Integrating Circular Economy Principles into Systems Engineering Processes for the Construction Industry

MSc Thesis

Department of Construction Management & Engineering

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August, 2024

UNIVERSITY OF TWENTE.

ProcessMinded
Progress in Process

Preface

I am proud to share with you my master's thesis, the final achievement of my journey as a master's student in the Construction Management and Engineering department at the University of Twente. This research, which uniquely explores the integration of Circular Economy principles into the Systems Engineering processes for the construction industry, reflects my belief in the critical importance of innovative practices for the future of construction. It is a culmination of my desire to learn, grow, and contribute meaningfully to the future of the construction industry.

This research was conducted in collaboration with ProcessMinded, which was an enriching experience, and provided the ideal environment for carrying out this research. Their innovative approach and expertise in Systems Engineering allowed me to delve deeply into the subject's complexities. I am profoundly grateful to my supervisors and teachers from the University of Twente, Robin de Graaf and Marc van den Berg, for their invaluable guidance and support. I also sincerely thank Wilco van Roekel and Ruben Herrebrugh, my supervisors from ProcessMinded, whose practical insights were instrumental throughout my research.

I am deeply grateful to my family and friends, whose support has been the bedrock of my academic journey. Their love and encouragement have been my guiding light, helping me navigate through the toughest moments. In particular, I want to express my heartfelt thanks to my mother, whose unwavering belief in me has been a constant source of strength. As Nietzsche wisely said, "He who has a why can bear any how" and it is your support that has helped me bear every 'how' along the way.

Lastly, I hope this thesis contributes to the ongoing dialogue in improving construction practices and encourages others to push the boundaries of what is possible in our field.

Enjoy the read.

Abdulrahman Alyamani
Enschede, August 2024

Colophon

Title:
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Integrating Circular Economy Principles into the Systems Engineering Process for the Construction Industry

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Abstract

The construction industry faces significant challenges in resource depletion and waste generation, necessitating a shift towards more circular and sustainable practices. This study, conducted in collaboration with ProcessMinded, a consultancy firm specializing in Systems Engineering (SE) in construction projects, addresses these challenges by investigating the integration of circular economy principles into the SE process. Focusing on four key circularity principles: closing, narrowing, slowing, and regenerating the resource loops. The research develops a framework to guide the implementation of these principles across each step of the SE process: Project start, requirements analysis, functional analysis and allocation, design synthesis, and verification and validation. The methodology comprised a narrative literature review synthesizing diverse sources for the integration. This literature review informed the development of a structured framework organizing circularity integration for each SE step into inputs, actions, and outputs. The framework also includes practical examples for some actions to illustrate real-world applications. To validate the framework, semi-structured interviews were conducted with five experienced systems engineers from ProcessMinded. These interviews provided insights into the framework's strengths, potential improvements, and applicability of implementing the suggested actions within the framework in practice. The project start and verification steps showed particular promise for circularity integration, according to interviewees, while the design synthesis step emerged as more challenging. The resulting framework offers a systematic approach to integrating circular economy principles within the SE process, from project start through to verification and validation. It addresses the need for sector-specific, interdisciplinary approaches to circular economy implementation in construction, as identified in recent literature. This study contributes both to the theoretical understanding of circularity integration in SE and practical applications within the construction industry. It provides a foundation for further research and implementation of circular economy principles in construction projects through the lens of SE. Future research should focus on refining the application of the framework in diverse contexts, considering the iterative nature of SE and the varying levels of detail in the SE process and possibly addressing the challenges identified across different SE steps.

Contents

1 INTRODUCTION

1.1 Background

The construction industry faces challenges as projects grow increasingly complex and global sustainability concerns intensify. These challenges arise in construction projects due to multiple factors: the involvement of multiple disciplines, a high number of stakeholders, large-scale operations, extended lifespans and execution periods, intricate decision-making processes, significant environmental impacts, and associated risks (de Bruijn & ten Heuvelhof, 2018; Maylor & Turner, 2017; Qazi et al., 2016; Shen et al., 2010; Wood & Ashton, 2010). Simultaneously, the world struggles with resource depletion, excessive waste generation, and escalating environmental damage. The construction industry is a major consumer of resources and generator of waste, accounting for approximately 32% of the world's resources (Yeheyis et al., 2013), and finds itself at the center of these challenges, necessitating a paradigm shift in its practices.

In response to these challenges, two distinct but potentially complementary approaches have gained attention: Systems Engineering (SE) and Circular Economy (CE) principles. SE, with its origins in post-World War II mainly from defense and aerospace industries, offers a holistic methodology for managing complex projects (Ferris, 2007a, 2007b; N. U. I. Hossain et al., 2020; Reid & Wood, 2023). It emphasizes cross-disciplinary and transdisciplinary integration, continuous evolution, and adaptation to complex technical systems (Brook et al., 2024; Dykes et al., 2011; Mesmer et al., 2022; M. Watson et al., 2022; M. D. Watson et al., 2016). SE, which is seen as a comprehensive approach to managing complex systems, has gained notable momentum in the construction industry due to its ability to handle the challenges of complex construction projects (O. Hoehne, 2023; O. M. Hoehne, 2012). Furthermore, SE is characterized by its comprehensive approach to project management and system design. According to the International Council on System Engineering (INCOSE), SE is defined as:

> An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. Systems Engineering integrates all the disciplines and specialty groups into a team effort, forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (INCOSE, 2015, p. 11)

This comprehensive definition highlights SE's potential to address the complexities inherent in construction projects. In the Netherlands, major clients like Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water Management, and Prorail, the governmental organization responsible for the national railway network, have mandated SE application in their projects since 2007 (Leidraad SE., 2007).

Concurrently, the circular economy model has emerged as a potential solution to the construction industry's sustainability challenges. The circular economy concept, rooted in Kenneth Boulding's 1960s "Closed" or "Spaceman Economy" idea (Boulding, 1966), has been further developed by organizations like the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2013), encouraging the construction industry to reconsider material use and waste management approaches. Circular economy principles aim to transition the industry from a linear "take-make-dispose" model to a more sustainable, circular approach. This shift is crucial, given that the construction industry generates about 37.5% of Europe's total waste (Eurostat, 2023). The urgency of adopting circular economy principles in the construction industry is emphasized by ambitious sustainability goals, such as the Netherlands aim to reduce emissions by 80% to 95% compared to 1990 levels by 2050 (Government of the Netherlands, 2019). This objective must be balanced with the country's plans to construct 900,000 new houses by 2030 (International Monetary Fund. European Dept., 2023), with the required infrastructure development with such a goal, highlighting the need for sustainable practices in an expanding industry.

The complexity and breadth of circular economy concepts have led to an increased number of definitions in the literature, with varying perceptions of these concepts. For example, Kirchherr et al. (2017) analyzed 114 definitions of circular economy to come up with the 115th definition. However, this research focuses on four comprehensive circular economy principles based on the work of N. Bocken et al. (2021), N. M. Bocken et al. (2016), and Çetin et al. (2021). These four principles are particularly relevant to the construction industry and are as follows: **Closing** (reusing and recycling materials to close the loop), **Narrowing** (using fewer resources per product), **Slowing** (extending the lifespan of products), and **Regenerating** the resource loop (using renewable materials and energy). These circular economy principles could offer a promising approach to addressing circularity in construction. Nonetheless, their implementation requires integration with existing practices like SE, which forms the core of this research. The focus of this research is elaborated on in the following subsection.

1.2 Research Focus

This research focuses on integrating circular economy principles into the SE process within the context of the construction industry. The research is motivated by and conducted in close collaboration with ProcessMinded, a consultancy firm that applies SE methodologies to a wide range of construction projects for various clients and has been operating since 2013. ProcessMinded acknowledges the challenges and the necessity for change in current practices to align with national and international sustainability goals. The company is actively seeking to further enhance its application of SE and aims to explore a widely applicable approach to incorporate circularity into SE. Due to the variety of projects they work on, their interest is to adopt a circular approach for SE that is generic enough to be used across different projects yet flexible enough to incorporate different circular economy principles

The integration of SE and circular economy remains relatively unexplored, particularly in practical and industry-specific applications within the construction industry. This research aims to address this gap by investigating the integration of circular economy principles into SE processes for construction projects. Previous attempts to integrate circular economy principles within the construction industry have utilized various management approaches, including Construction and Demolition Waste (CDW) management (Gálvez-Martos et al., 2018), systemic thinking, and multi-level circular economy methods (Sparrevik et al., 2021; Többen & Opdenakker, 2022). The ReSOLVE framework (Regenerate, Share, Optimize, Loop, Virtualise, and Exchange) has also been applied to enhance circularity in the construction industry and integrate circularity at early project stages (Iyer-Raniga, 2019). Additionally, a Circular Economy Interface Matrix Analysis (CEIMA) framework has been developed to identify critical interfaces between the circular economy and stakeholders, offering practical guidance for infrastructure organizations to transition toward circular practices (Coenen et al., 2020). However, these approaches have not explicitly addressed integration with SE methodology in the context of the construction industry.

This research strives to leverage these existing attempts while analyzing both SE and circular economy paradigms separately to identify possible concept synergies and potential integration points. For instance, established SE practices for defining performance targets could be enhanced to address the lack of knowledge about the construction industry's environmental performance, which has hindered broader circularity adoption (Eberhardt et al., 2022). Additionally, circular economy principles could potentially mitigate uncertainty in early-stage design decisions within SE processes by providing guiding principles for circular goals (Van Der Meer et al., 2015). By combining the systematic approach of SE with a focus on circular economy principles, this research seeks to develop a framework that can guide ProcessMinded towards more circular applications of SE in their projects. In addition, this research contributes to the broader body of knowledge on SE and circular economy integration by responding to several critical needs identified in recent literature:

1. The call for more practical applications and frameworks for implementing circular economy principles in the construction industry (Antwi-Afari et al., 2021; Guerra et al., 2021; M. U. Hossain et al., 2020).

2. The need for sector-specific frameworks and interdisciplinary approaches identified by Gasparri et al. (2023) in their analysis of knowledge gaps for circular economy implementation in construction.

3. The demand for new design typologies and decision-making guides for circular economy implementation, as highlighted by Eberhardt et al. (2022).

Focusing on the integration of circular economy principles into SE, with ProcessMinded as a key industry partner, this research aims to contribute to the body of knowledge in both SE and circular economy fields. The findings could have far-reaching implications, not only for ProcessMinded but also for other consultancies and organizations in the construction industry with similar challenges regarding circularity.

1.3 Research Questions

Building upon the identified need to integrate circular economy principles into the SE processes within the context of the construction industry and in collaboration with ProcessMinded, the main research question of this research is:

How can circular economy principles be integrated into systems engineering process, and what framework can be developed for ProcessMinded to implement this integration within the context of the construction industry?

To answer the main research question, this study sought to answer the following sub-questions throughout the different phases of the research:

Q1: What are systems engineering processes and circular economy principles in the construction industry?

Q2: How can circular economy principles be integrated into systems engineering process?

Q3: What framework can ProcessMinded use to integrate circular economy principles into systems engineering process?

These research questions align closely with the challenges and opportunities identified in the construction industry and in the context of ProcessMinded's work. By addressing these questions, this research seeks to contribute to the academic understanding of SE and circularity integration and practical applications for ProcessMinded within the construction industry.

