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Integration of resources valorization, costs, and reduced environmental impacts to apply circular indicators and strategies in buildings

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INTEGRATION OF RESOURCES VALORIZATION, COSTS, AND REDUCED ENVIRONMENTAL IMPACTS TO APPLY CIRCULAR INDICATORS AND STRATEGIES IN BUILDINGS

Doctoral Thesis presented to the Postgraduate Program in Civil Engineering: Construction and Infrastructure at the Universidade Federal do Rio Grande do Sul, as part of the requirements for obtaining the title of Doctor in Civil Engineering

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CIRCULAR INDICATORS AND STRATEGIES IN BUILDINGS: INTEGRATING RESOURCES VALORIZATION, COSTS, AND REDUCED ENVIRONMENTAL IMPACTS

This Doctoral Thesis was judged as part of the requirements for obtaining the title of DOCTOR IN CIVIL ENGINEERING, research area Construction - Sustainability and Risk Management, and approved in its final form by the Supervisor Professor and the Postgraduate Program in Civil Engineering: Construction and Infrastructure at the Universidade Federal do Rio Grande do Sul.

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To my family, for their unconditional love and support.

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“O correr da vida embrulha tudo, a vida é assim: esquenta
e esfria, aperta e daí afrouxa, sossega e depois desinquieta.
O que ela quer da gente é coragem.”

(Guimarães Rosa)

“É preciso diminuir a distância entre o que
se diz e o que se faz até que num dado momento a tua fala
seja a tua prática.”

(Paulo Freire)

RESUMO

TIMM, J. F. G. **Integração da valorização de recursos, custos e redução de impactos ambientais para aplicar indicadores e estratégias circulares em edifícios**. 2024. Tese (Doutorado em Engenharia Civil) - Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura, Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2024.

Os padrões atuais de produção e consumo são inconsistentes com a capacidade regenerativa do planeta e a construção civil é considerada um dos setores que mais consomem recursos. Um dos meios de alterar esses padrões é adotar um modelo de Economia Circular (EC), que permite adequar a gestão de recursos, estendendo a vida útil dos produtos e promovendo a circularidade. Entretanto, a redução de impactos promovidos pelas estratégias circulares (ES) não é clara. Desta forma, alinhá-las com outras ferramentas de gestão ambiental como o ecodesign pode facilitar o alcance do desenvolvimento sustentável. O objetivo principal da presente pesquisa é integrar desempenho ambiental, custos e valorização de recursos, transitar para uma EC no ambiente construído, através de da proposição de um *framework* multiatributo que utiliza ecodesign, estratégias circulares (EC) e indicadores (IC). A tese é baseada no *Design Science Research*, organizada em três fases principais (Compreensão, Desenvolvimento e Discussão) e composta de três artigos. No primeiro Artigo, realizou-se uma revisão sistemática sobre ES no ambiente construído e foi proposto um Framework baseado no ecodesign para auxiliar no processo de escolha e acompanhamento dos efeitos das ES para o desempenho ambiental, econômico e aumento da valorização dos recursos. Os resultados destacam que há reconhecimento sobre a relevância da EC no setor da construção e que existem muitas ESs, mas poucos estudos avaliam seu uso combinado e demonstram os benefícios de aplicá-las. Dessa forma, é necessário ampliar o número de estudos de caso que aplicam ES e analisar os resultados encontrados também favorecendo a redução de impactos. Nesse sentido, o Artigo 2 investiga as estratégias de reutilização e remanufatura, reciclagem e extensão da vida útil para sistema modular metálico interno e externo para paredes em dois estudos de caso brasileiros, através da Avaliação do Ciclo de Vida (ACV), Custo do Ciclo de Vida (CCV) e Índice de Circularidade da Edificação (BCI). O estudo de caso contribui para a investigação da modelagem de ACV considerando mais de um ciclo de vida, fornecendo dados para a tomada de decisão sobre o uso de ES e cenários de fim de vida. Os resultados também enfatizam que a aplicação de ES nas fases de projeto favorece outros cenários de fim de vida, mas que uma avaliação integrada é importante para a escolha e que são necessários mais ICs para comunicar a circularidade. Dessa forma, o Artigo 3 investiga e avalia ICs para medir a circularidade nos produtos de construção e incorporá-los no Framework, proposto no Artigo 1. Os resultados destacam que cada IC é baseado em dados e princípios de EC diferentes. Uma análise combinada do desempenho ambiental, da circularidade e dos custos pode contribuir para a transição para a EC. O Framework auxilia no processo de tomada de decisão e monitoramento dos efeitos das EC. O estudo de caso avaliado ilustrou o potencial do Framework e a capacidade visual de comunicação de dados. Portanto, as principais contribuições da pesquisa são: (i) identificação do potencial do Ecodesign, circularidade e análise de sensibilidade na transição para o desenvolvimento sustentável; (ii) proposta de framework para avaliação da circularidade em sistemas construtivos; (iii) integração de desempenho ambiental, custos e valorização de recursos no ambiente construído; (iv) avaliação de indicadores para acompanhar a evolução da EC e auxiliar na tomada de decisões de circularidade com redução do impacto ambiental.

Palavras-chave: Ecodesign. Economia Circular. Ambiente construído. Indústria da construção civil. Desempenho ambiental. Desenvolvimento sustentável.

ABSTRACT

TIMM, J. F. G. **Integration of resources valorization, costs, and reduced environmental impacts to apply circular indicators and strategies in buildings.** 2024. Thesis (Doctoral in Civil Engineering) - Postgraduate Program in Civil Engineering: Construction and Infrastructure, Engineering School, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2024.

Current production and consumption patterns are inconsistent with the planet's regenerative capacity, and construction is considered a sector that consumes the most resources. One of the ways to change these standards is to adopt a Circular Economy (CE) model, which allows for the adaptation of resource management, the extension of the useful life of products, and the promotion of circularity. However, the reduction of impacts promoted by circular strategies (CS) is unclear. In this way, aligning them with other environmental management tools such as ecodesign can promote sustainable development. The main objective of this research is to integrate environmental performance, costs, and resource valorization, moving towards a CE in the built environment through the proposition of a multiattribute framework that uses ecodesign, circular strategies (CS), and indicators (CI). The thesis is based on Design Science Research, organized into three main phases (Understanding, Development, and Discussion), and comprises three articles. In the first Article, we carried out a systematic review of CS in the built environment and proposed a Framework based on ecodesign to assist in the process of choosing and monitoring the effects of CS on environmental and economic performance and increasing the value of resources. The results highlight that CE is recognized in the construction sector and many CSs can be applied to the sector. However, few studies have evaluated their combined use and demonstrated the benefits of applying them. Therefore, it is necessary to increase the number of case studies that apply CS and analyze the results found, favoring the reduction of impacts. In this sense, Article 2 investigates reuse and remanufacturing, recycling, and service life extension strategies for internal and external metallic modular systems for walls in two Brazilian case studies through Life Cycle Assessment (LCA), Life Cycle Costs (LCC), and Building Circularity Index (BCI). The case study contributes to the investigation of LCA modeling, considering more than one life cycle and providing data for decision-making on using CS and end-of-life scenarios. The results also emphasize that applying CS in the design phases favors other end-of-life scenarios but that an integrated assessment is important for the choice and that more CIs are demanded to communicate circularity. Thus, Article 3 investigates and evaluates CIs to measure circularity in construction products and incorporate them into the Framework proposed in Article 1. The results highlight that each CI is based on different CE data and principles. A combined analysis of environmental performance, circularity, and costs can contribute to the transition to CE. The Framework assists in the decision-making process and monitoring the effects of CE. The evaluated case study illustrated the Framework's potential and visual data communication capacity. Therefore, the main contributions of the research are: (i) identification of the potential of Ecodesign, CE, and sensitivity analysis in the transition to sustainable development; (ii) proposal of a framework for evaluating CE in construction systems; (iii) integration of environmental performance, costs and appreciation of resources in the built environment; (iv) evaluation of indicators to monitor the evolution of CE and assist in making CE decisions and reducing environmental impact.

Keywords: Ecodesign. Circular Economy. Built environment. Construction industry. Environmental performance. Sustainable development**.**

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LIST OF ACRONYMS

ABNT: Brazilian National Standards Organization (in Portuguese *Associação Brasileira de Normas Técnicas*)
ABRECON: Brazilian Association for Recycling Civil Construction and Demolition Waste (in Portuguese *Associação Brasileira para Reciclagem de Resíduos da Construção Civil e Demolição)*
ADPN: depletion of abiotic resources – not fossil
ADPF: depletion of abiotic resources – fossil
AI: artificial intelligence
AP: acidification potential
BAU: business as usual
BCI: building circularity index
BIM: building information modelling
BR: Brazil
BRE: Building Research Establishment
BREEAM: Building Research Establishment Environmental Assessment Methodology
BS: British Standards Instituion
CAPES: Brazilian Federal Agency for Support and Evaluation (in Portuguese *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*)
CBB: Central Bank of Brazil (in Portuguese *Banco Central do Brasil*)
CE: Circular Economy (in Portuguese *Economia Circular* – EC)
CI: circular indicators
CIRCuIT: Circular Construction in Regenerative Cities
CO_2: carbon dioxide
CP: Circularity Potential
CS: circular strategies
DfE: design for environment
DfMA: Design for Manufacture & Assembly
DGNB: German Sustainable Building Council (in Germany *Deutsche Gesellschaft für Nachhaltiges Bauen*)
DOI: Digital Object Identifier
DSR: Design Science Research
ECI: Element Circularity Index
EE: Engineering School (in Portuguese *Escola de Engenharia*)
EMAS: Eco-Management and Audit Scheme
EMF: Ellen Macarthur Foundation
EOL: end-of-life
EP: Eutrophication
EPA: US Environmental Protection Agency
EPD: environmental product declarations
ES: ecodesign strategies
FRS: Final retention in society

GDP: gross domestic product
GHG: greenhouse gases
GWP: global warming potential
HDPE: high density polyethylene
ICLEI: International Council for Local Environmental Initiatives
IEA: International Energy Agency
IoT: internet of things
IPCC: Intergovernmental Panel on Climate Change
ISO: International Organization for Standardization
ISSN: International Standard Serial Number
JCR: Journal Citation Reports
LC: life cycle
LCA: Life Cycle Assessment
LCC: Life Cycle Cost
LCI: life cycle inventory
LI: Longevity Indicator
MCI: Material Circularity Indicator
MFA: Material Flow Analysis
NBR: Brazilian technical standard (in Portuguese *norma técnica brasileira*)
ODP: ozone layer depletion
OECD: Organization for Economic Cooperation and Development
OSB: oriented strand board
PCI: Product Circularity Indicator
PCR: Product Category Rules
PDCA: Plan-Do-Check-Act
Ph.D.: Doctor of Philosophy
POCP: photochemical oxidation
PPGCI: Postgraduate Program in Civil Engineering: Construction and Infrastructure (in Portuguese *Programa de Pós-Graduação em Engenharia Civil - Construção e Infraestrutura*)
PSS: product service system
QFDE: Quality Function Deployment for Environment
RoW: rest of the world
RPI: Reuse Potential Indicator
SCI: System Circularity Indicator
SINAPI: National System of Survey of Civil Construction Costs and Indexes (in Portuguese *Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil*)
UCR: uniform capital recovery
UFRGS: Federal University of Rio Grande do Sul (in Porttuguese *Universidade Federal do Rio Grande Do Sul*)
UN: United Nations
UK: United Kingdom
UOR: In-use occupation ratio
USA: United States of America

VT: Vermont
2D: two dimensional
3D: three dimensional

CONTENTS

1 INTRODUCTION

Rapid population growth and the increasing concentration of people in urban areas have configured cities as significant consumers of natural resources (ICLEI; EC, 2021). After 1945, a substantial and increasing discharge of pollutants into the environment was identified (STEPHAN; ATHANASSIADIS, 2018), leading to an overload in the planet's regenerative capacity. Civil construction is one of the leading sectors corroborating this anthropogenic stress in the natural environment. In 2022, the building sector was a significant energy consumer, accounting for 34% of the final energy demand (buildings' operation and production of construction materials), and a protagonist in carbon dioxide (CO_2) emissions, accounting for 37% of the global total anthropogenic emissions of GHG (UNEP; GLOBALABC, 2024).

