accuracy, construction efficiency, processing efficiency, level of integration, R-squared, testing performance, speed, constant speed, speed variance, laser power, scan speed

Table C.1: Themes of Secondary Studies Part 1

Theme	Codes
Environmental	weight, amount of scrap, amount of power consumed, energy cost, amount of material consumed, amount of energy consumed, emission level, amount of waste, amount of resources, amount of resources utilized, amount of material, energy emission per part, amount of energy saved, energy awareness, number of resources, herbage mass, dry matter, forage availability, herbage mass availability, weight of herbage mass, size of pasture, size of dry matter, maneuver environmental sustainability, energy consumption, vehicle emission, fuel consumption, carbon footprint, water footprint, light level, gas level, energy reduction, energy efficiency, energy productivity, density of material, contamination level, average energy usage, environmental pollution, water use, waste generation, environmental footprint, environmental effects, energy debt, energy supply, carbon emission, sustainability, energy usage, energy, fuel efficiency, environmental impact, output, energy optimization, materials, noise emission, carbon, carbon monoxide, carbon price, power generation, waste reduction
Process	type of work procedure, process complexity, completeness, difficulty of operation, consistency of situation, actuation guidance, risk level, purpose applicability, industry flexibility, market demand, market flexibility, result delivery, contract availability
Quantity	amount of storage space, amount of data, amount of tasks, amount of forage, number of livestock, amount of sampling, available grass cover, total grass cover, amount of fresh grass, amount of compression, number of satellites, data growth, floor area, average number of guests, number of features, large area, amount of energy, number of material captured, amount of energy captured, amount of revenue, amount of investment, amount of skilled workers, amount of capital, amount of research, number of services, number of functionalities, number of layers, number of hidden nodes, number of epochs, skills
Location	location of crime, direction of crime, latitude, longitude, measurement location, direction, position synchronization, longitudinal speed, node coordinates, vehicle position, directed path, longitudinal position, altitude, location tracking
Distance	trip distance, vehicle distance, road length, lane distance, distance trajectory, distances to merging-point, distance between vehicles, melt-pool length, distance trajectory
Temperature	temperature, temperature of measurement spot, product temperature, humidity, temperature and humidity control, average temperature, global temperature

Table C.2: Themes of Secondary Studies Part 2

Theme	Codes
Quality	quality, material type, quantity of components, amount of rework, quality, complexity, product quality, data quality, credibility, reliability, sustainability requirements, software design, visualization quality, programmability, compatibility, extensibility, reasoning complexity, prediction accuracy, level of camera coverage, LPR placement effectivity, grass type, connection strength, maneuver safety, sensed data, fused data, pre-processed data, road type, product quality, product safety level, interfacing quality, type of vaccine, data leakage, visual feedback, instrumentation failure, simplicity of model, soil type, classification accuracy, product quality, stock safety, frequency of use, usage conditions, equipment use, EPC rating, linear regression accuracy, material shape, material size, adaptability, adaptability score, geometry modification, fluidization, vibration, deformable structure, system control, level of maturity, bucket size selection, cable strength, performance quality, system changes, wheel material change, environment change, sensor quality, sensor reliability, distribution shift, financial quality, accuracy, component variation, model integration complexity, object quality, consistency, result reliability, design quality, error rate, level of accuracy, number of devices, number of data logs, number of sensing tasks, data accuracy, data fidelity, material quality, system integration, product value, product outcome, product health, design quality, equipment failure, process quality, model usability, precision
Time	processing time, availability, mean time to repair, setup time, scrap processing time, delivery time, lead time, time, rendering time, time of crime, change rate over time, time of trip, date of trip, start time, end time, vehicle travel time, discrete time, signal delay, available time, date, state of pasture, seconds, milliseconds, time to file report, time to market, fault repair time, time of day, elapse time, activation time, process time, labor hours, energy supply over time, time slots, reveal delay, generation time, collection time, continuous-time, discrete-time, clocked discrete-time, energy payback time, cycle time, years to change energy sector, time to normalize energy demand, uptime, downtime, time to market, design period, production time, simulation time, clamp time, weld time, release time