1.4 Structure of the Report

This report explores the integration of circular economy principles into the systems engineering process within the context of the construction industry. It is important to note that the terms 'circular economy principles' and 'circularity principles' are used interchangeably throughout the report. The report is structured as follows: this section introduced the background of the research and presented the research focus and questions. Section 2 elaborates on the research methodology, detailing the research design, literature review process, and validation interviews. Section 3 provides an in-depth look at systems engineering in construction, explaining its application across industries and detailing the steps of the SE process adopted in this research. Section 4 explores circular economy principles in construction, discussing various circularity frameworks and explaining the four key principles adopted in this study. Section 5 presents the core of the research, integrating circular economy principles into each step of the SE process and developing a framework for implementation with supporting examples from practice. Section 6 covers the validation of the framework through expert interviews, presenting insights for each SE step. Section 7 discusses the key findings, research contributions, limitations, and future research directions. Finally, Section 8 concludes the report, summarizing the main outcomes.

2 Methodology

This section explains the research methodology, starting by presenting the research design and the research method. It then details how the research was conducted and how the three research questions were answered and ends with an explanation of the validation process conducted in this study.

2.1 Research Design

The goal of this research is to integrate circular economy principles into SE. To achieve this, a set of research questions was developed to guide the development of a framework for the integration aimed at SE practitioners in the construction industry. This research addresses the relatively unexplored intersection of circular economy principles and SE to offer a new theoretical perspective through a literature review and semi-structured interviews for validation. The sequence of activities and the research design to address each research question are explained in this section and illustrated in Figure 1 below.

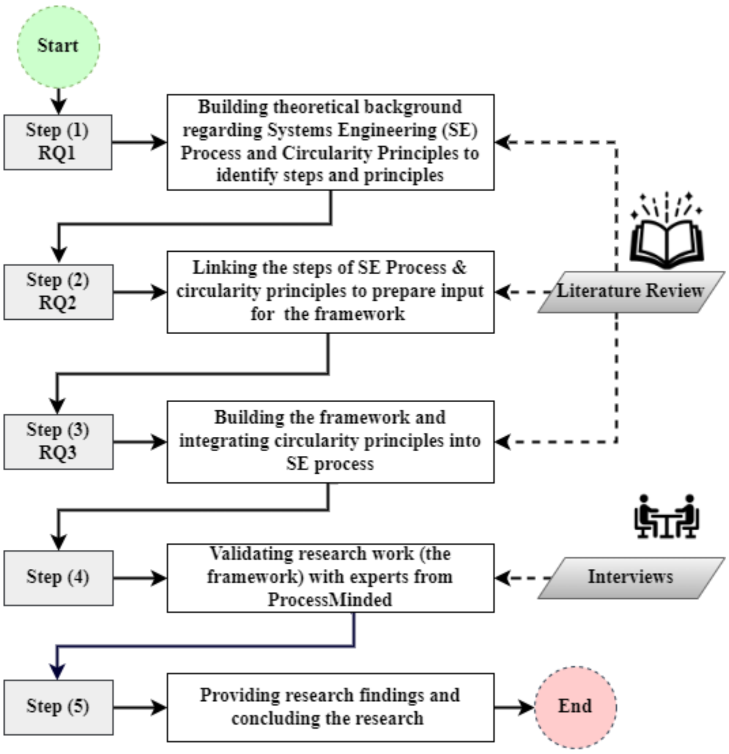

Figure 1: Research Design

2.2 Literature Review (Step 1-3)

In this study, a narrative literature review was employed, as it allows for the discussion of topics from theoretical and contextual perspectives (Baumeister & Leary, 1997; Snyder, 2019). Narrative reviews use less formal methods, avoiding rigorous reporting and criteria and allowing for interpretation and critique (Ferrari, 2015; Greenhalgh et al., 2018). This approach was chosen for its flexibility in synthesizing diverse sources and its suitability for exploring the emerging topic of integrating circularity principles into systems engineering processes. In addition, narrative reviews provide flexibility in searching for relevant literature and addressing the research questions, as they are suited for studies that do not aim to answer specific quantitative questions. Also, given the evolving nature of the circular economy and SE practices, no date restrictions were applied, providing a review of both historical and recent developments. Besides, the snowball technique was employed by reviewing references within identified sources that were relevant to the research topic. This technique helped uncover further studies that might not have been captured in the initial search (Badampudi et al., 2015).

2.2.1 Search Strategy

The literature search initially focused on the intersection of circular economy, systems engineering, and the construction industry using Scopus and Web of Science databases. The following query was used in the initial search attempt:

("circular economy" OR "circularity") AND ("systems engineering" OR "project management" OR "Reliability" AND "Availability" AND "Maintainability" AND "safety" OR "engineering management" OR "system thinking") AND ("construction industry" OR "built environment" OR "civil engineering")

After an initial screening of 52 unique records, it became evident that a different approach was needed to fully address the research questions. This is due to the fact that the results of this search were fragmented and not focused enough to capture the context of this research. Therefore, the search strategy was subsequently refined to better align with the research questions. The search involved linking specific SE processes with circularity principles, which guided a more focused review. This refined approach involved searching across multiple databases for themes connecting individual SE processes with circularity principles. Relevant grey literature was also included to provide a comprehensive view of current practices. The search strategy was tailored for each SE process, allowing for a detailed analysis and exploration of how circularity principles could be integrated into specific steps of systems engineering.

2.2.2 Step 1: Identifying Processes and Principles

This step involved gathering and synthesizing the theoretical knowledge related to SE, followed by the circular economy principles. Each was examined separately before integration. This approach helped build a foundational understanding that would inform the subsequent steps. This involved reviewing existing literature to identify the key processes of systems engineering for this research, as well as principles of circular economy within the context of the construction industry. SE principles were reviewed as well to comprehend the underlying reason for the technical processes employed in this research. This step led to the identification of five SE processes commonly used in the construction industry, which have been addressed in relevant research and are recognized by authoritative organizations in the field of SE, such as the U.S. Department of Defense and INCOSE. Additionally, four circularity principles were identified and compared to existing frameworks, thereby addressing the research question (Q1).

2.2.3 Step 2: Linking SE processes and CE principles

The analysis process involved extracting key themes and patterns related to current practices and integration methods. By examining each SE process individually in relation to the four identified circular economy principles, the literature was synthesized to identify potential integration strategies. The analysis focused on highlighting how each SE process can incorporate the four circular economy principles and suggested potential actions for incorporating these principles. In addition, the analysis addressed potential challenges resulting from the integration and outlined ways to manage them. This has led to the second research question (Q2) being addressed.

2.2.4 Step 3: Building Framework

For each SE process analyzed, inputs, actions, and outputs for integrating circular economy principles were summarized. This systematic approach led to the development of a framework that included the intersection of the five SE processes with the four circularity principles, providing a practical guide for integrating circularity principles into the SE process for ProcessMinded. The focus on inputs, actions, and outputs was chosen as it is a well-established SE practice, as outlined in ISO/IEC/IEEE 15288 (2015) and the US Department of Defense (ISO/IEC/IEEE 15288, 2015; US Department of Defense, 2001), where every process is defined by what goes in, what happens, and what comes out. In addition, practical examples were provided to support and further explain how some of the actions presented in the framework can be done in practice. Lastly, this approach has helped in overcoming the complexity of the integration and simplifying the framework, which has led to answering the third research question (Q3)

2.3 Validation Interviews (Step 4-5)

To validate the proposed framework, semi-structured interviews were conducted with five professionals from ProcsessMinded who are experienced in SE. Semi-structured interviews are widely used in qualitative research and include a set of open-ended questions with the possibility to address questions that might emerge through the interview (DiCicco-Bloom & Crabtree, 2006). The five systems engineers have experience ranging from 8 to 17 years in the construction industry. In addition, two out of the five participants are currently in sustainability-related roles. Participants were chosen based on their experience in the field and familiarity with circularity concepts in engineering projects. An interview guide was developed with three open-ended questions and one quantitative question, covering each step of the framework: Project Start, Requirements Analysis, Functional Analysis and Allocation, Design Synthesis, and Verification and Validation. For each step of the SE process, participants were asked about:

1. What strengths (tops) do you see in these actions?
2. Do you have any tips to improve these actions for better integration with the systems engineering process?
3. Can you provide examples from your experience related to these actions?
4. On a scale from 1 to 5, with 5 being highly applicable and 1 being not applicable at all, how applicable do you think these actions are for systems engineers to implement? Why?

Actions were the primary focus during the validation process because they provided new insights to systems engineers. By focusing on the actions, the validation aimed to assess their relevance, validity, and applicability, ensuring that these actions could be seamlessly integrated into the conventional SE processes familiar to systems engineers. This focus allowed for a more practical evaluation of how circular economy principles could be incorporated within established SE practices. Furthermore, interviews were conducted online via Microsoft Teams via video conference. Each interview lasted approximately 45-65 minutes and covered all steps of the proposed framework. With participants' consent, the interviews were recorded and auto-transcribed by Microsoft Teams for analysis. Following the interviews, the transcripts were carefully reviewed and corrected by the researcher, and key insights, strengths, and areas for improvement were extracted for each step of the framework. Applicability ratings for the actions per step of SE in the framework were compiled and averaged across all participants. Noteworthy quotes illustrating important points or examples were identified for inclusion in the validation results presentation. The analysis focused on the direct interpretation of the interviewees' responses, identifying both common perspectives and insights relevant to each framework step.

3 Systems Engineering in Construction

This section discusses the application of SE within the construction industry, exploring its methodologies and processes. The discussion highlights how SE is tailored to meet industry-specific needs. The analysis follows the structure of SE as outlined by key industry standards and explains the steps of the SE process, with a focus on its application in construction projects.

3.1 Systems Engineering Across Industries

Although widely applied today, Systems Engineering can be understood in various ways depending on the systems under development, organizations, and industries considered. The fundamental principles of SE are lifecycle focus, managing interactions, ensuring compliance, and meeting stakeholder requirements. It is a dynamic field that continuously evolves, balancing cost, quality, and constraints while making informed decisions under uncertainty (Presland et al., 2018; M. Watson et al., 2022). Given the diverse applications of SE across industries, it is important to consider how different sectors adapt the method to their specific needs. SE is usually tailored to the specific systems and their environments, with methods changing based on the needs, operational context, and goals. According to M. D. Watson et al. (2016), evidence shows that 72% of surveyed companies employ unique systems engineering processes suited to their products. In the construction industry, Systems Engineering is implemented by adopting industry-specific terminology and expanding processes tailored to the unique requirements of the field. Furthermore, R. de Graaf et al. (2016) noted that SE is applied differently in the industry, with differences in the number of elements applied from SE. They indicate that there is not one standardized method for SE. Instead, it depends on aspects such as the company, its employees, and clients, which impact the level of SE application in projects.

For further analysis, **this study primarily adopts the structure of the SE process as described by the US Department of Defense (DoD)** (US Department of Defense, 2001), while also incorporating relevant elements from the technical processes described by INCOSE and essential handbooks and guidelines for SE in construction (Buck et al., 2023; R. de Graaf, 2020; INCOSE, 2015; Presland et al., 2018). **This SE process has been studied and validated by different researchers, particularly in the context of the construction industry** (R. S. de Graaf et al., 2017; R. de Graaf et al., 2016; Lynghaug et al., 2022). In addition, the SE process adopted in this research is focused on the technical aspects of SE as they align with the work of ProcessMinded. ProcessMinded has a ten-step approach for SE as follows: organize the project, analyze documents, analyze requirements, determine object tree, determine work packages and activities, allocate system requirements to objects, draw up a verification plan, perform verifications, carry out inspections, and validate and deliver. Thus, **adopting the SE process as outlined by the DoD aligns with the study's goals and focus on ProcessMinded and keeps it in line with the broader application of SE in construction**. The DoD established the MIL-STD-499B standard for SE with the following key steps: process input, requirements analysis, functional analysis and allocation, design synthesis, verification and validation. The iterative nature of the SE process is considered in the analysis later for integration with circular economy principles, including the requirements and design loops, which involve revisiting and refining requirements and design based on feedback loops. Furthermore, the Dutch construction industry has developed its guidelines and framework for SE as a reference for the Dutch construction industry (Buck et al., 2023). This guideline by the leading Dutch organizations in the industry addresses the same SE process aligning with the DoD. In addition, according to Buck et al. (2023), SE applies to all contract types and supports the structured development of systems in the building and civil engineering sector. Thus, this research does not focus on specific contract types for further analysis and assumes that contractors and clients work together from the outset. The following sub-sections provide an overview of the Vee model and then delve into each step of the SE process.