This situation may become even more critical as the United Nations (UN) predicts that cities will house 70% of the world's population by 2050 (SALVADOR *et al.*, 2019), which will require several adjustments in the built environment to meet the increase in demand. The current environmental scenario results from years of economics based on the linear model (extract, produce, and discard), which relies on large quantities of easily accessible resources and energy and, as such, is increasingly unfit for the reality in which it operates (EMF, 2013). Also, this model is frequently not designed to satisfy the specific needs of the users but rather to keep profits at the required levels, increasing amounts of energy, labor, raw materials, natural resources, and capital that are "consumed" without any positive impact on social welfare (GENOVESE; PANSERA, 2020).

In addition, the linear model is ineffective in facing problems of contemporary society, such as poverty reduction, the depletion of natural reserves of inputs, coping with climate change, and water scarcity, as it relies on a short-term vision based only on cost reduction. Because of the impacts of the current model, the demand for new ways of producing and consuming is highlighted, which seek to reduce the environmental effects, value resources using them in more productive cycles, and sustainable development.

Such changes can also affect the role of cities through a shift in position because the built environment would no longer be responsible for the impacts and could assume a leading role in the search for sustainable development. This transformation is urgent because more significant rates of urbanization are expected in the coming decades, significant infrastructure investments and actions will be made, and there will be a concentration of human resources and technology, favoring the development of a fertile environment for innovation and collaboration (EMF, 2017; ICLEI; EC, 2021).

Among the alternatives to alter the linear production model is the Circular Economy (CE) model, which foresees a higher valorization and cyclical use of materials. A definition of the CE concept is proposed by Kirchherr et al. (2017):

> "…an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers".

This model has been gaining prominence because its strategies present a critical opportunity for the engagement of spheres and stakeholders that at first were not so intensely involved in sustainable development since they recognize the chance to guarantee profits, resilience, increased circularity, and innovation (KORHONEN et al., 2018). Furthermore, it can align production improvements with reductions in environmental impacts while aiming to increase economic profits through a paradigm shift to incorporate life cycle thinking into production, optimizing product value and benefits through engineering, assembly, service, maintenance, and disassembly (BIMPIZAS-PINIS *et al.*, 2021; PIGOSSO *et al.*, 2010).

In addition, this concept has been gaining more and more visibility, especially in the public sphere, where national governments and international organizations seek to develop strategies for implementing CE practices (PANSERA; GENOVESE; RIPA, 2021). The public sphere can support strategies that use fewer resources, reuse and recycle existing materials where and when possible, and limit the extraction of new materials while maintaining the economy of extracted materials for a long time to reduce waste (KIM *et al.*, 2020; XUE *et al.*, 2021).

CE is based on cycles and value, has a systemic and long-term vision, and has the potential to change society's consumption and production patterns based on a resource-efficient model. Also, the model offers a chance to make the needed step changes and has proven to be a robust new frame capable of sparking creative solutions and stimulating innovation (EMF, 2013).

This transition process requires a systemic multi-level change, including technological innovation, new business models, and stakeholder collaboration (WITJES; LOZANO, 2016), and is more urgent, especially in energy and materials-intensive industries (NASIR *et al.*, 2017). These types of industries and sectors are highlighted in the Circular Economy Action Plan (EC, 2020) because they have more significant potential for circular innovations, the most considerable environmental impact, and resource demand: built environment; electronics and information and communications technology; textiles; organic material and biowaste; packaging and plastics; water; and energy (CCD; EU, 2020).

1.1 CONTEXT AND THEME JUSTIFICATION

CE is an attractive alternative that seeks to redefine the notion of growth, focusing on benefits for the whole society. This alternative involves decoupling economic activity from the consumption of finite resources and eliminating waste from the system on principle, supported by a transition to renewable energy sources. The CE application in the built environment could help the sector become less impactful (impact reduction and circularity) and is an effective way to achieve sustainable development (NUÑEZ-CACHO *et al.*, 2018).

The adoption of CE in the built environment proposes better management of resources, which requires innovative systemic changes, especially for finite materials (KIM *et al.*, 2020; POMPONI; MONCASTER, 2017). Thus, strategies to use less, reuse, and recycle resources are identified as challenges that can bring innovation, cost reduction, new opportunities and business models, new technologies, collaborations between stakeholders, better products, a positive image for users, remodeling the scale of material use, increasing the value contained in buildings, incorporating life cycle thinking, and applying strategies that have a long-term effect (DENAC; OBRECHT; RADONJIČ, 2018; WITJES; LOZANO, 2016). These types of strategies can be named Circular Strategies (CS) because they help transition to a CE and contribute to increased resilience and flexibility by enabling independence in extracting raw materials (ZIMMANN *et al.*, 2016).

In addition, built environment projects also aim to meet humans' basic needs (such as living, socializing, and work) and basic desires (such as social inclusion/community, organization, and status) (FOSTER; KREININ, 2020). For all stakeholders' requirements to be met, it is necessary to adopt a holistic approach encompassing government policies, technological and infrastructure availability, social perception, and business innovation (MHATRE *et al.*, 2021). In this sense, it will be necessary to adapt the process by which projects are developed, contracted, built, operated, adjusted, and deconstructed because the resources must be better used and aimed at their use in more cycles (ZIMMANN *et al.*, 2016).

CE in the built environment has been advancing rapidly in recent years (HOSSAIN et al., 2020; XUE et al., 2021), with a wide range of research papers that have been published worldwide (MHATRE *et al.*, 2021) and the identification of significant concern with the need to change the linear model to the circular one (BENACHIO; FREITAS; TAVARES, 2020). The advancement of the CE in the built environment has much potential: the sector's characteristic of using materials in scale, the value contained in buildings, the workforce intensity, the long-term effect of the measures; the building can become a stock of resources to maintain as long as possible and to reuse or recycling at the end of its life, and to decouple the human well-being by resources consumption and waste generation (GIORGI; LAVAGNA; CAMPIOLI, 2019). However, there are fewer studies on this topic in the construction sector. This way, research still seeks to understand how to use CE in civil construction. More studies are necessary to investigate how to incorporate CE strategies in more stages of a building's life cycle (BENACHIO; FREITAS; TAVARES, 2020).

For the transition from the current model to CE in the built environment, some sector-specific challenges must be faced, such as the complexity of buildings and infrastructure, their long life cycle, and the possibility of having more than one user at a time throughout the life cycle, the number of actors involved (customer, designer, builders, regulatory bodies, and others), resistance to change, dependence on other sectors, adaptations in regulations, high costs, creation of new markets and their acceptance (KANTERS, 2020; MUNARO; TAVARES; BRAGANÇA, 2020). In addition, standardized and integrative methods are lacking, as well as practices that explore multiple steps (BENACHIO; FREITAS; TAVARES, 2020; RUIZ; RAMÓN; DOMINGO, 2020) and specific CE models for the construction industry (OSOBAJO *et al.*, 2020). The circular economy is an economical and productive model that aims at profits, resilience, increasing circularity, and reducing environmental impacts. However, only a few studies have proven such effects.

Furthermore, CE strategies and benefits are still uncertain in long-term products such as buildings. There is a demand for goals and metrics to achieve the multi-criteria that define sustainable development. Incentives from government and regulatory bodies can also accelerate the transition through waste taxation, resources for implementing specific strategies, and changing product prices to reflect their environmental and social costs, encouraging conscious and sustainable consumption (POLVERINI, 2021). Policy and regulatory support from regional and national governments can provide cities and industries with the incentives and, in some cases, funding to drive the circular agenda (ZIMMANN *et al.*, 2016).

In the civil construction sector, one of the most significant difficulties in contracting sustainable projects is the absence of metrics to assess the environmental impacts of products and buildings, considering other attributes besides the price and technical quality. Incorporating sustainability requirements has a significant inducing effect that will lead the productive sector to a progressive and constant review of its manufacturing practices, expanding the offer of sustainable goods. In technical terms, considering aspects and impacts on sustainability and measures to minimize negative impacts and maximize positive effects arising from purchasing the good or service must be applied in the set of documents for the acquisition. A systemic view is needed to define such requirements so that all impacts of goods and services throughout their life cycle (raw material extraction, production, transport, use, and disposal) are addressed by the requirements to be demanded of the products.

The transformation of environmental needs and demands into requirements is a challenging task. For this to occur, Marrucci, Daddi, and Iraldo (2019) suggest that researchers incorporate a holistic analysis of the entire life cycle and seek to integrate different tools that enable the reduction of environmental impacts, social justice, economic effectiveness, and means of producing more circularly. The Life Cycle Assessment (LCA) method has been widely accepted to assess and improve building performance, and it is at the heart of current standards for building sustainability assessment (RÖCK *et al.*, 2018). Also, the study by Marrucci, Daddi, and Iraldo (2019), which critically analyzed 35 articles, identifies Eco-Management and Audit Scheme (EMAS) and Ecodesign as the tools with the highest level of integration with CE, while the other tools seem to be characterized by an "autonomous" approach" – independent of CE.

Another method used in CE studies, sometimes in combination with LCA, is Life Cycle Cost (LCC) (DERVISHAJ; GUDMUNDSSON, 2024). LCC allows a more rigorous economic analysis because it is based on all relevant cash flows during the lifetime of projects (KRARTI; KARRECH, 2024). Thus, LCC has an expanded life cycle perspective, considering the investment cost, operating costs during the product's estimated life cycle, and end-of-life (EOL) costs (GLUCH; BAUMANN, 2004). This technique enhances the decision-making process to lead to appropriate judgments on the performance of the building through its lifecycle and is a good complement in the CE transition (ALASMARI; MARTINEZ-VAZQUEZ; BANIOTOPOULOS, 2022).

Such tools and techniques can help manage the complexity of the various aspects of incorporating sustainability into the procurement and project process, as they allow for a diagnosis of environmental performance and propose strategies to mitigate them. In the design stage, it is recommended that quantitative environmental requirements are incorporated to enable the evaluation of proposals. For this, benchmarks with market values, metrics for comparison, and standardized requirements are essential.

In contrast, in the project's initial stages, circular strategies make achieving circularity and reducing impacts more feasible. As seen before, the literature indicates that such requirements are based on Ecodesign. CS based on Ecodesign can be applied at all project stages. However, previous studies have emphasized the need to consider CE strategies in the earlier stages of a project, in the design phase, for better results (BENACHIO; FREITAS; TAVARES, 2020; MUNARO; TAVARES; BRAGANÇA, 2020).

When CE concepts are considered in the initial stages of the project, the reuse percentage of materials that will be used can be assessed. It helps decision-makers choose materials that best align with the CE mentality (BENACHIO; FREITAS; TAVARES, 2020). The circularity of a building project is related to the source of materials - virgin sources, reused or recycled, the use phase of these materials, and the EOL destination (MHATRE *et al.*, 2021). Moreover, all these configurations can be defined in the design phase, where the choices can also influence waste generation in construction projects (RUIZ; RAMÓN; DOMINGO, 2020).

