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SOBRE O PERIÓDICO MIX SUSTENTÁVEL

O Periódico Mix Sustentável nasceu da premissa de que o projeto englobando os preceitos da sustentabilidade é a única solução possível para que ocorra a união entre a filosofia da melhoria contínua com a necessidade cada vez maior de preservação dos recursos naturais e incremento na qualidade de vida do homem. A sustentabilidade carece de uma discussão profunda para difundir pesquisas e ações da comunidade acadêmica, que tem criado tecnologias menos degradantes na dimensão ambiental; mais econômicas e que ajudam a demover injustiças sociais a muito estabelecidas. O periódico Mix Sustentável apresenta como proposta a publicação de resultados de pesquisas e projetos, de forma virtual e impressa, com enfoque no tema sustentabilidade. Buscando a troca de informações entre pesquisadores da área vinculados a programas de pós-graduação, abre espaço, ainda, para a divulgação de profissionais inseridos no mercado de trabalho, além de entrevistas com pesquisadores nacionais e estrangeiros. Além disso publica resumos de teses, dissertações e trabalhos de conclusão de curso defendidos, tendo em vista a importância da produção projetual e não apenas textual.

De cunho essencialmente interdisciplinar, a Mix tem como público-alvo pesquisadores e profissionais da Arquitetura e Urbanismo, Design e Engenharias. De acordo com a CAPES (2013), a área Interdisciplinar no contexto da pós-graduação, decorreu da necessidade de solucionar novos problemas que emergem no mundo contemporâneo, de diferentes naturezas e com variados níveis de complexidade, muitas vezes decorrentes do próprio avanço dos conhecimentos científicos e tecnológicos. A natureza complexa de tais problemas requer diálogos não só entre disciplinas próximas, dentro da mesma área do conhecimento, mas entre disciplinas de áreas diferentes, bem como entre saberes disciplinares e não disciplinares. Decorre daí a relevância de novas formas de produção de conhecimento e formação de recursos humanos, que assumam como objeto de investigação fenômenos que se colocam entre fronteiras disciplinares.

Desafios teóricos e metodológicos se apresentam para diferentes campos de saber. Novas formas de produção de conhecimento enriquecem e ampliam o campo das ciências pela exigência da incorporação de uma racionalidade mais ampla, que extrapola o pensamento estritamente disciplinar e sua metodologia de compartimentação e redução de objetos. Se o pensamento disciplinar, por um lado, confere avanços à ciência e tecnologia, por outro, os desdobramentos oriundos dos diversos campos do conhecimento são geradores de diferentes níveis de complexidade e requerem diálogos mais amplos, entre e além das disciplinas.

A Revista Mix Sustentável se insere, portanto, na Área Interdisciplinar (área 45), tendo como áreas do conhecimento secundárias a Arquitetura, Urbanismo e Design (área 29), a Engenharia Civil (área 10) e, ainda, as engenharias em geral.

CLASSIFICAÇÃO QUALIS

No quadriênio 2017-2020 a revista MIX Sustentável está classificada como A3 em todas as áreas de avaliação.

MISSÃO

Publicar resultados de pesquisas e projetos, de forma virtual e impressa, com enfoque no tema sustentabilidade, buscando a disseminação do conhecimento e a troca de informações entre acadêmicos, profissionais e pesquisadores da área vinculados a programas de pós-graduação.

OBJETIVO

Disseminar o conhecimento sobre sustentabilidade aplicada à projetos de engenharia, arquitetura e design.

POLÍTICAS DE SEÇÃO E SUBMISSÃO

A) Seção Científica

Contém artigos científicos para socializar a produção acadêmica buscando a valorização da pesquisa, do ensino e da extensão. Reúne 12 artigos científicos que apresentam o inter-relacionamento do tema sustentabilidade em projetos

de forma interdisciplinar, englobando as áreas do design, engenharia e arquitetura. As submissões são realizadas em fluxo contínuo em processo de revisão por pares. A revista é indexada em [sumários.org](http://sumarios.org) e no [google acadêmico](http://google.academico).

B) Seção Resumo de Trabalhos de Conclusão de Curso de Graduação, Iniciação Científica e Pós-graduação

Tem como objetivo a divulgação de Teses, Dissertações e Trabalhos de Conclusão de Curso na forma de resumos expandidos e como forma de estimular a divulgação de trabalhos acadêmico-científicos voltados ao projeto para a sustentabilidade.

C) Seção Mercadológica

É um espaço para resenhas e entrevistas (espaços de diálogo). Apresenta pelo menos duas entrevistas com profissionais atuantes no mercado ou pesquisadores de renome, mostrando projetos práticos que tenham aplicações na esfera da sustentabilidade. Deverá ainda disponibilizar conversas com especialistas em sustentabilidade e/ou outros campos do saber. Todos os números possuem o Editorial, um espaço reservado para a apresentação das edições e comunicação com os editores.

PROCESSO DE AVALIAÇÃO PELOS PARES

A revista conta com um grupo de avaliadores especialistas no tema da sustentabilidade, doutores em suas áreas de atuação. São 211 revisores, oriundos de 67 instituições de ensino Brasileiras e 8 Instituições Internacionais. Os originais serão submetidos à avaliação e aprovação dos avaliadores (dupla e cega).

Os trabalhos são enviados para avaliação sem identificação de autoria. A avaliação consiste na emissão de pareceres, da seguinte forma:

- aprovado
- aprovado com modificações (a aprovação dependerá da realização das correções solicitadas)
- reprovado

PERIODICIDADE

Publicação quadrimestral com edições especiais. São publicadas três edições regulares ao ano. Conta ainda com pelo menos uma edição especial anual.

POLÍTICA DE ACESSO LIVRE

Esta revista oferece acesso livre imediato ao seu conteúdo, seguindo o princípio de que disponibilizar gratuitamente o conhecimento científico ao público proporciona maior democratização mundial do conhecimento.

ARQUIVAMENTO

Esta revista utiliza o sistema LOCKSS para criar um sistema de arquivo distribuído entre as bibliotecas participantes e permite às mesmas criar arquivos permanentes da revista para a preservação e restauração.

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A contribuição deve ser original e inédita, e não estar sendo avaliada para publicação por outra revista; caso contrário, deve-se justificar em “Comentários ao editor”.

O arquivo da submissão deve estar em formato Microsoft Word, OpenOffice ou RTF.

As URLs para as referências devem ser informadas nas referências.

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Enviar separadamente todas as figuras e imagens em boa resolução.

O texto segue os padrões de estilo e requisitos bibliográficos descritos em Diretrizes para Autores e na página <http://mixsustentavel.paginas.ufsc.br/submissoes/>.

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Felipe Augusto Melo de Oliveira
Diretor

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EDITORIAL

MIX SUSTENTÁVEL VOL. 11 N. 1 — EDIÇÃO REGULAR 2025

A MIX Sustentável chega nesta edição ao seu décimo ano. Nestes 10 anos, diversas mudanças na parte editorial foram realizadas, algumas na busca pelo aprimoramento contínuo, outras para atender as regras da CAPES e de outros indexadores.

Entre as mudanças que visaram o aprimoramento destacamos a internacionalização do Comitê Editorial com a inclusão de docentes pesquisadores do Equador, Itália, Espanha e Portugal; a ampliação da quantidade de artigos publicados em cada edição (de 12 para 15); a adoção do sistema de publicação em fluxo contínuo e a publicação de artigos apenas em inglês.

Já com relação as regras adotadas para atendimento dos órgãos indexadores, temos que ter em mente que estas regras nem sempre estão claramente estabelecidas em um mercado cada vez mais invadido por revistas predatórias, cujo objetivo é essencialmente financeiro. Nenhum processo editorial sério, que passa pelas etapas necessárias de validação científica pode ser realizado no espaço temporal que estas publicações predatórias prometem. Os órgãos indexadores (não generalizando obviamente) deveriam proteger e priorizar as revistas científicas que são vinculadas as IES, sem cobranças de taxas abusivas, e com objetivos prioritariamente educacionais.

A CAPES está ciente disso, ao que parece. Embora a decisão anunciada não seja uma unanimidade: o cancelamento do sistema Qualis e sua substituição por uma avaliação que parece, bastante indefinida ainda. Embora o Qualis seja alvo de críticas, por avaliar com extratos elevados revistas predatórias, e apresentar uma morosidade não compatível com o mundo moderno (estamos ainda usando o Qualis de 2017-2020); ainda assim, é um sistema muito usado na vida acadêmica e mesmo que restrito a avaliação da produção dos programas de pós-graduação, acabou por extrapolar sua finalidade: em concursos, em ingressos de programas de pós-graduação, em credenciamentos de docentes em programas de pós-graduação, em editais, enfim... temos sérias dúvidas se o que vier em sua substituição será melhor ou pior.

Nesta edição, temos como artigo 1: 16TH GOAL FOR SUSTAINABLE DEVELOPMENT: A CASE STUDY ON THE ROLE OF INTERIOR ARCHITECTURE, escrito em conjunto por docentes da UFMG e UEMG, cujo foco é a meta 16 dos ODS, tratando do desenvolvimento de capacidades para a prevenção de crimes, com estudo de caso para prevenção do crime através do projeto de ambientes.

O artigo 2 é proveniente da UFSC, com o título BUILDABILITY ASSESSMENT OF BRAZILIAN PROJECTS WITH INTERNATIONAL METHODS. O artigo investiga o potencial de aplicação e adaptação de métodos existentes de avaliação de construtibilidade para projetos em países estrangeiros.

Pesquisadores da UFRGS enviaram o artigo ADAPTING FLEXIBLE PAVEMENT INFRASTRUCTURE TO CLIMATE CHANGE: IMPLICATIONS AND SUSTAINABLE STRATEGIES, que discute as implicações das mudanças climáticas e as estratégias de adaptação para a infraestrutura de pavimento flexível sob condições climáticas não estacionárias.

Também da UFSC, o quarto artigo da edição, de título GREEN SPACES AND NATURAL ELEMENTS IN THE ARCHITECTURAL CONFIGURATION OF LONG-TERM CARE FACILITIES FOR OLDER ADULTS: A SYSTEMATIC LITERATURE REVIEW, mostra que o contato com a natureza é essencial na vivência institucionalizada de pessoas idosas, reforçando a importância de adaptações arquitetônicas sensíveis às suas preferências.

O artigo 5, proveniente da UFSM com participação da UFPel, intitulado IMPACT NOISE SOLATION OF FLOOR SYSTEMS USING PLASTERBOARD CEILING WITH AND WITHOUT PET WOOL, analisou o isolamento acústico ao ruído de impacto

de dois sistemas de piso, usando forro de gesso cartonado instalados sob uma laje pré-fabricada nervurada com vigotas protendidas, combinados com lâ PET no entreferro.

Pesquisadores da UFRJ enviaram o artigo STRATEGIC DECISIONS: A SUPPORT MODEL FOR PRIORITIZING PROJECTS IN THE BRAZILIAN TRANSPORT INFRASTRUCTURE, cujo resultado, ao integrar sustentabilidade e adaptação às mudanças climáticas, oferece uma estrutura holística para aprimorar o setor de transporte no Brasil e garantir sua resiliência a longo prazo.

O sétimo artigo da edição vem da Atitus Educação, e tem por título RISK ASSESSMENT OF A POTENTIAL EXTERNAL AND INTERNAL SULFATE ATTACK IN POZZOLANIC CEMENTITIOUS MATRICES, cujo objetivo foi a avaliação do comportamento de compósitos cimentícios frente ao ataque interno e externo por sulfatos ao longo do tempo, bem como o potencial mitigador de cimentos brasileiros considerados pozolânicos.

O artigo 8 identifica possíveis aspectos e impactos ambientais na indústria metal mecânica. Com o título LIFE CYCLE INVENTORY (LCI) OF A MECHANICAL GEARBOX MANUFACTURING PROCESS, é assinado por pesquisadores da UNISINOS. Da UFRGS, o artigo intitulado SUSTAINABLE MAINTENANCE OF AGING REINFORCED CONCRETE STRUCTURES: EVALUATING DIAGNOSTIC TECHNIQUES FOR EARLY DETECTION OF REINFORCEMENT CORROSION ressalta a necessidade de ferramentas diagnósticas mais precisas para a detecção precoce da corrosão, a fim de promover a manutenção sustentável e reduzir os custos ambientais e econômicos decorrentes de falhas estruturais.

O décimo artigo da edição vem da UFSM, com participação da UFPel. Intitulado SOUNDSCAPE AND NOISE MAP OF A HOSPITAL AREA IN A SMALL CITY, conclui que, mesmo em cidades menores, a poluição sonora afeta áreas sensíveis, como hospitais, sendo necessária a implementação de medidas de mitigação acústica para garantir o conforto dos usuários.

O artigo 11 é fruto de uma parceria entre USP, Universidade de Lisboa e UFC, e tem como título ANALYSIS OF THE APPLICATION OF LIMESTONE WASTE IN CEMENTITIOUS SYSTEMS BASED ON A SYSTEMATIC LITERATURE REVIEW. O objetivo da pesquisa foi identificar a aplicabilidade do resíduo de calcário proveniente de rochas em sistemas cimentícios e avaliar a partir de quais técnicas esses resíduos e seus produtos vêm sendo analisados.

Da PUC-Rio, o décimo segundo artigo da edição: FIRST STEPS TO N95: LOW-TECH AND ADAPTED EQUIPMENT FOR THE AUTONOMOUS DEVELOPMENT OF PLASTIC MICROFIBERS FOR MASK FILTRATION. O artigo destaca um dos desafios da época da pandemia, que foi a escassez de Equipamentos de Proteção Individual (EPI). Neste contexto, a manufatura aditiva emergiu como uma solução viável para enfrentar essa carência de EPIs.

O artigo 13 vem da parceria entre a UFSC e o IST de Lisboa, e tem por título: GREEN CREATIVE DESIGN FOSTERING A SUSTAINABLE MENTAL MODEL, cuja pesquisa contribui para o campo do design sustentável ao mostrar como a criatividade pode servir de catalisador para fomentar o engajamento duradouro e o desenvolvimento de modelos mentais sustentáveis.

O décimo quarto artigo, intitulado PROPOSITION AND DISCUSSION ON LOWCARBON BUILDING TECHNOLOGY – LCBT, vem do IAU-USP, e tem por objetivo propor e discutir princípios que contribuam para a formulação e o desenvolvimento de tecnologias construtivas de menor impacto.

Finalizando a edição, o artigo PARAMETRIC DESIGN FOR RESILIENT DESIGN IN LATIN AMERICA, de pesquisadores da Atitus Educação, cujos autores realizaram uma revisão sistemática conforme o método PRISMA.

Desejamos uma boa leitura.

Lisiane Ilha Librelotto e Paulo Cesar Machado Ferroli – editores.

16TH GOAL FOR SUSTAINABLE DEVELOPMENT: A CASE STUDY ON THE ROLE OF INTERIOR ARCHITECTURE

16º OBJETIVO PARA O DESENVOLVIMENTO SUSTENTÁVEL: UM ESTUDO DE CASO SOBRE O PAPEL DA ARQUITETURA DE INTERIORES

16º OBJETIVO DE DESENVOLVIMENTO SUSTENTÁVEL: UN ESTUDIO DE CASO SOBRE EL PAPEL DE LA ARQUITECTURA DE INTERIORES

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ABSTRACT

The 16th goal of the 2030 Agenda for sustainable development highlights the importance of developing capacities for crime prevention. Thus, the objective of this article was to verify whether in a Brazilian college entrance hall there are physical space components that reduce surveillance, encouraging unauthorized people to enter the building. At this college, a student was stolen inside their classroom by a supposed intruder. The method uses the Crime Prevention Through Environmental Design approach for on-site observation and analysis (qualitative part), the Space Syntax Theory using the DephtMapX software to produce the visibility map (quantitative part) and the Photoshop program for image processing. The results reveal that the large number of entry and exit points, the layout (control desk and turnstiles) and the positioning of the street access door, stairs and pillars are the elements of the physical space that reduce surveillance in the entrance hall. Finally, this work shows procedures for analyzing internal spaces with a focus on crime prevention, highlighting the role of Interior Architecture in achieving the 16th goal of the 2030 Agenda for sustainable development.

KEYWORDS

Sustainability; Architecture; Crime Prevention Through Environmental Design; Space Syntax.

RESUMO

O 16º objetivo da Agenda 2030 para o desenvolvimento sustentável destaca a importância do desenvolvimento de capacidades para a prevenção de crimes. Assim, o objetivo deste artigo foi verificar se em um hall de entrada de uma faculdade brasileira existem componentes do espaço físico que reduzem a vigilância, incentivando a entrada de pessoas não autorizadas na edificação. Nessa faculdade, uma aluna foi furtada dentro de sua sala de aula por um suposto intruso. O método utiliza a abordagem Prevenção do Crime por meio do Projeto de Ambientes para observação e análise no local (parte qualitativa), a Teoria da Sintaxe Espacial utilizando o software DephtMapX para produzir o mapa de visibilidade (parte quantitativa) e o programa Photoshop para processamento das imagens. Os resultados revelam que o grande número de pontos de entrada e saída, o “layout” (balcão de controle e catracas) e o posicionamento da porta de acesso à rua, das escadas e dos pilares são os elementos do espaço físico que reduzem a vigilância no hall de entrada. Por fim, este trabalho apresenta procedimentos de análise de espaços internos com foco na prevenção de crimes, destacando o papel da Arquitetura de Interiores no alcance da 16ª meta da Agenda 2030 para o desenvolvimento sustentável.



PALAVRAS-CHAVE

Sustentabilidade; Arquitetura; Prevenção do Crime Através do Projeto de Ambientes; Sintaxe Espacial.

RESUMEN

El Objetivo 16 de la Agenda 2030 para el Desarrollo Sostenible destaca la importancia del desarrollo de capacidades para la prevención del delito. Así, el objetivo de este artículo fue verificar si existen componentes del espacio físico en el hall de entrada de una facultad brasileña que reducen la vigilancia, favoreciendo el ingreso de personas no autorizadas al edificio. En esta facultad, el teléfono celular de un estudiante fue robado dentro de su salón de clases por un presunto intruso. El método utiliza el enfoque de Prevención del Delito a través del Diseño Ambiental para la observación y análisis in situ (parte cualitativa), la Teoría de Sintaxis Espacial utilizando el software DephtMapX para producir el mapa de visibilidad (parte cuantitativa) y el programa Photoshop para el procesamiento de imágenes. Los resultados revelan que la gran cantidad de puntos de entrada y salida, el diseño (mesa de vigilancia y torniquetes) y la ubicación de la puerta de acceso a la calle, escaleras y pilares son los elementos del espacio físico que reducen la vigilancia en el hall de entrada. Finalmente, este trabajo presenta procedimientos para el análisis de espacios internos con enfoque en la prevención del delito, destacando el papel de la Arquitectura Interior en el logro del Objetivo 16 de la Agenda 2030 para el Desarrollo Sostenible.

PALABRAS CLAVE

Sostenibilidad; Arquitectura; Prevención del Crimen a Través del Diseño Ambiental; Sintaxis Espacial.

1. INTRODUCTION

The 16th goal of the 2030 Agenda for sustainable development, that is, Peace, Justice and Strong Institutions, includes building capacities at all levels for crime prevention, especially in developing countries (United Nations, 2024).

16.a Strengthen relevant national institutions, including through international cooperation, for building capacity at all levels, in particular in developing countries, to prevent violence and combat terrorism and crime (United Nations, 2024, without page number).

In Brazil, the debate on crime prevention is stimulated by the Brazilian Public Security Forum (BPSF).

The Brazilian Public Security Forum is a non-governmental, non-partisan, non-profit organization whose goal is to build a benchmark environment in the area of public security.

Composed of police officers, public administrators, researchers, activists, and justice system operators, the BPSF contributes to the transparency of information on violence and the development of security policies, in addition to defending public security as a fundamental social right (Brazilian Public Security Forum, 2024a, without page number).

The BPSF promotes an annual event, named after the institution, which includes in-person and virtual meetings. In 2024, the 18th meeting took place, with the aim of bringing together different segments seeking solutions to reduce violence and insecurity. The focus was on developing prevention and qualified repression strategies to reduce homicides and other violent crimes, address violence against women, improve the prison system, weaken organized crime, and improve the financing and management conditions of public security policies. (Brazilian Public Security Forum, 2024b).

In addition, the BPSF has a journal for the dissemination of scientific works, called the Brazilian Journal of Public Security (Brazilian Public Security Forum, 2024c), and regularly publishes a report called Atlas of Violence. This document is produced in partnership with the Institute of Applied Economic

Research (IAER) (Brazilian Public Security Forum, 2024d). IAER is a federal public foundation linked to the Ministry of Planning and Budget (Institute of Applied Economic Research, 2024). The Atlas of Violence aims to portray violence in Brazil, based mainly on data from the Mortality Information System (MIS) and the Information System for Notifiable Diseases (SND) of the Ministry of Health. Therefore, it provides information on homicides analyzed from the perspective of gender, race, age group, among others (Brazilian Public Security Forum, 2024d).

Then it is clear that the BPSF is a Brazilian institution designed to build solutions for crime prevention in Brazil, in line with the 16th goal of the 2030 Agenda for Sustainable Development. However, in relation to crime prevention through design, Almeida, Costa and Engler (2021) highlight that in Brazil the subject is better known and debated in the military segment than in design schools.

Nevertheless, the same is not true in English-speaking countries. Founded in Canada, the International Crime Prevention Through Environmental Design Association (ICA) aims to promote crime prevention internationally with an approach focused on architecture and urban planning. As its name suggests, the organization uses the Crime Prevention Through Environmental Design (CPTED) approach, which will be described later in this paper. According to the International Crime Prevention Through Environmental Design Association (2024, no page number), the ICA's mission is to "create safer environments and improve the quality of life through the use of CPTED principles and strategies." Similarly, in the United States, the National Institute for Crime Prevention (NICP) is focused on promoting CPTED (National Institute for Crime Prevention, 2024).

In turn, in the United Kingdom, the Design Against Crime Research Lab, a research center linked to the University of the Arts London, develops research on the use of design (focused on Product and Graphic Design) for crime prevention (Design Against Crime Research Lab, 2024).

At the core of the Design Against Crime Research Lab's activity is research that serves the public and communities. The Lab's focus is "socially responsive design and innovation": its primary driver is social issues, its main consideration is social impact, and its main objective is social change. Overall, the team's approach embraces action research, user-centred and participatory design methods, as well as diverse ethnographic approaches (Design Against Crime Research Lab, 2024, without page number).

Thus, it is possible to see opportunities in Brazil to expand the discussion on crime prevention to the area of design and architecture, similarly to other countries. Consequently, this work aims to explore this opportunity, in order to contribute to the achievement of the 16th sustainable development goal in the country.

As a first thrust in discussing crime prevention, it is important to highlight that crime is a complex issue, so it is reasonable to assume that it requires complex solutions. However, society often claims prompt and simplistic solutions and some people view this issue as just a matter of policing. According to Bondaruk (2007) in 2006, the criminal organization called First Capital Command (in portuguese, Primeiro Comando da Capital (PCC)) carried out a series of attacks in the São Paulo city, a Brazilian metropolis, causing panic among the population.

In times of crisis, society demands fast solutions (...). The problem is that such quick and ready-made solutions do not exist.(...) The combination of an active community, a government focused on meeting public demands, an efficient and effective police force and, above all, a social environment better adapted to prevent the occurrence of crime and the fear of crime, might provide the solution we all desire for public safety (Bondaruk, 2007, p.53).

Unfortunately, attacks like this keep happening in the country. Trindade and Jácome (2023) reported that the government confirmed at least 259 attacks by criminal organizations on shops, vehicles and public buildings in a Brazilian state called Rio Grande do Norte, that occurred during 5 days in March 2023. Coincidence or organization?

Therefore, it is urgent to develop research to face and prevent crimes in Brazil. As Bondaruk (2007, p.53) said, one of the possible approaches is the creation of "a social environment better adapted to prevent the occurrence of crime and the fear of crime". However, how could this be done?

Although they are rarely known in Brazil, the Design Against Crime (DAC) and the Crime Prevention Through Environmental Design (CPTED) approaches can show a direction.

DAC approach develops products, environments and services to modify the potential offender's perception of the crime benefits (Silva *et al.*, 2018). The Design Against Crime Research Lab (2024) uses responsive design for:

Reduce the negative consequences of criminogenic (i.e., likely to cause criminal behavior or serving criminal goals) affordances

of products, services, environments, and communications and instead designing affordances that discourage the crime, but are "fit for purpose" "and contextually appropriate" (Design Against Crime Research Lab, 2024, without page number).

In addition, DAC modifies the opportunities network that makes the criminal practice easier.

Most crimes are committed because the offender sees an opportunity (...). The more insecure and vulnerable the offender feels to act, the less likely they are to commit a crime (Bondaruk, 2007, p. 56)

Opportunities for crime are highly specific - the theft of vehicles to use in races on public roads ("rachas") has a completely different pattern of opportunities than the theft of cars for disassembly and trafficking of their components ("desmanche") (Bondaruk, 2007, p.57)

According to Clarke (1997), Situational Crime Prevention (SCP) proceeds from an analysis of the circumstances that generate specific types of crimes, in order to introduce discrete management and environmental changes to reduce the opportunities for these offenses. Similarly, Clarke (2018) declares that most of us can recognize the role opportunities have played in our lives, although many people are unaware of this influence. Hence, for anyone engaged in explaining human behavior, which includes crime, it is important to consider the effects of opportunities.

In the same way, Crime Prevention Through Environmental Design (CPTED) establishes that the physical environment can be subtly manipulated to induce behavioral effects capable of reducing the occurrence of crimes and making criminal action less attractive to offenders (Crowe, 2013). Moreover, Hushen and Hushen (2020) state that CPTED is defined as the appropriate design and effective use of the built environment to reduce the fear and the crime occurrences, as well as to improve people's quality of life.

However, DAC, SCP and CPTED should not be confused with hostile architecture. According to Rosenberger (2020), hostile architecture is designing objects for public spaces to discourage specific uses and, consequently, discourage the presence of specific people (e.g., homeless people and skateboarders). Therefore, the idea of kicking out specific groups is incompatible with DAC, SCP and CPTED as they aim to dissuade potential offenders from

committing crimes (by reducing opportunities) rather than excluding them from using the space.

In contrast to common view, CPTED principles show that living in safer environments does not require oppression, hostility or social withdrawal. On the contrary, crime prevention suggests strengthening citizenship, appropriating spaces, promoting a sense of belonging between individuals and environments, as well as people's care and responsibility for the public spaces they use (Almeida, Costa and Engler, 2021, p.19).

Almeida, Costa and Engler (2021) say that CPTED has been studied in English-speaking countries for approximately half a century. However, according to these authors, in Brazil, publications on the topic appeared more consistently only at the beginning of the 21st century.

Stimulating knowledge of the design and architecture for crime prevention in Brazil is crucial to providing society with the scientific basis necessary to make more assertive decisions for preventing crime considering Brazilian specific contexts. Furthermore, research on crime prevention could help other countries to find similar solutions. So, how could architects contribute to crime prevention in a specific situation?

As each type of crime has a specific network of opportunities, it requires analyzes and solutions targeted to each case. Thus, the authors of this article realized that the case study was the most appropriate approach to address the issue. Consequently, the first step of this research was to find a building where a crime occurred.

Thus, a Brazilian college was chosen, because there a student was stolen by an alleged intruder inside their classroom in 2022. According to the faculty deans, after the theft, students said they had seen an unrecognized man inside the classroom. Although the college deans said they immediately notified police about the theft (in 2022), so far (in 2024) the college managers have not been getting answers and the perpetrator has not even been identified. It is important to say that, for preventing crimes according to the CPTED approach, it is not necessary to identify the aggressor. As the focus is on prevention, the main strategy is to reduce opportunities that stimulate crime. Investigating, prosecuting and catching the perpetrator is the duty of the police and justice. However, Architecture can make new occurrences difficult.

After that, the object of study was chosen: the first room that the alleged attacker managed to cross without being identified, that is, the building's entrance hall.

Hence, the problem of this research was elaborated: Is there any physical space component in the entrance hall that facilitates the entry of unauthorized people into the college? Then, the hypothesis emerged: In the entrance hall there are physical space components that reduce surveillance, encouraging unauthorized people to enter the college. Finally, the objective was created: to analyze the spatial configuration of the college's entrance hall.

Moreover, the research was defined as a mixed method, as it has qualitative analyzes (based on on-site observation) as well as quantitative analyzes (obtained through DephtMapX computer program).

This research can stimulate architects (in Brazil and other countries) to consider reducing crime opportunities in Interior Architecture design, not only making them aware of the importance of the topic, but also presenting alternatives for practical application. Consequently, Interior Architecture will be able to contribute to the achievement of the 16th goal of sustainable development, Peace, Justice and Strong Institutions.

2. ARCHITECTURE FOR CRIME PREVENTION

Crowe (2013) states that CPTED has three overlapping strategies: natural surveillance, natural access control and territorial reinforcement. Surveillance includes facilitating space observation by individuals, so that a potential offender realizes that it is risky to commit crimes there. Surveillance could be organized (police patrol), mechanical (lighting) or natural (windows). Natural surveillance can be defined as a by-product of the routine use of an environment. Hushen and Hushen (2020) suggest using lighting and transparent building materials to stimulate natural surveillance.