3.2 Systems Engineering Process and the Vee Model

Before explaining each step of the SE process, it is important to address the iterative nature of Systems Engineering across different levels of design detail in construction projects. The Systems Engineering process is applied throughout the project lifecycle, from initiative to demolition, focusing on the design phase. This design phase typically involves different levels of detail. At each level, the SE process is applied iteratively, refining the design and moving closer to realization (R. de Graaf, 2020; INCOSE, 2015). As the project progresses through these levels, the same fundamental SE principles are applied, but with increasing specificity and detail; this is shown in the Vee model; see Figure 2 below. However, this study keeps the discussion of the SE process generic except for the process input, as it is assumed to be the earliest phase as the project start. This approach allows for flexibility, as the process can be applied at different levels of detail depending on the project's needs and stage.

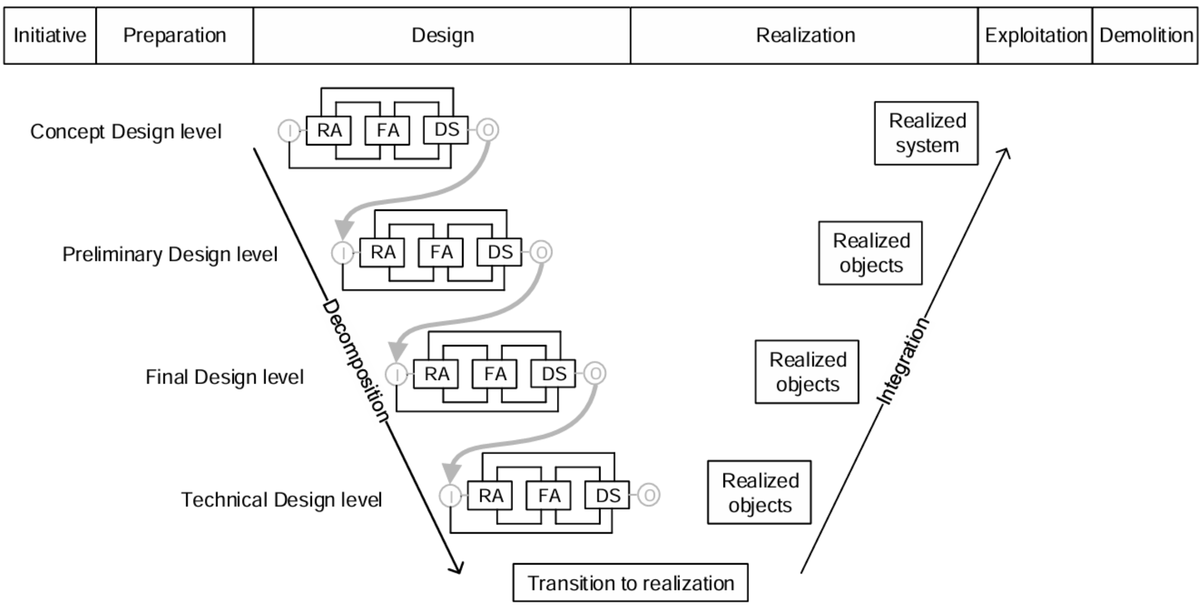

Figure 2: The Vee Model and the SE process adapted from: R. de Graaf (2020)

3.2.1 Process input (Project Start)

Project start in SE is the process input step and establishes the system's foundation. This process is described as the initiative phase by (US Department of Defense, 2001) and aligns with the earliest stages of starting a project, as shown in the Vee model above. This involves analyzing stakeholders and defining needs, goals, and objectives through techniques such as interviews, focus groups, and surveys. With consideration to Measures of Effectiveness (MoE), the system's environment, legal boundaries, and constraints to guarantee sufficient coverage of system complexities from the start. It involves gathering and documenting initial sets of stakeholders' requirements, wishes, and project constraints, additionally, documenting the analysis conducted in stakeholder communication documents or other documents for effective communication and to be checked in later stages (R. de Graaf, 2020; Forsberg & Mooz, 1992; Locatelli et al., 2014; US Department of Defense, 2001).

3.2.2 Requirements Analysis

Requirements analysis starts by taking the output of the project start step and analyzing these requirements further. It connects the SE process with external input sources, using stakeholder communication documents and analysis. Requirements analysis is an inquiry and resolution process that focuses on understanding the reason behind developing the system, customer expectations, user needs, system functions, compliance, and constraints. This process results in performance, technical, interface, and functional and non-functional requirements. These requirements are documented at the end of the process for use in the subsequent steps of the SE process and for effective verification and validation, serving as a reference and will be revisited with the requirements loop (INCOSE, 2015; US Department of Defense, 2001).

3.2.3 Functional Analysis and Allocation

The functional analysis start by taking the output of the requirements analysis as an input. The process deals with translating requirements into functions the system should perform, and involves breaking down the system into smaller, manageable functions and allocating these functions to specific components or objects (US Department of Defense, 2001). The project team decomposes functions to transform requirements into functionalities (Buede, 2000). This process only describes what should be done and not how to do it, providing a solution-neutral functions formed as actions with verbs and nouns. It is an implementation-independent process, which ensures that subsequent trade studies for design are unbiased toward pre-determined options (INCOSE, 2015; Kossiakoff et al., 2011). The process is connected to both the requirements analysis and design synthesis through iterative loops. Functions are refined throughout the process with the requirements and are revisited later to iterate and refine the design. Several tools can be used to facilitate this process, such as Functional Flow Block Diagrams (FFBD) or Function Analysis Systems Technique (FAST) diagrams to show sequence and relationships, Integration Definition for Function Modeling (IDEF0) diagrams to define process and data flow, Timeline analysis to link functions to time and present time critical functions, and requirements allocation sheets to keep track of allocated functions and for later verification and validation. Key considerations for this process includes identifying all functional interfaces and functional performance.

3.2.4 Design Synthesis

This process starts by taking the output of the functional analysis and allocation, beginning with the design efforts of the system and starting to think of solutions. The project team considers solutions that satisfy the required functionalities, developing and comparing alternative designs in trade studies to determine which performs best. This process considers modular designs by grouping components with singular functions, minimizing interdependence and enhancing cohesion, to facilitate development, testing, and later adjustments (US Department of Defense, 2001). Initially, a conceptual design is created, followed by iterative refinement through preliminary and detailed designs. Tools such as the Requirements Analysis Sheet (RAS), Concept Description Sheet (CDS), and Schematic Block Diagram (SBD) ensure performance traceability, while software tools aid in presenting drawings and documenting design efforts. Design synthesis employs System Modeling Language (SysML), Computer Aided Design (CAD), and simulation tools to facilitate the design process (Kossiakoff et al., 2011). Iterative feedback from testing and stakeholder reviews is used for refining the design, making this process dynamic, bridging functional requirements with physical implementation (Buede, 2000). The design synthesis process involves selecting and integrating technologies, components, and interfaces to realize functional requirements. Guided by the project team's expertise, it focuses on creating an efficient and feasible system design with consideration of RAMS (Reliability, Availability, Maintainability, and Safety), cost, and performance (Blanchard & Fabrycky, 2005; INCOSE, 2015). The iterative nature ensures that the design remains aligned with the functional needs and can adapt to new information or changes in the system.

3.2.5 Verification and Validation

Verification and validation (V&V) are the processes that ensure a system meets its specified requirements and performs its intended functions (INCOSE, 2015; US Department of Defense, 2001). Verification is linked to the requirements analysis step and involves confirming that the system components are built and integrated correctly according to the predefined specifications, the main purpose of this process is to make sure that "the system is built right" (INCOSE, 2015). The verification takes place at different points of time during the development of the system and checks if the requirements are met by comparing the outputs of each phase of the system's development lifecycle against the input requirements of that phase. Tools and methods such as inspections, reviews, walkthroughs, and testing (including unit tests, integration tests, system tests, and acceptance tests) are employed to achieve verification. Validation, on the other hand, is linked to the project start and assesses whether the final system fulfills its intended purpose and meets stakeholders' expectations in the operational environment. This process ensures that "the right system is built" by evaluating the system's performance in real-world conditions and scenarios (INCOSE, 2015). Validation activities include operational testing, user trials, simulations, and demonstrations to gather evidence that the system meets its overall goals and user expectations. These processes are iterative and intertwined with the system development lifecycle, ensuring continuous alignment with requirements and stakeholder needs. The iterative nature of V&V involves repeated cycles of checking and feedback, which allow for early detection of issues and continuous improvement and refinement of the system design.

4 Circular Economy Principles in Construction

This section explores the principles of the circular economy within the construction industry, offering an overview of key concepts and frameworks. In addition, the section discusses the four principles adopted in this study, supplemented with examples of their application in the construction industry. It sets the stage for examining the integration of these principles into the SE process.

4.1 Frameworks and Principles of Circular Economy in Construction

This study aims to develop a framework that incorporates key circularity principles into the SE process addressed in the previous section 3. The application of circular economy principles in construction is a rapidly evolving field, with various frameworks and strategies proposed by researchers and practitioners. The Ellen MacArthur Foundation's ReSOLVE framework, for instance, outlines six actions for businesses to adopt circular practices: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange (Ellen Macarthur Foundation, 2015). This framework provides a broad perspective on circularity that extends beyond material use to include business models and value creation. Moreover, the Dutch Platform CB'23 has also contributed greatly to this field, developing a framework that focuses on key circular design strategies. These strategies include prevention, design for quality and maintenance, design for adaptability, design for disassembly and reusability, design with reused parts of constructions, design with secondary raw materials, and design with renewable raw materials (Platform CB'23, 2023). Their framework provides practical guidance for implementing circular design strategies in construction project.

In addition to these practical frameworks, Pomponi and Moncaster (2017) developed a research framework identifying six key dimensions for studying and implementing circularity in construction: economic, environmental, technological, societal, governmental, and behavioral. Their work highlights the multifaceted nature of circularity in construction, emphasizing the need for a systemic approach that considers the entire lifecycle of construction projects. This framework supports a deeper understanding of the various factors influencing circularity and underscores the importance of an interdisciplinary approach. While these research and practical frameworks offer valuable insights, this study adopts a focused approach based on four key principles: closing, narrowing, slowing, and regenerating the resource loop. This choice is informed by the work of N. Bocken et al. (2021), N. M. Bocken et al. (2016), Çetin et al. (2021), and Konietzko et al. (2020) who have synthesized various circularity strategies into these four fundamental principles. The selection of these four principles is justified by several factors. **First**, these principles align closely with the construction lifecycle, addressing key stages from material sourcing to end-of-life considerations. They provide clear guidance on resource flows and lifecycle thinking, which are essential for effective integration with the SE process. **Second**, these principles have been successfully applied to study circularity within a digital built environment, demonstrating their relevance and applicability in addressing circularity challenges in the construction industry (Çetin et al., 2021). **Third**, these principles offer a simplified yet comprehensive approach, potentially encompassing strategies from both the Ellen MacArthur Foundation's ReSOLVE framework and Platform CB'23's design strategies. **Lastly**, these four principles can account for the repercussions regarding the six key dimensions identified by Pomponi and Moncaster (economic, environmental, technological, societal, governmental, and behavioral) (Pomponi & Moncaster, 2017). This balanced approach could help develop a framework for integrating circularity principles into the SE process in construction.