Table C.3: Themes of Secondary Studies Part 3

Theme	Codes
Financial	financial, price, cost, communication cost, implementation cost, fault cost, cost of processing, cost of maintenance, total cost, bill of material, amount of money, capital, installation cost, tax rates, income tax, cost increase, daily usage charge, production costs
Human	level of productivity, productivity, mood, effort spent, effort estimated, experience level, contribution type, sustainability effort, contribution, evaluation, experience, awareness, type of input, decision making capacity, driver's gaze, human behavior, handling of vaccine, effort to repair fault, level of collaboration, level of interest in data, value of stakeholders, value of domains, value of disciplines, number of jobs, context awareness, customer satisfaction, customer needs, quality of life, social effects, worker performance, job safety, job security, job creation, worker skills, customer demand, product usage, product experience, user satisfaction, level of experience, user experience, learning rate, ergonomic risks, rest, age, social, governance
Other	non-blocking files, quality-alert, critical issues ratio, well-defined issues jira, estimated ticket density, spent density, practical metric, decision-making metric, usefulness, scenario difference, probability of secondary errors, distribution density, grass height, height of dry matter, record update rate, difficulty rate, analytics methods, data strengths vs weaknesses, level of dataset diversity, data costs vs benefits, traffic light status, merging zone, influence zone, geo-fencing, weld current, dilution of vaccine, operation flow, sanitary conditions of storage area, pre-cooling technology, quality of packaging materials, packaging requirements, storage space control, security control, inbound/outbound operations, equipment sanitation, pre-cooling equipment failure, loading and unloading operations, cargo monitoring, extreme weather, traffic congestion, transportation equipment malfunction, processing error, inbound / outbound operations, posterior probability, mean square error, mean absolute error, standard deviation, context acquisition, processing, acting, objective, procurement data management level, delivery, procurement risk, feasibility, continuousness, data points, mean value, type of input protocol, evidence combination taking indicator value, indicator importance degree, entropy method, indicator importance, sum square error

Table C.4: Themes of Secondary Studies Part 4

D
Appendix 4

D.1 Remaining Themes of Secondary Studies

Theme	Codes
Performance	performance, throughput, sustainability performance, number of bottlenecks, utilization rate, throughput per hour, efficiency, capacity, material efficiency, energy efficiency, process effectivity, accuracy, consistency, performance of algorithm, lag order, degree of difference, size of moving average, current speed, advisory speed, speed limit, average speed of trip, vehicle speed, maneuver mobility, communication accessibility, speed of information, speed tracking error, vehicle acceleration, data processing error, manual operation error, communication error, technical problem, total layer, number of neurons, number of input delays, number of feedback delays, threshold level, threshold, availability of real data, network performance, performance accuracy, computational cost, associated links, update frequency, defect rate, platform size, platform change, equipment performance, process efficiency, payload volume, payload density, dig performance, blast performance, model performance, model robustness, scalability, weighted-sum, throughput constraints, packet latency, update frequency, max-weight-delay, performance acceptability, code efficiency, life-cycle performance, process performance, manufacturing capacity, product performance, functionality, performance level, plant optimization, design effectivity, production capability, building performance, R-squared, testing performance, speed, constant speed, speed variance, laser power, scan speed
Environmental	weight, amount of scrap, amount of power consumed, energy cost, amount of material consumed, amount of waste, amount of resources utilized, amount of material, energy emission per part, amount of energy saved, number of resources, herbage mass, dry matter, forage availability, herbage mass availability, weight of herbage mass, size of pasture, size of dry matter, maneuver environmental sustainability, energy consumption, vehicle emission, fuel consumption, carbon footprint, water footprint, light level, gas level, energy reduction, energy efficiency, energy productivity, density of material, contamination level, average energy usage, environmental pollution, water use, waste generation, environmental footprint, environmental effects, energy debt, energy supply, carbon emission, sustainability, energy usage, energy, fuel efficiency, environmental impact, output, energy optimization, materials, noise emission, carbon, car-

Theme	Codes
Quality	quality, material type, quantity of components, amount of rework, quality, product quality, data quality, credibility, sustainability requirements, software design, visualization quality, programmability, compatibility, extensibility, prediction accuracy, LPR placement effectivity, grass type, connection strength, maneuver safety, sensed data, fused data, pre-processed data, road type, product quality, product safety level, interfacing quality, type of vaccine, data leakage, visual feedback, simplicity of model, soil type, classification accuracy, product quality, stock safety, frequency of use, usage conditions, equipment use, EPC rating, material shape, material size, adaptability, adaptability score, geometry modification, fluidization, vibration, deformable structure, system control, level of bucket size selection, cable strength, performance quality, system changes, wheel material change, environment change, sensor quality, distribution shift, financial quality, accuracy, component variation, object quality, consistency, design quality, number of devices, amount of data logs, number of sensing tasks, data fidelity, material quality, product value, product outcome, product health, design quality, equipment failure, process quality, model usability, precision
Other	well-defined issues jira, estimated ticket density, spent density, practical metric, decision-making metric, usefulness, scenario difference, probability of secondary errors, grass height, height of dry matter, record update rate, difficulty rate, analytics methods, data strengths vs weaknesses, data costs vs benefits, traffic light status, merging zone, influence zone, geo-fencing, weld current, dilution of vaccine, operation flow, sanitary conditions of storage area, precooling technology, quality of packaging materials, packaging requirements, storage space control, security control, inbound/outbound operations, equipment sanitation, precooling equipment failure, loading and unloading operations, cargo monitoring, extreme weather, traffic congestion, transportation equipment malfunction, processing error, inbound / outbound operations, posterior probability, mean square error, mean absolute error, standard deviation, context acquisition, processing, acting, objective, procurement data management level, delivery, procurement risk, feasibility, continuousness, data points, mean value, type of input protocol, evidence combination taking indicator value, indicator importance degree, entropy method, indicator importance, sum square error

Table D.2: Remaining Themes of Secondary Studies Part 5