Access control means creating barriers between the potential aggressor and the crime target, as well as creating a perception of risk in potential perpetrators. Access control could be organized (guards), mechanical (locks) or natural (spatial definition). Restricting access to the target should preferably be done in a natural way, that is, a control that is a by-product of the routine use of the environments (Crowe, 2013). For Hushen and Hushen (2020), natural access control includes guiding people through spaces via a strategic design of streets, sidewalks, building entrances and landscaping. According to the authors, it is necessary to ensure that building entrances are easily identified, well lit and visible from windows.

Based on Hushen and Hushen (2020), it is possible to infer that people should not become lost or confused when moving around the space, as they would then be less susceptible to perpetrators' attacks.

Hushen and Hushen (2020) say territorial reinforcement is the creation of places that stimulate a deep sense of belonging in their users. Similarly, Crowe (2013) says that the concept of territoriality suggests that design can create or extend a sphere of influence so that users develop a sense of proprietorship, i.e., a sense of territorial influence, which is perceived by potential offenders. Hushen and Hushen (2020) exemplify a territorial reinforcement strategy. On a gate at South Florida University, there is a symbol of its football team. The design strategy, that is, this image in that place, is an attempt to strengthen the bonds of belonging between students and the university campus.

Crowe (2013) also highlights the importance of maintaining spaces for crime prevention. According to Crowe (2013, p.28), "Deterioration and blight indicate less concern and control by intended users of a site and indicate a greater tolerance of disorder.". In turn, Hushen and Hushen (2020) consider maintenance as a fourth strategy of CPTED and exemplify that trees without correct pruning can obstruct visibility, hindering natural surveillance. Similarly, Almeida, Costa and Engler (2021) highlight that the lack of tree pruning can also obstruct artificial lighting in public spaces.

According to Lamoreaux and Sulkowski (2020), recent research has shown that, in schools, the balance between meeting physical security needs and ensuring students' psychological comfort can be achieved through CPTED strategies.

The use of CPTED as a crime prevention approach can not avoid spatial analysis. Among various theories, Space Syntax is one of the possibilities for carrying out this type of analysis. Netto (2016) states that Space Syntax is a socio-spatial theory which emerged in the 1970s. The theory is a strong reaffirmation of space as a living dimension based on its inherent relationality (Netto, 2016). In turn, Alitajer and Nojoumi (2016, p. 341) declare that "Space syntax seeks to explain how spatial configurations express social or cultural meanings". According to Hillier (2007), a specific spatial configuration can define social patterns, such as land use models, movement, urban crimes and location of immigrants.

Based on Space Syntax Theory Turner and Varoudis (2024) created the DepthMapX software.

DepthmapX is a multi-platform software to perform a set of spatial network analyses

designed to understand social processes within the built environment. It works at a variety of scales from building through small urban to whole cities or states. (Turner; Varoudis, 2024, without page number).

Alitajer and Nojoumi (2016) highlight Depthmap was created by Alasdair Turner at University College London (UCL) and it is used to perform visibility analysis in architecture and urban planning. They used UCL DepthMap software to analyze behavioral patterns in the spatial configurations of traditional and modern houses in Hamedan, Iran. Similarly, Yaseen and Mustafa (2023) used Depthmap to try to find out the existence of biophilic design parameters and the proportion of naturalness of view from permeable openings in schools by assessing their spatial layouts and configurations.

3. METHODS

The authors of this paper are interested in developing crime prevention strategies in Brazil using the CPTED approach, mainly in preventing theft in public schools.

Consequently, the first author was looking for a school where thefts had occurred. Then, she heard from a friend about a theft at a public college. In fact, thefts at schools are common in Brazil and it is not difficult to find this type of situation. In this country, public elementary and high schools have similar architecture, however, public college buildings are usually different. Therefore, she saw, there, a chance to investigate the influence of physical elements on the opportunities network for this type of crime, due to the greater variability of the spatial definition. So, she quickly contacted the faculty deans, who authorized the research to be carried out there. Thus, the research began a few weeks after the theft had occurred.

Then, she was to talk to the college deans to understand the circumstances under which the theft had occurred. They said a student declared someone stole their cell phone inside their classroom. And, after the theft, students said they had seen an unrecognized man inside the classroom. The leaders said they immediately notified police about the crime, however, the police had not yet given answers.

Hence, the authors decided to investigate whether in the entrance hall, the faculty's first access control place, there were physical elements that facilitated the entry of strangers into the building. Thus, the problem, hypothesis

and objective were defined, as shown in the Introduction section of this article.

The authors chose not to publicize either the name or the address of the college, as this research will reveal security vulnerabilities in the building, which can facilitate other crimes. For the same reason, they chose to use images that show only the essential elements for this research.

The first author obtained the architectural plan in editable format (with .dwg extension) and, considering CPTED strategies, she produced a simplified architectural plan in AutoCAD software to show only the essential information for this research.

In July 2022, she was in the entrance hall to observe and analyze spatial conditions according to CPTED's overlapping strategies, that is, surveillance, access control, territorial reinforcement and maintenance. The authors consider uses, access, flows, layout, lighting, materials and the existence (or non-existence) of electronic devices as the physical aspects of the space that can influence surveillance. Using her on-site observation notes and the simplified architectural plan, she produced an image using the computer program Photoshop, adding arrows and legend to the original drawing. It was the qualitative part of this mixed research.

Afterwards, the researchers began the quantitative part. The authors modeled the room plan in the DephtMapX software to generate the visibility map. This computer program calculates the visibility from all internal points of a polygon based on all other points within the same polygon. They downloaded DephtMapX, produced by Turner and Varoudis (2024), for free from a specific website, whose access link can be found in the References section of this article.

Subsequently, the first author added the graphical representation of the control desk, texts and legend to the image generated in DephtMapX using Photoshop software. She did this treatment to facilitate the understanding of the spatial elements and the results generated by DephtMapX. Then, she observed the regions of space that had less visibility and crossed this information with that she obtained qualitatively, in order to identify possible elements of the physical space that hindered surveillance on site. After that, she discussed the results with other authors, to improve them. Such procedures allowed answering the problem-question and testing the hypothesis.

4. RESULTS

As shown in Figure 1, the entrance hall has approximately 361.7 m², a control point, where there are two guards (control desk), two restrooms for the guards (W.C.), five entry points (three doors for access from the street and two doors for parking access) and several points for access to other parts of the building. Furthermore, there are pillars and some turnstiles in the room. Next to the turnstiles, there are small doors that allow access for people in wheelchairs. However, when the first author was at the site, she observed that all the turnstiles were inoperative, there were no cameras as well as she did not find other electronic devices for surveillance. There is also a projection of the second floor, as well as a concrete awning, with the other parts of the room having a double ceiling height. The majority of the facade is a large wall of aluminum and transparent glass, on which are sliding doors made with the same materials that allow entry into the hall from the sidewalk. This pavement is used by a large number of people of different ages, nationalities and social levels. The room is adequately lit, both during the day and at night, as well as clean and orderly. As expected, the entrance hall is mainly used as a transit area.



Figure 1: Simplified architectural floor plan of the entrance hall.

Source: Made by the authors.

As shown in Figure 1, the college's entrance hall communicates with other spaces through several points. It is possible to enter the room from the public street, through one of the three doors. The second path is from the parking lot, crossing one of the two doors. However, the parking is only for professors and before entering in it, the person must identify themselves to a guard (organized access control).

The main entrance is from the street, where students and visitors enter. As Figure 1 shows, there is a door far from the control desk which allows a person from the sidewalk to reach elevators and a staircase without any access control (bottom right corner of the image). However, this door was locked when the first author was there as well as the door on its left side. Hence, it was only possible to leave the street and enter the hall by going through the door directly in front of the control desk.

Moreover, a person in the hall can access other parts of the building through doors, stairs and elevators (Figure 1). A part of this flow could be controlled by the turnstiles (mechanical access control), but they did not work. Consequently, the small doors close to the turnstiles were not locked. In addition, the guards' desk (control desk) is very far from the main entrance (access from the street), so it is hard to control the flow, especially during busy times. When the first author was there, she noticed that several people quickly crossed the room, went through one of the small doors and took the elevators, ignoring the guards.

Classes take place in the morning, afternoon and evening, and crowds may occur at student arrival times. At these times, the path taken by most students is as shown in Figure 2, that is, they go through the small door next to the turnstiles. Due to the intense student flow at this time, the guards keep the small door permanently open. Consequently, in this situation, there is no mechanical access control on the path between the entrance door (street access) and the elevators and stairs (Figure 2).



Figure 2: Path taken by most students before classes start.
Source: Made by the authors.

So, when analyzing access control, it was possible to identify three main elements of the physical space that make agents' work difficult. The first is a large number of entrances and exits, which requires guards to be aware of several locations simultaneously. This may be

one of the reasons why some doors were locked. The second is the layout, which placed the control desk far from the main entrance, as well as put the turnstiles in an inappropriate location (it is possible to access other college areas without going through them). And the third is the fact that the turnstiles were inoperative, therefore, an opportunity to carry out mechanical access control was lost. The authors realized that if the turnstiles work and they are next to the entrance door (street access), access control will be much easier.

Although the glass facade allows agents to see who is coming in advance, when analyzing the surveillance, the researchers realized that the pillars and staircase next to the control desk can reduce visibility inside the hall. The DephtMapX visibility map will help them to verify it.

Figure 3 shows the visibility map of the college entrance hall generated using DepthMapX software, with image editing using Photoshop App. Areas with colors close to red (warm colors) are regions with high visibility, from all points located in the entrance hall. Conversely, areas with colors close to blue (cold colors) are those with low visibility from all points located in the internal space.

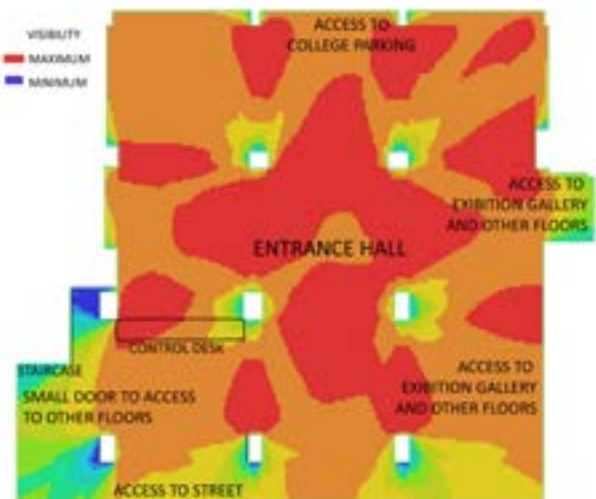


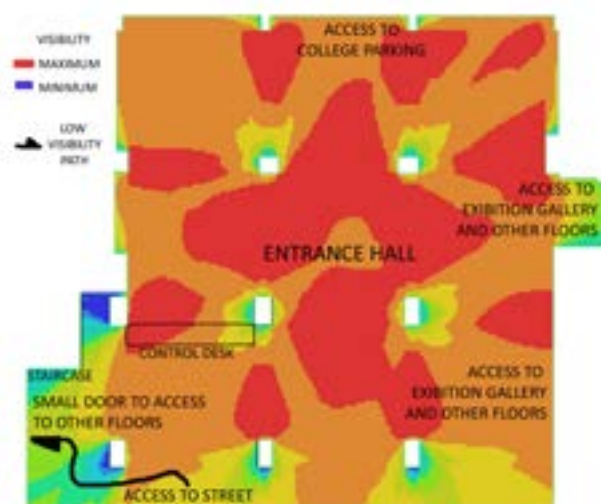
Figure 3: Entrance hall visibility map.
Source: Made by the authors.

In Figure 3, most areas are red or orange, so visibility is high or medium in most of the room. However, the pillars (white rectangles in Figure 3) and the staircase near the control desk reduce visibility in their surroundings, as they are partially surrounded by cyan and blue spots in Figure 3. Thus, the visibility map generated in DephtMapX (quantitative data) confirmed the question the authors did from qualitative data: the staircase and pillars generate a low visibility area on the left side of the

control desk (Figure 3). In addition, they noticed that a person can cross the entrance hall through a low-visibility path, as shown in Figure 4b.



(4a)



(4b)

Figure 4: Path taken by most students before classes start (4a) and path from the main entrance to access to the other floors through low visibility areas (4b).

Source: Made by the authors.

When comparing Figures 4a and 4b, the researchers realized that the low visibility path is close to the track taken by most students before classes start. Therefore, low visibility, crowding and the absence of mechanical access control at this time create opportunities for an offender to enter the building without being identified. So, DephtMapX visibility map helped them to identify the space surveillance vulnerabilities.

When analyzing territorial reinforcement, the authors did not find strong evidence of this process, as expected. The room is a transit place located in a building used by many people, including visitors. Therefore, the characteristics of the room are not very coherent with this

type of strategy. The authors also note that the room is properly maintained, clean and orderly. Thus, there are no problems related to maintenance. So, access control and surveillance are the main security strategies in this case.

So, in the entrance hall there are physical space components that facilitate the entry of unauthorized people, they are: the large number of entry and exit points; the layout (control desk and turnstiles positions); the positioning of the street access door, the staircase and the pillars. The researchers confirmed the hypothesis by proving that these components in those places reduce surveillance. First, the large number of entrances and exits, as well as the absence of working cameras and turnstiles, which requires guards to be aware of several locations simultaneously. Second, the control desk is far from the main entrance and the turnstiles are in inappropriate places making surveillance and access control difficult at busy times. Third, the positioning of the street access door, staircase and pillars creates a path through low visibility areas that is close to the student entrance path where crowding occurs and there is no access control. Consequently, the activation of turnstiles and the installation of surveillance cameras aimed at low-visibility areas would help minimize surveillance weaknesses.

Hence, the results show how Interior Architecture can contribute to achieving the 16th goal of the 2030 Agenda for sustainable development, building capacities for crime prevention. Through spatial analysis procedures, the authors demonstrate how architectural elements (such as layout) can help prevent crimes, reducing opportunities for crimes to occur, in line with CPTED principles.

However, they also highlight the limits imposed on solutions in a constructed building. It will be extremely difficult to move the staircase or pillars, and it will be hard to move the control desk and turnstiles, as they are fixed on the floor. Consequently, what remains are mechanical strategies for access control (operational turnstiles) and surveillance (cameras), which are not ideal CPTED strategies, as the approach suggests natural and subtle strategies. Therefore, it is possible to note that if crime prevention is considered at the design stage, it can generate subtle solutions capable of producing more aesthetically pleasing spaces.

Moreover, it is clear that crime prevention does not always require the use of expensive devices. Consequently, the use of CPTED principles in design contributes to ensuring the safety of everyone, regardless of social level. In addition to the benefit to students and professors, the researchers realized how a more suitable space for crime

prevention can help guards in their work, reducing stress levels and improving their quality of life.

Similarly, designing considering crime prevention in internal spaces does not always require high-end tools. DephtMapX is a free and user-friendly software, as well as it does not require high-end computers for data processing. However, their visibility map has limitations: the analysis carried out by DephtMapX only considers two dimensions, disregards points outside the perimeter of the space and disregards the properties of construction materials, such as the transparency of glass, for example. Nevertheless, it can be used in research and low-budget projects, boosting studies on the relationships between crime prevention and Interior Architecture.

5. CONCLUSION

The 16th goal of the 2030 Agenda for sustainable development encourages the creation of capacities for crime prevention. By applying spatial analysis procedures to prevent crimes in an internal space, this work showed how Interior Architecture can contribute to achieving the aforementioned target. Therefore, this article aims to encourage further research on the topic, thus contributing to improving people's quality of life through Architecture. Although they had already achieved the research objective, the researchers must provide an answer to university managers. In August 2022, the first author invited the college's dean and vice-dean for a meeting to show the spatial analyses. After the debate, the leaders chose the options they considered feasible and initiated actions.

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BUILDABILITY ASSESSMENT OF BRAZILIAN PROJECTS WITH INTERNATIONAL METHODS

AValiação de Construtibilidade de Projetos Brasileiros com Métodos Internacionais

Evaluación de Construcción de Proyectos Brasileños con Métodos Internacionales

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ABSTRACT

In the construction industry, it is usual to find that a design is harder to build than originally expected. This difficulty can be generally explained and assessed through the concept of buildability, which is also used to obtain better designs for projects. To assess buildability an assessment model well-adapted to the practices and aims of the local construction sector is required. This, in turn, demands consensus among industry players. This paper investigates the potential of applying and adapting existing buildability assessment methods to projects in foreign countries, serving as an easier route for general adoption. A case study was conducted in which the buildability of several Brazilian project designs was assessed, using foreign methods conceived for different places and contexts. It was found that the adaptation process required for the assessment was mostly successful, especially when the domestic designs matched the construction practices, size, and purpose of the original buildings for which the assessment method was conceived. However, the potential to direct designers to more buildable solutions was still limited in most cases.

KEYWORDS

Buildability; constructability; design optimization; construction industry.

RESUMO

Na indústria da construção, é comum descobrir que um projeto é mais difícil de construir do que o inicialmente esperado. Essa dificuldade pode ser geralmente explicada e avaliada através do conceito de construtibilidade, que também é utilizado para obter melhores projetos para empreendimentos. Para avaliar a construtibilidade é necessário um modelo de avaliação bem adaptado às práticas e objetivos do setor da construção local. Isto, por sua vez, exige consenso entre os players do setor. Este artigo investiga o potencial de aplicação e adaptação de métodos existentes de avaliação de construtibilidade para projetos em países estrangeiros, como um caminho mais fácil para adoção geral. Foi realizado um estudo de caso no qual foi avaliada a construtibilidade de diversos projetos brasileiros, utilizando métodos estrangeiros concebidos para diferentes lugares e contextos. Verificou-se que o processo de adaptação necessário para a avaliação foi bem-sucedido, especialmente quando os projetos domésticos corresponderam às práticas de construção, tamanho e finalidade dos edifícios originais para os quais o método de avaliação foi concebido. No entanto, o potencial para direcionar os projetistas para soluções mais edificáveis ainda foi limitado, na maioria dos casos.

PALAVRAS-CHAVE

Construtibilidade; otimização do projeto; indústria da construção



RESUMEN

En la industria de la construcción, es común descubrir que un proyecto es más difícil de construir de lo inicialmente esperado. Esta dificultad generalmente puede explicarse y evaluarse a través del concepto de constructibilidad, que también se utiliza para obtener mejores proyectos para emprendimientos. Para evaluar la constructibilidad, es necesario un modelo de evaluación bien adaptado a las prácticas y objetivos del sector de la construcción local. Esto, a su vez, exige consenso entre los actores del sector. Este artículo investiga el potencial de aplicación y adaptación de métodos existentes de evaluación de la constructibilidad para proyectos en países extranjeros, como un camino más fácil para la adopción general. Se realizó un estudio de caso en el que se evaluó la constructibilidad de diversos proyectos brasileños, utilizando métodos extranjeros diseñados para diferentes lugares y contextos. Se encontró que el proceso de adaptación necesario para la evaluación fue exitoso, especialmente cuando los proyectos locales se correspondían con las prácticas de construcción, el tamaño y la finalidad de los edificios originales para los cuales el método de evaluación fue diseñado. Sin embargo, el potencial para orientar a los diseñadores hacia soluciones más constructibles aún fue limitado, en la mayoría de los casos.

PALABRAS CLAVE

Constructibilidad; optimización del proyecto; industria de la construcción.

1. INTRODUCTION

In the construction industry, the term fragmentation is often used to describe the knowledge gap between the design of a building and the construction process of the same building (MOORE, 1996). Good design practices, better communication between players, and the increasing use of technological resources, such as Building Information Modelling, are some of the solutions proposed to help to narrow this knowledge gap. Nevertheless, this issue is far from being solved.

The idea of buildability addresses the problem by defining the "ease of construction", by which a less fragmented design process can provide better results for the overall project. Being studied since the 1980s, this concept has been developed and addressed from various perspectives. Measuring buildability as an attribute of the design is an idea that has found acceptance in some countries, often leading to more precise communication between stakeholders, when incorporated successfully and seamlessly in daily practice (OSUIZUGBO *et al.*, 2023; GAO; LOW; NAIR, 2018).

The buildability assessment methods available were often crafted with the intent of being country-specific, or even region-specific (JARKAS, 2016; ABREU, 2020). This is one of the factors that hindered a more widespread use and consideration of the buildability concept in the global scenario. This paper evaluates the use of well-studied, region-specific methods in a foreign territory, focusing on matching the specific design cases with the context used to derive the assessment methods.

Several designs of Brazilian buildings were evaluated through the BDAS and BAM buildability assessment methods, which are the better recognized and adopted methods for general construction both in the academy and the global market. Special attention was given to the adaptation processes necessary to accommodate the Brazilian design and construction context to that used to form the referred assessment methods, paying attention to the technology gap, which served as a basis for discussions and simulations.

It is noted that a BIM-based workflow promotes the participation of builders and environmental specialists in the initial stages of the project. Less polluting and more efficient projects can be developed by considering sustainability and constructability in the early design phases (AUGUSTO; BARROS; SOTELINO, 2023). Based on the results, and taking into consideration the continuous advancement of BIM design in buildability revisions

in Brazil (PRAIA *et al.*, 2024), it was possible to discuss the feasibility of adapting such methods to generate procedures and recommendations for the review and optimization of local projects.

2. LITERATURA REVIEW

A common characteristic of the construction sector is the separation between the activities of design and construction of a building. Frequently, the architectural design is the first to be finished, over which subsequent designs such as structural and MEP are specified. The construction processes then start with the intent of following the design instructions as closely as possible. This sequence not only divides the activities but also the knowledge and responsibility of the parties involved. Professionals tend to work separately and maintain a low degree of communication throughout project phases, a trend often referred to as "fragmentation" (ARDITI; ELHASSAN; TOKLU, 2002). Thus, it is not uncommon that designers are unable to see the project from the contractor's perspective, and vice versa, exposing the project to further risks regarding productivity and quality of the delivered product (GRIFFITH, 1986; DING; SALLEH; KHO, 2020).

The study of buildability emerged as a way to address these fragmentation issues (GAO; LOW; NAIR, 2018) and the term can be defined as "the extent to which the design of the building facilitates ease of construction, subject to the overall requirements for the completed building" (CIRIA, 1983). This idea can be traced back to the Emmerson Report of 1962, a report commissioned by the British Government, which advocated for new relationship frameworks between clients, designers, contractors, and other professionals (FRANCIS *et al.*, 1999).

Today, it can be said that there are two different approaches to the concept, accompanied by different terminology: buildability and constructability. Buildability looks at the issue through a narrower scope, focusing on the general assessment and measurement of a design's ease of construction. The more American term, constructability, tends to be used when other ideas are factored into the analysis, such as quality and environmental factors, looking beyond the design phase, up to project delivery (CHEETHAM; LEWIS, 2001). This generalization is not always true, which is evidenced by the interchangeable use of both terms in Australian publications (FRANCIS *et al.*, 1999).

Among the various definitions for the concept of buildability (or constructability), the guiding principles of simplicity, standardization, and clear communication (ADAM, 1989, apud CROWTER, 2002) tend to be a common ground for discussion.

2.1. Buildability assessment

Almost as old as the concept itself is the discussion about how to assess buildability. If certain factors are known to influence buildability, assessing them early in the project can help make decisions with lower cost than later. Initially, the idea of assigning a value to buildability was met with mixed reactions, as many saw the subject as too complex to base decisions on generic recommendations (AKINTOYE, 1994). More criticism came from designers who felt that rationalizing design in favour of construction practices could hinder design creativity, especially since "standardization" is one of the core principles of a more buildable design (MOORE, 1996).

Some of the main expected benefits of increasing buildability or constructability are summarized below (CIL, 2012; WONG, 2007):

- Reduction of intensive work.
- Increased speed of execution.
- Better quality of the finished product.
- Reduction of rework.
- Increased productivity.
- Improved crew relationships.
- Higher client satisfaction.

It is widely accepted in the literature that intervening in favour of more buildable solutions is better done sooner rather than later in the project (SAMIMPEY; SAGHATFOROUSH, 2020), as it is much easier to alter decisions in earlier stages. However, buildability assessment is not a common practice in many parts of the world. The Brazilian construction industry, which is the primary focus of this study, does not see buildability as a determining factor for project feasibility and most of its players are not aware of the concept (ABAURRE, 2014).

2.2. Buildability assessment methods

Authors such as Wong (2007) and Zhang (2016) reference and compare several buildability assessment methods

according to their attributes, such as "scope of application," "assessment principles," and "benchmarks provided." In this context, an assessment method is a set of procedures and rules to evaluate and, to a variable degree, score the buildability of a design. The various methods available in the literature can fit into different categories, with scope of analysis being one of the main points of differentiation. The scope determines whether the assessment looks at the whole design of the building or focuses specifically on certain subsets and systems.

Purely qualitative methods frequently rely on the opinion of a buildability specialist and do not provide repeatable results; that is, two specialists can significantly diverge about the constructability score of the same project (ESLAMI; SAGHATFOROUSH; RAVASAN, 2018). Today, with the increasing adoption of computer-aided design, automating buildability assessment is a possibility. However, it is made harder when it is heavily dependent on human subjectivity (DELEGREGO, 2017; ZOLFAGHARIAN, 2016).

As described by Maestri (2018), from the existing methods some of the more relevant are: BDAS - a system used to calculate the buildability scores of whole designs as a statutory requirement for government approval in Singapore (BCA, 2005); BAM - a system developed and used in Hong Kong to calculate buildability scores aimed at the high-rise sector of construction (WONG, 2007); a knowledge-based model for understanding conflict solving and automated buildability assessment (UGWU *et al.*, 2004); a multi-attribute system intended for assessment of a project according to six measurable principles (ZIN, 2004), and a quantitative method associated with a decision-making framework for early-stage assessment of the construction design (YANG *et al.*, 2003).

2.3. Choice between new and existing methods

In the literature regarding buildability assessment, new methods are often developed specifically for the case and context of the study. Wong (2007) used this process by incorporating the calculation procedures from Singapore's BDAS into his BAM method, as BDAS has already demonstrated applicability in the industry. However, Wong (2007) also introduced new variables, weights, and indices when proposing changes for BAM.

Developing a new method for each case study offers the advantage of increased specificity, as the calculation criteria can be tailored to the project context and

validated by experienced professionals, as defined by the researchers (ABREU, 2020). However, this approach also sacrifices the learning and improvement already achieved by existing and validated methods. They require almost starting from scratch every time the project context changes significantly, such as location, purpose, or construction method.

One example where past learning is useful is in dealing with the differential perception of buildability among various professionals and parties involved in construction (RODRIGUES, 2005). In such cases, using methods that are already tailored can direct the assessment results to a middle ground. For instance, Lam *et al.* (2011) showed in the context of BAM that the increased use of prefabrication led to a perception of increased buildability for most professionals, which was an expected result. However, construction of projects that occurred in restricted spaces and at altitude presented challenges related to lifting structural components, which could be made more difficult without adequate planning and crew familiarization with the process.

Some authors suggest testing and using existing methods first to ensure a continuity of past and future learning, but this view is not often addressed in studies. One, for instance, is Ying and Pheng (2007) which advocated the use of BDAS in Chinese construction, where the subsequent modification of the method would only occur over time and according to user requests based on practice.

When deciding between a new method or the use of an existing one, the objectivity of the criteria must also be considered. Zhang *et al.* (2016) proposed a buildability calculation process that used existing and validated methods, arguing that they already cover most of the

variables in buildability analysis. Furthermore, Zhang *et al.* (2016) added new variables of qualitative assessment only when the analysis would be enriched and facilitated by BIM data, that is, visual as well as documented information contained in BIM models. Delegregó (2017) demonstrated in addition that the use of BIM data can assist in the automation of assessment based on existing methods, its variables, weightings and computation procedures.

In summary, the choice between a new or existing buildability assessment method is a decision to be made by the researchers, considering their aims and the project context. A new method should bring more specificity to the analysis, while the use of an existing one can be a faster and safer route for adopting buildability considerations in projects. In either case, objectivity and applicability of the method must be ensured.

3. METHOD

The research followed the steps presented below:

- a) The general concept of buildability was discussed with local construction companies of various sizes, emphasizing the potential benefits of buildability assessment in a project.
- b) Various design documents of local building projects (6) were obtained, representing a general cross-section of construction practices in the region.
- c) Assessment methods were selected from the literature to best fit the evaluation of such designs.
- d) The selected methods were applied and adapted to the designs, and the results were discussed and summarized.

	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Built Area	170 m ²	1998 m ²	4462 m ²	8062 m ²	6030 m ²	3369 m ²
Funding	Public	Private	Private	Private	Private	Private
Storeys	1	4	6	32	25	30
Purpose	Social Care Centre	Residential Class C	Residential Class B	Residential Class A	Residential Class A	Residential Class A
Modelling Process	BIM	CAD	BIM	CAD	CAD	CAD
Context Category	A	A	A	B	B	B
Assessment Method	BDAS	BDAS	BDAS	BAM	BAM	BAM

Table 1: Project Characteristics

Source: Authors

3.1. Selection of project designs

Several meetings were conducted with representatives of institutions, including government agencies and construction companies restricted to the state of Santa Catarina in Brazil. The objectives of the research were explained, and the parties agreed to provide all necessary documentation. In some cases, access to engineers and personnel at the site was also granted, considering that most of the projects were either under construction or in the pre-construction phase. A more detailed description of this selection process can be found in the original studies (DELEGREGO, 2017; MAESTRI, 2018).

Project 1 is a model project for the state government. Projects 2 and 3 were selected from construction companies around Florianópolis, capital city of the Brazilian state of Santa Catarina, with a diversified construction market. Additionally, a more specific set of project designs (Projects 4 to 6) was obtained from a single company in Balneário Camboriu, a city known for its high-rise, luxury residential buildings, that hosts eight of the ten tallest buildings in Latin America. As a result, a total of six designs were evaluated, with some of their characteristics shown in Table 1. From the variety of projects selected, a diverse cross section of designs and characteristics were selected.