4.2 The Four Circular Economy Principles

This study adopts four key circularity principles as outlined by N. Bocken et al. (2021), N. M. Bocken et al. (2016), and Konietzko et al. (2020) and further developed by Çetin et al. (2021): closing, narrowing, slowing, and regenerating the resource loop. These principles form the foundation for integrating circularity into the SE process for construction projects. Figure 3 illustrates these principles and their relationship to resource flows in a circular economy.

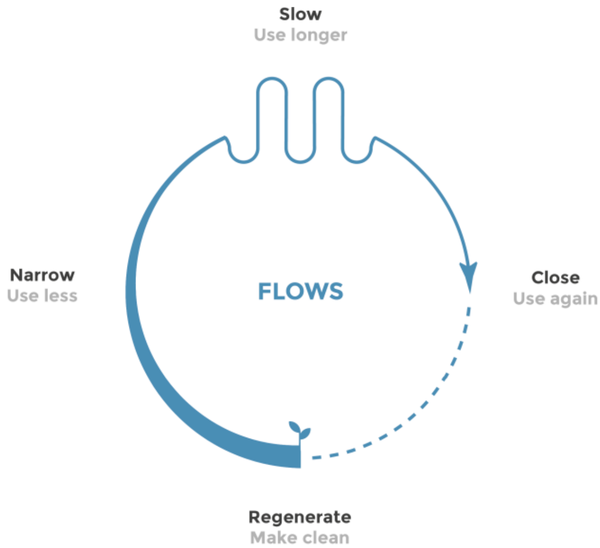

Figure 3: The Four Circularity Principles in Resource Flow Adapted From: Konietzko et al. (2020)

As shown in Figure 3, each principle plays a specific role in creating a circular flow of resources. The dotted line completing the circle represents closing, emphasizing material reuse and recycling. The thickest part of the circle illustrates narrowing, focusing on minimizing initial resource use. The wavy line at the top represents slowing, aiming to extend the lifespans of resources. Lastly, the plant icon indicates regenerating, representing the use of renewable resources and regenerative practices. The following subsections will explore these principles in depth and examine their application in construction projects.

4.2.1 Closing the Resource Loop (Use Again)

This principle emphasizes including secondary materials in new projects and ensuring that the resources used can be reused or recycled at the end of life. This principle focuses on minimizing waste by ensuring that end-of-life materials are reintegrated into the construction process rather than being disposed of as waste. *An example* of the application of this principle is the use of recycled materials in resin mortars, which demonstrates how old materials can be reused in new construction projects to reduce waste and contribute to closing the resource loop (Debska et al., 2024). In addition, this principle manifests in construction through key strategies such as designing for disassembly and material recovery, demonstrating how design choices significantly impact the potential for material recovery at the end of life of construction projects (Akinade, Oyedele, Ajayi, et al., 2017) Incorporating recycled or reclaimed materials into new projects is another strategy for closing the loop. However, it requires careful consideration of other factors such as sorting, processing, and proper reintegration of these recovered resources (Gálvez-Martos et al., 2018). On the same note, the "Building as Material Banks" (BAMB) project exemplifies the practical application of this principle by viewing buildings as temporary storage for materials, facilitating their future reuse (European Energy Innovation, 2017).

4.2.2 Narrowing the Resource Loop (Use Less)

Narrowing the resource loop focuses on resource efficiency, aiming to use fewer resources to achieve the same output. In construction, this principle is realized through various strategies that focus on reducing material use without compromising functionality or performance, such as longer-lasting products, modularisation and remanufacturing, and designing products with less material (Allwood et al., 2011). In addition, narrowing the resource loop includes utilizing advancements in technology and design to reduce the amount of raw materials and energy consumed in construction projects. *For example*, the use of 3D-printed clay-based mortars with innovative structures shows how efficient design can reduce resource consumption (Peng et al., 2024). Besides, better coordination among project stakeholders and accurate material estimates, which can be utilized with the use of BIM, could potentially lead to waste minimization (Liu et al., 2015).

4.2.3 Slowing the Resource Loop (Use Longer)

The principle of slowing the resource loop aims to extend the lifespan of materials and reduce the need for new resources. This principle is particularly relevant in construction, given the long-term nature of built assets. With the aim to use resources longer, designing for durability, adaptability, and flexibility are key strategies. *For example*, using durable and high-performance materials reduces the frequency of replacements during maintenance, resulting in lower resource consumption over the lifecycle of a project (Kibert, 2016). Additionally, planning for maintenance and repair are essential aspects for slowing the resource loop (Moraga et al., 2019).

4.2.4 Regenerating the Resource Loop (Make Clean)

This principle focuses on applying practices that positively impact the environment. This includes using materials and methods that help restore and regenerate the natural environment rather than depleting it. *For example*, organic wastes can be used for insulation in some construction projects (Indwar & Titiksh, 2024). The incorporation of biobased and renewable materials represents a key strategy in this context, offering opportunities for more circular material choices. The potential for materials that reduce environmental impact and contribute positively to ecosystems has been explored through biotechnologies and bioinspired materials in construction (Pacheco-Torgal & Labrincha, 2013). Moreover, implementing green infrastructure and nature-based solutions is another aspect of regenerating the resource loop (Maes & Jacobs, 2017)

5 Circular Systems Engineering Process

This section integrates the four circularity principles addressed earlier with the SE process. To integrate the four circularity principles into the SE process effectively, this study first analyzes the literature emerging from both paradigms and their intersections. Each step of the SE process is examined separately to identify potential areas for incorporating the four circularity principles. This critical assessment serves the development of a framework focusing on three primary elements: *inputs, actions, and outputs* within each step and for each circularity principle. The focus on the preceding three elements is grounded in the fact that each step is viewed as a process in itself. According to ISO/IEC/IEEE 15288 (2015), processes require clearly defined inputs, a set of actions or activities, and results in outputs. These elements are well-established in systems engineering processes (US Department of Defense, 2001), corresponding to the basic flow of processes: what goes in, what happens, and what comes out. The three elements are explained below:

- **Inputs** are the necessary resources and information that initiate each process step. By clearly identifying inputs, the framework ensures that all required elements are in place to proceed effectively.
- **Actions** are the specific activities undertaken within each process, considering circularity. These actions transform inputs into outputs.
- **Outputs** are the results that emerge from the actions taken during each process step. Clearly defined outputs allow for the process as a whole to proceed and enable evaluation of the integration's success and effectiveness.

While the framework focuses on inputs, actions, and outputs, the analysis in the following subsections expands to address challenges, opportunities, and potential solutions for integrating circularity principles with the SE process. This integration is presented in the framework in **Table 1** and supported by practical examples for certain actions shown in **Table 2** in section 5.6 is the result of a comprehensive synthesis of the literature. This comprehensive analysis forms the theoretical foundation and main reference for the framework. For clarity and practicality, the framework itself is structured around the core elements addressed above per SE step and distinguishes between the four circularity principles, providing a simplified, systematic approach for integrating circularity principles into the SE process.

Throughout the analysis, the term 'project team' is used to refer to the engineers and other professionals directly responsible for planning, designing, and executing the construction project, with systems engineers serving as the primary point of contact and main audience for this research. This inclusive terminology reflects the collaborative nature of integrating circularity into the SE process. The following subsections analyze each step of the SE process separately, providing the theoretical underpinning for the framework. The framework presented at the end will guide ProcessMinded in integrating circularity principles and form the core of this research.

5.1 Project Start

This section focuses on integrating the four circularity principles into the process input (project start) step of the SE process, providing an analysis of possible ways of integration and a theoretical foundation for developing a framework for integration. The project start is highlighted by the US Department of Defense (2001) as the process input, and it is viewed in this analysis as a distinct process due to its importance for integrating circularity principles as it paves the way for the succeeding steps. As explained before in section 3.2.1, the **inputs** of this step are initial demands and needs, systems environment and constraints, and measures of effectiveness (US Department of Defense, 2001). These inputs are considered to be the inputs from the initiative phase, coming from the earliest phase of a project. At this step, the inputs are the same for the four circularity principles: close, narrow, slow, and regenerate. However, if the SE process moves to the next level of detail, then the inputs will include previous development efforts.

At this step, setting clear circularity goals is essential, and equally important is the collaboration of stakeholders toward these goals (N. M. Bocken et al., 2016; Henderson et al., 2019; Kraaijenhagen et al., 2016). Setting circularity goals early in a project helps with decision-making, saving costs, and providing economic benefits throughout the project's lifecycle (Bragança et al., 2014). In addition, early-phase planning is essential for integrating circular economy principles (Sanchez & Haas, 2018). It helps guide decisions such as choosing between green-field construction and adaptive reuse, planning for closed-loop cycle construction, and optimizing the benefits of adaptive reuse. While SE is flexible and can adapt to changes (Dove & LaBarge, 2014), starting with clear circularity goals and involving experts from the outset is crucial to avoid costly adjustments later in construction projects (N. M. Bocken et al., 2014; N. M. Bocken et al., 2016; HM Treasury, 2013). Considering the four circularity principles, this translates to **actions** that concern setting targets for resource recovery, efficiency, longevity, and bio-based materials use; see **Table 1** for the related **actions**.

Furthermore, the project start in SE involves stakeholder analysis and defining objectives. However, conventional stakeholders like clients and designers often lack awareness of circularity principles (Adams et al., 2017). Therefore, it is necessary to *include circularity experts* and educate stakeholders on circularity to foster collaboration and effectively leverage circular economy principles (Gerding et al., 2021). The inclusion of circularity experts represents a transition from linear to circular engagement and requires proactive collaboration, in-depth dialogues, training, and addressing knowledge gaps through consultants and internal expertise (Fobbe & Hilletofth, 2023). However, this inclusion of circularity experts can help in setting the right targets at the project start (Adams et al., 2017). For such collaboration, the use of interactive and dynamic tools, such as circular design dashboards, can provide stakeholders with insights regarding circularity within the project, which can help them make informed decisions and identify effective circular building measures (van der Zwaag et al., 2023). Using such dashboards and sharing information could increase transparency and stakeholder commitment to circular goals from the start. Similarly, the power and interests of stakeholders differ and can potentially influence the innovative efforts of other stakeholders to consider circularity (Tookey et al., 2011). Clients have significant power and could have less interest in some cases due to a lack of awareness or financial concerns (Adams et al., 2017; Ahmed et al., 2023). The project team can work toward initiating a dialog that balances power, focusing on stakeholders who might have less power yet be of significant value for achieving a circular project (Bal et al., 2013). As such, the project team should prioritize circularity alongside conventional interests, considering non-human stakeholders such as nature, to achieve outcomes beyond usual standards (Phillips & Reichart, 2000; Senaratne et al., 2021; World Economic Forum, 2020).