The management of trade-offs is essential to guarantee the effectiveness of the CE actions and that the proposals do not have the opposite effect, where there is an increase in circularity, but this brings more significant environmental impacts. Incorporating environmental requirements in building projects can help implement sustainable development, and the study of Ecodesign strategies to achieve CE can help valorize resources while increasing circularity in line with the reduction of impacts. However, few studies have proven the benefits of CE strategies, and they are even more uncertain about long-term products such as buildings. Therefore, efforts must be made to identify strategies that can be applied in the built environment, considering how CE can be incorporated in the initial phases of building design (upstream approach), how to manage CE trade-offs in the built environment, and the goals and metrics to achieve the multi-criteria that define sustainable development.

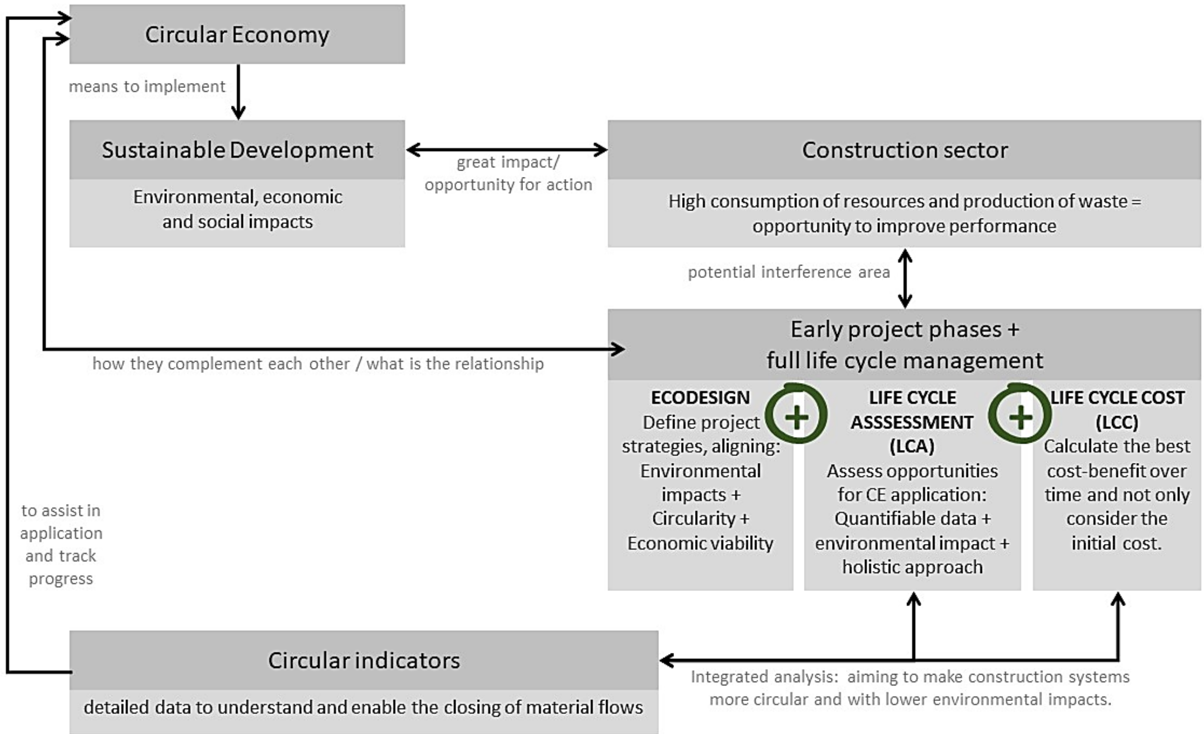
1.2 RESEARCH PROBLEM

CE strategies must be designed and implemented to meet certain principles: (i) eliminate waste and pollution from the beginning; (ii) keep products and materials in use; (iii) regenerate natural systems; (iv) redefine the notion of growth, with benefits for the whole society (PEÑA *et al.*, 2021).

In this sense, CE is a model that favors sustainable development, as seen in Figure 1 by seeking the circularity of resources, the reduction of impacts, and social equity. Its adoption in sectors with high environmental impact, such as civil construction, has great potential to reverse and optimize the current scenario of increasing overload and environmental degradation, as such sectors are large consumers of natural resources and discard considerable amounts of resources. These resources can have their production and consumption process reviewed since performance improvement can guarantee the appreciation of the resource and its cycles being better used.

For the circular economy model to be implemented more effectively in the civil construction sector, strategies must be adopted in the initial stages of designing new buildings or optimizing existing structures. However, such transition and implementation are not consolidated in the sector. This leads us to the following research question: "How can circular strategies (CS) and indicators (CI) be applied in buildings through ecodesign, integrating environmental performance, costs, and resource valorization?". Furthermore, it is necessary to investigate how we manage CE trade-offs in the built environment, aiming at sustainable development and preventing the rebound effect of strategies (when strategies that increase the circularity of resources can lead to less efficient or environmentally inappropriate solutions).

Figure 1. Diagram illustrating the relationship between Circular Economy and Sustainable Development and the opportunity to act in the civil construction sector through the alignment of Life Cycle Assessment, Life Cycle Cost and Ecodesign techniques.



Source: Author (2024).

Three techniques will be used to understand this research problem and investigate how CE strategies can be used in the initial phases of the project. The first is Ecodesign to define project strategies that best align impact reduction, resource circularity, and economic viability. Ecodesign is a systemic approach that considers environmental aspects intending to reduce environmental impacts throughout the life cycle (RHEUDE *et al.*, 2021). The incorporation of ecodesign in the initial phases of the project has great potential to transform environmental performance since many environmental impacts can be effectively reduced in this phase of the project (CHARTER *et al.*, 2018).

The second technique is the LCA, which evaluates the opportunity to apply the CE model through a holistic approach with quantifiable data on the potential environmental impacts of the evaluated strategies. Previous studies indicate that CE model indicators should be based on LCA, Material Flow Analysis (MFA), and economic material flow (PAULIUK, 2018). In the present study, we will address LCA because it is a fundamental technique to inform and improve CE strategies, comparing them in terms of sustainable performance and guaranteed basis for the most appropriate decision-making (PEÑA *et al.*, 2021). The LCA technique enables the verification of the possible impacts associated with products in their manufacture and consumption (ISO, 2009). The technique adopts a systemic view so that all impacts of goods and services throughout their life cycle (extraction of raw materials, production, transport, use, and disposal) are addressed. Considering the life cycle perspective, LCA can be applied to decision-making, as it allows mapping impacts and identifying opportunities for improvement in the environmental performance of buildings (RODRIGUES; FREIRE, 2014).

The third technique is LCC, calculated based on BS ISO 15686–5 (British Standard, 2008) and BS EN 16627 (British Standard, 2015b). LCC evaluates the total cost of a building (or its parts) over its life cycle while meeting technical and functional requirements, cost of project alternatives and identifies designs with the minimum total project cost (ALASMARI; MARTINEZ-VAZQUEZ; BANIOTOPOULOS, 2023). In addition, LCC is, to an increasing extent, an effective method for making economic assessments of the built environment (TOOSI *et al.*, 2020) through sustainability certification systems of buildings, such as BREEAM and DGNB (LARSEN *et al.*, 2022).

According to EN 15804:2012+A2:2019 (CEN, 2019), in the context of the building, there are four main modules: (i) A1-A3: Product (supply of raw materials, transport, and manufacturing); (ii) A4-A5: Construction (transport and construction); (iii) B1-B7: Use (use; maintenance; repairs, renovations, and replacements; operating energy; water consumption); (iv) C1-C4: EOL (demolition, transport, processing, and disposal). Furthermore, module D addresses the benefits beyond the life cycle through reuse, recovery, and recycling. For the transition from the linear to the circular model to be effective, there is a demand to combine actions in different stages of the building life cycle. In this sense, combining complementary policies with a systemic perspective is fundamental and must be based on feedback loops about efficiency and efforts throughout the product life cycle (HARTLEY; VAN SANTEN; KIRCHHERR, 2020). Milios (2018) mapped existing policies related to life cycle stages, which combined favor CE. He listed the adoption of circular design standards and norms in the design and production stage.

The circular economy marketing and promotion campaign and material flow accounting database run through all life cycle phases. The initial design stages are essential to reduce the environmental impact of the life cycle of buildings because, at this stage, it is possible to consider each component of the construction and its dimensions and decide on those with the lowest environmental impact (BASBAGILL *et al.*, 2013). For environmental impact information to be incorporated into the design process and allow the comparison of different alternatives, integrated tools are demanded to calculate environmental performance through LCA and project modeling (ANTÓN; DÍAZ, 2014).

Identifying CS is essential, because designers can, through ecodesign, choose the best option to value the resource. Previous studies have not wholly mapped the options available, making it necessary to investigate the CS available and their benefits, difficulties, and potential. Furthermore, in addition to understanding all the options available to apply CE, CS provide means of monitoring the evolution of the transition to identify indicators and metrics that communicate circularity and that can be aligned with other environmental and economic assessment techniques to achieve CE. The indicators are detailed and provide data to understand and enable the closing of material flows, evaluate how well the principle of CE is applied to a product or service, and are based on scientific data (CORONA *et al.*, 2019; HEISEL; RAU-OBERHUBER, 2020).

The resources' valorization in civil construction throughout the CE requires the mobilization of different stakeholders and the change of different practices in designing, contracting, constructing, managing, and deconstructing buildings. The analysis of available CS, case studies that apply the strategies, and circular indicators empower sector stakeholders in the decision-making process. In this sense, efforts must be made to map and standardize information.

1.3 HYPOTHESES

Based on the theme's appropriation and the research problem, some hypotheses were formulated:

- The transition from the linear production model to the CE has great potential in the construction sector and in achieving sustainable development goals;

- The use of CS in the initial design phases can favor the use of other CS in the EOL, increase circularity, and preservation of resources, favoring the transition to a CE;
- The application of CS can generate trade-offs with environmental impacts and costs since increasing the circularity of resources may not reduce impacts and incur higher costs;
- There is no verification of the effectiveness of the transition from the linear to the circular model in the construction sector, and decision-making occurs with little information.

1.4 OBJECTIVES

The main objective of this research is to integrate environmental performance, costs, and resource valorization, aiming at the transition to a CE in the built environment, through the proposition of a multiattribute framework that uses ecodesign, circular strategies (CS), and indicators (CI).