From the selected projects, the authors identified two categories of construction contexts:

A. General urban design: these are multipurpose buildings that use low-skilled labour, minimal machinery, and the most common materials in Brazilian construction, such as cast-in-situ reinforced concrete and non-structural brick walls. Such projects can be found in any urban area in the country.

B. High-rise littoral buildings: these are prevalent in the higher-end littoral areas and require specialized contractors, suppliers, and more qualified labour. Most of the construction companies working in this market are fully focused within that niche. Although the basic materials of category A are still used in such buildings, more technological and refined options are frequently incorporated.

3.2. Selection of buildability assessment methods

To select the best assessment method for each project, a broad spectrum of buildability literature was consulted, focusing on the different concepts and history of buildability assessment. The review started from academic theses and proceeded to referenced and correlated peer-reviewed articles on Google Scholar.

A pre-selection of buildability assessment methods was obtained from previous works that reviewed the method literature (MAESTRI, 2018; ZHANG *et al.*, 2016; WONG, 2007), namely: BDAS, BAM, UGWU, ZIN, YANG, ZHANG, JIANG, CII, CONPLAN. More information on each method can be found in the previously referenced sources (DELEGREGO, 2017; MAESTRI, 2018). Other methods exist but tend to be adaptations with still little practical validation or no significant innovation in calculation procedure.

Then, a process of elimination was conducted according to four criteria:

- a) Breadth of scope: the method must assess the entirety of the building design;
- b) Ease of use: the method must allow the assessment to be conducted with regular design documentation, delivering consistent results;
- c) Context matching: the context from which the methods were derived must have similarities with the case study context categories of this research;
- d) Practical use history: the method must have some form of market validation. This could range from continued adoption in a country to smaller local trials with results.

Most methods did not fulfil all four criteria above. Assessment procedures such as Ugwu (2004) and Jiang *et al.* (2015) were not selected because they concentrated only on the assessment of specific systems, components, and construction methods, not conforming with item (a) of the criteria.

Due to item (b), methods such as CII (1986) had to be discarded for not offering clear steps of assessment, focusing primarily on improving the processes for managing buildability. In addition, considering that Brazilian companies are mostly unaware of the concept of buildability, applying the CII method would bring challenges of its own because it depends on the collaboration of multiple parties. Other methods like Yang *et al.* (2003) were not eligible because they used complex procedures, such as fuzzy calculations, which do not produce consistent results among different practitioners. Due to Item (d) CONPLAN was eliminated as it was intended to be conceptual and was not calibrated or validated by real designs.

Method	Content	Scope of Application	Assessment Principles	Assessment Aspects
BDAS (BCA, 2005)	A system used to calculate buildability scores as a statutory requirement for government approval.	Virtually all new residential, commercial, industrial, and institutional buildings, as well as major alterations and additional works. There are some exceptions.	- Standardization - Simplification - Individual Integrated Elements	- Structural systems and roof systems - Wall systems (including finishing systems applied) - Other constructive features - Provision of bonus points for individual built in elements
BAM (WONG, 2007)	A system used to calculate buildability scores, aimed at the Hong Kong construction industry.	Virtually all new residential commercial, industrial, and institutional buildings, as well as major alterations and additional works. There are some exceptions.	- Standardization - Simplification - Individual Integrated Elements - Prefabrication	- Structural systems - Slab systems - Envelope systems - Roof systems - Internal wall systems - Finishing systems - Aspects of construction services - Construction elements - Site-specific factors

Table 2: Comparison between the buildability assessment methods applied in this study

Source: Authors

After the elimination phase, two methods remained which fulfilled all four criteria, being the BDAS and BAM methods. Their positive aspects for the purpose of this research were the simple and deterministic calculation process, the use of pondering factors to weigh the significance of subsystems in the design, and the consideration of several building materials and construction methods. A brief comparison of their characteristics can be seen in Table 2.

According to criteria (c), the context category A designs were assessed through the Buildable Design Appraisal System (BDAS) method. Mainly developed by the Building and Construction Authority (BCA) of Singapore, its original intent was to reduce the country's dependency on foreign labour, with successful results throughout the years due to its widespread use in that country (POH; CHEN, 1998; ONG, 1999; PHENG LOW, 2001). Passing a minimum BDAS score is now mandatory for almost every new design with a built floor area of more than 2000 m². The general urban buildings in the city of Florianópolis are best suited for this method. However, there are differences between the Brazilian construction industry and that of Singapore.

To factor in the technology lag between countries, the 2005 version of the rules and documentation was used (BCA, 2005), even though there are newer versions. That is because BDAS is being continuously tailored for the Singaporean industry, which is already dependent on off-site production and prefabrication, has the government actively pushing for an even lower dependency on manual labour through BDAS, among other measures.

This scenario is already challenging for some Singaporean firms (GAO; LOW; NAIR, 2018). Therefore, the older and less strict version of the BDAS method was selected for this study.

Through the BDAS method, the value of buildability is calculated by dividing the design into construction systems, with scores attributed to each of them. The values are then weighted by their proportional presence in the project and their relevance to overall buildability. This is determined by the Labour-Saving Indices (LSI), according to the tables and rules provided in the method's documentation (BCA, 2005). Adding the individual results gives the final buildability score. The method is based on three principles: simplicity, standardization, and single integrated elements, the last of which refers to modular construction technologies.

In turn, the Buildability Assessment Method (BAM) was developed specifically for the context of tightly packed high-rise buildings in Hong Kong and is closely related to the developments in the city of Balneário Camboriu, which are represented by the three projects in context category B. The researchers who developed BAM tried to emulate the simplicity and exactness of the BDAS. One significant difference is that while BDAS was derived by regressing productivity data, BAM was crafted from structured interviews with construction professionals of different backgrounds (WONG, 2007).

The resources for BDAS can be found on Singapore's Building and Construction Authority website, including the legislation and its code of practice (BCA, 2005). Those

for BAM come from academic publications outlining its construction and application (WONG, 2007; LAM, 2007; LAM, 2012). The resources are all in the English language.

In terms of calculation procedures, BAM and BDAS are similar methods. For projects 1, 2, and 3, the BDAS score was assessed according to the method's manual. The design was divided into three systems: "structural system," "wall system," and "other buildable features," with the addition of bonus points when eligible. The limiting top value is 50 for structural systems, 40 for wall systems, and 10 for other buildable features. Accordingly, projects 4, 5, and 6 were assessed with BAM. This method divides the design into nine building systems plus a "free score" of up to 10% of the maximum possible score.

Where specifications had to be adapted, the most similar Brazilian match was sought. If that was not possible or deemed unsuitable, the differential score associated with that section was ignored in the computation but discussed in the analysis. After obtaining the initial scores for each design, some thought experiments were conducted where qualitative characteristics of each project were modified, mainly materials specification and construction methods, in accordance with regular industry practices. The intention was to give plausible suggestions to enhance the buildability of the designs according to the formulae. Results were, then, compared.

4. RESULTS AND DISCUSSION

The assessment process is summarized below.

4.1. Project 1

It is a standardized design for a social assistance centre, with the architectural design presented in Figure 1. Since it has less than 200m² of floor area, it is legally exempt from BDAS compliance in Singapore. Therefore, it is also an evaluation of the method's applicability in smaller buildings.

According to the BDAS manual, the design can be best described as an institutional, one-story reinforced concrete building with concrete cast-in-situ. The wall systems are made of ceramic bricks with finishing. The materials and construction practices implied by the design are standard in Brazil, but very labour-intensive compared to East-Asian standards.

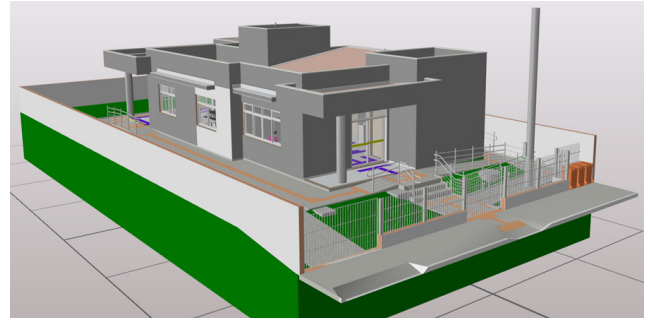


Figure 1: Architectural design of Project 1 in BIM

Source: Authors (Design provided by LaBIM-SC)

The assessment process was straightforward as most values and qualitative data were automatically extracted from the BIM model. The structural and wall scores are respectively shown in Table 3 and Table 4.

No score was attributed to the "other" category because it mostly relates to standardization within a design, and the building was too small to meet the standardization criteria as specified.

The use of cast-in-situ technology was heavily penalized by BDAS, so other design alternatives were explored. The recommended changes for increased buildability were to replace the ceramic roof tiles with metallic tiles and the cast-in-situ concrete with prefabricated beams and columns (Table 5). These structural options are common enough to prevent disruption or avoid insecurity to the project if adopted.

Floor	Description	BDAS Adaptation	LSI	Area (m ²)	Coverage	Score
Ground floor	Cast in situ concrete beams and columns	Two-directional beam (slab/beam 2) ≤ 10)	0.50	170.5	34%	8.51
Service floor	Cast in situ concrete beams and columns	Two-directional beam (slab/beam 2) ≤ 10)	0.50	170.5	34%	8.51
Roof	Ceramic tiles on timber frame	Tiled roof on timber beam	0.75	160.0	32%	11.98
			Total	501.0	100%	29 (58% of max.)

Table 3: Structural System score of unmodified Project 1

Source: Authors

Floor	Description	BDAS Adaptation	LSI	Lenght (m)	Coverage	Score
Ground floor	Ceramic brickwall	Brickwall	0.30	96.1	61%	7.34
Attic	Ceramic brickwall	Brickwall	0.30	60.35	39%	4.66
			Total	155.4	100%	12 (30% of max.)

Table 4: Wall system score of unmodified Project 1

Source: Authors

Floor	Description	BDAS Adaptation	LSI	Lenght (m)	Coverage	Score
Ground floor	Precast concrete slab	Precast slab only	0.75	170.5	0.34	12.76
Service floor	Precast concrete slab	Precast slab only	0.75	170.5	0.34	12.76
Roof	Metallic roof over timber frame	Metal roof on steel truss	0.85	160.0	0.32	13.75
			Total	501.0	100%	39 (78% of max.)

Table 5: Structural System score of Project 1 with combined adaptations

Source: Authors

In addition, the ceramic brick wall system was replaced by drywall on the internal areas of the ground floor (Table 6). Although this adaptation would require further analysis

of acoustics, thermal comfort, and general space usage, it was deemed a feasible suggestion and would not pose any technical or financial challenges to the project.

Floor	Description	BDAS Adaptation	LSI	Lenght (m)	Coverage	Score
Ground floor	Ceramic brickwall	Brickwall	0.30	30.4	0.2	2.35
Service floor	Drywall	Dry partition wall	1.00	64.6	0.42	16.64
Attic	Ceramic Brickwall	Brickwall	0.30	60.3	0.39	4.66
			Total	155.4	100%	24 (59% of max.)

Table 6: Wall system score of Project 1 with combined adaptations

Source: Authors

By implementing these design changes, the original buildability score of 41 for Project 1 could increase by 53%, reaching 63 points, which is above the BDAS legal threshold score of 60 required for the approval of institutional buildings.

For the following projects, the individual system tables are omitted as the calculation process followed a similar procedure to Project 1.

4.2. Project 2

The second project consists of six identical residential buildings on the same land area, along with shared leisure and service areas. As the buildings are identical, the analysis was restricted to a single design.

The structural system is made using precision structural concrete blocks, precast slabs, and cast-in-situ beams. This is a popular method in Brazil, especially for lower-end housing construction. The total structural system score was 38, which is 77% of the maximum value. In the assessment, the structural bearing brick walls were included in the wall system, as prescribed in the BDAS methodology. This was applicable to the entire building, with the only differentiation being whether it was an external or internal piece of wall. The total wall system score was 15, which is 37% of the maximum value. This low buildability score of the wall was expected as the method is very labour intensive. For the “other” score, the productivity benefit stemming from the repetition of the layout on multiple floors was accounted for, resulting in the addition of 2 points to the final score.

4.3. Project 3

The third project is a residential building composed of two annexed towers with underground garages. At the time of the calculation, not all design specifications had been completed, including the structure. Thus, the first assessment was already carried out on a proposed design for better buildability.

From the architectural design, the wall types were divided into curtain walls, concrete walls, and ceramic brick walls. These categories were found in BDAS, and the calculation was straightforward. The calculation was also made easier using BIM quantity take-off functions. The total wall system score was 34% of the maximum.

All the structural elements were accounted for as prefabricated concrete pieces. Steel frames were not considered because they are still unusual in Brazil for context category A buildings. The focus of BDAS on steel structures is an indication of cultural differences between the construction industries and the governments of Brazil and Singapore. Metallic tiles were applied to the roof. This scenario resulted in a high buildability score of 48 out of 50 (96%).

4.4. Projects 4-6

Projects 4-6 are luxury high-rise buildings designed and built by the same construction company. The architectural facades of Projects 4, 5, and 6 are shown in Figure 2.

Calculating the BAM score was more challenging than for previous designs as context category B buildings use a wider variety of materials and construction methods, which had to be fit into the relatively few categories of BAM. For example, finishings such as plaster, PVA coat and

PVA based paint; plaster, PVA coat or texture with acrylic paint; plaster and acrylic paint; and plaster with acrylic paint and signaling strips were adapted to "traditional plaster and paint" as the only available option in BAM.



Figure 2: Façades of buildings from projects 4,5 and 6, respectively
Source: Company X

The higher number of factors to be considered in BAM compared to BDAS and the fact that the quantitative information was obtained mainly from CAD drawings also increased the overall laboriousness of the process.

Table 7 summarizes the scores attributed to project designs 4,5 and 6 after the assessment, with almost no difference in the final buildability scores, despite differences in layout and size. In such cases, the similar selection of materials and construction methods has

essentially defined the buildability scores for each system. Also, an optimized scenario for Project 6, included in the table, was explored as to give it a score greater than 80% of the maximum.

During the optimization process, Project 6 underwent the following design modifications:

- Adoption of prefabricated concrete elements, such as prefabricated stairs, slabs, toilets, and shafts, allowing for more speed and ease of execution.
- Greater standardization of components and structural elements.
- Change of the internal brick walls to drywall.

Since Project 6 initially had a very similar buildability score compared to Projects 4 and 5, the suggested changes above could also be applied to the latter designs with similar results.

Table 8 and Figure 3 contain a summary of the results obtained from the assessment of each design. The "Adapted Systems" column shows the options deemed the best fit for the actual construction scenario. Additionally, the "Observations" column summarizes and compares the most significant assumptions and observations obtained from the buildability assessments.

System	Project 4	Project 5	Project 6	Optimized Project 6
Structural	52.39	52.39	52.39	57.71
Finishing	1.23	1.23	1.22	1.22
Building services aspects	1.54	1.55	1.55	2.26
Building elements	1.82	1.88	1.89	2.56
Site specific factors	9.29	9.52	9.52	9.29
Total	66.27	66.57	55.57	73.05
Percentage of maximum	74%	74%	74%	81%

Table 7: Partial Buildability Scores of projects assessed through BAM
Source: Authors

Project Index	Adapted Systems	Buildability Score	Observations
1	Cast-in-situ concrete beams and columns Ceramic tiles on timber frame Brickwall	41	Less than 2000m ² of floor area, would be legally exempt of BDAS in Singapore. Although a repeatable standard design, no learning process is factored in the score. The use of cas-in-situ technology was heavily penalized by BDAs; Using metallic roof tiles and prefabricated structure of beams and columns, the score would increase to 63.
2	Precast slab only Metal roof on timber truss Precision block wall	53	Consists of six identical residential buildings in the same land. There was no socre change due to the replicability of the design. The roof support is made of timber but was adap- ted to "steel truss" as the closest approximation. No suggestion for buildability improvement was offered due to the inflexibility of this construction method.
3	Full precast One-directional banded beam Metal roof on steel truss	82	At the time of assessment, the structural system and toher characteristics were only propositions. The calculation was eased by the use of BIM quantity take-off functions. It was decided not to use steel for this scenario becau- se it is not yet usual in Brazil for this type of building. The access ramps were factored in the analy- sis as "One-directional banded beam". The structural project was later designed with a waffle slab solution, with a buildability score of approximately 42.
4, 5 & 6	Structural: Cast-ini-situ reinfor- ced concrete frame and slab. Walls: Curtain wall, Brick, Traditional Plaster and Paint (Site applied), Tiling on Screed. Ceiling: Traditional Plaster and Paint (Site applied); No finishes (Fair Face). Floor: Granite; Tiling on Screed (Site applied), Tiling on Screed (Stie applied) Roof: Metal Roof Decking - Composite type.	66 - 67	The materials and construction methods adop- ted are practically identical for each building. There was little diversity of options to be chosen for some systems, including ceiling and floor finishing methods. The ceiling areas of the garage do not have finishing, this contributed positively with the BI of 1,00. There was a clear sequencing of activities with the ver- tical design adding to the simplicity attribute. The level of structural standardisation within floors and from floor to floor was no very significant, lowering the BS relarred to standardisation. This included free span len- ght, story height and beam and column dimensions, Projects were well cordinated, and components could easily be installed on site with simples instructions. Also, designs were well adapted to be built according to the local expertise of workers and partners. The difference in design, volume and shape of the buildings do not interfere significantly with the BAM buildability score.

Table 8: Summary of results and observation of the buildability assessment using foreign methods

Source: Authors

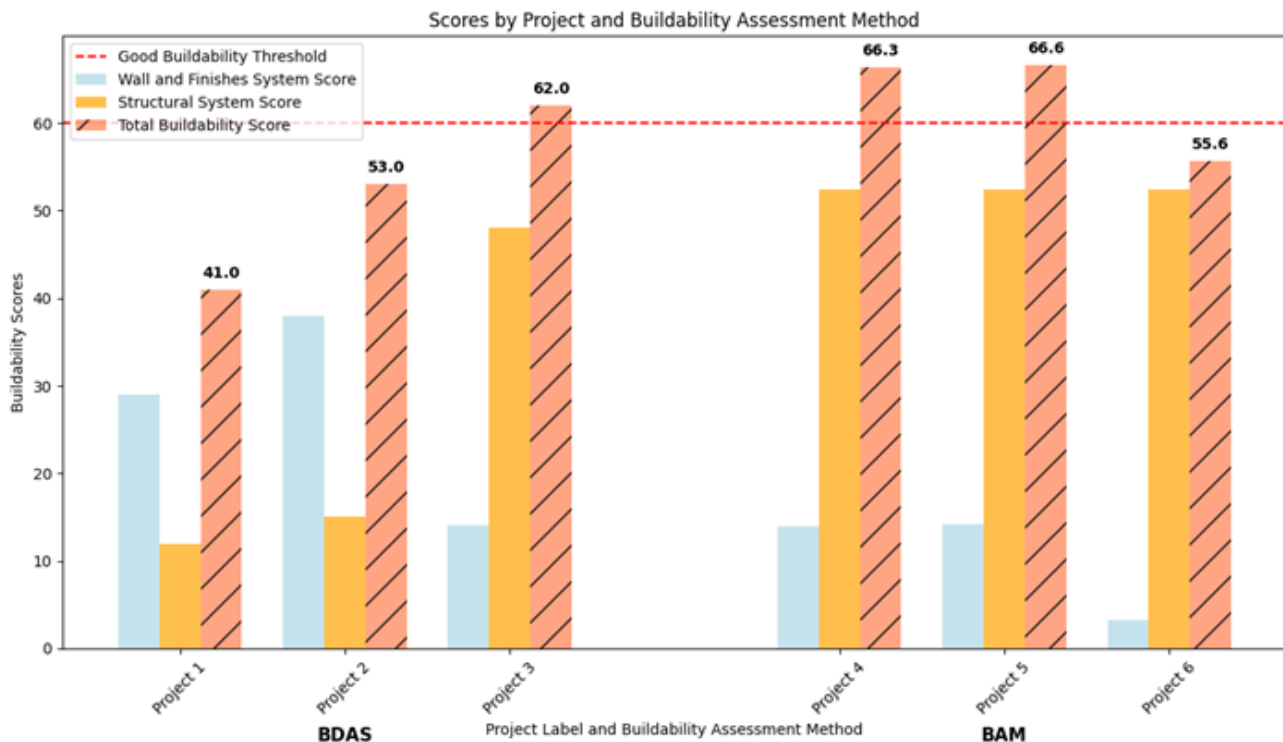


Figure 3: Graphic comparison of unmodified buildability scores and assessment methods for each project.

Source: Authors

5. DISCUSSION

The study found that both the BDAS and BAM assessment methods were applicable to the Brazilian projects studied, with no major hindrance in using the standard tables and calculation procedures specified in the methods' documents. Occasional adaptations were required, such as finding the best match for finishing materials that do not have an exact fit to the Brazilian construction market. The potential problems arising from the technology lag of the Brazilian construction market were successfully avoided by choosing older versions of the methods.

However, the study also found some limitations of the methods. BDAS was found to be rigid in giving buildability scores for repeatability, only considering repetitions within the same building. This was evident in Project 1, a repeatable public building, where the learning curve that would naturally be associated with its sequential construction should grant some additional repeatability score. For BAM, which focuses on bespoke high-rise buildings, this consideration did not seem so relevant.

The biggest limitation of the methods was their lack of support in aiding and influencing redesigns. This is important when there is enough flexibility regarding budget and technical requirements in the beginning of a project, and changes can be made without excessive disruption on budget and schedule expectations. The

study found that gains in buildability score could be achieved by changing the structural and wall construction methods to more usual options for the Brazilian sector, as was the case for the designs of Project 1 and 3.

For Project 2, however, any change in construction method preconized by BDAS would mean big changes in cost, schedule, and labour qualification. Constructions using structural precision blocks have a reputation for being inflexible and it is hard to increase such designs and keep them financially sound. When evaluated by BDAS, very few optimization options are possible, and none that would justify any change. Thus, this is a construction method that is bound to receive a low buildability score, regardless of other design optimizations.

The study also found that the methods were unable to quantify the buildability differences dependent on the shape and layout of already completed designs. The equal scores attributed to projects 4 to 6 showed that significantly different architectural decisions and construction details, such as external rounded areas and openings, were not adequately considered in the assessment. Thus, there is still much room for improvement in the most adopted buildability assessment methods by looking at spatial characteristics of the designs that go beyond standardization of distances and object dimensions.

Keeping in mind the limitation that the present work does not have the pretense of making a general

assessment of current Brazilian constructability standards, the generalized results show a construction industry that is still emergent and in evolution in respect to the South Asian market and, as seen from Table 8 and Figure 3, barely or not at all eligible for a theoretical construction and competitive for receiving the label buildable construction in a global market.

To address this issue, one possible solution is to explore new methods for computing differences in shapes, sizes, openings, and finishes of the projects, using BIM data. By leveraging the openBIM IFC model, automated procedures could be developed to improve upon these factors while retaining the original features of existing assessment methods. It is recommended that further research be conducted in this area to bridge this gap in buildability literature.

Nevertheless, the study found that the methodology of assessment proposed in the paper offers great potential for qualitative optimization of materials and construction methods when performed early in a project, as was the case for Project 3. Therefore, the research recommends the adaptation and application of the BDAS and BAM as a potential support tool for early design decisions.

6. CONCLUSION

The research investigated the adaptation and implementation of international buildability assessment methods for the Brazilian construction industry. This was accomplished by matching the methods developed in foreign countries with the socioeconomic and market context behind each project design. A total of six projects were obtained from local construction companies in the state of Santa Catarina, Brazil, and then divided into two context categories: the first containing more general construction designs found in Brazil, and the second focusing on luxury high-rise buildings in littoral areas. Two buildability assessment methods were chosen from the literature based on specific criteria: BDAS to evaluate the projects in the first context category, and BAM for those in the second.

For each design, a buildability score was calculated. The process was mostly straightforward, attributing values according to the methods' manuals and reference tables. Adapting the original Brazilian specifications to those of the methods proved feasible. However, the methods were heavily biased towards prefabricated structures and finishes, penalizing the usual construction methods in Brazil and providing little assistance in improving those designs.

In other cases, it was found that the assessment oversimplified or ignored design decisions, particularly those related to shapes and layouts, which are sure to impact buildability. Generally, the designs received low or average buildability scores, as defined by each method. Attempts were made to use the methods' criteria to optimize the design, which proved effective for some designs but impossible for others.

Considering both the benefits and drawbacks, this research recommends using the proposed adaptation methodology of buildability assessment as a powerful tool for qualitative design optimization during the early design stages, including materials and construction method selection. There is still room for improvement in the adaptation methodology, and further research focused on early design support tools, the interaction with BIM, and local adoption is encouraged.

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ADAPTING FLEXIBLE PAVEMENT INFRASTRUCTURE TO CLIMATE CHANGE: IMPLICATIONS AND SUSTAINABLE STRATEGIES

ADAPTANDO A INFRAESTRUTURA DE PAVIMENTOS FLEXÍVEIS ÀS MUDANÇAS CLIMÁTICAS: IMPLICAÇÕES E ESTRATÉGIAS SUSTENTÁVEIS

ADAPTACIÓN DE LA INFRAESTRUTURA DE PAVIMENTOS FLEXIBLES AL CAMBIO CLIMÁTICO: IMPLICACIONES Y ESTRATEGIAS SOSTENIBLES

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ABSTRACT

Road networks are vital links for people and freight transportation, influencing the environment and socio-economic development worldwide. Under restricted budgets, the sustainable management of massive roadway inventories to ensure adequate serviceability, safety, and durability has been a big challenge for infrastructure authorities. Climate change cannot be underestimated since it may require innovative practices, management strategies, and budgeting. This paper discusses the implications of climate change and adaptation strategies for flexible pavement infrastructure under non-stationary climatic conditions, addressing the following key issues: i) The effects of weather and climate on structural pavement performance; ii) The most relevant changes in weather and climate affecting the road transport infrastructure; iii) Projections of changes in weather and climate relevant to the road transport infrastructure; iv) Potential impacts of climate changes on pavement infrastructure throughout future years; v) Strategies to adapt flexible pavement infrastructure in response to a changing climate; and vi) The role of life cycle sustainability assessment of flexible pavement infrastructure to identify and manage economic, environmental and social impacts while ensuring its resilient capability to a changing climate. Considering the relevance of Brazil for South America, an emerging and continental country, the discussion establishes a link between the Brazilian road network context and the worldwide perspective.

KEYWORDS

Road infrastructure; climate change; adaptation strategies, resilience, life cycle sustainability assessment

RESUMO

As redes rodoviárias são ligações vitais para o transporte de pessoas e cargas, influenciando o meio ambiente e o desenvolvimento socioeconômico em todo o mundo. Sob orçamentos restritos, a gestão sustentável de extensos inventários rodoviários para garantir adequados níveis de serviço, segurança e durabilidade tem sido um grande desafio para as autoridades de infraestrutura. A mudança climática não pode ser subestimada, pois pode exigir práticas inovadoras, estratégias de gestão e alocação de recursos financeiros. Este artigo discute as implicações das mudanças climáticas e as estratégias de adaptação para a infraestrutura de pavimento flexível sob condições climáticas não estacionárias, abordando as seguintes questões-chave: i) Os efeitos do clima e do tempo na performance estrutural dos pavimentos; ii) As mudanças mais relevantes nas condições meteorológicas e climáticas que afetam a infraestrutura de transporte rodoviário; iii) Projeções de mudanças climáticas e meteorológicas relevantes para a infraestrutura de



transporte rodoviário; iv) Os potenciais impactos das mudanças climáticas na infraestrutura de pavimentos ao longo dos próximos anos; v) Estratégias para adaptar a infraestrutura de pavimentos flexíveis em resposta a um clima em transformação; e vi) O papel da avaliação da sustentabilidade do ciclo de vida da infraestrutura de pavimentos flexíveis para identificar e gerenciar impactos econômicos, ambientais e sociais, garantindo sua capacidade resiliente diante de um clima em mudança. Considerando a relevância do Brasil para a América do Sul, sendo um país emergente e de dimensões continentais, a discussão estabelece uma conexão entre o contexto da rede rodoviária brasileira e a perspectiva global.

PALAVRAS-CHAVE

Infraestrutura rodoviária; mudança climática; estratégias de adaptação; resiliência; avaliação da sustentabilidade do ciclo de vida

RESUMEN

Las redes viales son enlaces vitales para el transporte de personas y mercancías, influyendo en el medio ambiente y el desarrollo socioeconómico a nivel mundial. Con presupuestos restringidos, la gestión sostenible de extensos inventarios viales para garantizar niveles adecuados de servicio, seguridad y durabilidad ha sido un gran desafío para las autoridades de infraestructura. El cambio climático no puede subestimarse, ya que puede requerir prácticas innovadoras, estrategias de gestión y asignación de recursos financieros. Este artículo analiza las implicaciones del cambio climático y las estrategias de adaptación para la infraestructura de pavimento flexible bajo condiciones climáticas no estacionarias, abordando las siguientes cuestiones clave: i) Los efectos del clima y el tiempo en el desempeño estructural de los pavimentos; ii) Los cambios más relevantes en las condiciones meteorológicas y climáticas que afectan la infraestructura del transporte vial; iii) Proyecciones de cambios climáticos y meteorológicos relevantes para la infraestructura del transporte vial; iv) Los posibles impactos del cambio climático en la infraestructura de pavimentos a lo largo de los próximos años; v) Estrategias para adaptar la infraestructura de pavimentos flexibles en respuesta a un clima cambiante; y vi) El papel de la evaluación de la sostenibilidad del ciclo de vida de la infraestructura de pavimentos flexibles para identificar y gestionar impactos económicos, ambientales y sociales, garantizando su capacidad resiliente ante un clima en transformación. Considerando la relevancia de Brasil para América del Sur, siendo un país emergente y de dimensiones continentales, la discusión establece un vínculo entre el contexto de la red vial brasileña y la perspectiva global.