This way of collaboration presents challenges, such as limited incentives, collaboration barriers, decision-making complexities, and implementation risks, as highlighted by Shooshtarian et al. (2024). They show a case study of a construction project using recycled content, revealing stakeholders differing views on circularity and stressing the need for effective communication and early collaboration to align on circularity goals. Given these complexities, SE can *facilitate a strategic narrative* for a shared vision and values to create a sense of ownership among stakeholders toward circularity goals (Henderson et al., 2019). Aligning to a strategic narrative and early engagement at the project start can help address and manage misalignment issues before project complexity increases. On a similar note, the Concept of Operations (ConOps) in SE is a high-level tool that can be deployed to help stakeholders align to a unified vision, facilitating a better communication of goals (Madni, 2015; Mostashari et al., 2012). ConOps can be used to describe a project's circularity vision and objectives at the start to help everyone understand what would be considered a success later on (ISO/IEC/IEEE 15288, 2015). For circularity, concrete indicators to measure progress are needed (PwC, 2019). A high-level ConOps can define and communicate these goals to stakeholders, making it possible to measure progress. It can also help to involve stakeholders in the value creation and problem-solving process as a pragmatic and strategic engagement (Kujala et al., 2022). Additionally, it can be seen as a goal-oriented engagement with a focus on value and knowledge creation toward circular goals in a project (Oberholzer & Sachs, 2023). A stakeholder mindset shift towards viewing circularity as an intrinsic value can influence every decision and action, which is described as a leverage point for achieving circular SE by David et al. (2024). The project team can consider conducting an inventory analysis for material harvest and to identify possible local sources, such as existing projects that are put for deconstruction in the area (Blok, 2024; Bragança, 2019), which could help in setting targets for closing the resource loop. Similarly, identifying renewable resources within the project's local environment and conducting Preliminary Ecological Appraisal (PEA) (CIEEM, 2017) could improve the process of setting targets for regenerating the resource loop and could be used later in the process. The **actions** discussed above and their **outputs** within the four circularity principles are shown in **Table 1** below.

5.2 Requirements Analysis

This step starts with the input from the previous step, with goals and targets related to the four circularity principles, as well as an inventory analysis of local sources for reclaimed materials and renewable and bio-based sources. These inputs form the first set of requirements that the project team would work on analyzing. Ecodesign guidelines distinguish between generic and specific ecodesign requirements; generic requirements are related to overall environmental performance, and specific requirements are related to environmental aspects within a specific product (European Commission, 2009). Circularity requirements can be analyzed in a similar way to those explained by the ecodesign guidelines. Where generic requirements focus on lifecycle considerations within all system requirements, and specific requirements are explicit (e.g., full deconstruction and reclamation of building elements after a specified period). Generic requirements could result from integrating circularity principles and including targets for each circularity principle within the project, bringing new considerations for requirements analysis. Analyzing these requirements can be done to ensure they fulfill the circularity targets within the overall system's performance (Blyth & Worthington, 2002). In addition, they need to be analyzed with consideration of the project's environment to avoid compromising other environmental aspects. At the early stage of the project, it can be challenging to capture all generic and specific circularity requirements due to limited information and differing stakeholder's needs (Lehtinen et al., 2023). However, requirements analysis is a dynamic process where requirements are initially set based on available information and further refined as the project progresses (Jensen, 2011; Prins et al., 2014). Therefore, *distinguishing between generic and specific requirements* is considered as an **action** within the four circularity principles as it sets the ground for further analyzing every set of requirements with the right tools and involving the right people.

At this step, requirements are analyzed for circularity at the sub-system level; later, when the complete set of requirements is available, they can be combined to reflect the entire system's circularity performance. Frameworks like the Madaster Circularity Indicator, the CirculAbility Model, and the Measuring Circularity Guide emphasize measuring the reusability and recyclability of materials, evaluating material and energy flow, and the lifespan of materials (Heisel & Rau-Oberhuber, 2020; Inchainge, n.d.; Platform CB'23, 2022). Based on these frameworks and guidelines, requirements could be assessed for a closed-loop system by considering material recovery, EOL phase, and future reuse and recycling potential. EOL consideration could include aspects such as ease of disassembly, maintaining plans and documents, and reuse potential (Anastasiades et al., 2023). To narrow the loop within the project, the project team should consider analyzing requirements based on materials and energy consumption using LCA and ECI. For slowing the loop, analyzing requirements for longevity and repairability is essential. In addition, assessing possible bio-based and renewable alternatives for requirements is to move toward a regenerative project. See **Table** 1 for the **actions** within each principle. This integration includes other considerations; for example, the project team can involve demolition contractors to help analyse EOL requirements. According to Osaily et al. (2019), early demolition contractor involvement can be invaluable due to their experience regarding factors influencing the EOL of construction projects, helping formulate requirements that adhere to closing the loop. Similarly, technical experts can be included when needed for requirements related to the four circularity principles. However, adversarial relationships, increased costs, and time constraints might arise from such involvement (Osaily et al., 2022), which should be considered carefully by the project team. In addition, circularity requirements mandate openness to new and innovative ways of working, which could potentially cause adversarial relationships in the project (Rose & Manley, 2014). For that, the project team should consider managing relationships carefully in this step to guarantee a successful analysis of the requirements.

Furthermore, it is essential for the SE process that requirements are clearly documented to ensure traceability and clarity and to facilitate later verification and validation while remaining solution-neutral to minimize uncertainties and ensure they are actionable

(Arayici et al., 2005; Kamara & Anumba, 2002; Wheeler, 2004). There are different frameworks to facilitate sufficient documentation of requirements (e.g., making them SMART[1]) so they can be communicated and understood by everyone at different phases of the project (MannionMike & KeepenceBarry, 1995). However, measuring circularity is challenging due to the lack of standardized practices and the complexity of evaluating lifecycle impacts considering the uniqueness of construction projects (Incelli et al., 2023; Rahla et al., 2019). Several circularity indicators exist, but none can measure all aspects of circularity alone (Moraga et al., 2019). Therefore, using multiple indicators and metrics, such as the Environmental Cost Index (ECI/MKI), CO2 emissions reductions from Life Cycle Assessment (LCA), Material Circularity Index (MCI), and Material Flow Analysis (MFA), can help make circularity requirements measurable (González et al., 2021; UKGBC, 2019). The project team can make use of these existing tools to ensure the documentation of measurable requirements for each circularity principle. At the end of this step, all circularity requirements should be documented. These requirements can be integrated into a design brief and requirements verification traceability matrix (RVTM), which are common documents that are used within SE (INCOSE, 2015), with a distinction between generic and specific circularity requirements to proceed further in the SE process.

5.3 Functional Analysis and Allocation

Functional analysis and allocation start by taking the output of the requirements analysis step and analyzing them further for functionalities and allocating functions to objects. For circularity principles, the focus is on functionalities such as reusability, longevity, adaptability, and deconstructability, ensuring materials and components remain circular throughout their lifecycle (Adams et al., 2017; Hubmann & van Maaren, 2022). Circular thinking emphasizes considering the entire system and examining components and their interfaces separately, similar to functional thinking in SE. Aligning with this is the concept of approaching buildings as layers (site, structure, skin, services, space plan, and stuff) (Brand, 1995). The layers concept can boost circularity by allowing the project team to address each element with distinct rules to integrate circularity (Cheshire, 2016; Dams et al., 2021). In SE, it is up to the project team to decide on the decomposition of functions (Buede, 2000). Using the layers concept can help estimate the lifecycle of different components to group them together and move from higher-level to lower-level functions. Similar to the previous steps of the SE process, the project team might involve circularity experts for assigning functions to objects as this needs further multidisciplinary collaboration (Price, 1985).

As discussed in section 5.2, resulting from integrating circularity, there will be generic and specific circularity requirements. On the one hand, specific circularity requirements could result in basic functions such as, but not limited to, reusing components and recycling end-of-life products. These functions can be further decomposed into lower-level functions and then allocated to objects. The use of the FAST diagram can help break down functions related to specific circularity requirements following the how-why logic and moving to lower-level functions. On the other hand, generic circularity requirements would result in qualities that describe the desired characteristics of the system, such as reusability, efficiency, durability, and eco-friendliness, which can be treated as support-

[1]SMART stands for Specific, Measurable, Achievable, Realistic, and Timed.

ing functions similar to the RAMS (Reliability, Availability, Maintainability, and Safety) (Buck et al., 2023; R. de Graaf, 2020). Techniques such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Failure Mode and Effect Criticality Analysis (FMECA) are used for RAMS analysis (Al-Jibouri & Ogink, 2009). These techniques can similarly be used to identify and evaluate failure modes and performance related to reusability, efficiency, durability, and environmental impacts, ensuring these circularity requirements are covered within functions, see **Table 1** for related **actions**. For example, assessing the reusability of functions can provide insights regarding their value at the end of life (Platform CB'23, 2022, 2023). Based on these assessments, functions can be grouped together and allocated to modular components that are easy to disassemble and reuse, considering the principle of closing the resource loop. The same can be applied to narrowing, slowing, and regenerating the loop. The project team can decide their design ratios when grouping and allocating these functions to objects (Buede, 2000).

Furthermore, circularity principles and the functional analysis and allocation step have overlapping concepts, with this integration, their strengths could complement each other and enhance the overall circularity of the process. This step of the SE process takes a holistic approach through managing functions and their logical flow, emphasizing performance and functionality, yet, neglecting material flow. Conversely, circular economy principles constantly focus on material inputs and outputs but could lack a systemic view of functionality for operation and use (Hubmann & van Maaren, 2022). Additionally, functional analysis and allocation emphasize output thinking (what the system should achieve), while circularity principles focus on input and output thinking in terms of resources, like minimizing the system's waste output by managing inputs (Rahla et al., 2021). Thus, incorporating material flow thinking such as reusability, efficacy, and durability in this process can better align it with circular economy principles. In addition, physical and functional interface management can ensure the system's elements and materials interact efficiently for resource optimization and ease of assembly and disassembly. Managing interfaces, in this case, means ensuring that components and materials interact seamlessly, considering strategies such as reversibility, simplicity, and speed (Vandenbroucke, 2016). An Interface Control Document (ICD) can be used to specify physical and functional interfaces in the system, **actions** related to interfaces are addressed in **Table 1** below. In addition to the interface control document, the **outputs** of this step include the object tree with the different grouped objects based on the circularity principle considered and the requirements allocation sheet (RAS) for traceability and later use in the design synthesis step. Lastly, it is worth noting that incorporating circularity principles may impose immediate constraints on the design space (Çimen, 2021). Yet, this step of SE can still be carried out as a solution-neutral process, allowing for broader exploration of the design space in the next SE process.

5.4 Design Synthesis

The design synthesis step starts with the outputs from the previous step representing the functional architecture of the system and proceeds to develop design alternatives based on that. For circular design, the focus is on considering the whole life cycle and designing projects where materials are optimized and can be reused, recycled, or repurposed at the end of their lifecycle (Dewagoda et al., 2022; Schützenhofer et al., 2022). Designing for circularity in the construction industry requires a systemic and integral approach, considering both the lifecycle of each component individually and their interactions within the whole system (van Stijn & Gruis, 2020). In addition, the selection of materials, the modularity of design, and ease of assembly and disassembly for future reuse are prioritized during design (Dams et al., 2021; Minunno et al., 2020; Rahla et al., 2021). To design for circularity, there are various strategies, such as the use of standardized components that can be easily assembled and disassembled, promoting adaptability and prolonging the lifecycle of materials (Eberhardt et al., 2022).

In construction projects, many components are designed to be interlocked together, making it challenging to separate them when needed. These components are usually connected and depend on each other for stability and functionality. However, this step of the SE process focuses on developing systems that consist of subsystems with careful management of functional and physical interfaces, which could help overcome this issue. From the efforts of the previous step, as explained in section 5.3, the design process can proceed further with a design solution focusing on functional autonomy and facilitating modularity. The design synthesis in SE aligns with the circularity principle for managing interdependencies and interfaces. This alignment can advance circularity in construction projects by easing assembly, disassembly, repurposing, and maintenance activities. Vandervaeren et al. (2022) show through material flow analysis that when considering the interdependencies between building parts and assessing the environmental impacts of demountable buildings, a reduction in material consumption and waste occurs. Two examples demonstrate this as shown by Guy and Ciarimboli (2005); first, the Open House project by Bensonwood Homes, where they used a 3D-design approach with prefabricated elements, treating the building components as independent subsystems, which resulted in enhanced maintainability and future adaptability. Second, the R 128 house showcases how modular prefabricated systems can be designed for dismantling, ensuring that materials can be reclaimed for reuse or recycling (Guy & Ciarimboli, 2005). To take **actions** within the design synthesis step, the project team can consider designing for disassembly and reassembly for a closed loop system (Platform CB'23, 2023). With a focus on whole lifecycle considerations and demountable interfacing of components. For narrowing the loop, it is evident that a focus on minimal material use is needed. This can be achieved by considering optimizing geometries and lightweight structures (Durmisevic et al., 2019; Tingley, 2014). While slowing the resource loop, the project team can consider durable options within the design, considering maintenance and upgrade strategies for future changes (Eberhardt et al., 2022). For a regenerative design, the project team should incorporate renewable and bio-based alternatives when possible (Attia, 2018), utilizing inventory analysis and preliminary ecological appraisal conducted earlier in the SE process as highlighted in section 5.1. These **actions** are listed in **Table 1** below. However, it is important to note that these actions within the four principles complement each other, and the project team can include what is possible based on the project nature and evaluate design alternatives in trade studies for the optimal option.