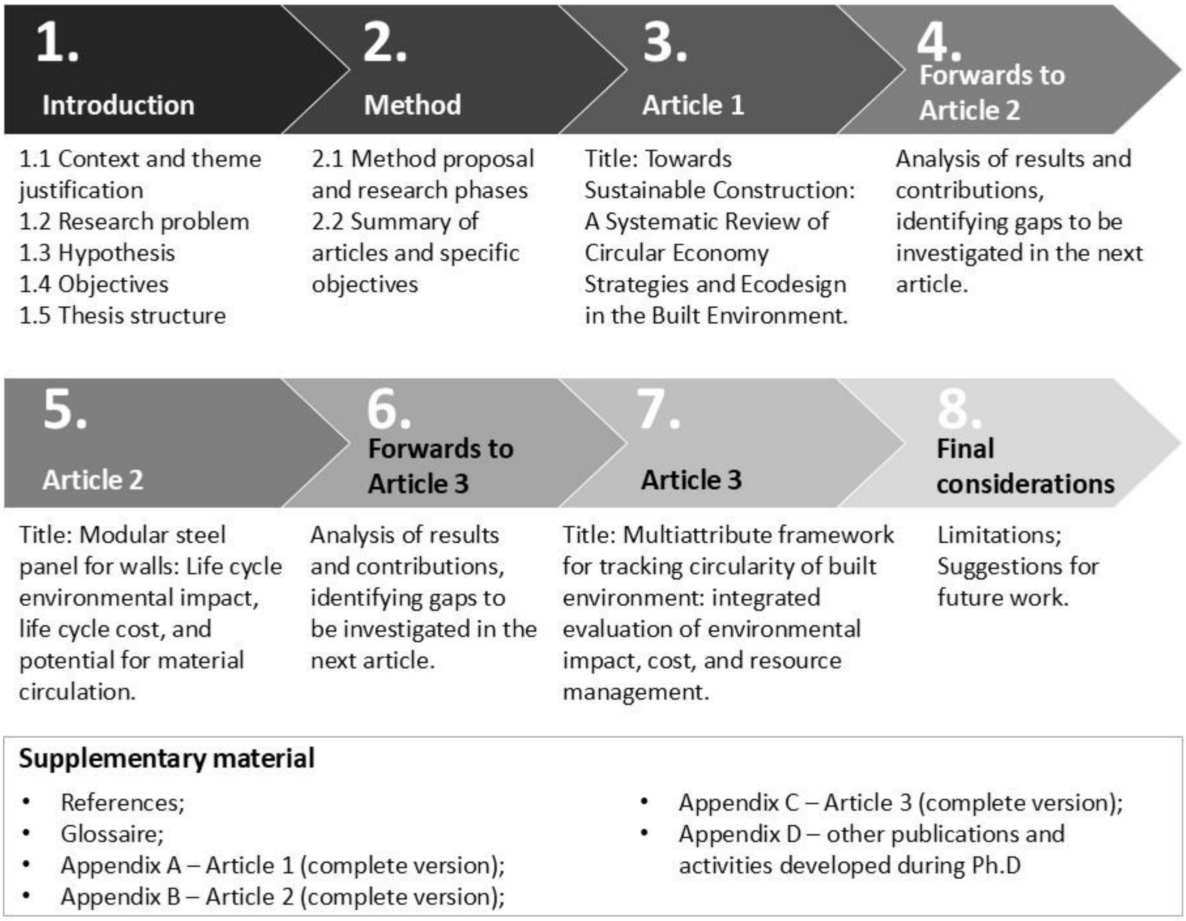
The secondary objectives are:

a) To investigate the potential of Ecodesign and CS in the built environment, aiming for a transition to sustainable development;
b) To propose a model to evaluate CS applied in construction systems through the integrated analysis of different criteria (environmental, economic, resources' circularity);
c) To assess the impact of variations for transport, damage/remanufacture, number of reuses, and recycling rates for decision-making on CS and the integrated analysis of different criteria;
d) To explore different circularity metrics and indicators for communicating results and instructions about how to facilitate the collection of information to calculate circularity in the construction sector;
e) To develop a framework through Ecodesign to assist in applying CS and indicators in buildings, aiming to make construction systems more circular and with lower environmental impacts;
f) To test the framework proposed in a case study to validate the multiattribute analysis in built products and discuss the process, benefits, and difficulties of applying it.

1.5 THESIS STRUCTURE

This document is structured in eight chapters, as illustrated in Figure 2.

Figure 2. Structure of the thesis document chapters.



Source: Author (2024).

The first chapter presents the introduction of the explored theme, containing the context and the chosen theme, the research problem, the objectives, and the structure of the thesis.

The second chapter presents the research method explained through the method proposal, the research phases, the summary of the articles, and the relation between the phases and secondary objectives.

The third chapter presents the first article (Article 1), developed and published in the Journal Buildings. This article seeks to provide a holistic view of CS and their potential to reduce impacts and foster sustainable development through a systematic literature review and the proposition of a framework for identifying demands and making and monitoring decisions.

The fourth chapter presents the Forwards to Article 2, an analysis of the results and contributions of the article presented in the previous chapter (Article 1), identifying gaps to be investigated in the following article.

The fifth chapter presents the second article (Article 2), developed and submitted to the Journal Building and Environment. The article's main objective is to evaluate CS applied at the design stage and different EOL scenarios through the definition of a case study (modular steel panel for wall) and the integrated application of techniques (LCA, LCC, and circularity potential).

The sixth chapter presents Forwards to Article 3, following the same objective of Chapter 4. This chapter is relevant because it highlights the integration of the Articles' results and how each of them contributes to achieving the main objective of the work.

The seventh chapter presents the third article (Article 3), under development and scheduled for publication in the Journal Sustainable Production and Consumption. This article evaluates indicators to measure the circular economy progress and align them with environmental and cost assessment through theoretical and comparative research to identify the indicators and their application in a case study of floor modules, concrete and metal beams, and wall systems.

The eighth chapter presents the final considerations of the thesis, listing the theoretical contributions, practices, limitations, and suggestions for future work.

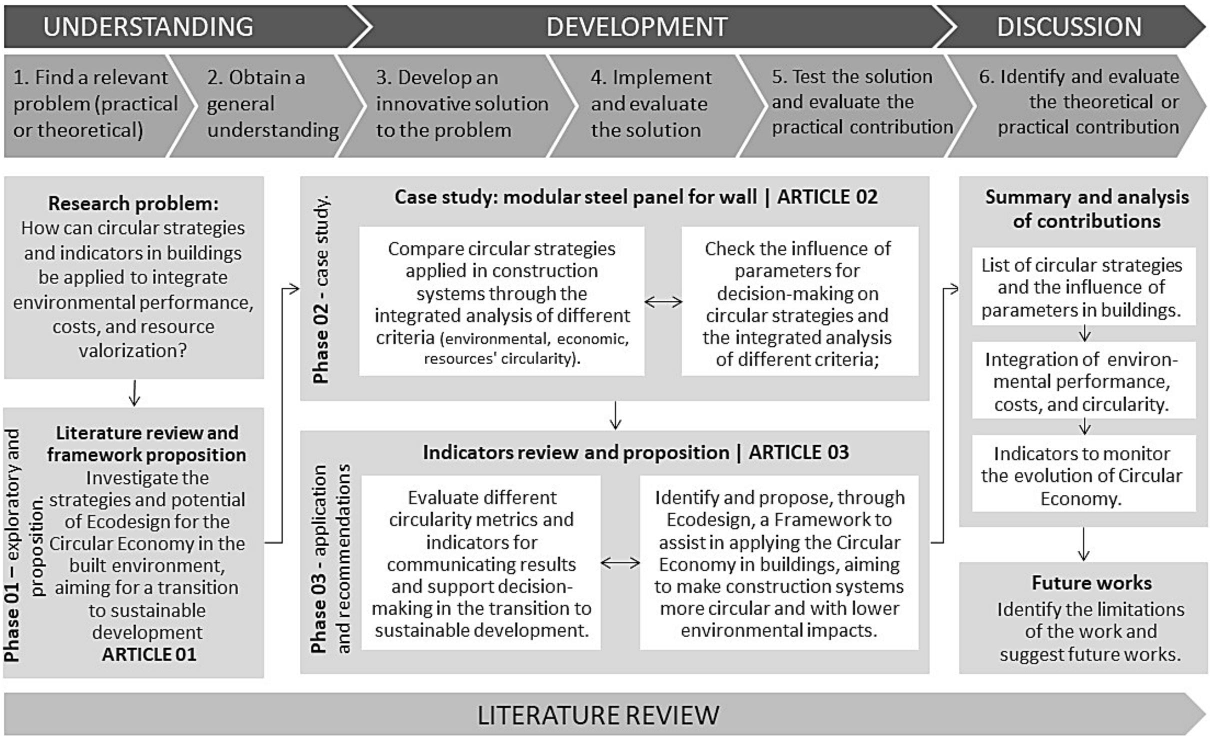
2 RESEARCH METHOD

The research method is based on the Design Science Research (DSR) which occupies an intermediate level between descriptive theories and real applications (VAN AKEN, 2004) and aims to develop an artifact that solves a real problem, while contributing to the advancement of the construction of scientific knowledge (LUKKA, 2003).

2.1 METHOD PROPOSAL AND RESEARCH PHASES

The research is structured in three main phases - Understanding, Development, and Discussion - subdivided into six sequential stages, according to Lukka (2003), illustrated in Figure 3 and described below.

Figure 3. Research flowchart indicating the phases and their respective content.



Source: Author (2024).

The understanding stage involves identifying a research problem with practical and theoretical relevance. The present study's research problem is: How can CS and indicators in buildings be applied to integrate environmental performance, costs, and resource valorization? Then, a general understanding of the research problem should be sought. For that, a bibliographic review is developed in Article 1, which investigates Ecodesign's strategies and potential for applying CE in the built environment, aiming for a transition to sustainable development. Also, a framework is proposed to help identify demands and make and monitor decisions.

The research method is defined in the development phase, and an innovative solution to the problem identified in the previous stage is developed. Article 2 explores the CS applied in a case study of a modular steel panel for a wall. In this way, it is possible to compare some CS applied in a construction system through the integrated analysis of different criteria (environmental, economic, and resource circularity) and check the influence of parameters for decision-making in EOL scenarios. Article 3 investigates different circularity metrics and indicators for communicating results and supporting decision-making in the transition to sustainable development. After that, the indicators are organized through Ecodesign into a Framework to assist in applying the CE in buildings, aiming to make construction systems more circular and with lower environmental impacts. The articles allow the testing of the CS and indicators available and the evaluation of their benefits.

The last stage, the discussion stage, aims to identify and evaluate the theoretical and practical contribution. The main contributions identified are:

- Identification of the potential of Ecodesign, circular strategies (CS), and sensitivity analysis in the transition to sustainable development through a systematic literature review that analyzed 51 CS;
- Multiattribute framework proposal to evaluate CS, assist in decision-making and monitor construction systems throughout the entire life cycle, integrating circularity and environmental, social, and economic performance;
- Integration of environmental performance (LCA), costs (LCC), and resource valorization (circularity potential indicator) in the built environment in a case study of a modular steel panel considering more than 1 life cycle and favoring the decision-making about EOL scenarios and the influence of some parameters;
- Evaluation of indicators to monitor the evolution of CE and assist in decision-making of CS and environmental impact reduction through EPDs case studies of modular products;

- Proposal of a simplified structure for visualizing and collecting data in EPDs because compiling information in these documents facilitates the application of circular indicators and can drive the transition towards CE;
- Discussion about module D and the possibility of communicating more than one EOL scenario and how it can influence the application of other CS and the supply of nonvirgin materials (resource valorization);
- Application of the proposed framework in a case study and integration of the results with circular indicators because using more indicators enriches decision-making based on the project's context, technological capacity, and objectives.

Then, the limitations of the present research and suggestions for future studies are identified.

2.2 SUMMARY OF ARTICLES AND SPECIFIC OBJECTIVES

Figure 4 summarizes the objective, method, results (achieved or expected), and the related status of each article that are part of the thesis.

Figure 5 shows the relationship between the research phases, objectives, and articles, and shows the integration and chaining of topics to meet the main and secondary objectives of the study.

Article 1 is "Towards Sustainable Construction: A Systematic Review of Circular Economy Strategies and Ecodesign in the Built Environment" and published in the Journal Buildings. The article's main objective is to provide a holistic view of CS and their potential to reduce impacts and foster sustainable development. The method comprises two stages: the first is a systematic literature review to find circular and ecodesign strategies, and the second is a framework proposition for identifying demands and making and monitoring decisions. As a result, it is highlighted that this research identified the Ecodesign strategies list and the deepening of the concepts, difficulties, and barriers linked to actions, and the relationship between Ecodesign and CE. The central forwards to the following article are that applying CS is not a guarantee of improving the resource's value or reducing impacts, and it is necessary to align CS with other evaluation techniques or criteria. The article is part of Phase 1, exploratory and proposition, and is attached in Appendix A.