PALABRAS CLAVE

Infraestructura vial; cambio climático; estrategias de adaptación; resiliencia; evaluación de la sostenibilidad del ciclo de vida

1. INTRODUCTION

The extensive climate change debate among scholars, practitioners, and officials led to a comprehensive list of scientific publications in assorted fields. However, regarding engineering practices, at which extension could climate change impose threats? According to the National Academy of Sciences (NASEM, 2019), curbing climate change and adapting to its impacts is one of the significant challenges for Engineering in the 21st century.

The 64 million km (Pörtner *et al.*, 2022) global road network is a vital link for people and freight transportation, influencing the environment and socio-economic development worldwide. In the US, highways and roads are responsible for nearly 72% of goods transport (USD 17 trillion), which requires a reliable road transport network. Nevertheless, the road transport system received a score of D on the 2021 ASCE Report Card for America's Infrastructure. About 43% of 6.4 million km of public roadways were in poor or mediocre condition (ASCE, 2021). The report highlights that USD 177 billion was invested in 2017 (62% for road system preservation) against a need of USD 786 billion. In addition, the rising temperature trend might cost USD 19 billion annually by 2040 (ASCE, 2021).

In Brazil, an emerging country with continental dimensions, the 1.7 million km roadway infrastructure is the primary mode of transport, responsible for more than 60% of freight and 90% of passenger moving (CNT, 2022). Despite the demand, only 12% of this network is paved, and 9% is planned (CNT, 2018). The demand for roadway transport by car will increase by 2035, with a rate of intercity passengers of 19 to 29% compared to 2017 (MI & EPL, 1021). In 2022, BRL 6.4 billion (USD 1.3 billion) of public investments were allocated to federal roads, from which BRL 4.4 billion (USD 908 million) were exclusively for maintenance services. Nevertheless, 23% of federal paved roads are classified as bad (MT, 2022).

Climatic change cannot be underestimated and neglected since it may require innovative engineering practices, management strategies, and budgeting (Abreu *et al.*, 2022). Schweikert *et al.* (2022) indicate that pro-active adaptations of road infrastructure to climate change in all ten countries studied result in lower costs than the reactive no-adaption approach for the years 2050 and 2100. The research confirms that developed nations will face relatively higher annual fiscal costs. In contrast, developing countries will endure higher opportunity costs – the amount of future road infrastructure development that will not materialize as resources are

currently directed to cover climate change costs, whether due to pro-active or reactive actions (Schweikert *et al.*, 2022; Chinowsky *et al.*, 2011)

Therefore, this paper aims to contribute to the state-of-the-art regarding the impacts, resilience, and sustainability of flexible pavement infrastructure under non-stationary climatic conditions. Considering the relevance of Brazil for South America, an emerging and continental country, the discussion establishes a link between the Brazilian road network context and the worldwide perspective. The paper's relevance lies in dealing with a vital asset, considering the protagonism of road transport infrastructure and the vast territorial extension, potentially one of the most threatened by climate change. The subject is in line with the 2030 United Nations Agenda for Sustainable Development (UN, 2015), especially those related to making cities inclusive, safe, resilient, and sustainable (Goal 11), building resilient infrastructure (Goal 9) and taking urgent action to combat climate change and related impacts (Goal 13).

Based on a comprehensive literature review, the paper discusses the effects of non-stationary climatic conditions on flexible pavement infrastructure, addressing the following key issues: i) The effects of weather and climate on structural pavement performance; ii) The most relevant changes in weather and climate affecting the road transport infrastructure; iii) Projections of changes in weather and climate relevant to the road transport infrastructure; iv) Potential impacts of climate changes on pavement infrastructure throughout future years; v) Strategies to adapt flexible pavement infrastructure in response to a changing climate; and vi) The role of life cycle sustainability assessment of flexible pavement infrastructure to identify and manage economic, environmental and social impacts while ensuring its resilient capability to a changing climate.

The paper synthesizes publications resulting from the widespread scientific debate around the effects of climate change on the global road transport network, focusing on the impact of non-stationary climatic conditions on the flexible pavement infrastructure. The scope was established based on the issues presented in the introduction, which resulted in the following keywords: climate change, flexible pavements, impacts, adaption strategies, resilient infrastructure, and life cycle sustainability assessment. The gathering prioritized journal articles issued over the last ten years, encompassing different continents and countries, to give a big picture of the subject. Specific publications

reporting the Brazilian context were emphasized, given the scarcity and urgent need for research on the country's road transport infrastructure and its relevance in the South American context.

2. THE EFFECTS OF WEATHER AND CLIMATE ON STRUCTURAL PAVEMENT PERFORMANCE

The discussions on the interference of weather and climate on structural pavement performance comprise physical and chemical mechanisms through which meteorological phenomena may affect flexible pavement infrastructure performance, influencing design, operation, maintenance, and repair approaches (Taylor & Philp., 2015).

The climate is a combination of meteorological phenomena (e.g., cloudiness, humidity, temperature, wind, barometric pressure) that characterize, over a long period, the average state of the atmosphere and its evolution in a particular geographic area (Medina & Motta, 2015). In contrast, the weather is a temporary and often exceptional setting of those atmospheric elements. Thus, the climate might be constant while the weather is supposed to change. Although only long-term climate changes were supposed to occur, scientists have noticed and discussed intense stressors that can drastically speed up the related disturbances (Medina & Mota, 2015). Climate Stressors disturb the energy and moisture balance, impacting the pavement deterioration rate and, consequently, the infrastructure performance, maintenance, and life-cycle costs (Qiao *et al.*, 2015). The effects of temperature and precipitation generally accelerate road pavement damage (Lnett *et al.*, 2019a; Knott *et al.*, 2019b; Nemry & Demirel, 2012), but other factors such as cloud cover, wind speed, and thermal properties of materials also affect the energy balance (Qiao *et al.*, 2015).

Daily and seasonal temperature variations change pavement stiffness (Medina & Motta, 2015), and the temperature gradient can determine the water movement in the vapor form. In desertic places where days are hot and nights are cold, there is a probability of vapor condensation under the wearing course. Temperature raising reduces the stiffness of asphalt materials, reducing the capability to spread loads and resist permanent deformations (Harmaeni *et al.*, 2018); it also accelerates the asphalt mixture aging, resulting in cracking due to brittleness (Qiao *et al.*, 2015). On the other hand, a reasonable period of low temperature

may impact the pavement subbase and subgrade by the expansion of frozen water (frost heaving) if the water that fills the pores can break down or weaken the soil mass or pavement layers. Furthermore, the freezing process increases the negative pore pressure by reducing the soil humidity, and more water may then be attracted to the frozen subgrade and pavement (Medina & Motta, 2015).

Precipitation, flooding, and rising sea levels in regions where the groundwater level is shallow may influence unbound materials, soil, and the adhesion between bitumen and aggregates (Mallick *et al.*, 2017; Nivedya *et al.*, 2020). The runoff can reach the subgrade through shoulders by infiltration not intercepted by drains, especially those with no coating layer, through cracking, not sealed joints, and pores. The groundwater level variation changes the subgrade humidity (Medina & Motta, 2015), which may decrease the resilient modulus and the shear strength of unbound materials and soil, reducing the subgrade rutting resistance and causing permanent deformation that can lead to collapse (Elshaer & Daniel, 2019). A pavement structure with an elevated proportion of fine materials can exacerbate the damage due to excessive moisture. In addition, asphalt layers' saturation escalates asphalt raveling (Qiao *et al.*, 2020). Precipitation also affects the pavement top, reducing the skid resistance of tires and increasing the hydroplaning risk when the surface is wet or ice-covered (Khan *et al.*, 2017; Lu, Tighe & Xie, 2020), which can be worsened by climate changes.

The combined effects of solar radiation and precipitation induce the weathering of mineral aggregates and bituminous materials, which usually get worse due to traffic (ICF International, 2010). The disintegration leads new surfaces to the chemical-physical action, resulting in asphalt oxidation and polymerization that stiffens the asphalt mixtures, causing embrittlement, mainly at lower temperatures (Medina & Motta, 2015). Temperature and moisture also cause freeze-thaw cycles in cold regions that affect pavements (ICF International, 2010). The significant reduction in resilient modulus and rutting resistance expected during thawing can be worsened by climate change, resulting in more extended periods of thawing and traffic load restrictions (Qiao *et al.*, 2020).

Therefore, climatic data (temperature, precipitation, wind speed, cloud cover, and relative humidity) have been used to predict pavement layer temperature and moisture conditions and estimate pavement performance throughout the life cycle (AASHTO, 2008). Considering the limited availability of weather stations, Hasan and Tarefder

(2018) proposed an interpolation method to estimate the annual average temperature and precipitation in New Mexico State, US. Predictions incorporating average temperature and precipitation data increased rutting and fatigue in hotter regions by 45% and 225% compared to cold ones for the same pavement type and traffic conditions, highlighting the importance of accurately considering the climate conditions.

In an era of climate change debate, it is fundamental to anticipate how changes in the intensity and frequency of global temperature and precipitation patterns can impact the existing road transport infrastructure.

3. RELEVANT CHANGES IN WEATHER AND CLIMATE AFFECTING THE ROAD TRANSPORT INFRASTRUCTURE

Changes in weather and climate, such as the intensity/frequency of average temperature, heat/cold extremes, average/extreme precipitation, drought, flood, landslide, wildfire, wind speed, sea level rise, heavy snow, hurricanes, and tornados, threaten the integrity and serviceability of the road transport infrastructure.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2017) noticed relevant facts: i) The globally averaged combined land and ocean surface temperature increase of 0.85°C from 1880 to 2012, ratifying the successive Earth's surface warming since 1850; ii) The annual precipitation over land raised in some regions while reduced in others in a range up to 100mm from 1951 to 2010; iii) The snow cover extent in the Northern Hemisphere diminished by 1.6% per decade (March and April) and 11.7% per decade (June) from 1967 to 2012; iv) in the Arctic Sea the annual average of ice extent reduced at a rate range of 3.5 to 4.1% per decade from 1979 to 2012, while that of Antarctic Sea increased by 1.2 to 1.8% per decade, and finally; v) the global average sea level rose by 0.19m from 1986 to 2005.

The American Society of Civil Engineers (ASCE) Committee on Adaption to a Changing Climate depicts extreme weather metrics in the US for recent decades through the report *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate* (Mills *et al.*, 2009). The report alerts for observed changes in temperature and precipitation that may affect engineering: i) Reduction in the quantity of unusually cold days and nights globally; ii) Rise in the amount of unusually warm days and nights globally; iii) Increase in length or quantity of heat waves in many regions; and iv)

Substantial statistic increases in the number of events of heavy precipitation (e.g., 95th percentile) in more areas than those with significant statistic decrease.

Mills *et al.* (2009) and Tighe *et al.* (2008) agree that future variations in temperature and rainfall associated with traffic growth are the main factors that will influence pavement performance. An investigation on the sensitivity of flexible pavement performance to temperature, precipitation, wind speed, percent sunshine, and groundwater level, performed by Qiao *et al.* (2013), confirmed the protagonism of the seasonal variation and the average annual temperature increase. In turn, Sultana *et al.* (2016) investigated the impact of unprecedented flooding events from 2010 to 2015 on pavements of Queensland, Australia. The 2010-2011 floods compromised 19,000km of roads, while the January 2013 floods and heavy rainfall resulted in the closure of 5,845km of roads. The researchers observed the rapid deterioration of pavements by monitoring roughness and rutting after inundations.

In Brazil, whose territory accounts for approximately half of South America's land extension, relevant events related to climate change have already been observed. Among the extreme and unprecedented climate events in Brazil, the following stand out: flooding that hit 60 municipalities in the Itajaí valley in 2008, being the biggest catastrophe in the state of Santa Catarina (G1, 2018); flooding and landslides in 7 cities in the state of Rio de Janeiro in 2011, being the biggest landslide in Brazil and the 8th in the world in the last 100 years; the worst drought in almost a century in the Center-South of Brazil in 2021 (Busch & Amorim, 2011); flooding and landslide on the coast of the state of São Paulo in 2023, the record rainfall in 24 hours in the country - 683mm in the municipality of Bertioga (G1, 2024); 66 additional days of extreme heat from May/2023 to May/2024, while the annual average was 26 days (Central Climate, 2024). In 2024, the country's most significant climate catastrophe hit the state of Rio Grande do Sul, where at least 14 municipalities recorded, in 24 hours, a volume of rain higher than the expected monthly average (Governo do Estado do Rio Grande do Sul, 2024). The subsequent flooding affected 90% of the southern state of Rio Grande do Sul, washed away roads, collapsed bridges, and caused landslides across the state. The flooding affected 97 municipalities, causing severe damage to 79 roads and leading to 170 road network disruptions.

Figure 1 illustrates hazards to the Brazilian road infrastructure mapped by Pörtner *et al.* (2022) in the IPCC

Sixth Assessment Report. The main hazards projected and observed correspond to the increase of high mean temperature, extreme heat (heat waves), and floods/ landslides in all regions. It is interesting to note the rise in extreme precipitation observed in the South (SES) despite the reported projection and the sea level rise confirmed in the NSA, NES, and SES regions.

4.PROJECTIONSOFCHANGESINWEATHER
AND CLIMATE RELEVANT TO THE ROAD
TRANSPORT INFRASTRUCTURE

The climate models, or General Circulation Models (GCM), are formulated using mathematical equations to characterize the energy and matter interaction over the ocean, atmosphere, and land (NOAA, 2022). Such models

have been improved over the last 60 years, incorporating physical, chemical, biological, and biogeochemical parameters for the numerical simulations of the Earth system, aiming to determine human-related emissions released to the climate system.

Climate scenarios are established as inputs for global climate simulations through GCM based on greenhouse gas concentration pathways (time-dependent values in the future). Such Representative Concentration Pathways (RCP) are identified by numeric values (2.6, 4.5, 6.0, and 8.5 for the worst case, in Watts /m2), corresponding to the change in radiative forcing at the tropopause by 2100 relative to preindustrial levels (Wuebbles *et al.*, 2017). The outputs of climate model simulations are spatial-temporal projections of several climate parameters such as temperature (e.g., average, minimum, maximum daily temperature, number of heat wave days), precipitation

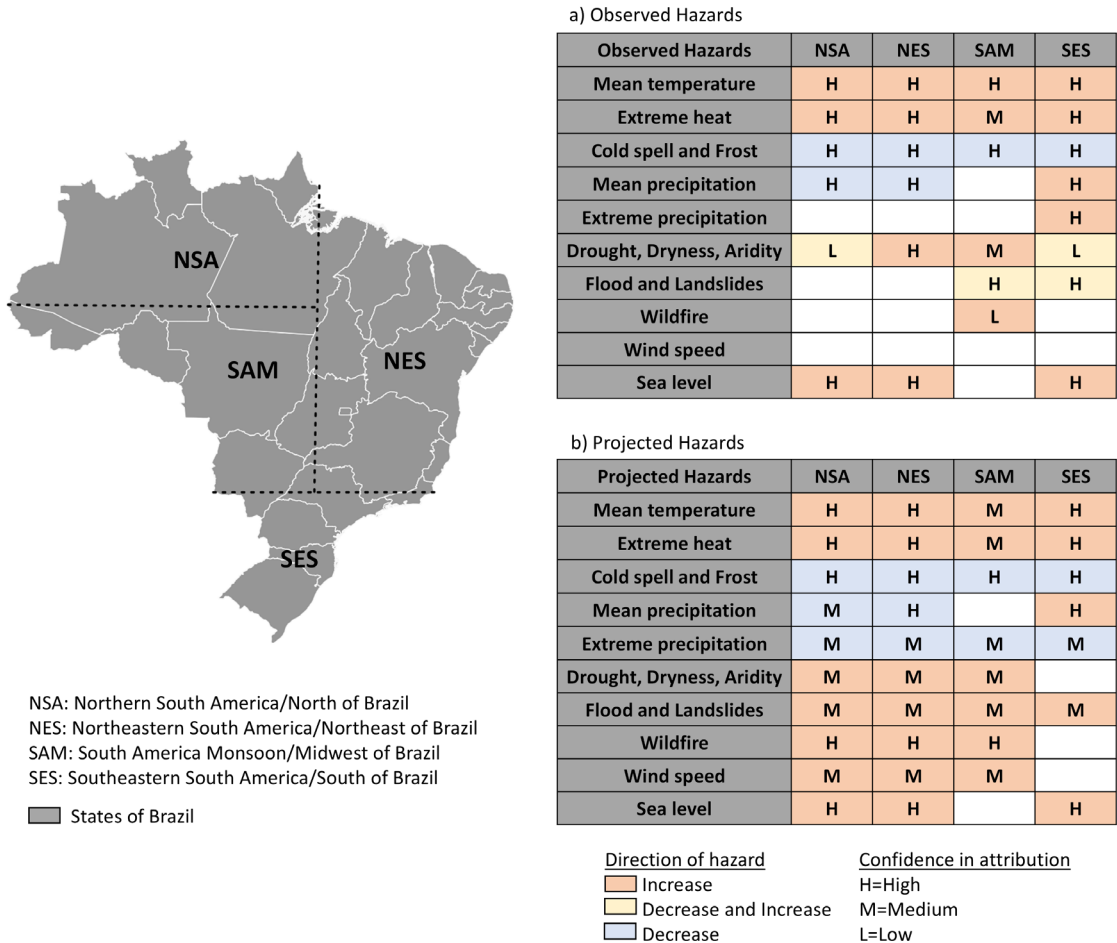


Figure 1: Hazards to the Brazilian road infrastructure.
Source: authors.

(e.g., average daily precipitation, number of days with extreme rainfall, periods of severe drought), moisture (e.g., soil moisture index), and wind (e.g., annual maximum wind speed), as illustrated in Figure 2, with a certain level of uncertainties (Galiana *et al.*, 2015). Such uncertainties are inherent to climate models because establishing physical interactions between atmosphere, land, ocean, and sea ice is challenging, especially considering the Earth's size and complexity. The uncertainties in the projected climate change throughout time may be a result of (Wuebbles *et al.*, 2017; Hawkins & Sutton, 2009): i) Limitations in modeling and understanding Earth's climate system, that is, different models respond differently to the same radiative forcing (scientific uncertainty); ii) Human activity and future emission levels of greenhouse gases emissions (scenario uncertainty); and iii) Variations in climate resulted from natural fluctuations, not related to radiative forcing (internal variability).

In this sense, confidence and probability of occurrence are metrics used in climate models to verify the prediction's certainty. The confidence level is a qualitative measure based on the level of the evidence and the degree of agreement. At the same time, the probability of occurrence is quantified based on a statistical analysis of observations, model results, or expert judgment (Mastrandrea *et al.* 2017), as shown in Figure 3.

Thus, adopting existing climate models requires a previous approach to compare the projections delivered by the models with observed regional data. In addition, it is also relevant to take into account that as climate scenarios range from the most optimistic to the most pessimistic regarding greenhouse gas emissions, the projections cannot be dissociated from related regional socio-economic conjectures.

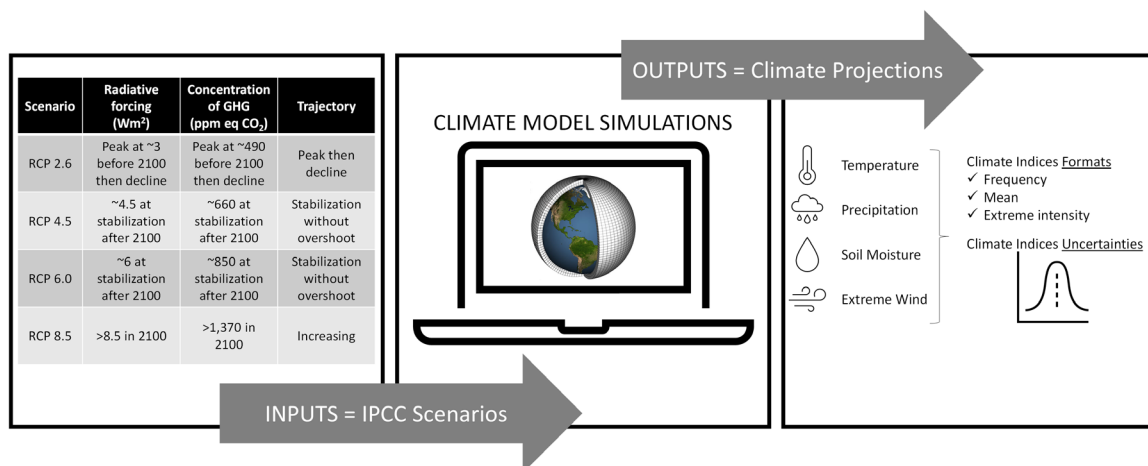


Figure 2: Global climate model simulation pathway.

Source: authors.

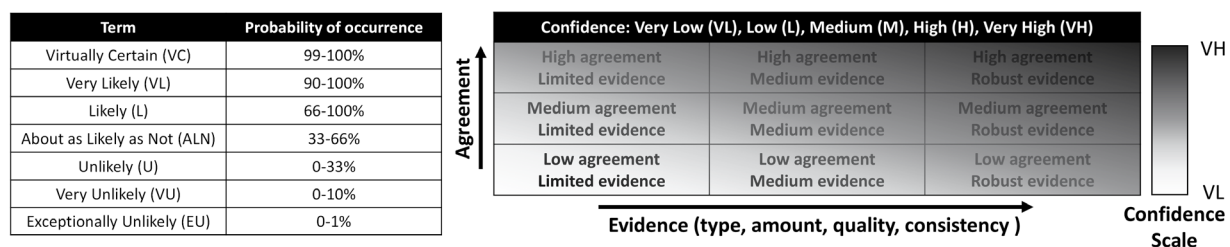


Figure 3: Levels of uncertainty.

Source: authors.

Table 1 summarizes projected changes for weather and climate variables at a global scale and the related probability of occurrence, as issued by IPCC and discussed in Field *et al.* (2012). Tables 2 and 3 summarize changes and impacts on the physical environment based on IPCC projections and the most crucial potential climate changes to US transportation systems, as highlighted in the TRB Special Report 290 (TRB, 2008).

Variable	Projected changes related to weather and climate variables
Temperature	- Decrease in frequency and magnitude of unusually cold days and nights ($\geq 99\%$) - Increase in frequency and magnitude of unusually warm days and nights ($\geq 99\%$) - Increase in length, frequency, and/or intensity of heat waves ($\geq 90\%$)
Precipitation	Increase in frequency of heavy precipitation events or increase in the proportion of total rainfall from heavy falls over many areas of the globe, particularly in high altitudes and tropical regions, and in winter in the northern mid-latitudes ($\geq 66\%$)
Tropical Cyclones	- Increase in mean maximum wind speed, but possibly in not all basins ($\geq 66\%$) - Increase in heavy rainfall associated with tropical cyclones ($\geq 66\%$) - Decrease or no change in frequency ($\geq 66\%$)
Extratropical Cyclones	- Impacts on regional cyclone activity ($\geq 66\%$). However, low confidence in detailed regional projections due to only a partial representation of relevant processes in current models - Reduction in the number of mid-latitude storms (medium confidence) - A poleward shift of mid-altitude storm tracks (medium confidence)
Monsoons	Projected change in monsoons presented low confidence because of insufficient agreement between climate models
El Niño	Projected change in El Niño presented low confidence because of insufficient agreement of model projection

Table 1: Projected changes at a global scale.

Source: authors.

Variable	Projected impacts
Droughts	Increase in duration and intensity, including Southern, Mediterranean, and Central Europe, Central and North America, Northeast Brazil, and Southern Africa (medium confidence)
Floods	- Projected increases in heavy precipitation would contribute to rain-generated local flooding in some regions (medium confidence based on physical reasoning) - Earlier spring peak flows in snowmelt and glacier-fed rivers ($\geq 90\%$) - Low confidence in global magnitude and frequency because of insufficient evidence
Extreme Sea Level and Coastal Impacts	- Mean sea level rise will contribute to upward trends in extreme coastal high-water levels ($\geq 90\%$) - Locations with current coastal erosion and inundation will continue to be exposed to it due to increasing sea levels in the lack of changes in other contributing factors (high confidence)
Landslides	Changes in heavy precipitation will affect landslides in some regions (high confidence)

Table 2: Projected impacts on the physical environment at a global scale.

Source: authors.

Variable	Projected critical changes related to weather and climate variables
Temperature	- Increases in very hot days and heat waves - Decreases in very cold days - Increases in Arctic temperatures - Later onset of seasonal freeze and earlier onset of seasonal thaw
Precipitation	- Sea level rise - Increases in intense precipitation events - Increases in drought conditions for some regions - Changes in seasonal precipitation and flooding patterns
Storms	- Increases in hurricane intensity - Increases in intensity of cold-season storms, wind, waves and storm surges

Table 3: Critical changes to transportation systems in the US.

Source: authors.

Figure 4 illustrates long-term climate projections (2081-2100) relevant to pavement planning, design, construction, and maintenance in Brazil at the end of the 21st century. Data were generated using the IPCC Interactive Atlas tool (IPCC, 2023), setting the Coupled Model Intercomparison Project Phase 6 (CMIP6) models and the baseline period of 1850-1900 for temperature and precipitation and 1995-2014 for sea level rise. Data for Representative Concentration Pathways (RCP) 2.6, 4.5, and 8.5 (change in radiative forcing at the tropopause by 2100 relative to preindustrial levels in Watts/m²) scenarios show: i) An annual average temperature rising to 3, 4, and 7°C; ii) An annual number of days with maximum temperature above 40°C increasing to 34, 60, and 120 days; iii) An annual total precipitation increase of 12,17, and 28% in the south and decrease of 10,14, and 28% in the north; iv) An annual sea level raising more intense in the south coast, up to approximately 0.5, 0.6, and 0.8m.

These data ratify the projected hazards for the vast Brazilian territory illustrated in Figure 1. It is interesting to highlight that although climate modeling and impact analysis are suitable for strengthening discussions on the resilience and sustainability of flexible pavement infrastructure, case studies and empirical data are essential to validate the model predictions. As the models' outputs are valid for the set initial climatic conditions and geographical location, the projections for other countries may lead to different consensus. Regional-specific assessments performed by researchers and skilled

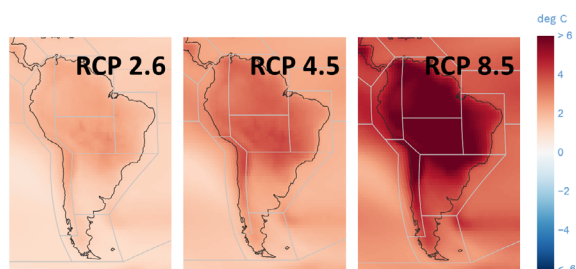
professionals will undoubtedly support decision-makers committed to implementing infrastructure resilience and sustainability policies worldwide.

5. POTENTIAL IMPACTS OF CLIMATE CHANGE ON PAVEMENT INFRASTRUCTURE THROUGHOUT FUTURE YEARS

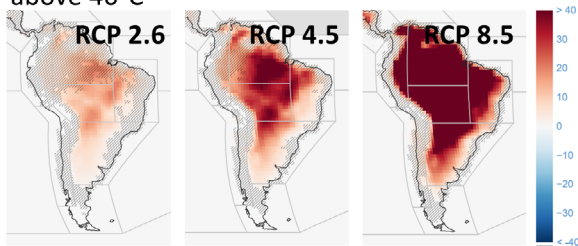
The potential impacts of climate change on pavement infrastructures have been debated among scholars, practitioners, and officials since it may affect the current performance, design, operation, maintenance, and rehabilitation of pavements. The Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance report, issued in 2015 by the US Department of Transportation Federal Highway Administration (FHWA), highlights the following impacts on flexible pavements due to climate stressors [40]: i) Pavement rutting/shoving and concrete joint heaving due to extreme heat; ii) Road closures (frequency, duration) and washouts related to flooding (rain-driven or coastal); iii) Road closures as a result of wind; iv) Pavement cracks due to extreme droughts; v) Potholes as a result of freeze/thaw cycles; and vi) Timing of permafrost thaw.

The Transportation Research Board highlights that the impacts of weather and climate extremes of importance for transportation in the US can be either negative or positive, as summarized in Table 4 (TRB, 2008).

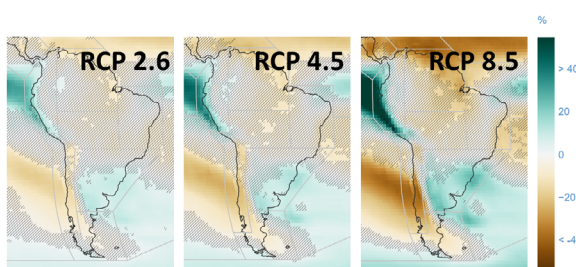
a) Average temperature



b) Number of days with maximum temperature above 40°C



c) Precipitation



d) Sea level rising

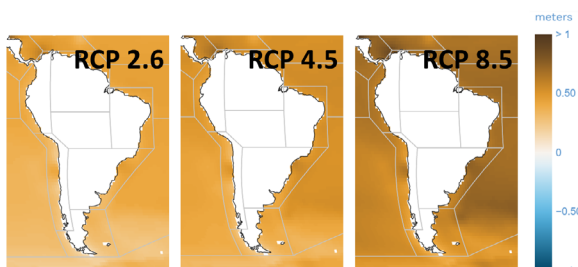


Figure 4: Long-term projections (2081-2100) for South America.