Furthermore, the project team should provide disassembly plans with a sequence of activities for disassembly alongside construction, operations, and maintenance plans (Tingley, 2014). These plans will be needed at the end-of-life and can be used for repurposing or replacing certain parts during the lifecycle of the project (Bouyarmane et al., 2020). Early in the design process, end-of-life considerations such as disassemblability assessment can help generate and compare alternatives for design trade studies (Desai & Mital, 2003;

Zhu et al., 2020). In addition, materials passports can be used to facilitate documenting information and tracking materials (Göswein et al., 2022; Heinrich & Lang, 2019). The use of material passports can be utilized for closing the loop through the traceability of materials for reclamation at the end-of-life and also for slowing the resource loop by facilitating maintenance tasks through extracting important information needed easily. In addition, BIM can be utilized to simulate certain circularity concerns, such as assembly and disassembly workflows, easy accesses for maintenance, and detect clashes for feasible and executable designs (Akinade, Oyedele, Omoteso, et al., 2017; Azhar et al., 2012; HM Government, 2013; Van Den Berg et al., 2021). The **outputs** of this step are the design alternatives based on the level of detail of the SE process, with the consideration of the four circularity principles. The outputs could be integrated to complement and reinforce each other or be compared in trade-off studies to find the optimal circular design solution. See more for the related **actions** and **outputs** in **Table 1** below.

5.5 Verification and Validation

The verification and validation process could take place at different times of the SE process for iteration, as discussed in section 3.2.5. In this section, the focus is on verifying and validating the circularity aspects of the design once the design synthesis step is completed. This narrowed focus on verification and validation makes it easier to address issues related to integrating circularity, ensuring that key elements are thoroughly evaluated for the integration.

In the CE, Conformity Assessment (CA) ensures that products and processes meet circularity requirements with similar concepts to the verification and validation process in SE (ISO, 2022; Vehring, 2023). Both aim to systematically assess system compliance with specific requirements, utilizing tools to ensure transparency and traceability. Verification has been deployed for checking compliance with environmental impact reports in the CHSTP project (O. M. Hoehne, 2012). In the same way, when circularity requirements are considered in the system, verification can incorporate checks for circular design compliance, such as ensuring that components and materials are verified for their reusability, recyclability, and environmental impact, see the related **actions** for each principle in **Table 1**. For instance, materials can be inspected and tested for their lifecycle performance and potential for future reuse based on the system's requirements.

Validation, on the other hand, could be expanded to include circularity metrics, assessing whether the system's operational performance aligns with circular goals and targets set earlier for the project as discussed in section 5.1. This could include validating the system's effectiveness in minimizing waste and checking the disassemblability and recyclability of components for EOL. Moreover, Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and Environmental Impact Assessments (EIA) can be used for validation purposes (Antwi-Afari et al., 2023). Nevertheless, the validation process will rely mainly on simulations and estimations as many of the circularity considerations are reflected in the future. Tools discussed for assessing functional performance in section 5.3 similar to RAMS could also be employed for validation based on future scenario analysis. For this integration, validation is focused on the goals and targets set at the project start, **actions** are derived accordingly as shown in **Table 1**.

However, traditional methods of verification and validation might require some changes when considering the integration with circularity principles, as these principles might require to be checked based on future scenarios. For example, checking if parts of the system meet disassembly requirements might require considering the disassembly scenario of the system as a whole. The use of BIM could help the project team conduct checks for verification and validation considering circularity (Andrich et al., 2022; van der Zwaag et al., 2023). In addition, sustainable design standards such as BREEAM, LEED, and DGNB can be used for the verification and validation of circular aspects (Pelsmakers et al., 2022; RIBAJ, 2022). This necessitates using models and simulations that fit circularity requirements, as stated by INCOSE (2021) in their 2035 vision for SE that verification and validation will require new methods and models in the future. Based on the way the project team finds it suitable to conduct verification and validation, the **outputs** of this step should include the verification and validation reports, verification matrix, and conformity assessment.

5.6 Framework and Examples

The following tables present the framework for integrating circular economy principles into the SE process. Table 1 outlines the key inputs, actions, and outputs for each SE step across the four circularity principles, while Table 2 provides practical examples for the actions with indices. The numbers in parentheses next to some actions in Table 1 correspond to the indices of practical examples provided in Table 2, offering concrete illustrations of how these actions might be implemented in real-world scenarios.

5.6.1 Circularity Integrated SE Process Framework

Table 1: Framework for Integrating Circularity Principles into the Systems Engineering Process

SE/CE	**Close**	**Narrow**	**Slow**	**Regenerate**
		Project Start		
Inputs	Initial demands and needs System environment and constraints Measures of Effectiveness (MOE)	Initial demands and needs System environment and constraints Measures of Effectiveness (MOE)	Initial demands and needs System environment and constraints Measures of Effectiveness (MOE)	Initial demands and needs System environment and constraints Measures of Effectiveness (MOE)
Actions	Include circularity experts Set targets for resource recovery for the EOL (e.g., 70% recyclability of materials) **(1)**. Identify possible local sources for material harvest **(2)**.	Include circularity experts Set targets for resource efficiency targets (e.g., 25% reduction in materials use and energy consumption) **(3)**.	Include circularity experts Set targets for longevity, maintainability, and repairability.	Include circularity experts Set targets for bio-based materials use. Identify renewable resource opportunities within the local environment **(4)**. Conduct Preliminary Ecological Appraisal (PEA) **(5)**.
Outputs	Goals and targets for early materials recovery and the EOL. Materials inventory (e.g., secondary and reclaimed materials availability from local sources)	Goals and targets for material reduction	Goals and targets for longevity, maintainability, and repairability	Goals and targets for bio-based materials use. Inventory of local bio-based sources. Preliminary Ecological Appraisal (PEA)
		Requirements Analysis		
Inputs	Output of the previous step	Output of the previous step	Output of the previous step	Output of the previous step
Actions	Distinguish between specific and generic circularity requirements. Analyze requirements considering EOL phase (e.g., potential reuse and recycling using MFA and LCA) **(6)**. Analyze requirements for opportunities to include secondary or reclaimed materials **(7)**.	Distinguish between specific and generic circularity requirements. Analyze requirements based on materials and energy consumption (e.g., using LCA and ECI)**(6)**.	Distinguish between explicit and general circularity requirements. Analyze requirements for longevity, maintainability, and repairability (e.g., using LCEA) **(6)**. Determine the expected lifespan of requirements **(6)**.	Distinguish between specific and generic circularity requirements. Assess possible bio-based, eco-friendly alternatives for a requirement.

SE/CE	**Close**	**Narrow**	**Slow**	**Regenerate**
Outputs	EOL requirements (e.g., integrated into the design brief and RVTM). List of requirements for secondary and reclaimed materials use.	Resource efficiency requirements (e.g., integrated into a design brief and RVTM).	List of longevity and adaptability requirements (e.g., integrated into the design brief and RVTM). Maintenance and repair strategy document.	Bio-based alternatives integrated into requirements (e.g., integrated into the design brief and RVTM).
Functional Analysis and Allocation				
Inputs	Output of the previous step	Output of the previous step	Output of the previous step	Output of the previous step
Actions	Include specific circularity requirements as basic functions and generic as supportive functions **(8)**. Consider reusability as a supporting function when assessing functional performance. Allocate functions to modular components for easy disassembly **(10)**. Assess and manage physical interfaces for seamless interaction **(9)**.	Include specific circularity requirements as basic functions and generic as supportive functions **(8)**. Consider efficiency as a supporting function when assessing functional performance. Identify opportunities for multifunctional components. Allocate functions to optimize material use (e.g., multifunctional components) **(10)**. Assess and manage functional interfaces for resource optimization.	Include specific circularity requirements as basic functions and generic as supportive functions **(8)**. Consider durability as a supporting function when assessing functional performance. Assess and manage physical and functional interfaces for easy repair and replacement.	Include specific circularity requirements as basic functions and generic as supportive functions **(8)**. Consider eco-friendliness as a supporting function when assessing functional performance. Assess functions for their environmental impact. Allocate functions considering possible symbiotic relationships with the local environment.
Outputs	Object tree, including modular components. Requirements Allocation Sheet (RAS). Interface Control Document (ICD).	Object tree, including multifunctional components. Requirements Allocation Sheet (RAS). Interface Control Document (ICD).	Object tree, including upgradeable and long-lasting components. Requirements Allocation Sheet (RAS).	Object tree, including the environmental performance of components. Requirements Allocation Sheet (RAS).
Design Synthesis				
Input	Output of the previous step	Output of the previous step	Output of the previous step	Output of the previous step
Action	Design for disassembly and reassembly (e.g., reusable and recyclable materials, reversible connections, and modular components) **(10)**. Utilize material passports for traceability of materials (e.g., for EOL recovery and reuse) **(11)**. Document disassembly plans (e.g., using BIM to model the sequence of deconstruction activities and store information for capabilities needed at the EOL).	Design for minimal material use (e.g., lightweight structures, optimized geometries, and prefabrication techniques) **(12)**. Use parametric design tools and standardize components. Utilize BIM models for precision in material quantity surveying.	Design for durability and easy maintenance (e.g., accessible systems, robust materials) **(13)**. Incorporate upgrade pathways into the design **(13)**. Utilize material passports and BIM models for maintenance tasks.	Design using renewable and bio-based materials (e.g., green infrastructure and nature-based solutions) **(12)**. Apply bioregional design methods
Output	Design alternatives baed on the level of detail (including EOL and disassembly plans, the use of reclaimed materials)	Resource-efficient design alternatives based on the level of detail	Long-lasting and adaptable design alternatives (including maintenance and upgrade plans)	Regenerative design alternatives (including bio-based materials and green infrastructure)
Verification & Validation				
Inputs	Output of the previous step	Output of the previous step	Output of the previous step	Output of the previous step

SE/CE	Close	Narrow	Slow	Regenerate
Actions	Verify EOL requirements (e.g., recyclability and recoverability of design choices) **(14)**. Validate achieving material recovery targets (e.g., using simulation software for future scenarios and BIM for disassembly workflow).	Verify design meets resource efficiency requirements (e.g., test resource efficiency performance) **(15)**. Validate achieving material reduction targets.	Verify that designs meet longevity and adaptability targets (e.g., conduct durability and adaptability testing) **(16)**. Validate longevity, maintainability, and repairability targets (e.g., aging tests, and using BIM and simulation to check the feasibility of repair and maintenance processes).	Verify design meet regenerative requirements **(17)**. Validate the inclusion of bio-based material and achieving environmental impact targets (e.g., using EIA and LCA tools).
Outputs	Verification and Validation reports (e.g., EOL recyclability assessment, disassembly simulation results). Verification matrix (e.g., showing compliance for material recovery requirements). Conformity Assessment (CA) (e.g., report on adherence to recycling and reuse targets).	Verification and Validation reports (e.g., resource efficiency test results, material consumption reduction analysis). Verification matrix (e.g., showing compliance for resource efficiency requirements). Conformity Assessment (CA) (e.g., report on adherence to material and energy efficiency targets).	Verification and Validation reports (e.g., durability test outcomes, maintenance and repair feasibility assessments). Verification matrix (e.g., showing compliance for longevity and adaptability requirements). Conformity Assessment (CA) (e.g., report on adherence to product lifetime extension targets).	Verification and Validation reports (e.g., bio-based material compliance checks, environmental impact assessments). Verification matrix (e.g., showing compliance for regenerative design requirements). Conformity Assessment (CA) (e.g., report on adherence to regenerative and eco-friendly material targets).