Figure 4. List of proposed articles with their respective objectives, method, results, status and forwards for the following article.

	ARTICLE 01	ARTICLE 02	ARTICLE 03
Identification	**Title:** Towards Sustainable Construction: A Systematic Review of Circular Economy Strategies and Ecodesign in the Built Environment. **PHASE 01:** exploratory and proposition.	**Title:** Modular steel panel for walls: Life cycle environmental impact, life cycle cost, and potential for material circulation. **PHASE 02:** case study.	**Title:** Multiattribute framework for tracking circularity of built environment: integrated evaluation of environmental impact, cost, and resource management. **PHASE 03:** application and recommendations.
Goal & method	Provide a holistic view of circular strategies and their potential to reduce impacts and foster sustainable development. 1. Systematic literature review; 2. Framework for identifying demands, making and monitoring decisions.	Evaluate circular strategies applied at the design stage and different end-of-life (EOL) scenarios. 1.Case study: modular steel panel for wall; 2. Techniques: Life Cycle Assessment, Life Cycle Cost, and circularity potential.	Evaluate indicators and propose a Framework to measure the circularity and align them with environmental and cost assessment. 1. Circular indicators (CIs) evaluation; 2. Inclusion of CIs into the framework.
Results	Identified Ecodesign strategies list and the deepening of the concepts; difficulties and barriers linked to actions and the relationship between Ecodesign and Circular Economy.	Study with LCA modeling considering more than one life cycle, providing quantitative data for decision-making on strategies and EOL scenarios, and identifying the influence of parameters on results.	It evaluated indicators for communicating circularity and summarized the items usually evaluated to facilitate calculation. It tested the model for integrated assessment and included indicators.
Status	**Published:** Journal Buildings	**Submitted:** J. Building and Environment	**Under development:** J. Sust. Prod. & Cons.
Forwards	1. Applying circular strategies is not a guarantee of improving the resources value or reducing impacts; 2. Necessary align circular strategies with other evaluation techniques or criteria;	1. More than a single result to indicate circularity (%) is needed – integrated analysis; 2. Need to investigate how to map the transition to the Circular Economy.	**Future studies:** Evaluate the integration of other circular indicators, ways of communicating results, and other drivers to help disseminate circular practices
Other publications:	**1.Congress article (CILCA 2021):** CE and buildings LCA: a systematic literature review. **2.Book chapter (2023):** Employing CE principles to enhance sustainability in the Built Environment. **3.Congress article (SDEWEWS 2024):** Building Ecodesign Strategies towards Circular Economy: a review.	**1.Congress articles (ACLCA 2023):** LCA modeling challenges of grid mix change of a small single-family house in Brazil **&** LCA modeling of future grid mix scenarios: comparison between USA and Brazilian residential buildings. **2.Article (Energy and Buildings, 2024):** Life cycle integrated analysis of thermal, environmental and cost performance of building envelope system: Small house case study considering grid mix change in Brazil.	**1. Article (Submitted Sustainable Production and Consumption, 2024):** Evaluation of circularity scenarios for retail store furniture, including module D in southern Brazil. **2. Article (Int. Journal of Construction Management 2021):** Green Public Procurement model for environmental assessment of constructive systems

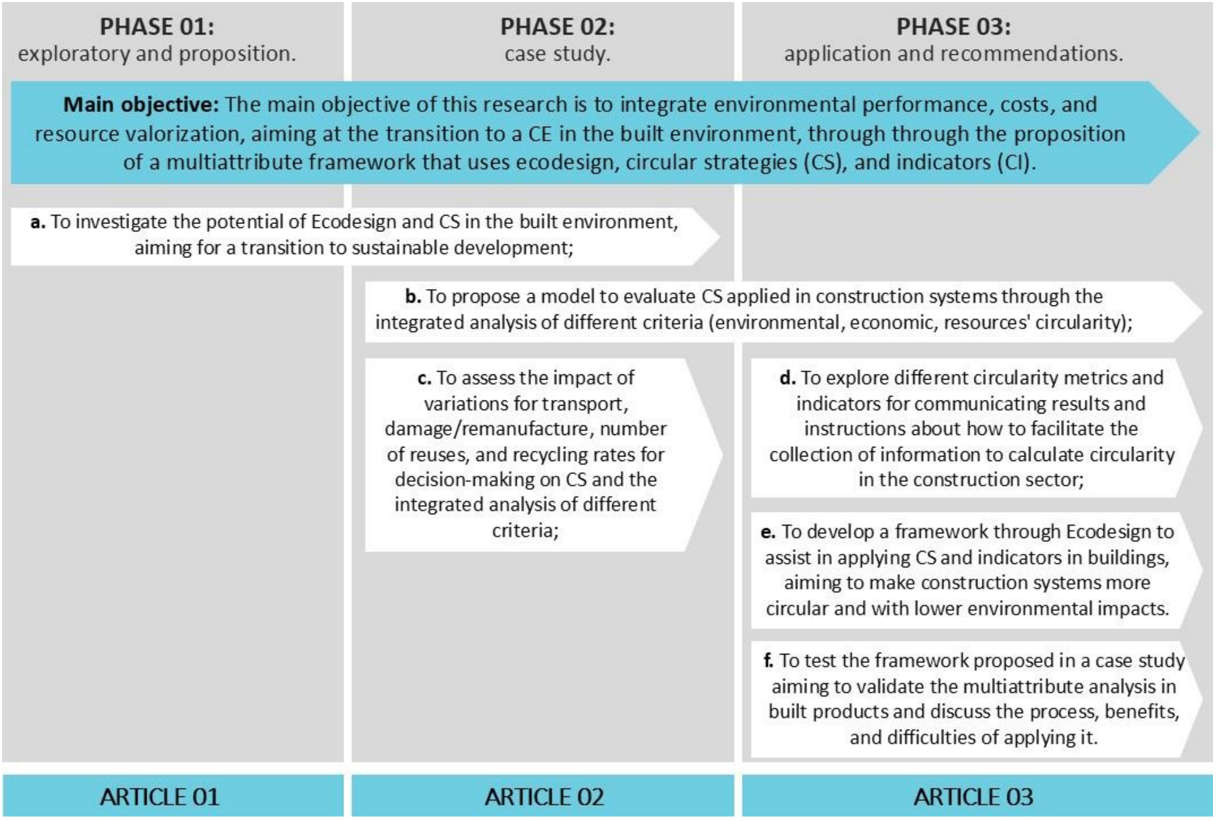
Source: Author (2024).

Article 2 is in the submission process to the Journal Building and Environment, named "Modular steel panel for walls: Life cycle environmental impact, LCC, and potential for material circulation". The article's objective is to evaluate CS applied at the design stage and different EOL scenarios throughout a case study of a modular steel panel for a wall and the application of different techniques: LCA, LCC, and circularity potential. This study with LCA modeling considers more than one life cycle, provides quantitative data for decision-making on strategies and EOL scenarios, and identifies the influence of parameters on results. However, some topics are identified to be explored in the following article: a single result to indicate circularity (%) is not enough; an integrated analysis is necessary, and metrics and indicators must be evaluated to map the transition to the Circular Economy. The article is part of Phase 2, case study, and is attached in Appendix B.

Article 3 entitled “Multiattribute framework for tracking circularity of built environment” is in the revision process. The goal is to evaluate indicators and propose a Framework to measure the circularity and align them with environmental and cost assessment. The method is composed of 3 stages: (i) circular indicators evaluation; (ii) inclusion of circular indicators into the framework; (iii) recommendations. We evaluated indicators for communicating circularity and summarized the items usually evaluated to facilitate calculation. We also tested in a case study the Framework for integrated assessment and included CIs. The article is part of Phase 3, application and recommendation, and is attached in Appendix C.

The other publications and activities developed during the Ph.D. are listed in Appendix D.

Figure 5. Relationship between the phases, research objectives and the articles.



Source: Author (2024).

3 ARTICLE 1: Towards Sustainable Construction: A Systematic Review of Circular Economy Strategies and Ecodesign in the Built Environment

Article published, in English, in the journal Buildings (ISSN 2075-5309) - Journal Rank: JCR Journal Rank #28/170, Percentile 83rd for Engineering: Architecture[1]; Qualis A1 for Engineering I[2]. DOI: https://doi.org/10.3390/buildings13082059 .

Abstract: This review discusses the unsustainable nature of current production and consumption patterns, particularly in the civil construction sector. To address this, the circular economy model has been proposed as a solution, but the impact reduction of circular strategies (CS) is not well understood. Thus, aligning CS with ecodesign can help achieve sustainable development. We conducted a systematic review of studies on CS and ecodesign strategies (ES) in the built environment, which led us to identify 23 essential strategies, including reuse, recycling, design for disassembly, and design for life extension. This article expands on previous research by identifying 51 CS and ES, some of which are interconnected, and adopting one strategy may benefit another. The authors propose a framework based on the Plan-Do-Check-Act (PDCA) concept to support and manage trade-offs when selecting strategies and to facilitate a collaborative decision-making process. The framework can also help manage the effects of using these strategies on circularity and environmental, social, and economic performance, ultimately improving the construction sector's environmental performance.

Keywords: Construction industry. Life cycle perspective. Life cycle assessment. Environmental performance. Circular economy (CE). Ecodesign.

[1] Available in: < https://www.scopus.com/sourceid/26980#tabs=1>. Accessed: May/ 2024.
[2] Available in: <https://sucupira.capes.gov.br/sucupira/public/consultas/coleta/veiculoPublicacaoQualis/listaConsultaGeralPeriodicos.jsf>. Accessed: May/ 2024.

4 FORWARDS TO ARTICLE 2

Article 1 developed a systematic literature review providing a comprehensive analysis of ES and CS in building construction. We analyzed 69 scientific articles and 7 gray literature sources and found 51 CS. Among the literature review strategies, reuse, recycling, design for disassembly, design for life extension, studying alternatives, and improved energy efficiency stand out. In the gray literature, the most common strategies are design for life extension, disassembly, reuse, recycling, flexibility and adaptability, and design for modularity and demountable parts. We also propose a framework based on the PDCA concept to assist in decision-making on strategies and their monitoring throughout the entire life cycle, integrating circularity and environmental, social, and economic performance. The results indicate that using Ecodesign is important to ensure the mitigation of environmental impacts and a holistic view of the project and must be aligned with the CS, as their main objective is to increase circularity.

The results of Article 1 highlight that there is awareness about the relevance of CE in the construction sector and its benefits for advances in sustainable development. There are many strategies, but a few studies evaluate their combined use and demonstrate the benefits of applying them. Therefore, it is necessary to expand the number of case studies that apply CS and analyze the results found beyond circularity, as applying circularity does not guarantee improving the resource's value or reducing impacts.

We list some recommendations for future work aiming to continue discussions in this area: (i) check the economic viability of the application of CS and ES and compare with traditional practices; (ii) apply CS and ES in different case studies and, preferably at different scales, to verify the relationship between increased circularity and reduced impact; (iii) examine the effects of combining strategies and determine if there are specific building types, materials, or construction systems to which they are better suited; (iv) analyze whether there is a particular strategy that should be prioritized or that offers more significant environmental benefits based on the stage of the building, whether it is existing, historic, new, temporary, or other; (v) check how the context can affect the application of CS and ES and which factors should be analyzed carefully; (vi) determine how to communicate the levels of circularity (or possible paths) and its benefits to decision-makers; (vii) determine how to automate the inclusion of strategies in modeling software such as building information modelling (BIM), facilitating the inclusion of the practice in the routine of design offices.