Source: authors.

	Potential Climate Change	Road Operations Impacts	Road Infrastructure Impacts
Temperature	Increases in very hot days and heat waves	Periods of construction activity restrictions; vehicle overheating; tire deterioration	Need to change construction practices of pavement and concrete; thermal expansion of paved surfaces; traffic-related rutting; liquid asphalt migration
	Decreases in very cold days	Snow/ice removal costs; use of deicing salts/chemicals; cold-related restrictions for maintenance activity	-
	Increases in Arctic temperatures	-	Subsidence due to the thawing of permafrost
	Later onset of seasonal freeze and earlier onset of seasonal thaw	Changes in seasonal weight restriction; improvement in mobility and safety; longer construction season	Reduction of pavement deterioration
	Sea level rise	Interruptions on coastal traveling	Erosion of road base; land subsidence
Precipitation	Increases in intense precipitation events	Delays; traffic disruptions; flooding routes of evacuation; disruptions in construction and maintenance activities	Overloading of drainage systems; landslides and mudslides; change in levels of soil moisture affecting the structural integrity of roads; standing water on road base
	Increases in drought conditions for some regions	Reduction of visibility and road closures due to wildfires	Mudslides in the deforested areas by wildfire
	Changes in seasonal precipitation and flooding patterns (snow to rain)	Benefits for safety; less interruptions	More risk of floods, landslides, slope failures, and damage to roads
Storms	More frequent strong hurricanes	More debris on roads; emergency evacuations	Reduction of expected highways (exposed to storm surge) lifetime

Table 4: Potential climate change impacts on road operations and infrastructure.

Source: authors.

In 2012, the European Commission released the report *Impacts of Climate Change on Transport: A Focus on Road and Rail Transport Infrastructures* (Nemry & Demirel, 2012), concluding that changes in design and maintenance are expected due to warming trends in Europe. The report shows the annual cost for asphalt binder upgrading due to temperature increase levels in 27 countries of Europe by 2040-2070 and 2070-2100 periods under distinct climate scenarios: E1 (more favorable), A1B (intermediate) and RCP8.5 (worst case). The incremental cost for the A1B scenario results in 38.5 to 135 million €/year by 2040-2070, which represents 0.1% to 0.5% of current maintenance road costs (~26 €/year); while for the long term, by 2070-2100, it results in 65 to 210 million €/year, corresponding to 0.2% to 0.8% of current maintenance road costs. In contrast, milder winter projections, considering frost depth and freeze-thaw cycles, might reduce materials

and maintenance costs in Europe. Thus, costs regarding asphalt binder upgrading are expected to be moderate, and costs due to hotter summers are expected to be outweighed by milder winters.

Swarna *et al.* (2022) assessed 16 flexible pavement sections throughout Canada under climate change scenarios tracking the deterioration evolution along the future years intervals 2010-2040, 2040-2070, and 2070-2100 caused by two non-stationary environment factors: increase in air temperature and change in precipitation pattern. Figure 5 summarizes the mechanisms leading to declining pavement performance, as reported by Swarna *et al.* (2022). The increased air temperature raises pavement temperature, reducing the elastic modulus of the asphalt concrete layer, which becomes softer and augments the asphalt concrete rutting

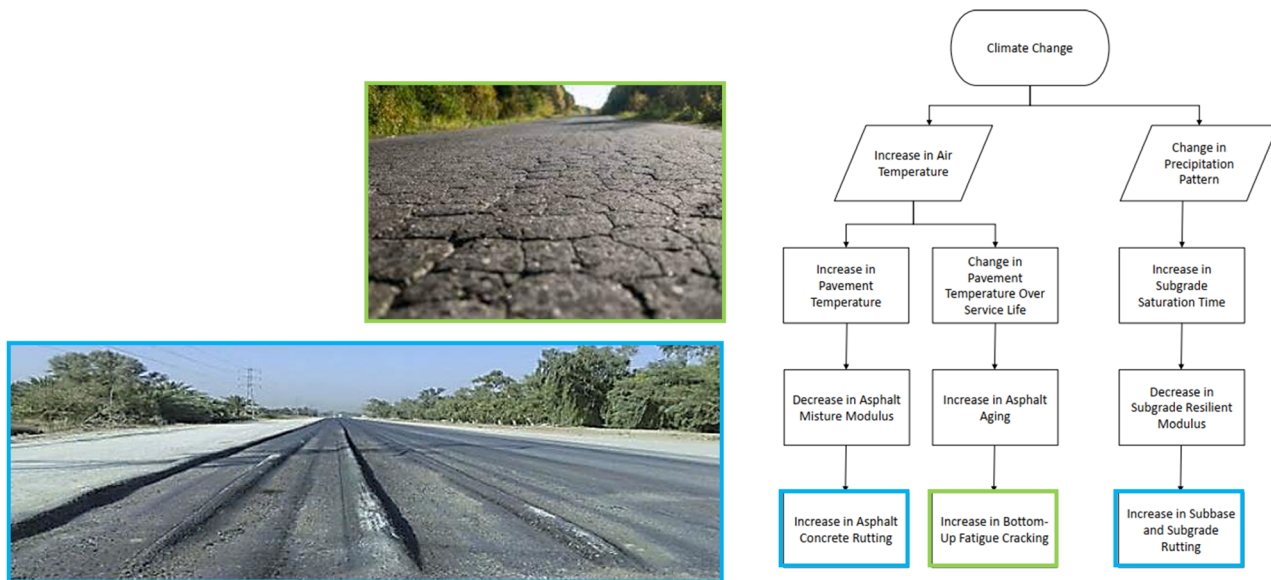


Figure 5: Mechanisms through which climate change affects flexible pavement.
Source: authors.

The increase in air temperature also contributes to the asphalt binder aging, which becomes stiffer (principally for thin pavements), increasing bottom-up fatigue cracking. Furthermore, precipitation increases contribute to water infiltration into the subgrade, boosting subbase and subgrade saturation, reducing the subgrade resilient modulus, and resulting in subbase and subgrade rutting (Khan *et al.*, 2017; Matini, Gulzar & Castorena, 2022).

Underwood *et al.* (2017) report that 35% of 799 asphalt pavement locations across the US suffer from inappropriate material selection due to the assumption of stationary temperatures in the design stage. Once the Superpave Performance Grading (PG) system is utilized in the US, which attributes a grade to the asphalt related to the maximum and minimum temperatures between which it must perform adequately, with climate changes, the first concern is the need for grade modifications for high temperatures – it corresponds to 26% of incorrect material selection, resulting in faster degradation, which will demand more maintenance services and earlier reconstruction. The authors report that in comparison to an adequate pavement expected to last 20 years, a pavement in which the asphalt grade was incorrectly assigned by 6°C increment will need premature rehabilitation starting at 16-17 years, while wrong by 12°C increments will need rehabilitation even earlier at 14-16 years, incurring extra costs. Keeping the current practice for material selection in the mid and long term may add approximately US\$26.3 and US\$35.8 billion to pavement costs by 2040 and 2070, respectively,

under the worst-case scenario (RCP8.5). These impacts are equivalent to roughly 3-9% of construction and maintenance costs for the entire country's infrastructure over 30 years.

Climate change consequences are not limited to pavement deterioration, but the impacts may also extend to maintenance methods, budget, and the environment. Taking no action regarding infrastructure adaption strategies can impact users' safety, time, and additional costs with fuel consumption. Furthermore, the indirect impacts of climate change as traffic volume increases or decreases due to demographic changes may affect pavement performance, design, operation, maintenance, and rehabilitation (Qiao *et al.*, 2020).

A study conducted by Espinet *et al.* (Espinete *et al.*, 2016) projected an extra cost for road maintenance and repair in Mexico that ranges from USD\$1.3 to 4.8 billion by 2050 due to climate change impacts, with temperature the main driver for climate change impacts compared to precipitation in the country.

In contrast to the abovementioned studies, Blaauw *et al.* (2022) discussed how potential climate change might benefit flexible pavements in South Africa, highlighting a trend of South African climate becoming increasingly arid, reducing pavement deterioration and road user emissions. A simulation using the Highway Development and Management 4 (HDM-4) software for a 30-year analysis with pavement deterioration trends quantified through the International Roughness Index (IRI) revealed that pavements in arid zones perform better than in humid

zones under the same traffic and maintenance conditions. The IRI only exceeded the 6m/km threshold for the humid scenario. Maintenance costs significantly increase for low-volume roads as the climate zone becomes wetter, while maintenance costs remain constant for high-volume roads.

Although reports considering the Brazilian scenarios are rare, Shuster *et al.* (2022) assessed the impact of climate change in the selection of binders in Brazil since considering the Performance Grade (PG), which consists of the maximum and minimum asphalt temperature along the pavement lifespan, established in the SUPARPAVE method. The PG for 1961-1990 compared to 1991-2020, obtained from 115 meteorologic stations throughout the country, showed an increment in the maximum temperature of the PG in almost 15% of the stations. The effects can be even worse in the medium and long term.

6. STRATEGIES TO ADAPT FLEXIBLE PAVEMENT INFRASTRUCTURE IN RESPONSE TO A CHANGING CLIMATE

"Curb Climate Change and Adapt to Its Impacts" is one of the "Grand Challenges for Engineering in the 21st Century" of the National Academy of Sciences agenda (NASEM, 2019). Engineering usually assumes weather and climate as stationary; however, planning, designing, constructing, operating, and maintaining infrastructures must accommodate changes affecting the flexible pavement infrastructure. Assuming that weather and climate are stationary implies that statistical properties

(mean and variance of a stressor distribution) remain constant. This assumption is ineffective since stressors may significantly vary with time (NHI, 2023), as illustrated by the hypothetical normal distribution curves for temperature shown in Figure 6.

In Figure 6 (c) against (a), focusing exclusively on the mean, whose value does not change from present to future, would lead one to neglect the increment in temperature amplitude (e.g., this knowledge is fundamental for concrete pavement expansion joints design) and the intensification of maximum and minimum temperatures (e.g., awareness of the magnitude of extreme temperatures is crucial to specify the asphalt binder in flexible pavements). In this sense, long-term recorded data availability allows for developing a statistical distribution of indispensable weather or climate parameters to obtain the probability of occurrence of a value above or below an established threshold of interest in engineering design (Field *et al.*, 2012).

The American Society of Civil Engineers (ASCE), in the published report *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate* (ASCE, 2015), pinpointed two distinct models for vulnerability assessment: top-down and bottom-up (Figure 7). In the top-down approach, the projections generated by global climate models are downscaled to a local or regional scale to estimate the consequences on the system. The opposite path, bottom-up, consists of establishing thresholds where the system fails and assessing the possibility of exceeding that threshold.

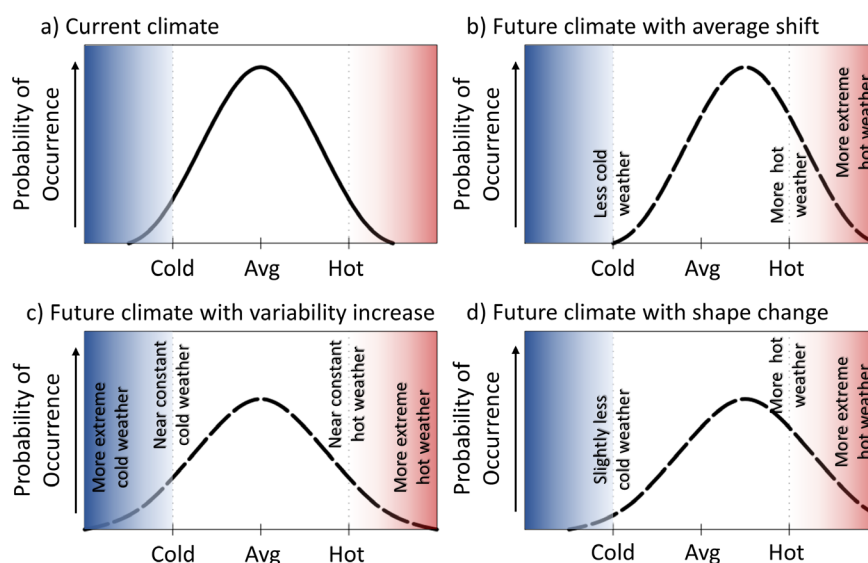


Figure 6: Normal distribution curves for temperature.

Source: authors.

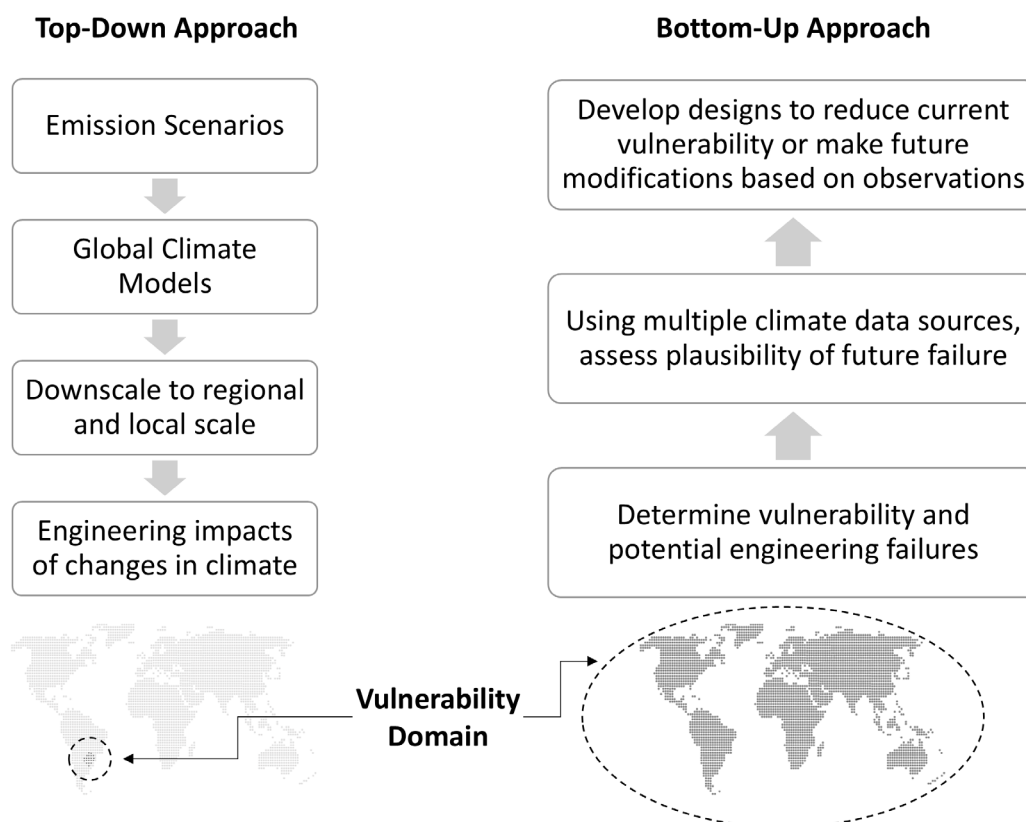


Figure 7: The Top-Down and Bottom-Up approaches as recommended by ASCE to assess the vulnerability level of infrastructures to climate change.
Source: authors.

Table 5 shows examples of governmental documents regarding the Climate Change Adaption Policy on different continents, showing worldwide efforts in addressing resilient infrastructures. These documents show a growing concern on the subject, based on the data recorded since the 20th century that clearly show a temporally and spatially-dependent non-stationary temperature tendency varying from one location to another. Therefore, planning, designing, constructing, operating, and maintaining infrastructures should accommodate these changes (TRB, 2008).

In the US, the Federal Highway Administration issued the Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance to subsidize departments of transportation (DOT) regarding infrastructure vulnerability and responses to adapt them. The report highlights that pavement designed must resist specific temperature thresholds – high temperatures may cause rutting, while cold conditions may lead to potholes. Different maintenance approaches in the future might consider: i) boost inspection and

following of road conditions (short-term); ii) evaluation of projected temperatures to define if modifications in pavement mix are necessary (medium-term); and iii) application of modified asphalt mixture where necessary when repaving takes place (long-term). Those actions may result in allocation and budgeting distinct from today regarding operation, maintenance, and emergency management (Asam *et al.*, 2015).

Qiao *et al.* (2020) affirm that pavement adaption requires pavement design and modification of usual life cycle management practices. Similarly, Blaauw *et al.* (2022) state that selecting appropriate design and adopting rigorous maintenance are critical factors in addressing pavement infrastructure resilience.

In addition, road authorities may benefit from considering future projections instead of historical data. Underwood *et al.* (2017) point out four key factors to adapt asphalt pavement infrastructure: i) Increase air temperature and year-to-year variation; ii) Geo-spatial location – especially latitude; iii) Current engineering practices; and iv) Roadway type. Swarna *et al.* (Swarna

et al., 2022) utilized the following adaption strategies in their research: i) Change in asphalt binder grade, asphalt mixture gradation, and thickness of asphalt layer for asphalt concrete rutting; ii) Increase in asphalt layer thickness for bottom-up fatigue cracking; iii) Change in thickness of base and subbase layers, and use stabilized bases for subbase and subgrade rutting.

In a comprehensive literature review, Abreu *et al.* (2022) identified potential measures to adapt the road infrastructure to climate threats, especially related to the temperature-increasing trend. Such measures range from implementing pavement irrigation and vegetation around highways to mitigate the effects of heat waves to adapting pavement materials to minimize the impact of sensible heat flow. To adapt the binder selection in

response to changes in temperature patterns for Brazil, Shuster *et al.* (2022) signalize the utilization of polymer-modified asphalt, whose impact on road infrastructure costs should be expected. Asphalt binders that are more flexible to support a broad range of temperatures and moisture conditions can lead to more durable asphalt mixtures, while lighter-colored pavement materials that reflect sunlight and absorb less heat might reduce the deleterious effects of urban heat islands..

Strategies to conserve and recover existing biodiversity, accompanied by strengthening the monitoring of precursor variables of natural disasters through reliable meteorological and climate forecasts, are essential actions to be implemented in road infrastructure adaptation plans (Garcez, 2024).

Location	Documentation	Governmental Agency/Organization
Australia	• Climate Change Risk and Adaption Assessment Framework for Infrastructure Projects (DTMR, 2020a)	• Department of Transport and Main Roads
	• Engineering Policy 170 – Climate Change Risk Assessment Methodology (DTMR, 2020b)	• Department of Transport and Main Roads
Brazil	• Plano Nacional de Adaptação à Mudança do Clima – Relatório Final de Monitoramento e Avaliação Ciclo 2016-2020 (Silva et al., 2021)	• Ministério do Meio Ambiente
	• Relatório Final de Monitoramento e Avaliação do Plano Nacional de Adaptação à Mudança do Clima Ciclo 2016-2020 – Síntese e Análise dos Resultados do Levantamento Realizado Junto ao Setor Empresarial (Silva et al., 2021)	• Ministério do Meio Ambiente
	• Plano Nacional de Adaptação à Mudança do Clima – Estratégia Geral – Volume I (Silva et al., 2016a)	• Ministério do Meio Ambiente
	• Plano Nacional de Adaptação à Mudança do Clima – Estratégias Setoriais e Temáticas – Volume II (Silva et al., 2016b)	• Ministério do Meio Ambiente
	• Estratégia de Adaptação às Mudanças Climáticas da Cidade do Rio de Janeiro (La Rovere & Sousa, 2016)	• City Hall of Rio de Janeiro, COPPE/UFRJ, Centro Clima
Europe	• European Climate Adaptation Platform Climate-ADAPT (EC & EEA, 2022)	European Commission and European Environment Agency
	• Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures (Nemry & Demirel, 2012)	• European Commission – Joint Research Centre
Japan	Practical Guidelines on Strategic Climate Change Adaption Planning – Flood Disasters (RB, 2010)	• River Bureau – Ministry of Land, Infrastructure, Transport and Tourism, Japan
South Africa	• National Climate Change Adaptation Strategy Republic of South Africa (DEFF, 2019)	• Department: Environment, Forestry and Fisheries – Republic of South Africa
United States	• Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance (Asam et al., 2015)	• US Department of Transportation – Federal Highway Administration

Table 5: Normal distribution curves for temperature.

Source: authors.

Zanetti, Souza Jr & Freitas (2016) assessed significant risks of climate change to infrastructure and communities other than temperature (i.e., extreme rainfall and sea level rise). The authors proposed seven related indexes using the municipality of Santos, in Brazil (the largest port in Latin America and an insular area of Pre-Salt Oil and Gas projects) as a case study: i) Landslide; ii) Flooding; iii) Wave exposure; iv) Coastal erosion; v) Population density; vi) Socio-economic level; and vii) Land use to quantify the socio-environmental vulnerability of coastal cities in a scale from 1 to 5. This classification allows for supporting adaption strategies for critical infrastructure. Approximately 70% of the studied area, including major roads and streets, received level 4 (high vulnerability) for the IPCC scenario RCP 4.5. Although vulnerability assessments based on climate change projections have been performed, i.e., Rio de Janeiro (Barata *et al.*, 2020), Minas Gerais (Quintão *et al.*, 2017), Amazon (Menezes *et al.*, 2018), and Maranhão (Vommaro, Menezes & Barata, 2020), there is still a lack of sector-specific research towards adaptations strategies for flexible pavement infrastructure in Brazil.

Future research to support public policies that address adaptation measures in the Brazilian road infrastructure network context is critical, as Abreu *et al.* (2022) reported in a recent bibliometric study. Adaption technologies and methods that meet the country's particularities comprehend innovation in drainage systems, adding non-stationary climate modeling in design specification, robust monitoring and data processing systems for climate changes, and space-time-dependent road infrastructure maintenance plans.

7. THE ROLE OF LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA) IN IDENTIFYING AND MANAGING FLEXIBLE PAVEMENT INFRASTRUCTURE IMPACTS

Sustainable pavements are those that: i) Achieve the engineering goals for which it was constructed; ii) Preserve and (ideally) restore surrounding ecosystems; iii) Use financial, human, and environmental resources economically; and iv) Meet basic human needs such as health, safety, equity, employment, comfort, and happiness (Van Dam *et al.*, 2015). Several stakeholders have pursued sustainable pavement projects; nevertheless, assessing the economic, environmental, and social aspects throughout the life cycle is still in the initial stage in many countries. The challenge is even more far-reaching in examining the three pillars of sustainability from a climate change condition perspective. According to the international guidelines issued by the United Nations Environment Programme (UNEP/SETAC, 2011), LCSA evaluates all environmental, social, and economic impacts and benefits in decision-making processes throughout the life cycle.

Thus, sustainable road infrastructure projects might consider the different life cycle stages (Van Dam *et al.*, 2015). Potential strategies to implement sustainability aspects in the road pavement infrastructure through the life cycle stages, illustrated in Figure 8, encompass a life cycle thinking commitment. Especially in the use stage, integrating socio-economic impacts linked to pavement deterioration and maintenance services under changing climatic conditions will provide a more holistic view of sustainability. Due to the extent and complexity of the subject, this approach is only feasible in practical applications if linked to education and cross-collaboration.

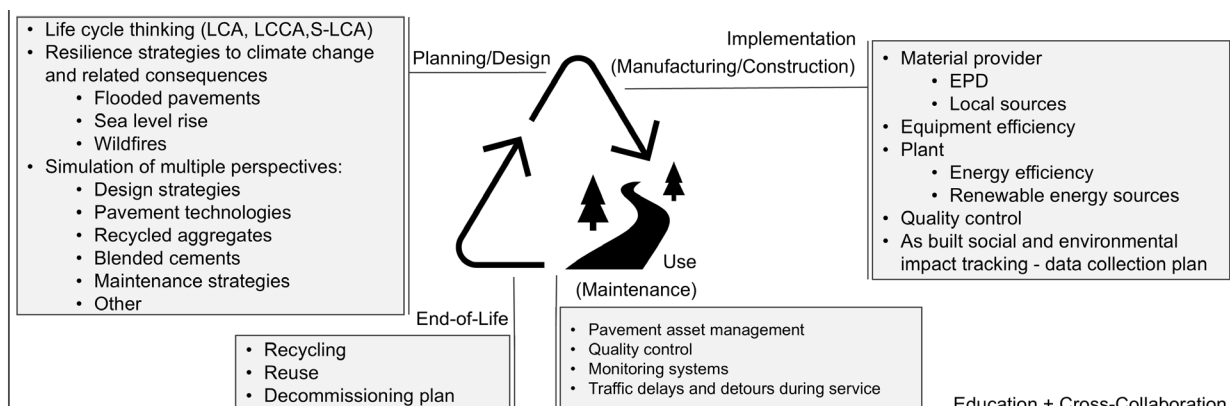


Figure 8: Pavement life cycle.

Source: authors.

The frameworks to carry out environmental Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA) are similar, comprising four phases: i) Goal and scope definition; ii) Inventory; iii) Impact assessment; and iv) Interpretation [65]. The Life Cycle Costing (LCC) comprises aggregating costs by cost categories to the third phase. Since all cost inventory refers to a single unit of measure, a currency, this phase yields a direct measure of the financial impact (Swarr *et al.*, 2011).

Regarding LCA, ISO 14040 (ISO, 2006) states the principles and framework for products or services, while ISO 15686-6 (ISO, 2004) is devoted to buildings and constructed assets. According to the respective ISO standards, an LCA encompasses the following steps: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. The scope defines the life cycle stages (i.e., product, construction, use, and end of life – Figure 9) considered to build the inventory, which consists of background (gathered from reference databases - e.g., Ecoinvent) and foreground (collected directly from the product system). Specifically for the pavement sector, the FHWA issued extensive guidelines through the Pavement Life Cycle Assessment Framework (Harvey *et al.*, 2016), whose principles comprehend the translation of materials and energy inputs and the respective waste and emissions outputs into environmental and social impacts. Different LCA tools can be used to generate environmental and social impacts, whose results depend on the selected impact assessment method (e.g., CML, ReCiPe, EN 15804 + A2, TRACI). The FHWA report (Harvey *et al.*, 2016) recommends the inclusion of a broad set of impact

categories such as fuel (renewable and non-renewable), resources (renewable and non-renewable), climate change, ozone layer depletion, acidification, tropospheric ozone, eutrophication, human toxicity (respiratory, carcinogenic, non-carcinogenic), ecotoxicity (freshwater, marine water, soil), freshwater use, waste (hazardous and non-hazardous).

Most LCA studies use environmental LCA to focus on the environmental pavement footprint. While some data sources are well consolidated, others are generated by inaccurate research that may compromise results and conclusions (Santero, Masanetb & Horvath, 2011). Potentially environmentally friendly strategies, such as warm-mix asphalt (WMA) and reclaimed asphalt pavement (RAP), have been pursued in the pavement sector, which is not enough to achieve sustainability (Zheng *et al.*, 2019) as a whole in its social, economic, and environmental pillars.

The main challenges to implementing LCA in the road infrastructure field rely on the various stages and unit processes involved, the scarcity of databases and specialized tools, the considerable heterogeneity of functional units, system boundaries, and study periods (Picardo *et al.*, 2023). Furthermore, transparency, heterogeneity, and the lack of information on road design parameters and materials used in the case studies make the results not reproducible (Hoxha, 2020).

Another issue related to the LCA results reported in the literature is that different impact methods may lead to different scenario results, which is not the case for the global warming potential (GWP) indicator, whose results are generally consistent regardless of the impact

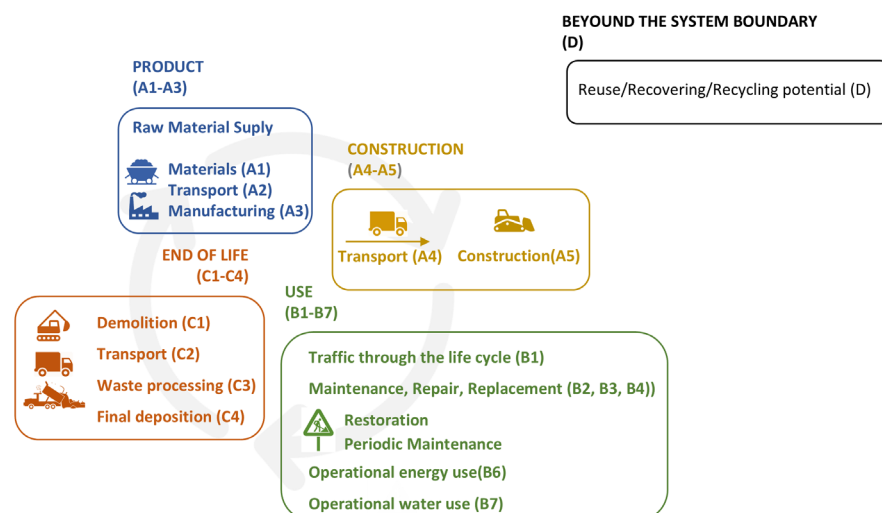


Figure 9: Life cycle stages and processes.

Source: authors.

method (Koch, Friedl & Mihalyi, 2023). The GWP indicator contains subcategories (e.g., biogenic carbon and land use change) to process relevant CO₂-eq flows. The GWP reference unit (CO₂-eq) does not change for the different impact methods, which is an advantage considering that different reference units may be used to quantify the same impact category (e.g., PO₄-eq, NO₃-eq, N-eq, P-eq, for eutrophication potential).