Note: *Numbers between parentheses next to some actions are indices for examples from practice for these actions shown in Table 2.*

5.6.2 Examples from Practice

Table 2 below presents practical examples from pracitce that illustrate the implementation of seventeen actions from the framework, these examples provide practical insights and further support for the suggested actions in the framework.

Table 2: Supporting examples for the actions in the framework

Action Index	Example	Source
1	The Philips Circular Lighting project set a target to achieve 80% recyclability for their LED lighting products.	(Philips, 2015)
2	The Dutch company New Horizon Urban Mining identifies and harvests reusable materials from buildings scheduled for demolition within a certain radius of their project sites.	(New Horizon, n.d.)
3	The Empire State Building retrofit project set a target to reduce energy consumption by 38%.	(Buildings, 2012)
4	The Bullitt Center identified opportunities to use local rainwater and geothermal for energy, setting a target to be net-zero water and energy.	(B. Pena, 2014)
5	The HS2 railway project in the UK conducted PEAs along the entire route to identify key ecological features.	(GOV.UK, 2022)
6	The new update of EU's Ecodesign for Sustainable Products Regulation requires analysis of product requirements with consideration for durability, reparability, recyclability, ease of end-of-life disassembly and reuse, and recycled content.	(Ecochain, 2024; EUR-Lex, 2022)
7	The Dutch company Stonecycling analyzes building material requirements to incorporate up to 60% waste-based content in their bricks.	(Treggiden, 2020)
8	In the design of Philips' pay-per-lux lighting system, the basic function is providing light (with specific circularity requirements like energy efficiency), while supportive functions include recyclability and upgradability.	(Ellen Macarthur Foundation, 2022)
9	In the guideline of the EU-funded Buildings as Material Banks (BAMB) project, building components are assessed for interfaces to enable future disassembly and reuse.	(Cornet et al., 2016)

10	The Dutch company Superuse Studios designs buildings using reclaimed materials, allocating functions to these materials based on their inherent properties demonstrating how to close and narrow the resource loop through reuse and optimization.	(Baldwin, 2021)
11	EPEA and Madaster creates digital material passports for buildings, documenting all materials used in construction to facilitate future reuse and recycling.	(Madaster, 2022)
12	The MycoTree project by Karlsruhe Institute of Technology and ETH Zurich created a load-bearing structure using mycelium (mushroom roots) combined with bamboo, showing the potential of both bio-based materials and lightweight structures.	(World Architects, 2017)
13	The Edge office building in Amsterdam is designed with accessible systems and durable materials, facilitating easy maintenance and upgrades.	(ArchDaily, 2016)
14	The DGNB (German Sustainable Building Council) certification system includes criteria for verifying the recyclability and recoverability of building materials at EOL.	(DGNB, n.d.)
15	The Embodied Carbon in Construction Calculator (EC3) tool helps verify the resource efficiency of designs by comparing the embodied carbon of different material choices.	(Carbon Leadership Forum, 2023)
16	The BRE (Building Research Establishment) in the UK conducts durability testing on construction materials and systems to verify their longevity and long term impact.	(BRE, n.d.)
17	The Living Building Challenge have certification program to verify designs meet regenerative requirements, such as net-positive energy.	(Living Future, n.d.)

6 Framework Validation

This section outlines the framework validation process, starting with an overview of the procedure followed and details about interviewees. It then presents insights for each SE step of the framework. The validation focuses primarily on qualitative insights, supplemented by quantitative data in the form of applicability scores for integrating circular economy principles at each SE step.

6.1 Procedure and Interviewee Details

The framework developed in this study aims to incorporate four circular economy principles into the SE process. This was validated through semi-structured interviews with systems engineers from ProcessMinded as explained in section 2.3. The validation seeks to assess the framework and identify its strengths and potential improvements. In addition, the framework validation focuses on the actions that a system engineer should consider within every step of the SE process and addresses the applicability of these actions on a score from 1 to 5, with 5 being highly applicable and 1 not applicable at all. Information about the interviewees' roles and years of experience can be seen in Table 3 below.

Table 3: Interviewees code, role, and experience.

Participant code	Expertise	Years of Experience
P1	Sustainability advisor, previously a systems engineer	13
P2	Systems Engineer	15
P3	Sustainability advisor, previously a systems engineer	17
P4	Process manager previously a Systems Engineer	8
P5	Project manager, previously a Systems Engineer	12

6.2 Validation Insights Per SE Step

As the framework was presented to interviewees per SE step, the validation insights are presented in a similar way. These insights are then summarized in Table 4 at the end of this section, which shows the strengths and potential points of improvements for the actions per SE step in the framework and the average score of applicability of each step rated by the five participants.

6.2.1 Circularity Integrated Project Start

The Project Start step, with an average applicability rating of 4.2, was generally well-received. However, the interviews revealed an interesting tension between the perceived importance of this step and the ambiguity surrounding the systems engineer's role. **P3** raised an important question about responsibility:

> "It is really hard to say if these actions are a responsibility of the system engineer. Or does it come from the ambitions of the project."

This points to a potential need for assigning roles and responsibilities when implementing circularity principles, especially at the project's inception.

An interesting suggestion came from **P5** regarding ownership of circularity goals:

> "Try to acknowledge the targets to a person to making them responsible to create ownership that you can need for the next actions."

This idea supports the framework's emphasis on setting clear circularity targets at the start yet highlights that personal accountability for circularity targets could be a powerful tool for ensuring these principles are carried through the entire project effectively.

6.2.2 Circularity Integrated Requirements Analysis

The Requirements Analysis step received an average applicability rating of 4, reflecting a mix of optimism and concern among the interviewees. A key insight from this phase was the challenge of translating broad circularity goals into specific, actionable requirements. **P2** observation that

> "Nothing was explicit enough, I guess" ... "especially in civil engineering, It is such a new topic, they are not used to thinking at least in the setting of requirements for this, they are not used to it"

This highlights a common struggle in implementing circularity principles. This suggests that the framework is beneficial in providing more guidance on how to make circularity requirements more concrete and measurable. Furthermore, an interesting perspective came from **P1**, who pointed out a potential conflict between different circularity principles:

> "If I have an element with a short lifetime and I have to replace it several times, but it is circular because it's made of biobased, I do not know that it might be a better solution than an oil-based product, but last maybe longer."

This insight underscores the complexity of circularity and the need for balanced decision-making in requirements analysis within the different circular targets. These observations validate the framework's approach to distinguishing between specific and general circularity requirements. The moderate applicability rating (4) compared to the other steps reflects the inherent challenges in this step but also suggests that the framework provides a viable starting point for translating broad circularity requirements into concrete requirements.

6.2.3 Circularity Integrated Functional Analysis and Allocation

With an average applicability rating of 4, this step was viewed positively by most interviewees. The discussions around this step revealed a strong focus on the practical aspects of integrating circularity principles within the systems engineering process. **P2** provided valuable insight into the role of the systems engineer in this phase:

> "These are real actions for the systems engineer only at first, of course, then, with the support of all the technical engineers again."

This comment validates the framework's approach of integrating circularity considerations into the core systems engineering processes while also recognizing the need for collaboration with those who have the needed technical expertise. An important aspect of this step is the management of interfaces, which is crucial for integrating circularity principles. **P5** highlighted this:

> "You can say prioritize and manage the conflicts, manage their interfaces."

This observation aligns with the framework's emphasis on interface management as a key aspect of functional analysis and allocation for integrating circularity. **P3** underscored the importance of this phase, stating:

> "I think in this phase it is important to make the interfaces between the materials clear for the reversibility, so if they can release the walls from the floor for example."

The insights from this step strongly validate the framework's approach to integrating circularity considerations into the functional analysis and allocation step. The framework's emphasis on physical and functional interface management for the different circularity principles and its guidance on allocating circularity functions appear to resonate with practitioners' experiences and needs while also recognizing the collaborative nature of this process.

6.2.4 Circularity Integrated Design Synthesis

The Design Synthesis step received the lowest average applicability rating of 3.6, revealing some challenges in integrating circularity principles into this phase of the SE process. The interviews uncovered a tension between the desire to influence design for circularity and the traditional role of systems engineers. **P3** pointedly asked:

> "It says design for minimal material use, for example, but the system engineer is not responsible for the design."

This comment highlights a key challenge in implementing the framework to further consider systems engineer's influence on design decisions to facilitate circularity implementations without overstepping their conventional boundaries. An interesting perspective came from **P1**, who suggested a broader view of circularity in design:

> " I think you should use the MKI as well. Because you do not want to be circular, despite of other environmental impacts."

This insight underscores the importance of considering the impact of circularity in the design trade studies in broader sense, rather than in isolation.

6.2.5 Circularity Integrated Verification and Validation

The Verification and Validation step received an average applicability rating of 4.2, indicating that interviewees saw this as an area where systems engineers could readily incorporate circularity principles. However, the discussions revealed some challenges in verifying and validating circularity requirements. **P1** highlighted a key difficulty:

> "The most complicated part is to say it is recyclable at the end of the lifetime, but that is in 20 years. So how are you going to verify it now, especially when you have new products?"

This points to a fundamental challenge in circularity regarding how to verify long-term outcomes in the short term. **P2** offered an interesting perspective on the familiarity of the process:

> "This is everyday work for me. Of course the topic is different, but the topic of every requirement is different. So it is just verifying and validating like an everyday job."

This suggests that while the content may be new, the process of verification and validation is a well-established practice for systems engineers, making the integration of circularity principles more straightforward to comprehend and implement.

6.2.6 Framework Validation Summary and Conclusion

Table 4 below summarizes the validation insights of the developed framework into strengths, potential improvements, and applicability score of actions for each step of the SE process. The validation process showed that the framework is effective and applicable, especially in integrating circular economy principles during the project start and verification phases. Industry professionals from ProcessMinded confirmed its practical relevance but pointed out areas that need refinement, particularly in the design synthesis phase and the role of systems engineers. While the framework has strong potential, the validation suggests that further iteration and adaptation are needed to fully address the complexities of real-world application in construction projects. Overall, the framework is well-validated but requires targeted improvements for comprehensive implementation.

Table 4: Strengths, potential improvements, and framework applicability.

Framework steps	**Framework Strengths**	**Potential Improvements**	**Applicability (out of 5)**
Project Start	Clear starting point for integration. Encourages consideration of all circularity principles.	Assign ownership of targets. Clarify the role of the systems engineer in setting targets.	4.2
Requirements Analysis	Distinguishes specific and general circularity requirements. Encourages end-of-life considerations.	Involve technical experts. Provide more guidance on making circularity requirements SMART.	4
Functional Analysis & Allocation	Integrates circularity into functional thinking. Emphasizes interface management.	Provide more guidance on incorporating circularity into function allocation. Include examples of circularity-influenced functional architecture.	4
Design Synthesis	Encourages circularity in design decisions. Promotes documentation of disassembly plans.	Clarify systems engineer's role in design decisions. Provide strategies for balancing circularity with other design constraints.	3.6
Verification & Validation	Addresses long-term circularity goals. Distinguishes between verification and validation for circularity.	Develop new validation methods for long-term goals. Provide guidance on verifying circularity requirements.	4.2

Note: *Applicability score ranges from 1 to 5 for the actions in the framework, with 5 being highly applicable and 1 not applicable at all.*

7 Discussion

This study explored how circular economy principles can be integrated into the systems engineering process within the construction industry. The research resulted in the development of a framework through literature review and expert validation aimed at guiding ProcessMinded and other practitioners in implementing this integration. This section interprets the key findings, compares these findings with existing literature, discusses scientific and practical contributions, and addresses limitations and future research directions.