Furthermore, for advances in circularity to contribute to sustainable development, it is necessary to align CS with other evaluation techniques or criteria. The alignment must cover the tripod of sustainability: environmental, economic, and social.

The results of the first article indicate the need to test CS in Article 2, verifying how their choice in the design phase can affect EOL scenarios and the valorization of resources. To that, LCA and LCC techniques must be aligned with a circularity assessment tool to ensure advances including environmental impact reductions and competitive costs considering the life cycle perspective. The results shall contribute to the growth of data for decision-making on CS, highlight items that require sensitivity analysis, and indicate how integrated analysis can favor sustainable development.

5 ARTICLE 2: Modular steel panel for walls: life cycle environmental impact, life cycle cost, and potential for material circulation

Article submitted, in English, in the journal Building and Environment (ISSN 0360-1323) – Journal Rank #17/350, Percentile 95th for Engineering: Civil and Structural Engineering[1]; Qualis A2 for Engineering I[2].

Abstract: The impacts of civil construction are widely recognized and justify the transition from a linear to a circular economy. Furthermore, with building users increasingly demanding greater adaptability, strategies such as modularity and flexibility to adapt to changing uses are being discussed. Modular wall panels allow quick installation and have the potential for disassembly, refurbishment, reuse, and recycling. We evaluate a modular steel panel system in two Brazilian case studies through life cycle assessment (LCA), life cycle cost (LCC), and building circularity index (BCI). The study applies the circular reuse and remanufacture, recycling, and service life extension strategies for internal and external walls. For the external panel, the life extension strategy (SE02) stands out positively in all impact categories, with the lowest environmental impact and costs. However, the SE02's BCI does not have the best result. The second best option is reuse (SE03), with the highest percentage of circularity. Furthermore, the differences between SE02 and SE03 are reduced in several impact categories, and the sensitivity analysis (transport, damage, and the number of reuses) shows that the differences could be even smaller. For the internal panel, service life extension (SI02) and reuse (SI03) scenarios are the best options. Recycling (SI04) has the highest environmental impact and the best potential for circularity. BCI communication must be aligned with LCA and LCC, such that an increase in circularity is accompanied by a decrease in environmental impacts or with infeasible costs, especially for developing countries.

Keywords: Circularity. Modularity. Modular Steel Panel. Reuse. Recycling. Service life extension.

[1] Available in: < https://www.scopus.com/sourceid/26874>. Accessed: May/ 2024.
[2] Available in: <https://sucupira.capes.gov.br/sucupira/public/consultas/coleta/veiculoPublicacaoQualis/listaConsultaGeralPeriodicos.jsf>. Accessed: May/ 2024.

6 FORWARDS TO ARTICLE 3

Article 2 continued the investigation of CS and evaluated them applied at the design stage and different EOL scenarios. The analysis took place through a case study of a modular steel panel for a wall with the integrated application of the LCA, LCC, and circularity potential techniques. The study contributed to research on LCA modeling, considering more than one life cycle, providing quantitative data for decision-making on strategies and EOL scenarios, and identifying the influence of parameters on results. Furthermore, the results demonstrate that implementing CS at the design stage, including material selection, modularization, and flexibility, promotes the use of EOL strategies and enhances the circularity of inputs.

The study also indicated gaps that demand further analysis. The case study results indicate that more than a single tool is needed to evaluate circularity (%) because a single metric may not map the benefits of some strategies. It was exemplified by the results referring to SL extension scenarios, which are indicated considering the environmental perspective but did not score in the tool applied in Article 2. Furthermore, the LCA results enriched the decision-making process, indicating that increasing circularity does not always reduce impacts in all categories. The LCC results illustrate that the initial costs of applying the strategies are similar to current linear practices. In the long term, the values of CS are lower than those of linear practices and recycling. Therefore, it is identified that integrated analysis is beneficial for advances in sustainability. However, it is necessary to investigate how to map the transition to the CE with more tools and information translated into indicators.

Thus, Article 2 results indicate that Article 3 should explore the circularity potential of new materials and construction systems, focusing on a holistic assessment that includes indicators such as environmental performance, cost, and circularity potential. Therefore, there is a claim to identify and test existing indicators suitable for buildings and construction systems. Article 2 also highlighted that circular indicators should be aligned with other metrics such as LCA and LCC. Therefore, a model that allows integrated analysis of results facilitates decision-making considering the tripod of sustainability and the advancement of the application of CE in civil construction.

7 ARTICLE 3: Multiattribute framework for tracking circularity of built environment: integrated evaluation of environmental impact, cost, and resource management

Article under development, in English, to be submitted in the suggested journal Sustainable Production and Consumption (ISSN 2352-5509) - Journal Rank #13/184, Percentile 93rd for Environmental Science: Environmental Engineering[1]; Qualis A1 for Engineering I[2].

Abstract: Civil construction is responsible for a large portion of environmental impacts and remains strongly linked to the linear model of production and consumption. The transition to the Circular Economy (CE) is urgent and can be facilitated using project strategies and monitoring progress through indicators. The literature highlights many existing circular strategies (CS) and circular indicators (CI). However, the choice of CS is permeated with uncertainty, as increasing the circularity of resources does not guarantee the reducing environmental impacts that favor sustainable development. Thus, conducting an in-depth analysis to evaluate the CS, align them with environmental and cost assessment, and communicate the results to the CIs is necessary. This research aims to investigate and evaluate CIs to measure circularity in construction products and incorporate them into the Framework for decision-making on CSs based on ecodesign and the integration of environmental performance, resources valorization (circularity), and cost. The method comprises three stages: (i) CI evaluation through literature analysis and application of indicators in Environmental Product Declarations (EPDs); (ii) inclusion of CI into the Framework and application of the Framework in a case study; and (iii) recommendations for data collection and communication of results. The results highlight that each CI is based on different data and CE principles. The combined analysis of environmental performance, circularity, and cost can drive the transition towards CE. The Framework assists in the decision-making and CS monitoring process. The evaluated case study illustrated the Framework's potential and the visual capacity for communicating data.

Keywords: Circular Economy (CE); Life Cycle Assessment (LCA); Life Cycle Cost (LCC); Sustainable Development; Metrics.

[1] Available in: <https://www.scopus.com/sourceid/21100416081>. Accessed: May/ 2024.
[2] Available in: <https://sucupira.capes.gov.br/sucupira/public/consultas/coleta/veiculoPublicacaoQualis/listaConsultaGeralPeriodicos.jsf>. Accessed: May/ 2024.

8 FINAL CONSIDERATIONS

This thesis discussed ways of integrating environmental performance, costs, and resource valorization in the built environment through ecodesign, CS, and CI. The research was divided into three phases to enable the transition to CE in building projects. The results and contributions of each phase are listed below.

The Phase 1, exploratory and proposition, contributes to achieving the first secondary objective: “a) To investigate the potential of ecodesign and CS in the built environment, aiming for a transition to sustainable development.”. Through a systematic literature review, it was identified that research addressing CE has grown in recent years in different sectors; in the civil construction sector, there is awareness of the demand and benefits of carrying out the transition from the linear to the circular model, and there is still fragmentation in the literature regarding appropriate concepts, strategies, and indicators. Regarding the CS, the review identified 51 strategies, illustrating the potential to implement the CE principles in the built environment. The most cited strategies are reuse, recycling, design for disassembly, design for life extension, studying alternatives, and improved energy efficiency. However, the review also illustrated that few studies apply the strategies in case studies, and there is a demand to investigate the relationship between increased circularity, reduced impacts, and related costs in more depth. Another source of uncertainty is about the effects of the combined application of strategies and how project definitions can affect CS adopted in other phases of the life cycle, such as use and operation, disassembly, and use in new cycles. The research develops a framework model, illustrated in Figure A8, to facilitate the choice of strategies and monitor the effects on economic and environmental performance. The framework proposition facilitates the management of trade-offs when choosing strategies and allows a collaborative view of the decision-making processes of strategies and the management of their effects on circularity and environmental, social, and economic performance.

The results of Phase 1 are compiled in Article 1 and presented in Appendix A. They contribute to the comprehensive analysis of ecodesign and CS in building construction and to the identification of the potential of integrating circularity into the ecodesign process to favor the transition to a CE and the achievement of sustainable development goals.

Phase 2, case study, contributes to the second and third secondary objectives: b) to propose a model to evaluate CS applied in construction systems through the integrated analysis of different criteria (environmental, economic, resources' circularity); c) to assess the impact of variations for transport, damage/remanufacture, number of reuses, and recycling rates for decision-making on CS and the integrated analysis of different criteria. This Phase explored the application of CS through a modular wall case study with 4 scenarios for external and 4 for internal walls. The case study allowed us to verify the influence of CS in the initial phases for more options in the EOL scenarios and the relevance of an integrated analysis with LCA and LCC. The integrated analysis is relevant, as increasing circularity does not always result in lower environmental impacts, as with recycling scenarios. Furthermore, the sensitivity analysis allowed us to identify that the choice of EOL scenarios must consider factors such as distance, losses, number of reuse and recycling processes, and recycling rate. Regarding the circularity indicator, the results highlight that more than a single result is needed because a single metric may not map the benefits of some strategies. It was exemplified by the results referring to SL extension scenarios, which did not score in the tool used.

Furthermore, the LCA results enhanced the decision-making process by revealing that increased circularity does not always lead to reduced environmental impact, mainly because the transition from the linear model to the circular one is not complete. The LCC results show that the initial costs of implementing these strategies are comparable to current linear practices. In the long term, the costs of circular strategies are lower than those of linear practices and recycling. Thus, the study highlights the benefits of integrated analysis for advancing sustainability. However, further investigation is needed to map the transition to the circular economy with additional tools and information translated into indicators.

The results of Phase 2 are compiled in Article 2 and presented in Appendix B. Thus, the research contributes to the benchmark for decision-making, expanding the number of case studies that apply CS and illustrating how integrated analysis can favor sustainable development.