The S-LCA approach is more recent and has not been standardized yet (Blaauw *et al.*, 2022). The S-LCA allows for the evaluation of potential social impacts on several stakeholders over the life cycle (Zheng *et al.*, 2019). The Guidelines for Social Life Cycle Assessment of Products and Organizations establishes an S-LCA framework built upon six stakeholder categories – workers, local community, consumer, society, children, and value chain actors; and six impact categories – human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions; to identify and manage potential social impacts (UNEP/SETAC., 2009). In addition to cost and environmental impacts, Zheng *et al.* (Zheng *et al.*, 2019) investigated social implications through the behavior of company management toward the stakeholders (Figure 10) during materials production, construction, use, and maintenance activities. The authors highlight the concern for workers' physical and psychological well-being due to the arduous work environment and the local communities and consumers' protagonism due to the long service life of pavements.

Managing vast roadway networks under a limited budget, reducing environmental pollution, and guaranteeing social well-being has been a widespread challenge. Historically, the introduction of the life cycle cost-benefit concept for pavements was published in 1960 by the American Association of State Highway Officials (AASHTO). At that time, two pioneer projects – Flexible Pavement System (developed by the Centre for Highway Transportation Research and the Texas Transportation Institute) and the Rigid Pavement System (created by the Texas Department of Transportation), initiated the use of LCC principles for the selection of pavement type/design. Under the Intermodal Surface Transportation Efficiency Act in 1991, LCC became mandatory in the US to design and construct tunnels, bridges, or pavements (Babashamsi *et al.*, 2016). The Federal Highway Administration continues to foster the application of LCC for transportation assets through technical guidance, tools, training, case studies, and other resources to the public (FWHA, 2023). The European Union determines the regulation for LCC conduction on public procurement (EC & ICLEI, 2022) in Article 68 of Directive 2014/24/EU [80] and Article 83 of Directive 2014/25/EU (EU, 2014). In Canada, except Prince Edward Island, New Brunswick, and Newfoundland, all provinces apply LCC for roadway management plans (Swarma *et al.*, 2022). The two components for pavements are agency cost – initial pavement structure and future maintenance and rehabilitations; and user cost – vehicle operation, user delay, and crash (Walls & Smith, 1998).

	workers	• working hours • health and safety • professional growth
	local community	• access to material resource • safe/healthy living conditions
	society	• public commitments to sustainability • technology development
	consumer	• health and safety

Figure 10: Stakeholder categories in the S-LCA framework proposed by Zheng *et al.* [71].

Source: authors.

Despite growing concern about implementing sustainability principles in road management, modeling LCSA towards pavement alternatives is in the beginning stage; by far, LCC+LCA studies outnumber LCSA for pavement, probably because LCSA modeling demands management concepts instead of just physical or monetary quantification. In this context, Zheng *et al.* (2019) proposed an all-inclusive LCSA methodology comprised of life cycle cost analysis (C-LCA), environmental life cycle assessment (E-LCA), and social life cycle assessment (S-LCA) through a case study applied in Southeast China by combining an Analytical Hierarchy Process (AHP) and VIKOR model to unify the economic, environmental, and social results.

In one of the few reports considering climate change effects on the LCA and LCCA of asphalt pavement, Swarna, Hossain & Bernier (2022) discussed three engaging scenarios for several locations in Canada: i) No climate change; ii) With climate change; and iii) Adaption to climate change including asphalt binder upgrading, increasing hot mix asphalt thickness, different mix gradation, and base stabilization (with lime, cement, or polymer). Despite the initial cost and emission increase to implement the adaption strategies, the authors identified an offset along the life cycle of the pavements in most locations. The most costly and highest emitting adaption alternatives were increasing hot mix asphalt thickness and using base stabilizations; however, these solutions are required for extreme coastal climate change regions such as Newfoundland (east coast) and British Columbia (west coast), which also must be taking into account. Although concluding that climate change adaptation strategies are beneficial from the economic and environmental point of view, the social aspect was not investigated.

Despite addressing material optimization, design, construction technologies, or maintenance strategies, none of the previous research addresses flexible pavement infrastructure adaption measures to face non-stationary climatic conditions throughout the life cycle from an LCSA perspective. This lack of knowledge demands further investigation to ensure that the infrastructure conceived today remains resilient through a potential climate change, considering time-space-dependent climate change stressors.

8. LIMITATIONS AND PERSPECTIVE FOR FUTURE RESEARCH

The discussions presented in the paper highlight the need for future research to face the challenges imposed by extreme climate events that will demand robust strategies to adapt the existing road infrastructure. Some suggestions can be drawn as follows:

- Overcoming the gap in developing or identifying existing climate models appropriate for the Brazilian specificities demands highly skilled research efforts to minimize internal variability and scientific uncertainty.
- There is a lack of knowledge on LCSA applied to the road infrastructure, addressing simultaneously time-space-dependent climate change stressors conditions and resilient solutions to endure climate change.
- Adapting flexible pavement infrastructure to climate change requires innovation, focusing on sustainability from a triple-bottom-line perspective that balances economic aspects, people's needs, and planet regeneration.
- From a technical point of view, addressing particularities of Brazilian Infrastructure in the future might require consideration of climate change-related factors and performance parameters as part of the pavement design process, where local specificities are conditioning factors.

9. CONCLUSIONS

The discussions presented in this paper ratify the importance of not underestimating the effects of climate change on the existing and planned road transport infrastructure, leading to the following conclusions:

- Changes in the intensity and frequency of global temperature and precipitation patterns affect pavements' performance, design, operation, maintenance, and rehabilitation regarding engineering, costs, and social development, demanding a deep upgrading of engineering practices and design standards to assume time-space-dependent stressors.
- Research and development fostering LCSA may reveal management strategies for vast roadway networks under a limited budget, reducing environmental pollution while promoting social well-being.

- Efforts and investments in resilient infrastructures depend on climate projections, whose accuracy is influenced by the uncertainty of climate models. Risk analysis may offer support in the decision processes as numerical simulations evolve.
- Investments in climate science are necessary to reduce prediction uncertainties.
- The main practical implication in pavement design and maintenance strategies resulting from the discussions proposed in the paper is the need to incorporate life cycle thinking in decision-making to allow the pavement infrastructure to adapt to future climate conditions, which might include:
- Allocating budget for adaptation to climate actions in road infrastructure business models to incorporate mitigation strategies throughout all life cycle stages.
- Combining LCA, LCCA, and S-LCA results in pavement infrastructure's design, implementation, use, and decommissioning stages.
- Setting appropriate asphalt grading considering non-stationary climate conditions, especially regarding high temperatures and potential traffic volume increases due to demographic effects related to climate change.
- Developing less polluting pavement materials accompanied by durability assessment considering climate and weathering-related extreme events.
- Boosting inspection and following of existing road infrastructure.

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GREEN SPACES AND NATURAL ELEMENTS IN THE ARCHITECTURAL CONFIGURATION OF LONG-TERM CARE FACILITIES FOR OLDER ADULTS: A SYSTEMATIC LITERATURE REVIEW

ESPAÇOS VERDES E ELEMENTOS NATURAIS NA CONFIGURAÇÃO ARQUITETÔNICA DE INSTITUIÇÕES DE LONGA PERMANÊNCIA PARA IDOSOS: UMA REVISÃO SISTEMÁTICA DE LITERATURA

ESPACIOS VERDES Y ELEMENTOS NATURALES EN LA CONFIGURACIÓN ARQUITECTÓNICA DE INSTITUCIONES DE LARGA PERMANENCIA PARA ANCIANOS: UNA REVISIÓN SISTEMÁTICA DE LITERATURA

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ABSTRACT

The aging process entails changes that require attention to ensure the well-being of older people. The difficulty of families in offering support in the face of daily demands often leads them to search for care facilities. Although the rights to housing and well-being are legally guaranteed, the effective implementation of these rights is hampered by inadequate approaches by facilities, which often disregard the cognitive needs of older people. Given the influence of built spaces on quality of life, it is crucial to ensure that Long-Term Care facilities for Older Adults provide facilities conducive to successful aging. Although studies recognize the benefits of green spaces for older adults, integrating these elements in built environments can be better explored. This Systematic Literature Review (SLR) seeks to identify the preferences of older people regarding green spaces and natural elements in the architecture of Long-Term Care facilities. The research covers articles in the Science Direct, Scopus, and Web of Science databases. Results indicate a preference for comfortable, safe, accessible, familiar environments with vegetation and natural views. It is concluded that contact with nature is essential in the institutionalized experience of older people, thus reinforcing the importance of architectural adaptations sensitive to their preferences.

KEYWORDS

Elderly, Long-term Care Facilities for Older Adults; Green spaces; Natural elements.

RESUMO

O processo de envelhecimento acarreta mudanças que exigem atenção para assegurar o bem-estar das pessoas idosas. A dificuldade das famílias em oferecer apoio diante das demandas diárias muitas vezes leva à busca por instituições de acolhimento. Apesar de os direitos à habitação e ao bem-estar serem legalmente garantidos, a implementação efetiva desses direitos é prejudicada por abordagens inadequadas das instituições, que muitas vezes desconsideram as necessidades cognitivas das pessoas idosas. Dada a influência dos espaços construídos na qualidade de vida, é crucial garantir que as Instituições de Longa Permanência para Idosos proporcionem instalações propícias ao envelhecimento bem-sucedido. Embora estudos reconheçam os benefícios dos espaços verdes para as pessoas idosas, a integração desses



elementos em ambientes construídos é pouco explorada. Esta Revisão Sistemática de Literatura (RSL) busca identificar as preferências das pessoas idosas quanto aos espaços verdes e elementos naturais na arquitetura de Instituições de Longa Permanência. A pesquisa abrange artigos nas bases Science Direct, Scopus e Web of Science. Resultados indicam a preferência por ambientes confortáveis, seguros, acessíveis, familiares, com vegetação e vistas naturais. Conclui-se que o contato com a natureza é essencial na vivência institucionalizada de pessoas idosas, reforçando a importância de adaptações arquitetônicas sensíveis às suas preferências.

PALAVRAS-CHAVE

Pessoas idosas; Instituições de Longa Permanência para Idosos; Espaços verdes; Elementos naturais.

RESUMEN

El proceso de envejecimiento conlleva cambios que exigen atención para garantizar el bienestar de las personas mayores. La dificultad de las familias para ofrecer apoyo ante las demandas diarias a menudo lleva a buscar instituciones de acogida. Aunque los derechos a la vivienda y al bienestar están legalmente garantizados, su implementación efectiva se ve perjudicada por enfoques inadecuados de las instituciones, que frecuentemente ignoran las necesidades cognitivas de las personas mayores. Dada la influencia de los espacios construidos en la calidad de vida, es crucial asegurar que las Instituciones de Larga Permanencia para Ancianos proporcionen instalaciones propicias para un envejecimiento exitoso. Si bien estudios reconocen los beneficios de los espacios verdes para las personas mayores, la integración de estos elementos en entornos construidos está poco explorada. Esta Revisión Sistemática de Literatura (RSL) busca identificar las preferencias de las personas mayores respecto a espacios verdes y elementos naturales en la arquitectura de Instituciones de Larga Permanencia. La investigación abarca artículos en las bases Science Direct, Scopus y Web of Science. Los resultados indican una preferencia por entornos cómodos, seguros, accesibles, familiares, con vegetación y vistas naturales. Se concluye que el contacto con la naturaleza es esencial en la vivencia institucionalizada de las personas mayores, reforzando la importancia de adaptaciones arquitectónicas sensibles a sus preferencias.

PALABRAS CLAVE

Personas mayores; Instituciones de Larga Permanencia para Ancianos; Espacios verdes; Elementos naturales.

1. INTRODUCTION

The aging process carries several transformations related to the biological, psychological, and social spheres. They demand attention (ARAÚJO, 2007) since the quality of life of older people is closely linked to the ability to overcome these changes that accompany aging, either autonomously or with the support of family members (LIMA; LIMA; RIBEIRO, 2010). This issue plays a crucial role in promoting the well-being of older people since, due to daily demands and professional obligations, families often face difficulties in providing the necessary support, sometimes resulting in the search for care facilities.

The right to housing for older adults is guaranteed by instruments such as the 1988 Constitution and the 2003 Statute of the Elderly, which stand out for ensuring decent housing for this population, whether within the family or in public or private facilities. Among the facilities that provide this housing support are the Long-Term Care Facilities for Older Adults (LTCFs), characterized by Anvisa's Collegiate Board Resolution No. 502 as a modality of care that aims to guarantee, in addition to a welcoming environment, the respect and preservation of the identity and autonomy of the older person (Anvisa, 2021).

Even though they are guaranteed from a legal perspective, the effective implementation of the rights to housing and well-being of older adults remains inadequate due to factors such as negligence in the treatment of this population segment (FERNANDES; SOARES, 2012), as well as issues related to the facilities themselves that sometimes adopt an approach focused exclusively on the provision of care services, relegating the cognitive needs of the older person (JÚNIOR *et al.*, 2019). Because it is historically marked by these negative reports about care for older people, the institutional modality is not yet entirely accepted as adequate social support (DEZAN, 2015).

The guarantee of a healthy and autonomous old age depends on how the older person can interact with the spaces they attend. Thus, the concern with the relationship of the older person with the environment is of paramount importance since the planning of the built environment is what will ensure the quality of life in the aging process (JÚNIOR; ARÊAS; ARÊAS; BARBOSA, 2013). Hence, it is essential to ensure that LTCFs are supported by facilities that preserve health and guarantee the comfort and safety of this group, aiming at successful aging (CAMARANO; KANSO, 2010).

When exploring the interaction between individuals and the environment, several investigations seek to examine the connection between green areas and the quality of human life. Among them, the analyses by Maas, Verheij, Vries, Spreeuwenberg, Schellevis, and Groenewegen (2009) about medical reports from hospitals in the Netherlands stand out, revealing that people who live near green spaces are less likely to contract diseases. These findings are supported by studies conducted in Japan, the Netherlands, and the United Kingdom, indicating that vegetation exposure is associated with reduced blood pressure and a greater production of white blood cells (BRASIL, 2016). These data are fostered by research by Gitlin (2003) and Leith (2006) that reinforces the importance of nature to ensure a healthy and independent old age.

Although several studies highlight the universally recognized positive impacts of green spaces for humans, especially for older adults, studies investigating the integration of these environmental elements in built environments, such as LTCFs, are scarce. Therefore, this Systematic Literature Review (SLR) aims to identify older people's preferences regarding green spaces and natural elements in the architectural configuration of LTCFs, helping to verify the biopsychosocial aspects of older people in the context of the relationship between aging, green spaces, and quality of life.

2. METHODOLOGY

This SLR aims to answer the following research question: What do older people prefer concerning green spaces and natural elements in the architectural configuration of Long-Term Care Facilities for Older Adults?

The inclusion criterion adopted for selecting the articles was to consider studies that address the relationship between older people, institutionalized or not, and vegetation and/or natural elements in architecture, and of these, articles in journals and with institutional signature. Notably, to collect references on aspects related to the aging process and the benefits that nature may bring to older people, some studies that were not conducted with institutionalized older people were also considered in this review.

As exclusion criteria, the following topics were considered: a) articles addressing the relationship between older people and animals (assisted therapy), b) sustainability and accessibility in long-term care facilities, c) relationship of

the older person with the community, d) articles addressing “aging in place”; e) the benefits of physical activity for older people, f) articles that did not have the older person as a group to be studied, g) the housing market for older people, and h) literature review articles.

The search was performed without any temporal limitation through the Science Direct, Scopus, and Web of Science databases in August 2023 from the following search string: (“homes for the aged” OR “old age home” OR “old age homes” OR “residential aged care facility” OR “long-term care facilities” OR “senior housing”) AND (“biophilia” OR “green space” OR “natural elements in architecture”).

Zotero Software was used as a support tool for filtering and extracting content from the selected articles. The selection process of the articles took place in two phases, initially with the analysis of the titles and abstracts of the collected articles, followed by their full reading. The articles were included or excluded in the preliminary stage based on the eligibility criteria adopted. After this screening, the articles that met the inclusion

criteria were examined fully for a comprehensive analysis of their contents. Then, the articles selected in the second phase had their content tabulated in order to extract essential information for a better understanding of the selected studies, such as a) year of publication, b) article title, c) authors, d) test population, e) place of research application, f) research gap, g) objective, h) methodology, i) results found, and j) discussion.

3. RESULTS

The Science Direct, Scopus, and Web of Science databases search string found 403 articles. After reading the titles and abstracts of each of the articles found, 33 articles with potential for inclusion were accepted. In the second round of evaluation, after reading the articles in full, 17 articles met all the inclusion criteria. The filtration process presented can be observed through the following flowchart:

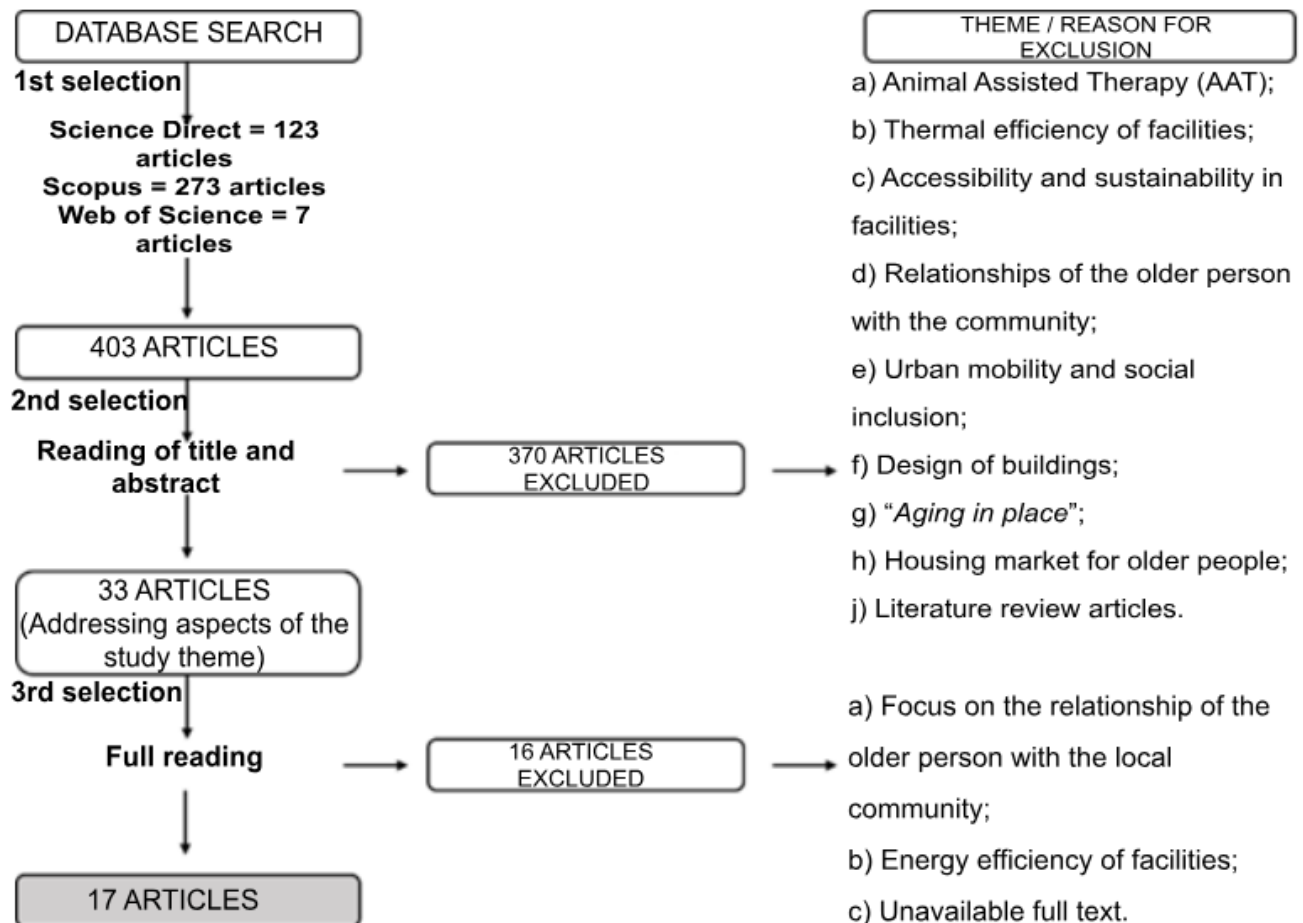


Figure 01 – Flowchart of the SLR stages.

Source: Authors.

The articles not included in a general analysis involve studies that mainly address: Animal Assisted Therapy (AAT), observing the relationship of the older person with animals; issues related to thermal efficiency, sustainability, accessibility, and design of facilities to support the older person; the relationship of the older person with the local community and their ways of appropriating urban green spaces, relating issues about urban mobility and social inclusion in the community; research aimed at “aging in place,” a term that can be defined as “[...] ability to age in

a stable environment and aims to enable older adults to maintain independent living circumstances in their own home.” (TISSOT, 2022); benefits of physical activity for older people, involving the relationship with the urban environment; real estate market, focusing on the social inclusion of the older person; literature review articles; articles with unavailable full text. Articles that passed the third selection stage were read in full and evaluated using a data extraction form. Table 01 summarizes the 17 selected articles with their main contents tabulated.

Authors	Location / Year	Objective	Methods	Sample	Main results
A. R. Kearney; D.I Winterbottom	United States (2005)	To investigate how nature is related to the psychological well-being and quality of life of residents in Long-Term Care Facilities.	Interview	40 older adults from 3 different facilities	Residents value access to green spaces and derive benefits from those spaces, but they spend relatively little time in those environments.
S. D. Rodiek; J. T. Fried	United States (2005)	To investigate the visual preferences of images that portray different environmental conditions of Long-Term Care Facilities.	Visual preferences	133 older adults from 14 different facilities	Residents preferred the characteristics of the modified images with the prevalence of plant elements, such as viewing for nature and garden furniture.
A. Bengtsson; C. Hägerhäll; J. Englund; P. Grahn	Sweden (2015)	To discover the ideal composition of outdoor environmental factors in homes for older people.	Semantic description of the environment	26 older adults and 26 staff from 3 different facilities	The environment that came closest to the ideal environment was a park environment, larger and with greater vegetation variation than the other environments.
L. Reynolds	United States (2016)	To examine how older people value nature, how they use the outdoor spaces of the garden, and what personal factors influence their use of the gardens.	Interview, focus group, and behavior mapping	32 older adults from 2 different facilities	The views of nature are of fundamental importance for the well-being of the older residents; in addition, access to nature influences the choice of facilities.
V. Cerina; F. Fornara; S. Manca	Italy (2017)	To analyze the effects of the design characteristics of residential facilities on the psychosocial responses of older people.	Visual preferences and questionnaire	192 non-institutionalized older adults	Equipment characterized by a certain architectural style and surrounded by green spaces can increase older people's comfort and satisfaction levels.

Authors	Location / Year	Objective	Methods	Sample	Main results
K. Strout; J. Jemison; L. O'Brien; D. Wihry; T. Waterman	United States (2017)	To evaluate the feasibility of installing gardens in homes for low-income older people and assess the effects of gardening on nutrition and cognitive outcomes.	Focus group and application of the "Mini-Mental State Examination (MMSE)" and "Mini Nutritional Assessment (MNA)"	10 older adults living in a private housing project	Participants increased their protein, vegetables, and water intake, demonstrating improvements in health and cognition. They expressed a desire to expand the study to include indoor gardening during the winter months.
C. K.Y. Lai; R. Y.C. Kwan; S. K.L. Lo; C. Y.Y. Fung; J.n K.H. Lau; M. M.Y. Tse	China (2018)	To examine the effects of horticultural therapy on the psychosocial well-being of nursing home residents.	Behavioral And Comparative Observation	111 older adults from 4 different facilities	Horticultural therapy has been shown to be effective in promoting subjective happiness for older people. Its favorable effect suggests that horticultural therapy should be used to promote psychosocial well-being.
X. Wang; S. Rodiek	China (2019)	To explore common landscape and "hardscape" features to learn which ones users prefer.	Visual Preferences	283 non-institutionalized older adults	Small gender differences in visual preferences and increased preference for seat access with advancing age were found.
C. Freeman; D. L. Waters; Y. Buttery; Y. Van Heezik	New Zealand (2019)	To explore the impacts of age-related health conditions of older people on connection with nature and identify the types of connections with nature and green spaces.	Photographic voice and Geographic Information System	72 older adults, with only 13 living in *facilities *Unspecified Quantity	Older people valued the ability to engage with nature and, even when limited by health, still valued contact through the care of small gardens and potted plants. The loss or reduced contact with nature can be deeply felt by them.
M.H. E. M. Browning; K. Lee; K. L. Wolf	United States (2019)	To examine the relationship between green space coverage and depressive symptoms in older people living in care facilities	Tree cover mapping and mental health data collection	30 facilities *Unspecified number of older people	An inverse relationship between tree canopy cover and depressive symptoms was observed. Homes for older people should invest in nature-based therapy to improve the mental health of residents.

Authors	Location / Year	Objective	Methods	Sample	Main results
M. Elsadek; Y. Shao; B. Liu	China (2021)	To investigate the impacts of physiological relaxation from the visualization of bamboo images.	Visual stimuli and questionnaire	34 non-institutionalized older adults	Visual stimulation with a bamboo image significantly decreased the heart rate of older people. Indirect contact with nature enhances physiological and psychological conditions.
W. Peng; H. Shi; Mengying Li; Xinghui Li; T. Liu; Y. Wang	Shanghai (2021)	To explore the associations between exposure to green areas and geriatric depression among older people.	Interview	1.066 non-institutionalized older adults	Higher residential exposure to vegetation is significantly associated with a lower prevalence of geriatric depression.
C. H. Hsieh; C. M. Chen; J. Y. Yang; Y. J. Lin; M. L. Liao; K. H. Chueh	Taiwan (2021)	To explore the physiological and psychological benefits of immersive garden experiences.	Virtual reality device, interview, and use of physiological data sensor	14 older adults living in *facilities *Unspecified quantity	Continuous trend of decreasing heart rate throughout the experiment, meaning participants felt calmer after the experience, which brought short-term cardiovascular and psychological benefits and helped relieve stress.
W. Noor Anira W. A. Yaacob; N. H. M. Hussain; N. M. Nayan; M. Abdullah; M. Z. Teh	Malaysia (2022)	To investigate the care requirements of older people with green gardens to support their active aging and green garden design preferences.	Interview and use of the observation tool entitled "Senior Outdoor Survey (SOS)"	16 older adults and 4 staff from 1 facility	Landscaping design considerations in green gardens were identified as prominent in the preferences of older people in homes intended for this population.
T. Sugiyama; A. Carver; M. Sugiyama; A. Lorenzon; T. E. Davison	Australia (2022)	To examine associations of views of vegetation in residential facilities for older people with changes in multiple measures of psychological well-being.	Interview and behavioral observation	52 older adults from 13 different facilities	The results revealed changes in depression, stress, anxiety, and quality of life of older people. The visible vegetation of the common areas beyond the perimeter of the equipment contributed favorably to the residents' stress and quality of life.

Authors	Location / Year	Objective	Methods	Sample	Main results
V. S. Klemenci; V. Ž. Leskovar	Slovenia (2022)	To analyze the importance of green areas in creating an inclusive living environment for older people during COVID-19, in addition to detecting a possible correlation between outdoor areas and the risk of infection.	Use of the "Secure and Connected" tool	259 older adults from 3 different facilities	Accessibility to outdoor space plays a key role in physical health and well-being. The presence of rooms with balconies and terraces, eye contact with outdoor areas, and more open spaces and green areas are associated with fewer infections.
J. Guo; S. Yanai; T.Kodama	Tokyo (2022)	To examine the effects of the characteristics and perceptions of community gardens on the frequency of gardening activities, the absence of leisure activities, and the attitudes of facility managers towards gardening activities.	Questionnaire	44 managers of *facilities *Unspecified quantity	The use of vegetable gardens was positively associated with the number of equipment and the absence of barriers. The availability of support affected residents' ability to use the gardens. The most important benefits were the pleasure of cultivating and harvesting and promoting interaction and health.

Table 01: Synthesis of the selected articles

Source: Authors.

From tabulating the selected articles, one can perceive that the issues about the preferences and behaviors of older adults concerning contact with green spaces and natural elements in facilities, in their own homes, or even through community gardens were addressed with greater emphasis from 2019, and 10 out of the 17 articles were published in the last five years (2019 to 2023). It highlights the relevance of this field of research, in addition to the limited exploration of the subject in Brazil in articles indexed in these databases covered, given the lack of articles produced in the country addressing this theme.

3.1 Location of the studies

Seven studies from this group were conducted in Asia, four of them, in particular, in China; five in North America, all of them in USA; three in Europe and two in Oceania. South America did not appear in studies from databases selected.

3.2 Analysis of objectives

When verifying the objectives of each study, it was possible to divide them into 3 groups with different focuses and directions. The first group, composed of 4 articles, addresses visual, environmental and design preferences of older adults about the built spaces and the landscapes. The second group, composed of 10 articles, is formed by studies that seek to relate nature to the quality of life and health, investigating how older people value green spaces and what benefits come from this contact with nature. Finally, the third group, composed of 3 articles, presents studies exploring the indirect contact that can be established with nature and how this strategy can benefit older people.

In the first group are located the studies by Rodiek e Fried (2005); Bengtsson, Hägerhäll, Englund, and Grahn (2015); Cerina, Fornara, and Manca (2017); Wang and Rodiek (2019), which propose to investigate the visual preferences and composition of environmental factors of older people in LTCFs, in the outdoor environments of

these facilities, in the design of buildings, and common landscapes and “hardscapes,” respectively.