7.1 Summary of Key Findings

This study has yielded several significant findings regarding the integration of circular economy principles into the SE process. The research demonstrates that incorporating circularity principles into each step of the SE process is applicable and potentially transformative. This finding aligns with the evolving nature of SE as a dynamic field capable of adapting to new challenges (Presland et al., 2018; M. Watson et al., 2022). The successful integration of circularity principles across all steps of the SE process suggests that SE is a suited comprehensive approach for incorporating circular economy principles in construction projects.

The study revealed that the project start step is crucial for setting the foundation for circularity throughout the project lifecycle. This finding underscores the importance of early-phase planning in circularity integration, as highlighted by Sanchez and Haas (2018). By incorporating circularity principles at the outset, projects can establish clear goals, align stakeholders, and create a shared vision for circularity outcomes. This early integration can help overcome traditional barriers to circularity implementation, such as lack of awareness or commitment among stakeholders, as identified by Adams et al. (2017) in their study on circularity challenges in construction. In the requirements analysis step, the framework's approach to distinguishing between specific and generic circularity requirements emerged as a key finding. This distinction offers a clear way to address circularity requirements, covering both broad requirements and specific measurable requirements. This aligns with the approach suggested by the European Commission (2009) in their ecodesign guidelines, which differentiate between generic and specific ecodesign requirements. However, the study also indicated ongoing challenges in translating broad circularity goals and targets into concrete requirements, reflecting the complexities of requirements engineering (Arayici et al., 2005; Kamara & Anumba, 2002; Wheeler, 2004). Furthermore, the functional analysis and allocation step showed strong potential for circularity integration, particularly in its emphasis on interface management and allocation of circularity functions. This step can extend traditional functional decomposition to include circularity aspects aligning with circular design strategies, especially the principles of designing for disassembly and adaptability (Eberhardt et al., 2022). This phase of SE can be leveraged to embed circularity thinking into the functional thinking of SE for construction projects, potentially leading to a more circular process. The design synthesis step emerged as the most challenging for circularity integration based on the expert's validation. This finding reflects a tension between the desire to influence design for circularity and the traditional role of systems engineers as process facilitators rather than design specialists. It highlights a potential need for redefining roles and responsibilities within SE for circular construction projects. The study also uncovered challenges in verifying and validating long-term circularity outcomes. This finding underscores the need for new methods and models for verification and validation, as suggested by INCOSE (2021) in their 2035 vision for systems engineering. The long-term nature of many circularity requirements, such as end-of-life recyclability or adaptability over long periods, poses unique challenges for traditionally accepted verification and validation methods.

Although circularity principles can be integrated into all steps of the SE process, the degree of integration and the challenges encountered differ between steps. This indicates that the tailored, step-specific approach of the framework developed in this study is effective for integrating the four circular economy principles of closing, narrowing, slowing, and regenerating the resource loop. This makes the framework useful for organizations that apply all the steps of the SE process or those focused on specific steps within the process. This finding is consistent with R. S. de Graaf et al. (2017) and R. de Graaf et al. (2016), who noted that in some construction projects, only certain steps of SE process are applied. For the application of the framework, this is considered good as systems engineers can use the framework focusing on the processes they need or apply.

7.2 Research Contribution

This study makes several contributions to the scientific understanding of how circular economy principles are integrated into the SE process and to the practical application of these principles in the construction industry.

Firstly, this research addresses the gap identified by Gasparri et al. (2023) for sector-specific frameworks and interdisciplinary approaches to circular economy implementation in construction. By developing a framework that integrates circular economy principles into the established SE process, this study provides a novel approach that bridges two previously distinct fields. This integration contributes to the broader body of knowledge in both SE and circular economy studies, offering a new theoretical perspective on how these concepts can be combined.

Secondly, the framework developed in this study responds to the call for more practical applications and frameworks for implementing circular economy principles in the construction industry, as highlighted by Antwi-Afari et al. (2021) and Guerra et al. (2021). By providing a structured approach for integrating circularity into each step of the SE process, this research offers a framework that can be applied and further studied in real-world construction projects. This addresses the critical need for actionable methodologies to translate circular economy theory into practice within the construction industry.

Thirdly, this study contributes to addressing the demand for new design typologies and decision-making guides for circular economy implementation, as identified by Eberhardt et al. (2022). The framework's approach to integrating circularity considerations into the functional analysis and allocation, and design synthesis steps provides a new perspective on how circular design principles can be systematically incorporated into the design process. This contribution has the potential to influence how circular design is conceptualized and implemented in construction projects.

Furthermore, for the practical contribution, this research offers considerable value to ProcessMinded and similar organizations in the construction industry. The developed framework provides ProcessMinded with a structured approach to incorporating circularity principles into their existing SE practices. This addresses ProcessMinded's specific need for a widely applicable approach to incorporating circularity into SE that is generic enough to be used across different projects yet flexible enough to incorporate different circular economy principles. This contribution has the potential to enhance the current practices of organizations toward circularity in the construction industry. In addition, the validation of the framework through interviews with industry professionals provides initial evidence of its applicability and relevance to real-world practices. This not only contributes to the practical validation of the framework but also highlights areas for future refinement and research, paving the way for further studies in this field. By focusing on the integration of circular economy principles into SE, this research contributes to the ongoing evolution of SE as a discipline, aligning with the vision set out by INCOSE (2021) for the future of SE, which emphasizes the need for evolution to address complex interconnected challenges.

7.3 Limitations and Future Research

While this research contributes valuable insights, limitations exist that should be acknowledged, providing a basis for future research. These limitations are discussed below, then suggestion for future research are provided.

7.3.1 Limitations

The primary limitation arises from the framework validation process, which relied on interviews with only five professionals from ProcessMinded. This small sample size, confined to a single company, limits the generalizability of the findings and may not fully represent the diverse perspectives within the broader construction industry. The validation focused heavily on the actions in the framework within the different SE steps. While informative for the study, this may not capture the full complexity of integrating circularity principles in real-world projects. In addition, the iterative nature of SE processes and the different levels of detail are not sufficiently addressed in the framework presented in this study, which could make differences in the framework structure and expand it further or imply changes. Another noteworthy limitation is the framework's theoretical nature. Although validated by experts, the framework has not been tested in actual construction projects. This lack of practical implementation means that unforeseen challenges or limitations in applying the framework may exist that were not captured in this study.

Additionally, the research also focused primarily on the technical aspects of SE, specifically the technical SE process, potentially overlooking important organizational and management processes that could influence the integration of circular economy principles. The framework's emphasis on the SE process and ProcessMinded's ten-step approach to systems engineering may limit its applicability to organizations with different SE methodologies. Also, the study's approach to circularity, focusing on four main principles (closing, narrowing, slowing, and regenerating the resource loop), while comprehensive, may not capture all nuances of circular economy concepts for and within the construction industry. The integration of these principles into each SE step was based on theoretical connections based on literature, which may oversimplify the complexities of real-world application. An additional limitation to consider is the potential for misinterpretation of context-specific terms with the integration. The study draws from diverse fields such as but not limited to systems engineering, circular economy, construction management, product manufacturing, stakeholders management, and requirements engineering. While efforts were made to accurately interpret and synthesize literature, there is a possibility that some context-specific meanings may have been misunderstood. This is particularly relevant when applying concepts from one field to another, where terminologies and methodologies may not always align perfectly. For instance, the interpretation of circular economy principles and their application to systems engineering steps relied on the researcher's understanding and synthesis of various sources. While care was taken to maintain accuracy, the complexity of both fields leaves room for potential misinterpretations that could affect the framework's theoretical foundation. Lastly, the research did not extensively address the potential conflicts between different circularity principles. This limitation was highlighted in the validation interviews, where tensions between different circularity aspects (e.g., durability vs. recyclability) were noted but not fully explored within the framework.

7.3.2 Future Research

Building upon these limitations, the following future research directions are recommended to further build on this study:

- Diverse Sample Validation: Future research could validate the framework with a larger and more diverse sample of professionals across various organizations in the construction industry. This broader validation would enhance the framework's generalizability and provide a more comprehensive understanding of its applicability.

- The Iterative nature of SE and different levels of details: Further investigation of the iterative nature of SE and how the framework could be applied at different levels of detail can potentially reveal valuable insights. Additionally, the actions could be extended to include the requirements analysis loop and design loop reflecting what the integration would require when revisiting previous steps throughout the whole process.

- Real-World Application: To move beyond theoretical validation, future research could implement the framework in actual construction projects. Longitudinal studies could provide valuable insights into the practical application of circular economy principles at each step of the SE process. This could help explore and identify real-world challenges and insights.

- Exploration of Organizational and Management Aspects of SE: Future research could investigate how different organizational structures and management processes within SE affect the integration of circular economy principles. This includes exploring potential differences between client and contractor organizations when applying SE methods and how these variations influence the framework's adoption and effectiveness.

- Addressing Conflicts in Circularity Principles: Future research could study further the conflicts between various circularity principles within the SE process. For example, exploring the trade-offs between different circular strategies streaming from different principles can provide systems engineers with practical insights for balancing these aspects in project implementation.

By addressing these limitations and pursuing these suggested research directions, the academic and professional communities can build on this study's foundation. This continued exploration could refine the integration of circular economy principles into SE practices and eventually contribute to more sustainable and circular practices within the construction industry.

8 Conclusion

This research set out to explore the integration of circular economy principles into the SE process for the construction industry, with a specific focus on developing a framework for ProcessMinded to implement this integration. The study has successfully addressed its main research question and associated sub-questions, providing valuable insights into how circularity can be integrated within SE.

First, the study provided a comprehensive understanding of the systems engineering processes and circular economy principles relevant to the construction industry. It established the foundational concepts necessary for integrating the four key circular economy principles: closing, narrowing, slowing, and regenerating the resource loop with the five SE processes: project start, requirements analysis, functional analysis & allocation, design synthesis, and verification & validation.

Second, a structured framework was developed, presented in the form of inputs, actions, and outputs for each SE process to guide the integration of these four principles across each step of the SE process. The framework offers a systematic approach, detailing specific actions and expected outputs for systems engineers. Validation through expert interviews confirmed the framework's applicability, with particular strength in the project start and verification steps. However, challenges were noted in the design synthesis step, where the integration of circularity proved more complex and technically demanding, highlighting areas for further development. This variation in applicability based on systems engineers' assessments suggests that they may find the integration of circularity principles more straightforward in certain steps that they are familiar with and more technically challenging in others, particularly when specific technical expertise is needed.

Third, the research delivered a practical, actionable framework that ProcessMinded and similar organizations can use to integrate circular economy principles into their SE practices. The inclusion of practical examples for some actions enhances the framework's relevance and utility, addressing the pressing need for more circular approaches in the construction industry.

In summary, while the study has its limitations, particularly concerning the scope of validation and its theoretical nature, it lays a solid foundation for future research. The identified areas for further investigation, including practical implementation, offer promising research directions for further studies in this field. This research not only advances the theoretical understanding of integrating circularity with the SE process but also provides practical applications for ProcessMinded, serving as a stepping stone toward more circular practices through SE in the construction industry.

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