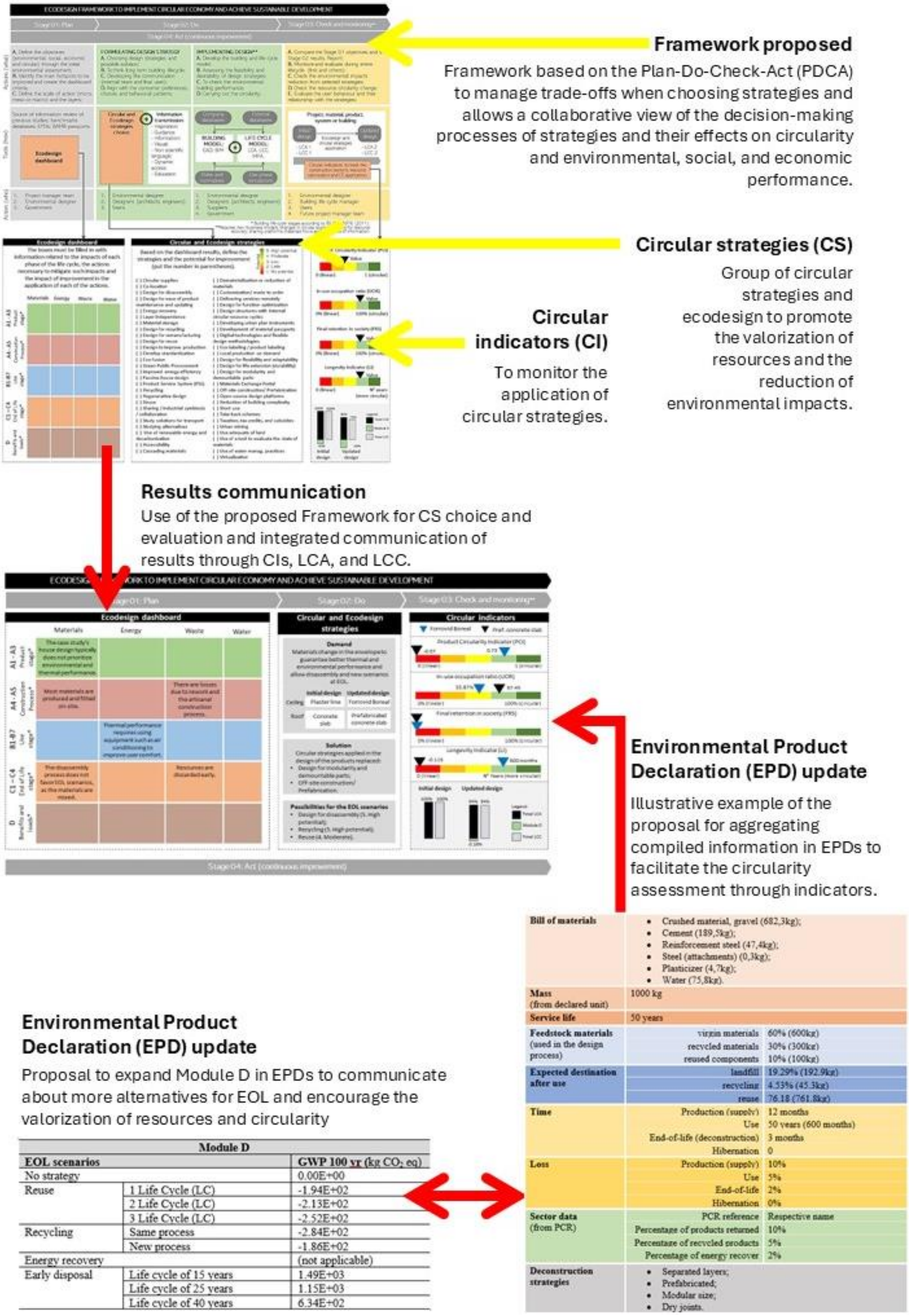
Phase 3, application and recommendation, contributes to the fourth, fifth, and sixth secondary objectives: d) to explore different circularity metrics and indicators for communicating results and instructions about how to facilitate the collection of information to calculate circularity in the construction sector; e) to develop a framework through Ecodesign to assist in applying CS and indicators in buildings, aiming to make construction systems more circular and with lower environmental impacts; f) To test the framework proposed in a case study aiming to validate the multiattribute analysis in built products and discuss the process, benefits, and difficulties of applying it.

This Phase investigated and evaluated CIs to measure circularity in construction products and incorporate them into the Framework proposed in Stage 1 for decision-making on CSs based on ecodesign and integrating environmental performance, resources valorization (circularity), and cost. The study contributed to investigating different circularity metrics and indicators for communicating results and supporting decision-making in the transition to sustainable development. The exploratory review allowed the identification of CIs for buildings and construction systems to be applied in different case studies of modular civil construction products. Each indicator is fed with different information, contributing to understanding different CE principles. Using more indicators enriches decision-making, as project and EOL strategies do not contribute to just one principle. Environmental and cost data from LCA and LCC allow the analysis to integrate environmental and economic spheres. Furthermore, much of the data in the EPDs feeds the circular indicator formulas but is not organized to facilitate analysis. In this sense, we propose a simplified structure for visualizing and collecting data for calculations. Compiling data facilitates the application of indicators and can drive the transition towards CE.

Regarding the Framework update, the inclusion of CIs allows the communication of the results of the application of CS and the assessment of whether they favor the valorization of resources and sustainable development. With data communication, it is possible to assist in decision-making processes and the collaboration of different stakeholders involved in the construction sector. Applying the Framework in a case study allowed us to identify that Ecodesign favors the choice of CS and an integrated assessment. The results of Phase 3 are compiled in Article 3 and presented in Appendix C.

Figure 6 illustrates the alignment between the proposed Framework, CS, and circular indicators. The framework is based on the PDCA to manage trade-offs when choosing strategies and allows a collaborative view of the decision-making processes of strategies and their effects on circularity and environmental, social, and economic performance.

Figure 6. Alignment of the proposed framework with circular indicators.



Source: Author (2024)

The group of circular stratefies (CS) and ecodesign aims to promote the valorization of resources and the reduction of environmental impacts. The strategies are selected in the Plan Stage through the dashboard and applied in the Do phase. Finally, CI are applied in the Phase Check and Monitoring and help to map the effectiveness of strategies and monitor the transition towards sustainable development with greater circularity of resources. To facilitate data collection for calculating indicators and visualization, a simplified structure with essential information was proposed, which can be added in EPD format, compiling information in these documents and facilitating the application of circular indicators. Finally, the case study allowed the discussion about module D and the possibility of communicating more than one EOL scenario and how it can influence the application of other CS and the supply of nonvirgin materials (resource valorization).

Thus, the present study investigates the potential of CE in the built environment based on a literature review of CSs and CIs, testing different CSs, investigating how to facilitate the choice of CSs, communicating the results, and mapping the progress of the application of CE principles in the built environment. Therefore, the framework proposed allow a holistic approach and the management of trade-offs with ecodesign. The framework is based on multiattribute performance (circularity, environmental, and economic performance) to help transition to a CE, assisting in decision-making and monitoring construction systems throughout the entire life cycle. Also, the proposed framework was applied in a case study and highlighted that more indicators enrich decision-making based on the project's context, technological capacity, and objectives.

In addition to the contributions of the present study, there are still items to be investigated in future studies:

- To check the economic viability of the application of CS and ES and compare it with traditional practices;
- To apply CS and ES in different case studies and, preferably at different scales, to verify the relationship between increased circularity and reduced impact;
- To examine the effects of combining strategies and determine if there are specific building types, materials, or construction systems to which they are better suited;

- To analyze whether there is a particular strategy that should be prioritized or that offers greater environmental benefits based on the stage of the building, whether it is existing, historic, new, temporary, or other;
- To check how the context can affect the application of CS and ES and which factors should be analyzed;
- To determine how to automate the inclusion of strategies in modeling software such as BIM, facilitating the inclusion of the practice in the routine of design offices;
- To evaluate the integration of other CIs;
- To improve the ways of communicating results;
- To test the Framework in new case studies;
- To integrate the Framework with BIM and LCA modeling software.

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GLOSSAIRE

Abiotic Depletion Potential (ADP): refers to the global reduction of non-living, or abiotic, natural resources, such as mineral, metal, and fossil resources. The ADP indicator is usually separated into fossil and non-fossil resource depletion, known as Abiotic Depletion Potential for Fossil Resources (ADPF) and Abiotic Depletion Potential for Non-Fossil Resources (ADPN), respectively. Its calculation for each raw material extraction is based on the remaining reserves and extraction rate. Definition by: One Click LCA (available in https://oneclicklca.com/en/resources/articles/construction-lca-glossary).

Acidification potential (AP): impact category resulting from the increase in the acidity content in the air, water, or soil caused by the disposal of acid waste, measured in relation to the effect of 1 kg of SO2. Definition by: SILVA, G. A. da et al. Avaliação do Ciclo de Vida: ontologia Terminológica. Brasília, DF. 2014.

Building information modelling (BIM): building information modeling (BIM) is the holistic process of creating and managing information for a built asset. It is based on an intelligent model enabled by a cloud platform. Also, it integrates structured, multi-disciplinary data to produce a digital representation of an asset across its lifecycle, from planning and design to construction and operations. Definition by: Autodesk (available in https://www.autodesk.com/solutions/aec/bim).

Circular Economy (CE): is a production and consumption model involving sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible, thanks to recycling. These can be productively used again and again, thereby creating further value. Definition by: European Parliament (available in https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits).

Circular indicators (CI): based on metrics and detailed data, it measures how well the principle of CE is applied to a product or service and enables the closing of material flows.

Circular strategies (CS): strategies that help implement the circular economy model by applying the principles of eliminating waste and pollution from the beginning, keeping products and materials in use, regenerating natural systems, and redefining the notion of growth, with benefits for the whole society.

Ecodesign: considers environmental aspects at all stages of the product development process, striving for products with the lowest possible environmental impact throughout the product life cycle. It seeks to integrate environmental aspects into the product development process by balancing ecological and economic requirements. Definition by: European Environment Agency (available in https://www.eea.europa.eu/help/glossary/eea-glossary/eco-design).

Eutrophication (EP): impact category resulting from the increase in the concentration of nutrients in water or soil caused by waste disposal, consequently causing a potential increase in species in the ecosystem. Definition by: SILVA, G. A. da et al. Avaliação do Ciclo de Vida: ontologia Terminológica. Brasília, DF. 2014.

Environmental product declarations (EPD): a declaration of a product's performance about different environmental parameters during the product's life cycle. An EPD requires gathering quantified environmental data for a product with pre-set categories of parameters (raw material, energy use, others). It also includes additional product and company information. Definition by US EPA (available in https://sor.epa.gov/sor_internet/registry/termreg/searchandretrieve/).

Ecodesign strategies (ES): strategies that help implement the ecodesign.

Greenhouse gases (GHG): emission of any gas that absorbs infrared radiation in the atmosphere. Definition by US EPA (available in https://sor.epa.gov/sor_internet/registry/termreg/searchandretrieve/).

Global warming potential (GWP): impact category resulting from the increase in the capacity to retain infrared radiation in the stratosphere, generated by the increase in the concentration of certain gases from atmospheric emissions, consequently causing a potential increase in global temperature (measured in relation to the effect of 1 kg of CO_2). Definition by: SILVA, G. A. da et al. Avaliação do Ciclo de Vida: ontologia Terminológica. Brasília, DF. 2014.

Life cycle (LC): successive and linked stages of a product system, from obtaining natural resources to final disposal. Definition by: SILVA, G. A. da et al. Avaliação do Ciclo de Vida: ontologia Terminológica. Brasília, DF. 2014.

Life Cycle Assessment (LCA): compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Definition by: ISO. ISO 14040: Environmental management – life cycle assessment – principles and framework. Geneva, Switzerland: 2006.

Life cycle cost (LCC): is an economic analysis that evaluates the cost of a building (or its parts) over its life cycle while meeting technical and functional requirements. Definition by: BSI. BS EN 16627 Sustainability of Construction Works. Assessment of the Economic Performance of Buildings. 2015.

Life cycle inventory (LCI): a set of quantified data on inputs and outputs in an LCA study. Definition by: SILVA, G. A. da et al. Avaliação do Ciclo de Vida: ontologia Terminológica. Brasília, DF. 2014.

Material Flow Analysis (MFA): is a tool for material management that supports the detailed study of the flows of input, processing and output of materials in different production systems. It includes quantification, evaluation, improvement, and strategic planning. Definition by: Helena Xavier L, Ottoni M, Picanço Peixoto Abreu L (2023) A comprehensive review of urban mining and the value recovery from e-waste materials. https://doi.org/10.1016/j.resconrec.2022.106840

Ozone layer depletion (ODP): impact category that results from an increase in the amount of ultraviolet rays reaching the Earth's surface, caused by the increased concentration of certain gases in the ozone layer from atmospheric emissions generated by human actions. The reduction of the ozone layer can result in the growth of diseases, interference with the ecosystem, and damage to various materials. It is measured in relation to the effect of 1 kg of CFC-11. Definition by: SILVA, G. A. da et al. Avaliação do Ciclo de Vida: ontologia Terminológica. Brasília, DF. 2014.