In the second group, we highlight the studies by Kearney and Winterbottom (2005), Reynolds (2016), Strout, Jemison, O'Brien, and Waterman (2017), Lai, Kwan, Lo, Fung, Lau, and Tse (2018), Freeman, Waters, Buttery, and Heezik (2019), Browning, Lee, and Wolf (2019), Peng, Shi, Li, Li, Liu, and Wang (2021), Yaacob, Hussain, Nayan, Abdullah, and Teh (2022), Klemencic and Leskovaar (2022), and Guo, Yanai, and Kodama (2022), which have, in general, objectives to examine how nature relates to psychological well-being, quality of life, health, and active aging of older people, how older people value nature, what are the effects of gardening, community gardens, and horticultural therapy on nutrition, cognition, and well-being of older people and to examine the relationship between vegetable covers, green areas, depressive symptoms.

In the third group are located the studies by Elsadek, Shao, and Liu (2021); Hsieh, Chen, Yang, Lin, Liao, and Chueh (2021); Sugiyama, Carver, Sugiyama, Lorenzon, and Davison (2022), which investigate the impacts of psychological well-being from the visualization of bamboo images, explore the physiological and psychological benefits of immersive experiences in gardens, and analyze the impact of views of outdoor vegetation in residential facilities for older people, respectively, investigating the indirect contact of the older person with nature.

3.3 Means of publication and methodological strategies

Regarding the means of publication, journals related to the fields of housing for older adults and for aging, landscaping and urbanism, environmental science and pollution, medicine, environmental research and public health, design of health environments, community health nursing, and city planning stand out, with no great uniformity in journals. Among the methodological strategies, it was possible to identify a predominance of interviews (n=5), followed by the visual preferences method (n=3), questionnaire (n=3), behavioral observation (n=2), focus group (n=2), visual stimuli (n=2), mapping of tree cover or vegetation (n=2), comparative observation (n=1), behavior mapping (n=1), photographic voice (n=1), geographic information system (n=1), psychological examinations (n=1), semantic description of the environment (n=1), “Senior Outdoor Survey (SOS)”

tool (n=1), “Secure and Connected” tool (n=1), “Mini-Mental State” tool (n=1), and “Mini Nutritional Assessment (MNA)” tool (n=1). Among the 17 articles, 6 applied a single methodology, 9 applied two methodologies, and only 2 studies applied three methodological strategies.

3.4 Research subjects

Among the 17 articles analyzed, 16 had older adults as their target group, and only one dealt with the perspective of managers of the facilities on the behavior of the older residents. Regarding these 16 studies, 11 worked with institutionalized older people, and, of these, only 2 also considered the employees of said facilities for data collection.

Among the 5 articles that did not consider institutionalized older adults, the following studies stand out: Cerina, Fornara, and Manca (2017), which analyzed the psychosocial responses of the older population on the design characteristics of facilities, having interviewed 192 older adults who were recruited voluntarily in places such as urban parks, shopping malls, and squares, located in different places in the city of Sardinia, Italy; Strout, Jemison, O'Brien, Wihry, and Waterman (2017), who evaluated the feasibility of installing gardens in a private housing complex; Xinxin Wang, and Susan Rodiek (2019), who evaluated the landscape preferences of 283 older adults who walked through urban parks in the city of Nanjing, China; Mohamed Elsadek, Yuhan Shao, and Binyi Liu (2021), who measured the impact of indirect natural stimuli on the physiological and psychological states of 34 older volunteers; and Peng, Shi, Li, Li, Liu, and Wang (2021), who conducted a cross-sectional survey among people older adults living in urban areas of Shanghai city.

3.5 Main results found

Analyzing the articles again in 3 different groups, the first group is characterized by addressing the visual preferences of older people, the second is formed by studies that seek to relate nature to the quality of life and health, and the third group is characterized by articles that explore the indirect contact between nature and older people, it is possible to highlight the main results found by these 3 dimensions of studies.

3.5.1 Visual preferences

Among the articles that form the first group is the photographic comparison study by Rodiek and Fried (2005), which demonstrated that institutionalized older adults prefer photographs that represent conditions that have been identified as encouraging outdoor use, such as abundance of paths, comfort, abundance of vegetation, access to views beyond the limits of the facility, presence of windows, and preview of outdoor spaces. The fact that the least preferred images in the study portray the real conditions of the facilities suggests that facilities could be designed more efficiently to support the behavioral needs of older people for outdoor access.

The study by Bengtsson, Hägerhäll, Englund, and Grahn (2015), on the other hand, showed that both older adults and the employees of the facilities prefer outdoor environments that are not very open and not very closed in order to generate a certain level of security and privacy, but at the same time, to guarantee the visualization beyond the limits of the facility, in order not to create the feeling of enclosure. In this study, the authors concluded that the outdoor environments in facilities for older people should offer a uniform balance, without extremes in the forms and content of their elements, ensuring recognition and familiarity by the resident older person. In contrast, originality must also be present, characterizing a stimulating environment.

Also, about the group characterized by addressing visual preferences, there is the study by Cerina, Fornara, and Manca (2017), who demonstrated that older people expressed more positive evaluations for residential facilities with an architectural style similar to a house that provides a feeling of "being at home" and continuity with their own place identity. Regarding green spaces, it was possible to identify a preference for places with vegetation, noting a more positive attitude towards short-term relocation and a decreased feeling of broken attachment to home.

Finally, the study by Wang and Rodiek (2019) found that when comparing digitally modified photographs of the same park environment, which represented 7 different environmental conditions, the research participants especially preferred "ground cover plants," suggesting a preference for observing continuous vegetation along the paths instead of barren lands, followed by "bench with back and arm support" and "colored flowers." The "available seats" feature was preferred over features that include "plant diversity," followed by "visual accessibility"

and "canopied trees." Regarding the images that portrayed "visual accessibility," the participants preferred the views of water elements more than those that allowed viewing of grassy areas. All 7 environmental conditions that depicted natural elements and urban furniture were significantly preferred by participants over images that did not feature any of these features.

3.5.2 Nature and quality of life

Among the articles that form the second group, characterized by relating nature to the quality of life and health, is the Kearney and Winterbottom (2005) study, which collected data about the daily lives of 40 institutionalized older people, who indicated that the outdoors makes them feel mentally and physically better. Other benefits mentioned were the fact that they felt invigorated, the possibility of moving away from the facilities, the possibility of meeting people, the change in attitude or perspective, the feeling of longing, exposure to the sun, and the healing effect. Regarding the views from the windows, residents stated that they like to view gardens, plants, birds, people, and landscapes, in addition to viewing the climate, wild and pet animals, and the sky. The authors also suggest guidelines for designing gardens in facilities for older people, such as providing easy access to nature, ensuring the diversity of vegetation, maximizing opportunities for passive interactions with nature, optimizing window views, and taking advantage of nearby green spaces.

Emphasizing the intrinsic relationship between older people and nature, in the study by Reynolds (2016), the value that participants reported having for nature was described as an affinity with life, and plants were perceived almost as people. According to the author, it seemed comforting for older adults to care for plants, a role very similar to the family routine of caring for children and grandchildren, as if they were affirming their self-identity and competence from significant activities, such as gardening. From the results, it was possible to perceive that although a well-designed and planned garden is ideal for promoting the active involvement of older people, ensuring an outdoor environment that provides a connection with the natural processes of life, such as growing plants, animals interacting with nature, seasonal changes in plants, and blooming flowers, can also be critical.

Regarding plant care and examining the effects of the characteristics and perceptions of community gardens on the frequency of gardening activities, the absence of leisure activities, and the attitudes of facility managers toward gardening activities, Guo, Yanai, and Kodama (2022) found that the most important benefits of this practice were the improvement of health, the promotion of social interaction, and the pleasure of cultivating and harvesting. The study also showed that the tendency to attend and perform activities in community gardens is directly associated with barrier-free design elements, the variety of types of equipment, the area occupied by the garden, interaction, community aesthetics, and a sufficient number of participating members. Moreover, the study pointed out that the availability of support from employees, volunteers, and family members affected the ability of older people to access and use the community garden. This issue is aggravated by the fact that, many times, these spaces are the only means that residents have to be in contact with nature.

Following the theme of activities conducted with nature, Strout, Jemison, O'Brien, and Waterman (2017) assessed the effects of gardening on the nutrition and cognition of older people. They found that the study participants increased their protein intake and consumption of vegetables and water, in addition to demonstrating improvement in self-assessment of health and nutritional status. The scores of participants on the Mini-Mental State Examination (MMSE) tool improved over the 17-week intervention. This was followed by a significant improvement in social interactions through joint garden care and sharing surplus vegetables with others. Finally, the older adults participating in the intervention also found a desire to expand the study to include indoor gardening during the winter months, which demonstrates the need to adapt indoor spaces to accommodate activities and elements that may be connected with nature.

Presenting different data, the research by Lai, Kwan, Lo, Fung, Lau, and Tse (2018) with institutionalized older adults who performed horticultural activities shows that only the score of the "Subjective Happiness Scale" had a significant interaction effect and that there was a downward trend in the mean score of the "Geriatric Depression Scale." The authors state that the findings provide preliminary support for the biophilia hypothesis and that horticulture should be used to promote the psychosocial well-being of the most frail older people, but that although previous studies report that horticulture can improve many psychosocial

problems, health parameters, and quality of life in frail older people, the results of the present study did not show such positive effects, except for the report of participants on subjective happiness.

Regarding the importance of nature for older people, Freeman, Waters Buttery, and Heezik (2019), in their survey of 72 older adults in New Zealand, found that 90% rated nature as 4 or 5 on a scale of 1 to 5. All participants who experienced a certain fragility in their health reported actively seeking natural experiences, even if only through a window view. Older people especially valued this element and reported having their favorite windows. Therefore, the authors point out that homes for older adults should be designed with a view to green spaces and/or natural resources since these views can be the main or only way to engage with nature. These data corroborate the results of Kearney and Winterbottom (2005). Additionally, it should be noted that when a change in health resulted in the loss of access to the garden and the ability to practice gardening, this was felt in a deeply negative way since, for many, socialization and green space are closely linked.

In line with the theme of proximity to vegetation, the study by Browning, Lee, and Wolf (2019), who examined the relationship between green space coverage and depressive symptoms in institutionalized older people, obtained results that demonstrated inverse associations between the percentage of tree canopy coverage in the vicinity of facilities and the percentage of residents who were depressed. According to the analyses, this association becomes weaker as the vegetation is further away from the facility. Combined with previous work, this study provides early evidence that homes for older people should invest in nature-based therapy to improve the mental health of residents.

Related to these results is the research by Yaacob, Hussain, Nayan, Abdullah, and Teh (2022) that confirmed that going to the green space was perceived as good for the mind and self-satisfaction of employees and older people, who consider it essential to see plants and observe nature. Participants exposed to outdoor garden space also had lower scores for feelings of anger and fear. It was possible to conclude that the most necessary items for the garden in the care facility were the abundance of vegetation since older adults showed a significant correlation between vegetation and safety, as well as easily accessible or elevated plants and seats with a pleasant view.

Peng, Shi, Li, Li, Liu, and Wang (2021) explored the associations between exposure to green areas and geriatric depression, obtaining results that suggest that greater residential exposure to vegetation is significantly associated with a lower prevalence of depression.

In the study on the importance of green areas during the COVID-19 period, Klemenci and Leskovar (2022) presented different situations for the 3 facilities analyzed since only two had generous green areas that allowed a variety of passive and active uses by older people. These two facilities also stood out for having more rooms with balconies and terraces, eye contact with outdoor areas, and, mainly, for being associated with fewer infections. The facility with the worst situation in terms of outdoor space was the one with the highest degree of infections among residents. In this sense, the authors confirmed that, among many other factors, accessibility to outdoor space plays a key role in the physical health and well-being of residents of homes aimed at older adults.

3.5.3 Indirect contact with nature

Regarding the research that forms the third group, characterized by articles that explore the indirect contact between nature and older people, there is the study by Elsadek, Shao, and Liu (2021), who demonstrated that after viewing bamboo images, older people presented higher scores for the feeling of comfort, relaxation, and joy. The results also showed that participants were more alert and focused when viewing bamboo images than urban images. Bamboo images resulted in a slight decrease in sympathetic nerve activity, thus relieving stress and promoting well-being. The study provides scientific evidence of the benefits of indirect contact with nature, and it is possible to conclude that people who cannot have direct contact with green spaces can obtain similar benefits by making contact indirectly.

Corroborating the findings, the research by Hsieh, Chen, Yang, Lin, Liao, and Chueh (2021), which sought to explore the physiological and psychological benefits of immersive garden experiences, found that there was a continuous trend of decreasing heart rate throughout the experiment, meaning the emotions of the 14 participating older people changed from a state of excitement, in the pre-test phase, to a calmer state. The authors state that after summarizing the interviews, it was found that the videos watched by the participants recalled their past and allowed them to relive happy moments, in addition to relieving stress. The results

prove that the virtual reality device provided an alternative outdoor experience for older people who could not leave the nursing home due to COVID-19, bringing positive emotions even for residents with dementia, who became calmer and more stable.

In contrast to these studies, there is the study by Sugiyama, Carver, Sugiyama, Lorenzon, and Davison (2022) that sought to examine the relationship between the visualization of vegetation from dormitories and common areas and the levels of depression, stress, anxiety, and quality of life of recently admitted older people in care facilities. The results indicate that the amount of vegetation within the limits of the facilities, visible from common areas, was not associated with depressive symptoms or anxiety, but was adversely associated with stress and quality of life. The presence of vegetation in the participant's dormitory was not associated with any result, which may be related to the small presence of visible vegetation in this location.

According to the authors, possible explanations for the unexpected discoveries relate to the fact that residents may feel frustrated if they are not allowed to access the garden areas. In addition, vegetation quality plays a key role since some facilities have neglected or very dark gardens shaded by adjacent buildings. However, viewing vegetation beyond the perimeter of the facilities was associated with a lower increase in stress levels, a decrease in anxiety, and an improvement in quality of life. The results suggest, therefore, that viewing vegetation outside the limits of the facilities can protect against the decline of the psychological well-being of the residents.

4. DISCUSSION

From a comparative analysis, it was possible to observe that research related to visual preferences indicates a predilection of older people for comfortable, safe, (physically and visually) accessible, familiar environments that offer a uniform balance between their forms and content of their components and with the presence of vegetation and windows that offer the visualization of these elements. Rodiek and Fried (2005) found that older adults prefer images of encouraging outdoor spaces, while Bengtsson, Hägerhäll, Englund, and Grahn (2015) preferred moderately open outdoor environments, offering security and views beyond the facilities. Cerina, Fornara, and Manca (2017) revealed a preference for residential facilities with an architectural style similar to

a house, providing a sense of familiarity, while Wang and Rodiek (2019), by focusing on aspects related to parks, found that older people prefer continuous vegetation, benches, and colorful flowers in outdoor environments, also valuing natural elements and urban furniture.

Regarding research that seeks to relate nature and quality of life, the physical and mental well-being aspects that contact with green spaces can bring stand out. All studies reported great satisfaction from older people when in contact with nature, even from visualizing vegetation through windows, emphasizing the innate connection between humans and the natural environment, even from indirect contact. Kearney and Winterbottom (2005) revealed that the outdoors brings mental and physical benefits, while Reynolds (2016) highlighted the affinity of older people with nature, especially through gardening. Regarding horticultural therapies, Guo, Yanai, and Kodama (2022) identified the benefits of gardening for health and social interaction, emphasizing the importance of accessible design in gardening areas. Strout, Jemison, O'Brien, and Waterman (2017) observed improved nutrition and cognition through gardening, and Lai, Kwan, Lo, Fung, Lau, and Tse (2018) associated horticulture with subjective happiness.

Fostering the theme, there is the research by Freeman, Waters Buttery, and Heezik (2019), who showed the active search for natural experiences, emphasizing the importance of window views for green spaces, in addition to Browning, Lee, and Wolf (2019) who found an inverse relationship between vegetation cover near facilities and depressive symptoms. Yaacob, Hussain, Nayan, Abdullah, and Teh (2022) highlighted the mental benefits of exposure to green areas, while Peng, Shi, Li, Li, Liu, and Wang (2021) associated green areas with improved physical and mental health, including geriatric depression, data emphasized by Klemenci and Leskovar (2022) that highlighted the importance of access to green areas during the COVID-19 pandemic for the physical health and well-being of institutionalized older adults. In general, these studies emphasize the need to design accessible and green outdoor spaces and promote activities of contact with nature to improve the quality of life and health of older people.

Among the research in the third group, which explores the indirect contact between nature and older people, Elsadek, Shao, and Liu (2021) found that viewing bamboo images resulted in greater comfort, relaxation, and joy, in addition to reducing stress and promoting well-being, suggesting that indirect contact with nature

can bring similar benefits to direct contact. Hsieh, Chen, Yang, Lin, Liao, and Chueh (2021) observed a reduction in heart rate and calmer emotions in older people after immersive garden experiences through virtual reality, providing an outdoor alternative for those who could not leave due to COVID-19. However, Sugiyama, Carver, Sugiyama, Lorenzon, and Davison (2022) found that the amount of vegetation visible within the facilities was not associated with depressive symptoms or anxiety, but rather with stress and quality of life. On the other hand, the visualization of vegetation outside the facilities was linked to an improvement in the psychological well-being of the residents.

The discussions reveal the complexity of the relationships between older adults and nature, highlighting the importance of varied approaches that include both the design of outdoor spaces and residential facilities and the promotion of activities that provide direct or indirect contact with nature, given that it is not always possible to guarantee direct access to green areas, especially in contexts where the older person is frail. Ultimately, research suggests that ensuring access to nature and incorporating natural elements into residential environments can play a key role in promoting the physical, emotional, and social well-being of older people, and it is essential to consider individual preferences and the cognitive and physical capacities of this group when designing spaces and promoting activities.

5. CONCLUSION

This systematic literature review sought to identify the preferences of older adults concerning green spaces and natural elements in the architectural configuration of Long-Term Care Facilities for Older Adults. The systematization of the selected articles made it possible to reflect on the theme from 3 research axes: visual preferences, nature and quality of life, and indirect contact with nature.

In analyzing the subjects participating in the studies, it was possible to identify that 16 studies had older adults as their target group. At the same time, only one dealt with the perspective of the facilities managers. Of these 16 studies, 11 worked with the institutionalized group; of these, only two also considered the employees of said facilities for data collection. This inclusion could open other perspectives on the theme, given that it is a group closely related to the dynamics of Long-Term Care

Facilities and the experience of older people inserted in these spaces. Also, it is noteworthy to include, in future research and consider the circumstances of the sample, the family members of the institutionalized older person in order to enrich the research data by obtaining different perceptions and understandings about the facilities and the older person's well-being.

Regarding the methodological strategies, it was possible to identify a predominance of the application of interviews and the visual preferences method combined with questionnaires. The stimulus to conversation and measurement of visual preferences may be related to the greater ease of obtaining data from the referred group, which may present difficulty in participating in methods that include writing and locomotion, especially in the case of frailer older people.

The selected articles could be divided into three groups according to their different research focuses. In this sense, it was possible to point out three themes related to the objectives of each group, the first being characterized by investigating the visual preferences and composition of environmental and design factors that older people presented about built spaces and landscapes, the second formed by studies that seek to examine how nature is related to psychological well-being and quality of life, and the third group that presents studies that investigate the indirect contact of the older person with nature.

From the results presented and the proposed discussion, it is concluded that research related to visual preferences indicates a predilection for comfortable, safe, accessible, familiar environments with plenty of vegetation and views of natural elements. Among the research that seeks to relate contact with nature, directly and indirectly, and quality of life, only one does not present positive results regarding immediate proximity to vegetation. However, the other studies confirmed the aspects of physical and mental well-being that contact with green spaces can bring. It is pointed out that the divergent results may suggest specific issues regarding the particularities of the facilities that were the object of study of this research.

Notably, the contact established with nature is presented as an innate impulse to the human being, and green spaces play an essential role in the experience of the institutionalized older person, especially for the frailest, where this contact can be established through viewing outdoor spaces. Hence, it is vital to highlight that no study mentions the direct connection between built space and natural elements, either through materials,

colors, shapes, or the very vegetation present inside the facilities, which could be of great value to older people who, due to health and mobility issues, sometimes spend more time inside the environments of the facilities and do not establish a direct and sufficient contact with nature to benefit from this connection. Therefore, the need to conduct more specific investigations on the subject is highlighted to foster the development of this study area and present more in-depth information on the experience of older people living in Long-Term Care Facilities.

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IMPACT NOISE ISOLATION OF FLOOR SYSTEMS USING PLASTERBOARD CEILING WITH AND WITHOUT PET WOOL

ISOLAMENTO AO RUÍDO DE IMPACTO DE SISTEMAS DE PISOS UTILIZANDO FORRO DE GESSO COM E SEM LÃ DE PET

AISLAMIENTO AL RUIDO DE IMPACTO DE SISTEMAS DE PISOS UTILIZANDO TECHO DE YESO CON Y SIN LANA DE PET

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ABSTRACT

The acoustic insulation against impact noise of two floor systems was evaluated, using plasterboard lining installed under a prefabricated ribbed slab with prestressed joists, combined with PET wool in the lining. The tests followed the requirements of the ISO 16283-2 standard (ISO, 2020), and the data in accordance with the ISO 717-2 standard (ISO, 2020). Performance was classified by the values of the $L'_{nt,w}$ results established in the Brazilian standard NBR 15575-3 (ABNT, 2021). The flooring systems were composed of ceramic floors, vinyl floors, laminated wood floors and mechanical decoupling of the subfloor with glass wool and recycled rubber. Two situations were tested, with plasterboard lining (150 mm gap), and the second with filling the gap with 50 mm PET wool. From the experiments it was possible to conclude that the placement of 50 mm of PET wool blanket in the gap improved impact noise isolation by up to 3 dB, only in systems where there is no mechanical decoupling. Note that the better the impact noise insulation of the flooring system without PET wool in the lining, the less efficient the placement of this fibrous material will be.

KEYWORDS

Architectural acoustics. Sound insulation. Building performance.

RESUMO

Avaliou-se o isolamento acústico ao ruído de impacto de dois sistemas de piso, usando forro de gesso cartonado instalados sob uma laje pré-fabricada nervurada com vigotas protendidas, combinados com lã PET no entreforro. Os testes seguiram os requisitos da norma ISO 16283-2 (ISO, 2020), e os dados de acordo com a norma ISO 717-2 (ISO, 2020). O desempenho foi classificado pelos valores dos resultados de $L'_{nt,w}$ estabelecidos na norma brasileira NBR 15575-3 (ABNT, 2021). Os sistemas de piso eram compostos por pisos cerâmicos, pisos vinílicos, pisos laminados de madeira e com desacoplamento mecânico do contrapiso com lã de vidro e borracha reciclada. Foram testadas duas situações, com forro de gesso acartonado (entreforro 150 mm), e a segunda com preenchimento do entreforro com lã PET 50 mm. A partir dos experimentos foi possível concluir que a colocação de 50 mm de manta de lã PET no entreforro melhorou em até 3 dB no isolamento de ruído de impacto, apenas em sistemas onde não há desacoplamento mecânico. Nota-se que quanto melhor for o isolamento de ruído de impacto do sistema de piso sem lã PET no entreforro, menos eficiente será a colocação desse material fibroso.



PALAVRAS-CHAVE

Acústica arquitetônica. Isolamento sonoro. Desempenho de edificações.

RESUMEN

Se evaluó el aislamiento acústico al ruido de impacto de dos sistemas de piso, utilizando techo de yeso cartón instalado debajo de una losa prefabricada nervada con viguetas postensadas, combinados con lana PET en el entretecho. Las pruebas siguieron los requisitos de la norma ISO 16283-2 (ISO, 2020), y los datos de acuerdo con la norma ISO 717-2 (ISO, 2020). El rendimiento fue clasificado según los valores de los resultados de $L'_{nT,w}$ establecidos en la norma brasileña NBR 15575-3 (ABNT, 2021). Los sistemas de piso estaban compuestos por pisos cerámicos, pisos vinílicos, pisos laminados de madera y con desacoplamiento mecánico del contrapiso con lana de vidrio y goma reciclada. Se probaron dos situaciones, con techo de yeso cartón (entretecho de 150 mm), y la segunda con el llenado del entretecho con lana PET de 50 mm. A partir de los experimentos, se pudo concluir que la colocación de 50 mm de manta de lana PET en el entretecho mejoró hasta 3 dB en el aislamiento del ruido de impacto, solo en sistemas donde no hay desacoplamiento mecánico. Se observa que cuanto mejor sea el aislamiento acústico al ruido de impacto del sistema de piso sin lana PET en el entretecho, menos eficiente será la colocación de este material fibroso.

PALABRAS CLAVE

Acústica arquitetônica; Aislamiento acústico; Desempeño de edificaciones.

1. INTRODUCTION

The growing verticalization of cities has driven a search for new technologies that allow for lower costs and greater agility in construction times. Furthermore, the use of increasingly larger spans in projects has brought a demand for construction techniques that meet this need, such as, for example, the use of slab prestressing systems. Thus, it became imperative that this search for optimizing construction processes did not compromise the quality of the products delivered to users (PEREYRON; SANTOS, 2007).

In view of the improvement in Brazilian housing, the Brazilian performance standard, NBR 15.575 (ABNT, 2021a), came into force in Brazil in July 2013, which determined the requirements regarding safety, habitability and sustainability in residential housing, relating them to the construction systems that make up these buildings. In 2021, this regulation was updated.

Therefore, among the requirements set out in NBR 15,575 (ABNT, 2021a), it is essential that a reflection be carried out on the acoustic performance of the materials that make up the flooring systems, even in the design, execution and use phases of residential buildings.

This research aimed to evaluate the acoustic insulation behavior against impact noise of two different flooring systems, using a plasterboard lining installed under a prefabricated slab of prestressed joists and ceramic tiles, combined or not, with PET wool in the interior of the gap. Furthermore, it classifies the acoustic performance of the tests according to the requirements established by the Brazilian standard ABNT NBR 15.575-3 (ABNT, 2021).

2. LITERATURE REVIEW

The Brazilian standard NBR 15.575 (ABNT, 2021) established requirements for the safety, habitability, and sustainability of residential buildings to improve the performance of dwellings. Thus, it is important to evaluate the impact of sound insulation performance on different floor systems. A few studies were found in the literature. For instance, Lee et al. (2016) stated that designers must evaluate the sound insulation conditions between apartments, whether by a wall or slab. Oliveira and Mitidieri Filho (2012) emphasized the significance of acoustic performance in the design process, considering various types of noise generated by activities such as walking, moving furniture, or objects falling (MORENO; SOUZA; PENTEADO, 2017). Post-occupancy studies conducted on dwellings

indicated that the main complaint of users was related to the annoyance produced by impact noise caused by neighbors (ANDARGIE; TOUCHIE; O'BRIEN, 2021.; FRESCURA and LEE, 2021.; SANTANA; MAUÉS; SOEIRO, 2017).

Additionally, an on-site assessment carried out in four different apartments complexes with one hundred (100) residents from each location, totaling four hundred people (400), found that the answers were significantly affected by impact noise sensitivity and the properties of the floor system used (PARK and LEE, 2019). An example of a solution to noise insulation for floor systems was the execution of a suspended ceiling in the noise reception area for airborne and impact noise (SANTOS, 2012).

Impact noise is propagated through structural links, so mechanical decoupling of rigid structures is the best solution (SANTOS, 2012). Studies like this one are necessary to investigate potential solutions, such as ceiling systems, which are normally used for airborne noise isolation when decoupling is not possible.

Some studies indicated the inefficiency of ceilings for homogeneous floor systems like reinforced concrete slabs (MEDEIROS, 2003.; RYU; SONG; KIM, 2018.; MAXIMILIAN; PAUL; THOMAS, 2021). Unlike what was found (in computer simulations) when it was compared to slabs composed of hollow clay blocks with more complex materials to impact sound propagation (OLIVEIRA; PATRÍCIO. 2017.; SOUZA; PACHECO; OLIVEIRA, 2020).

Although the execution of a suspended ceiling can be inefficient for the sound insulation of homogeneous slabs like reinforced concrete, this technique could be efficient for heterogeneous slabs since there are layers of materials and, consequently, change the impedance due to the vibrational responses of the systems (MAXIMILIAN; PAUL; THOMAS, 2021). Alonso, Patrício and Suárez (2019) evaluated the impact of sound insulation and concluded that the acoustic behavior of floors differs significantly, whether homogeneous or not.

Thus, it is important to determine the efficiency of installing ceiling systems to mitigate the impact noise of heterogeneous flooring systems like hollow clay floor slab blocks. As mentioned by the authors (NOWOTNY and NURZYNSKI. 2020), the effect of floor coating on decreasing impact sound pressure level needed to be corrected because the acoustic properties of the coating depend on the number of layers over the slab (NOWOTNY and NURZYNSKI. 2020).

Light wooden ceilings and floors had the potential to provide superior insulation compared to systems based only on concrete slabs, if mechanically decoupled from

external elements (CHUNG et al., 2010). This type of ceiling needs to include systems components such as tie rods with damping, fiberglass wool, and layers of sawdust mixture to avoid vibration (CHUNG et al., 2010).

The studies that used wall-to-wall ceilings (without connections to the slab) were compared with the performance of suspended ceilings under the slab. Differences of 2 to 7 dB and 2 to 8 dB were found for tests done with a standard impact machine and rubber ball, respectively (KIM; CHO; KIM, 2021). For floating floors, a low resonant frequency of mass-spring-mass systems and the high damping in the resilient layer material allow frequency-dependent improvements of up to 10 dB (MAXIMILIAN; PAUL; THOMAS, 2021).