Product Category Rules (PCR): provides the rules, requirements, and guidelines for developing an EPD for a specific product category. Thus, it provides instructions for how the

LCA should be conducted, such as the system boundaries, functional unit, use phases, end-of-life options, and impact categories to be considered. Definition by: EPD System (available in https://www.environdec.com/product-category-rules-pcr/the-pcr).

Photochemical oxidation (POCP): under the influence of UV light, nitrogen oxides react with Volatile Organic Substances (VOCs), producing the photochemical oxidants that cause smog. Definition by: SILVA, G. A. da et al. Avaliação do Ciclo de Vida: ontologia Terminológica. Brasília, DF. 2014.

APPENDIX A – ARTICLE 1

APPENDIX B – ARTICLE 2

APPENDIX C – ARTICLE 3

APPENDIX D – OTHER PUBLICATIONS AND ACTIVITIES DEVELOPED DURING PH.D.

1. OTHER PUBLICATIONS AND ACTIVITIES DEVELOPED DURING PH.D.

This Appendix will present other scientific publications and activities developed during the Ph.D. period that are directly related to the research or indirectly helped in the researcher's training.

1.1 PERIOD ABROAD

·Exchange student internship under a J-1 visa at the Powell Center for Construction and Environment, University of Florida, supervised by Robert Ries, from March 15th, 2023, through September 15th. During this period, Janaine developed a case study on modular walls, assessing the application of circular economy strategies in EOL scenarios. The evaluation involved integrating environmental, economic, and circularity assessments through LCA, LCC, and Circularity Potential (CP). Additionally, the student contributed to the required article for the subject, a partnership between the two educational institutions. The article explored topics such as LCA, LCC, and changes in the energy grid mix in Brazil. Continuing with the energy grid mix theme, the student collaborated with a colleague from the Powel Center on the development of two articles: "LCA Modeling Challenges of Grid Mix Change for a Small Single-Family House in Brazil" and "LCA Modeling of Future Grid Mix Scenarios: A Comparison between USA and Brazilian Residential Buildings." These articles were presented at the ACLCA 2023 Conference, held between September 26-28, 2023, in Burlington, VT, USA.

1.2 ARTICLES IN SCIENTIFIC JOURNALS

- Bertoli, Gabriela; Timm, Janaine; Ries, Robert; Torres, Maurício; Passuello, Ana. Life cycle integrated analysis of thermal, environmental and cost performance of building envelope system: Small house case study considering grid mix change in Brazil. **Energy and Buildings**, v. 310, p. 114096, 2024. https://doi.org/10.1016/j.enbuild.2024.114096
- Timm, Janaine Fernanda Gaelzer; Maciel, Vinícius Gonçalves; Passuello, Ana. Towards Sustainable Construction: A Systematic Review of Circular Economy

Strategies and Ecodesign in the Built Environment. **Buildings**, v. 13, p. 2059, 2023. https://doi.org/10.3390/buildings13082059

- Timm, Janaine Fernanda Gaelzer; Casarin, Roberta Picanço; Silva, Deividi Maurente Gomes Da; Bellaver, Gustavo Bridi; Pagnussat, Daniel Tregnago; Viana, Daniela Dietz. Proposta de ferramenta para diagnóstico do grau de inovação percebido em empresas do ambiente construído. **Ambiente Construído (Online)**, v. 23, p. 7-27, 2023. https://doi.org/10.1590/s1678-86212023000200660
- Timm, Janaine Fernanda Gaelzer; Passuello, Ana. Potential use of environmental product declaration to support green public procurement in civil construction. **Ambiente Construído (Online)**, v. 21, p. 263-276, 2021. https://doi.org/10.1590/s1678-86212021000200525
- Timm, Janaine F. Gaelzer; Maciel, Vinícius Gonçalves; Passuello, Ana. Green public procurement model for environmental assessment of constructive systems. **International Journal of Construction Management**, v. 00, p. 1-11, 2021. https://doi.org/10.1080/15623599.2021.1920162
- Barreto, M. F. M.; Timm, J. F. G.; Passuello, A.; Molin, D. D.; Masuero, J. Life cycle costs and impacts of massive slabs with varying concrete cover. **Cleaner Engineering and Technology**, v. 5, p. 100256, 2021. https://doi.org/10.1016/j.clet.2021.100256
- Timm, J. F. G.; Morales, M. F. D.; Passuello, A.. Sensitivity Analysis of Life Cycle Impacts Distribution Methods Choice Applied to Silica Fume Production. **IOP Conference Series. Earth and Environmental Science (Online),** v. 323, p. 012131, 2019. https://doi.org/10.1088/1755-1315/323/1/012131

1.3 COMPLETE WORKS PUBLISHED IN PROCEEDINGS OF CONFERENCES

- Zortea, R. B.; Passuello, A.; Klas, J.; Timm, J. F. G.; Cassel, J.; Martinez, C.; Strybos, J. Use phase positive social impacts in a local community of a sustainable development center: the case of William R. Sinkin Ecocentro ? San Antonio, 2021, Porto Alegre. Anais do **VII Congresso Brasileiro em Gestão do Ciclo de Vida:** volume 2. Porto Alegre, 2021.
- Timm, J. F. G.; Zanettini, M.; Dalmoro, J. M.; Klas, J.; Passuello, A. Mudanças no transporte público no cenário pós-pandêmico: percepções do usuário da região metropolitana de Porto Alegre, 2021, Evento virtual. Anais IV Encontro Latino-

americano e Europeu sobre Edificações e Comunidades Sustentáveis (**EuroELECS 2021**). Porto Alegre: ANTAC, 2021.

- Anapolski, Anelise; Timm, J. F. G.; Zitto, Ingrid; Sattler, Miguel Aloysio. Avaliação da Energia Incorporada, Carbono Incorporado e Pegada Hídrica associadas à etapa de produção dos materiais utilizados no projeto da sede do CERES., 2020, Palhoça, SC. **ENSUS 2020** - VIII Encontro de Sustentabilidade em Projeto, 2020. v. 8. p. 110-121.
- Timm, J. F. G.; Zanettini, M.; Dalmoro, J. M.; Passuello, A. Proposta de inclusão de critérios de compras públicas verdes em um estudo de caso do transporte coletivo em Porto Alegre - RS, 2020, Porto Alegre, RS. Anais do XVIII Encontro Nacional de Tecnologia do Ambiente Construído - **ENTAC 2020**: Futuro da Tecnologia do Ambiente Construído e os Desafios Globais. Porto Alegre: ANTAC, 2020.
- Timm, J. F. G.; Ferreira, Brenda; Passuello, A.; Torres, M. Requisitos de desempenho e eficiência energética presentes em certificações ambientais: LEED e BREEAM, 2020, Porto Alegre, RS. Anais do XVIII Encontro Nacional de Tecnologia do Ambiente Construído - **ENTAC 2020**: Futuro da Tecnologia do Ambiente Construído e os Desafios Globais. Porto Alegre: ANTAC, 2020.
- Cazanova, R.; Timm, J. F. G.; Maciel, V. G.; Petroli, P. A.; Passuello, A. Estrutura de ferramenta baseada em ACV para comunicação do desempenho ambiental no setor da construção civil, 2020, Porto Alegre, RS. Anais do XVIII Encontro Nacional de Tecnologia do Ambiente Construído - **ENTAC 2020**: Futuro da Tecnologia do Ambiente Construído e os Desafios Globais. Porto Alegre: ANTAC, 2020.
- Timm, J. F. G.; Passuello, A. Consideração do desempenho ambiental em Compras Públicas com viés sustentável: análise de casos do setor da construção civil, 2020, Gramado, RS. Anais do **VII Congresso Brasileiro em Gestão do Ciclo de Vida**: volume 1. Porto Alegre, 2021. p. 48-53.
- Silva, V. G.; Baiochi, A. G.; Pulgrossi, L. M.; Zara, O. O C.; Guimarães, G. D.; Morales, M. F. D.; Timm, J. F. G.; Passuello, A.; Da Silva, M. G. Einstein’s insanity concept revisited: why different results for the same whole building LCA are acceptable?, 2020, Gramado, RS. Anais do **VII Congresso Brasileiro em Gestão do Ciclo de Vida**: volume 1. Porto Alegre, 2021. p. 74-79.

1.4 EXPANDED SUMMARY PUBLISHED IN PROCEEDINGS OF CONFERENCES

- Timm, J. F. G.; Bertoli, G.; Passuello, A.; Ries, R. Circularity indicator for buildings: integrated evaluation of environmental impact and resource management. 2024. Snowbird, UT. EUA. Anais: **ACLCA Conference**, 2024.
- Timm, J. F. G.; Passuello, A. Building Ecodesign Strategies towards Circular Economy: a review. 2024, Viña del Mar, Chile. Anais: **4th La Conference on Sustainable Development of Energy, Water and Environment Systems (LASDEWES)**, 2024.
- Timm, J. F. G.; Leichter, M.; Dalmoro, J.; Passuello, A. Implementation of Green Public Procurement in public transport: criteria analysis and proposals evaluation. 2024, Viña del Mar, Chile. Anais: **4th La Conference on Sustainable Development of Energy, Water and Environment Systems (LASDEWES)**, 2024.
- Timm, J. F. G.; Bertoli, G.; Passuello, A.; Ries, R. LCA Modeling Challenges of Grid Mix Change for a Small Single-Family House in Brazil. 2023, Burlington, VT, EUA. Anais: **ACLCA Conference**, 2023.
- Kouhirostamkolaei, M.; Timm, J. F. G.; Bertoli, G.; Passuello, A.; Ries, R. LCA Modeling of Future Grid Mix Scenarios: A Comparison between USA and Brazilian Residential Buildings. 2023, Burlington, VT, EUA. Anais: **ACLCA Conference**, 2023.
- Brenner, B. L.; Timm, J. F. G.; Passuello, A. Economia Circular E ACV De Edifícios: Uma Revisão Sistemática, 2021, Buenos Aires. Anais: IX **International Conference on Life Cycle Assessment in Latin American** (LALCA), 2021.

1.5 PUBLISHED BOOK CHAPTERS

- Timm, J. F. G.; Moraga, G.; Passuello, A. Employing circular economy principles to enhance sustainability in the built environment. In: Assed N. Haddad; Ahmed W.A. Hammad; Karoline Figueiredo. (Org.). **Materials Selection for Sustainability in the Built Environment.** 1ed.: ELSEVIER, 2024, v., p. 87-115. ISBN (print): 978-323-95122-7. ISBN (online) 978-323-95123-4

1.6 PRESENTATIONS OF WORK

- Timm, J. F. G.; Passuello, A. Building Ecodesign Strategies towards Circular Economy: a review. 2024, Viña del Mar, Chile. Anais: **4th La Conference on Sustainable**

Development of Energy, Water and Environment Systems (LASDEWES), 2024. (Presentation/Congress).

- Timm, J. F. G.; Leichter, M.; Dalmoro, J.; Passuello, A. Implementation of Green Public Procurement in public transport: criteria analysis and proposals evaluation. 2024, Viña del Mar, Chile. Anais: **4th La Conference on Sustainable Development of Energy, Water and Environment Systems (LASDEWES)**, 2024. (Presentation/Congress).
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