This can be achieved by a low rigidity of the support system and the choice of a ceiling with high mass (MAXIMILIAN; PAUL; THOMAS, 2021). From the point of view of the two possibilities of acoustic conditioning (insulation and sound absorption), ceilings with microperforated panels using glass wool in the interlining performed a reduction of 6 dB for the weighted impact sound pressure level. Also, they presented a coefficient of absorption of 0.6 in the 100 Hz band (RYU; SONG; KIM, 2018).

Furthermore, among the variety of options for ceiling systems found on the market, there is the possibility of using a plasterboard ceiling with sound-absorbing material in the ceiling to improve the insulation against impact noise. One material that could be used for this purpose is fibrous, such as those composed of polymeric waste like polyethylene terephthalate (PET), widely used in the packaging industry and mainly in producing plastic bottles (KLIPPEL FILHO; LABRES; PACHECHO, 2017).

In Brazil, fibrous materials such as glass or rock wool are commonly used in civil construction. These materials have specific conditions such as thermal conductivity, bulk density, chloride, fluoride, silicate, sodium content, and moisture absorption (ABNT, 2014.; ABNT, 2013).

For example, Medeiros (2003) tested several compositions of plasterboard ceilings executed under a solid slab, some of which contained rock wool. In these tests, the rock wool placed in the ceiling had a minor influence on the impact noise insulation provided by the floor system, although it improved the performance for low frequencies. Also, it is important to note that the materials used as sound absorbers comply with the technical standards and current fire safety legislation (TORMOS; FERNÁNDEZ; RAMIS-SORIANO, 2011).

3. MATERIALS AND METHODS

The Brazilian Standard ABNT NBR 15.575-1 (ABNT, 2021) established the minimum building performance requirements. Different aspects are mentioned, such as acoustics, thermal, lighting, structural, fire safety, and water impermeability. For impact noise, the required performance criteria are divided into three categories: minimum (M), intermediate (I), and superior (S) (ABNT, 2021). Furthermore, the methodology of measurements must be carried out according to the ISO 16.283-2 standard (ISO, 2020). Finally, the values provided in NBR 15.575-3 (ABNT, 2021) were used to classify the performance of floor systems in terms of impact noise, for cases of separation of autonomous housing units, as presented in Table 1.

Separating element	$L'_{NT,w}$ (dB)	Performance
The floor system of autonomous housing units over dormitory.	66 to 80	Mínimum (M)
	56 to 65	Intermediate (I)
	≤ 55	Superior (S)
Flooring systems areas for collective use (leisure and sportsactivities, such as home theater, gym, party room, games room, collective bathrooms and changing rooms, kitchens, collective laundries, and circulations) over dormitory of autonomous housing units.	51 to 55	Mínimum (M)
	46 to 50	Intermediate (I)
	≤ 45	Superior (S)

Table 1: Weighted standardized impact sound pressure level classification ($L'_{NT,w}$)

Source: ABNT, 2021.

3.1. TESTS SETUPS

The acoustic tests were carried out at the building and material laboratory of the Federal University of Santa Maria in a chamber built specifically for impact noise tests, according to standard ISO 16283-2 (ISO, 2020). The chamber walls were made of solid concrete block masonry with nineteen centimeters (19) of thickness and coated with three (3) centimeters of roughcast and plaster on both sides of the walls.

Above these walls, a prefabricated slab was built with prestressed slab joists with clay elements and a total

thickness of 13.5 cm. The prestressed joists had dimensions of 10 cm in width, a height of 8.5 cm, and 4 longitudinal steel bars with a diameter of 5 mm. The clay tiles had dimensions of 37 cm, 8 cm, and 20 cm for width, height, and depth, respectively. The distance between the axis of the joists was 47 cm. The thickness of the concrete above the slab was five (5) centimeters and was made with characteristic compressive strength of 25 MPa and a steel mesh of 4.2 mm, spaced every 15 to 15 cm. Also, it was positioned electrical conduits of 0.75 inches in diameter embedded in the concrete.

Figure 1 shows an image of the tested prestressed slab joists with clay elements. Figures 2 (a) and (b) present the dimensions of the concrete chamber, showing the floor plan of the chamber and the section with the details of the emission and reception room and the support of the slab.

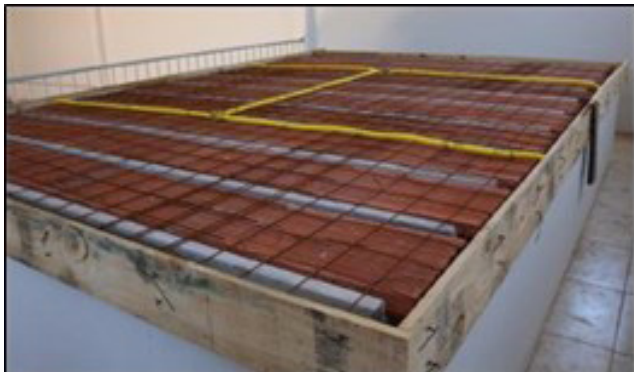


Figure 1: Slab assembled in the test site
Source: The authors.

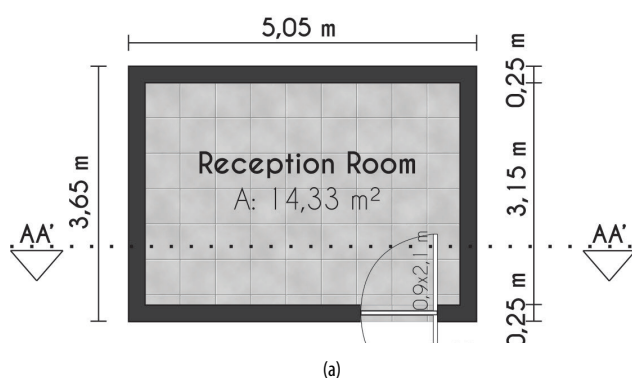
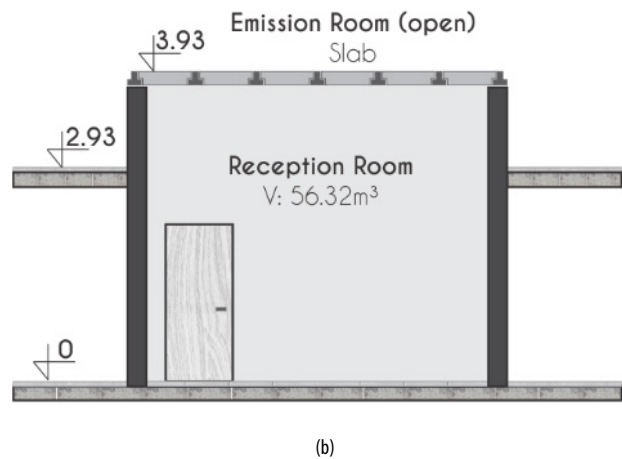


Figure 2: Details of test: (a) floor plan and (b) section AA'
Source: The authors.



3.2. MATERIALS USED IN THE TESTS

An accredited PET wool blanket supplier was chosen, whose material was classified as Classes II-A or higher, according to IT n° 10 of CBPMESP (OLIVEIRA and MITIDIERI FILHO, 2012). PET wool was composed of polyester fiber without any addition of resin, with a surface density of 0.350 kg/m², a thickness of 50 mm, and an apparent specific mass of 7 kg/m³.

To make it possible to conduct tests with different coatings and resilient materials, a subfloor plate was positioned superimposed on the slab, together with different types of coatings. This research simulates, in a laboratory, the field situation, using elements of structural connections and electrical installations on the slab to represent an evaluation of the finished construction situation. Thus, according to what is prescribed in the ISO 10140-3 and ISO 10140-4 standard (ISO, 2021), the subfloor size used had dimensions of 1 per 1 m. In addition, the minimum dimensions established must exceed 0.35 per 0.35 m.

The subfloor plates were produced with mortar, and cement and sand proportions in volume were 1:4, reaching a mean compressive strength of 20 MPa. Figure 3 presents an example of the subfloor used in tests. The coating materials used in this research are shown in Table 2 and illustrated in Figures 4 (a), (b), and (c).



Figure 3: Tested subfloor sample.
Source: The authors.

Coating	Characteristics	Dimensions	Density (kg/m ³)
Ceramic Figure 4 (a)	Porcelain	500 x 500 x 9	2200
Vinyl Figure 4 (b)	Plate	200 x 1220 x 4	600
Wood laminate Figure 4 (c)	Clicked ruler	445 x 1357 x 8	800

Table 2: Coating materials used in measurements.

Source: The authors.

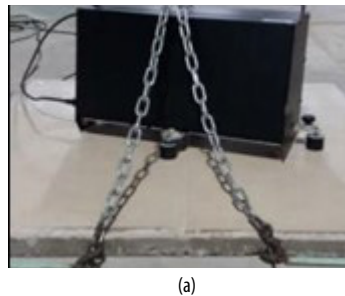
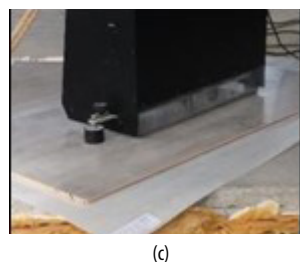
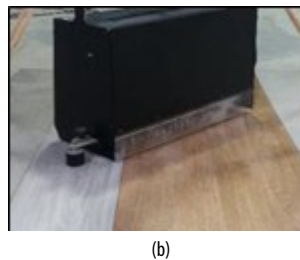


Figure 4: Coatings used in the tests: (a) ceramic, (b) vinyl and (c) wood laminate
Source: The authors.



A glass wool blanket with a density of 60 kg/m³ (thickness of 15 mm) and a recycled rubber pad with a density of 600 kg/m³ (thickness of 5 mm) were used as resilient materials, used to improve system performance, and evaluate the ceiling's ability to improve this sound insulation for impact noise further. Figure 5 demonstrates an example of the presentation of glass wool (a) and recycled rubber (b) tested in this study.

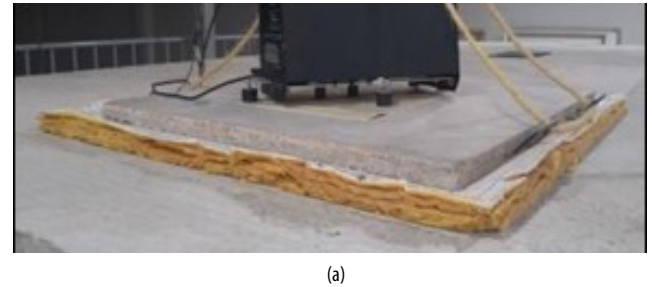
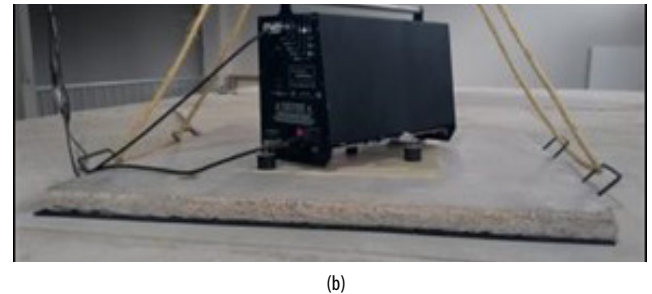


Figure 5: Resilient materials for floating floor: (a) 15 mm glass wool, (b) 5 mm recycled rubber
Source: The authors.



The metal structures were fixed along the chamber's perimeter at 150 mm below the slab for ceiling mounting, as depicted in Figure 6. For each metal bar, five supports were used to fix the metal structures to the joists.

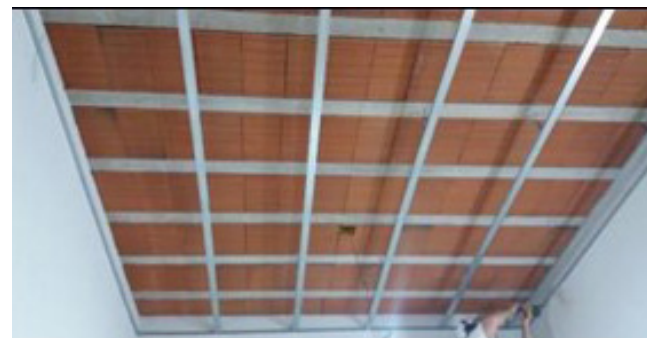


Figure 6: Metal bars for the plasterboard ceiling system
Source: The authors.

The plasterboard plates were fixed to the metallic bars using a combination of two systems of materials compositions to test the impact noise insulation as follows, the first one was called the reference or "PB", and was composed of a plasterboard ceiling and a plenum of 150 mm gap; the second one was called "PB+PW", and was composed of 50 mm of PET wool blanket to the reference component of the lining. Thus, after the first tests, the PET wool blanket was positioned on the plasterboard with a laser level and a metallic beacon. In both cases, the detail of the execution of the lining at the encounter with the wall was done respecting the angle and joint treatment. Figure 7 shows the PET wool in the lining and the metal structure fixed to the joist.



Figure 7: PET wool positioned in the lining
Source: The authors.

Finally, a treatment was done between gypsum boards with a plaster-based putty coat and micro-perforated tape, ending with another putty coat. Gypsum-based putty was also applied in the spots where the plates were perforated. Figure 8 presents the final appearance of the ceiling under the slab.

3.3. INSTRUMENTS OF TEST



Figure 8: Executed plasterboard ceiling
Source: The authors.

The material and building construction laboratory provided the equipment for the tests listed in Table 3.

Equipment	Manufacturer	Model
Amplifier	01 dB	AMPLI 12
Sound level calibrator	01 dB	4230, classe 1
Dodecahedral acoustic source	01 dB	OMNI 12
Standard impact machine	01 dB	CALPEST-one
Sound pressure level meter	01 dB	Black Solo, classe 1
Capacitive microphone	GRAS	MCE 212

Equipment	Manufacturer	Model
Microphone preamp	Metravib	PRE 21 S
Digital thermo-hygrometer	Instruterm	THB 100

Table 3: Instruments of test
Source: The authors.

The 01dB sound level meter black solo is a class 1 accuracy equipment according to specifications provided by the manufacturer. The calibrator used is by the procedure of CETAC-LCA-PC06 “sound pressure level meter calibration” and CETAC-LCA-PC-03 “sound pressure level meter calibration” found in IEC 61672-3:2013 (IEC, 2013) and IEC 60942:2017 (IEC, 2017) requirements for the calibration of sound pressure level meter and sound level calibrator, and the equipment was calibrated before its use by an accredited institute.

The methodological procedures for the test field followed the recommendations of ISO 16.283-2 (ISO, 2020). The test simulation of different field situations was carried out at the acoustic laboratory. The ISO standard 16.283-2 (ISO, 2020) establishes the test procedure to obtain the impact noise insulation measurements for standardized impact sources obtained in a room with a volume between 10 m³ and 250 m³, for 1/3 octave frequency bands of 50 Hz and 3150 Hz. A free field fixed microphone was used, although the sound level meter used had the inside correction for diffuse field measurement. Table 4 explains the number of impact source points and mic positions in the ISO standard 16283-2 (ISO, 2020).

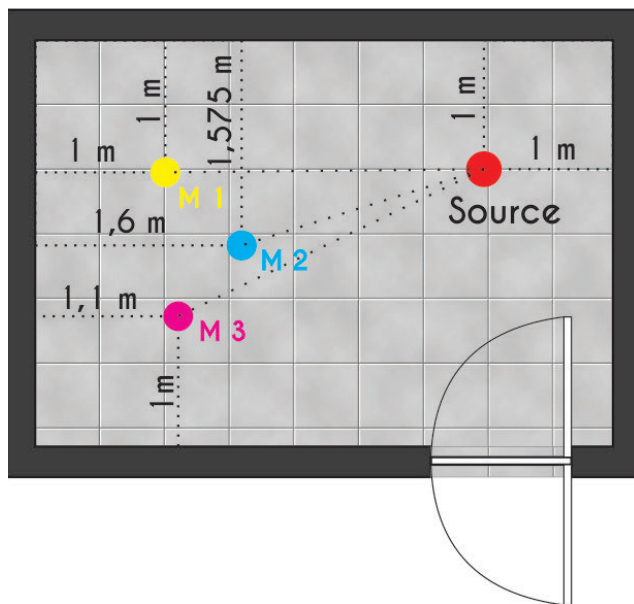
Reception room area (m ²)	Equipment	Number of positions
< 20 m ²	Standard impact machine	4
	Fixed microphone	4

Table 4: Instruments of test
Source: (ISO, 2020).

3.4. MEASUREMENTS PROCEDURES AND DATA ANALYSIS

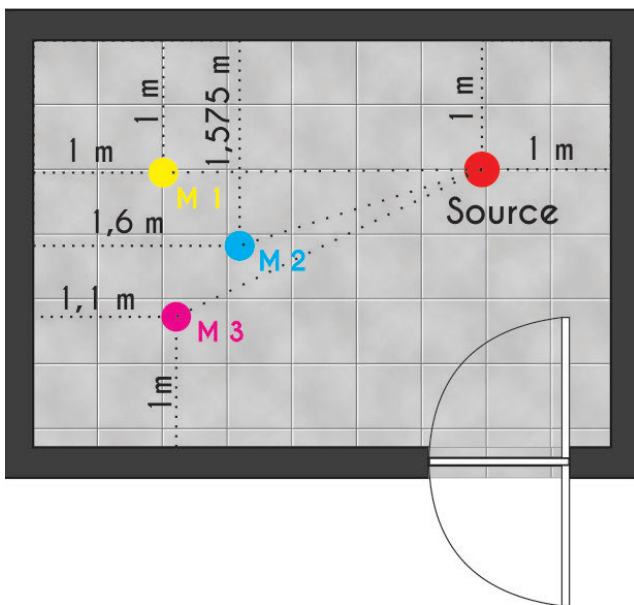
The Brazilian standard ABNT NBR 15.575-3 (ABNT, 2021) indicates that impact noise tests for floor systems must be carried out in accordance with ISO standard 16.283-2 (ISO, 2020). Therefore, the reverberation time, background noise level, and standardized impact sound pressure level were determined at the experimental tests.

The reverberation time was measured using the interrupted noise method described by NBR ISO 3382-2 (ABNT, 2017). Three microphone positions were used for the measurements for each sound source position. Two measurements were done for each microphone position to determine the reverberation time, totaling 12. The microphone height used in tests was 1.30 m; 1.90 m, and 2.3 m for microphones M1 and M6; M2 and M5, and M3 and M4, respectively. The microphone and sound source distance used in reverberation time measurement are depicted in Figures 9 (a) and (b).



(a)

Figure 9: Positions of sound sources and microphones (M) for reverberation time measurement
Source: The authors.



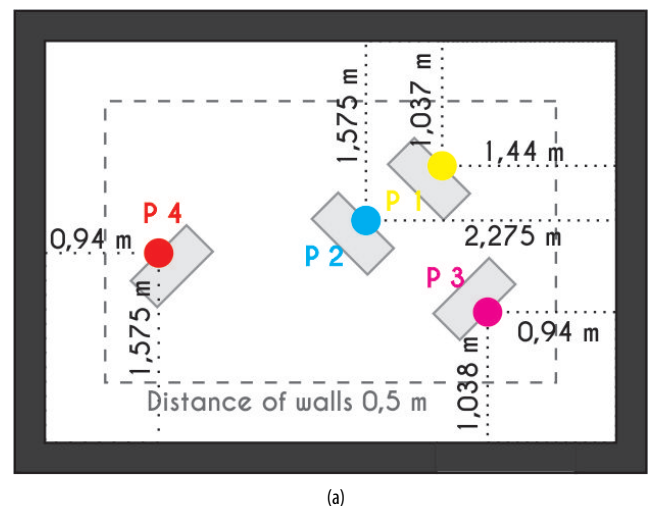
(b).

Background noise level and the standardized impact sound pressure level (L'_{nt}) measurements were carried out for ranges of 100 Hz to 3150 Hz for third-octave bands, according to the procedure described in ISO standard 16.283-2 (ISO, 2020). Four positions were used to measure the standardized impact sound pressure level (mic and tapping machine), distributed respecting the distance of 0.50 m from the edges of the floor.

The impact test machine used five hammers with 500 grams each, falling freely and repetitively from a height of 40 mm. Invariably, the hammer's positions were over the slab joists and at a direction angle of 450 degrees. Also, four microphones were positioned for each impact machine position.

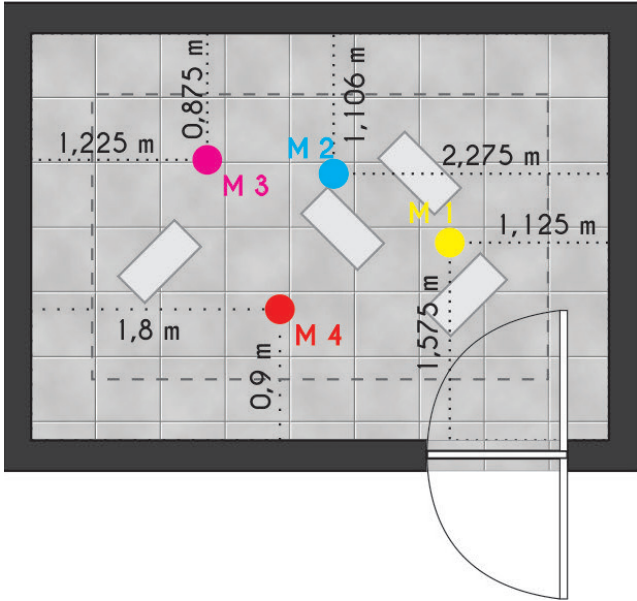
The microphone distribution followed the minimum distances of 0.70 m between the positions of the fixed microphones; 0.50 m between the microphone and the room reception limit; and 1.0 m between any microphone and the excited slab by the impact machine. Two measurements were taken for each microphone position, totaling a number of thirty-two (32) for background noise level and 32 measurements for standardized impact sound pressure level. For each microphone position, the following heights were used: M1 (1.20 m); M2 (1.60 m); M3 (2.10), and M4 (1.50 m). Figures 10 (a) and (b) depict the position of the impact machines and microphones distributed in a measurement room.

The L'_{nt} and $L'_{nt,w}$ calculations were performed according to the standards ISO 16283-2 (ISO, 2020) and ISO 717-2 (ISO, 2020), respectively.



(a)

Figure 10: Positions of sources (P) and microphones (M) for impact sound measurement.
Source: The authors.



(b).

Sample	Material
CF	Ceramic Floor
PB	Plasterboard
RR5	Recycled rubber pad of 5mm
GW15	Glass wool of 15 mm
VF	Vinyl Floor
LW	Laminated wood floor
S	Prefabricated slab with prestressed joists and ceramic tiles
SUB	The subfloor of 40 mm
PW	PET wool of 50 mm

Table 5: Material designations

Source: The authors.

	Composition of the floor system	$L'_{nT,w}$ (dB) Without PET wool	$L'_{nT,w}$ (dB) With PET wool
References	S: Prefabricated slab of 135 mm (HAAS et al., 2022)	91	-
	S+SUB: Prefabricated slab (135 mm) + Subfloor (40 mm) (HAAS et al., 2022)	84	-
	PB (reference): Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	74	71
	PB+SUB: Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	67	66
Ceramic floor	CF+PB: Ceramic floor (9 mm) + Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	68	65
	CF+RR5+PB: Ceramic Floor (9 mm) + Subfloor (40 mm) + Recycled Rubber (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	54	54
	CF+GW15+PB: Ceramic Floor (9 mm) + Subfloor (40 mm) + Glass Wool (15 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	50	50
Vinyl floor	VF+PB: Vinyl floor (4 mm) + Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	62	60
	VF+RR5+PB: Vinyl Floor (4 mm) + Subfloor (40 mm) + Recycled rubber (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	52	51
	VF+GW15+PB: Vinyl Floor (4 mm) + Subfloor (40 mm) + Glass Wool (15 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	46	46
Laminated wood floor	LW+PB: Laminated wood floor (8 mm) + Expanded Polypropylene (2 mm) + Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	57	55
	LW+RR5+PB: Laminated wood floor (8 mm) + Expanded Polypropylene (2 mm) + Subfloor (40 mm) + Recycled rubber (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	53	50
	LW+GW15+PB: Laminated wood floor (8 mm) + Expanded Polypropylene (2 mm) + Subfloor (40 mm) + Glass Wool (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	47	46

Table 6: $L'_{nT,w}$ resume of flooring system compositions with and without PET wool.

Source: The authors.

Comparing the results of Table 6, it was possible to identify the slab type's influence and the suspended ceilings' presence as a solution for impact noise isolation without floor covering. Impact noise is structural, system stiffness and mass can significantly change the values. In this case, adding a subfloor improved the results by 7 dB.

For PB floor system composition, the $L'_{nT,w}$ was 74 dB, showing an improvement in the impact sound isolation of about 17 dB in relation to the slab without plasterboard ceiling ("S") and 10 dB in relation to the slab and subfloor ("S+SUB") (HAAS et al., 2022). Plasterboard is a strategy generally used for airborne noise insulation, but for the slab under test, the results show an improvement when there are no floor coverings.

Also, Medeiros (2003) and Oliveira et al. (2021) found a similar reduction in direct impact noise transmission with ceilings for slabs types T, massive and hollow. The authors concluded that adding layers to the slab could provide lower values of $L'_{nT,w}$.

Adding 50 mm of PET wool blanket in the interlining improved the impact noise insulation of the PB floor composition by 3 dB (Figure 11). The same direction was found in the studies of Pagnoncelli and Morales (2016). The authors improved the impact noise insulation to 5 dB with rock wool over the ceiling. Just as PET wool improved

impact noise by 3 dB, when there is no mechanical decoupling of the upper floor, there is more high-frequency energy in the lower floor and, therefore, a sound-absorbing material improves the results. Thus, to improve the acoustic performance, using a PET wool blanket was a helpful solution only when it was impossible to mechanically decouple the upper floor with rubber or glass wool.

Different floor coverings were tested herein, as presented in Table 6. Among the compositions that used PET wool in the plenum, the systems with laminate floors such as LW+PB, LW+RR5+PB and LW+GW+PB obtained the best $L'_{nT,w}$ compared to those systems like vinyl or ceramic floors. For example, when the ceramic floor was changed by laminate, in the exact composition of the construction system, there was an improvement in $L'_{nT,w}$ from 65 dB (CF+PB) to 55 dB (LW+PB). Without PET wool in the plenum, the differences in $L'_{nT,w}$ were from 68 dB (CF+PB) to 57 dB (LW+PB), respectively. The same was identified in the study of Pagnoncelli and Morales (2016), who tested different combinations of floor systems. The authors got that the wooden floor reduced by 3 dB the impact noise by when compared to the ceramic floor for the same slab typology. The wool aided in the absorption of a high-frequency band, possibly improving the weighted result.

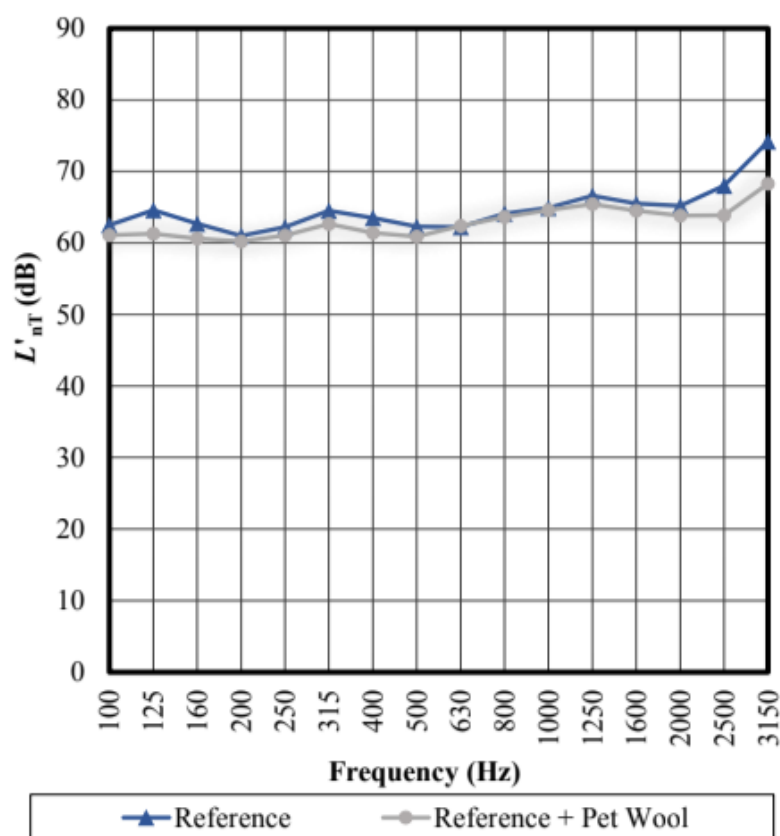


Figure 11: L'_{nT} values per third-octave frequency band in the tests for the "PB" reference samples with and without PET wool
Source: The authors.

The analyses show that adding the subfloor improved the system's performance in impact noise isolation. Initially, adding 40 mm of subfloor over the slab provided an insulation of 7 dB, the same value found by Haas et al. (2022). The results are presented in Figure 12.

It is identified that adding a subfloor adds mass to a slab typology filled with ceramic tiles. (LOURENÇO et al., 2022.; PARK; YOON; CHO, 2020). The impact noise insulation improvement of 50 mm of PET wool in the plenum was only 1 dB, which has negligible influence on the experimental results.

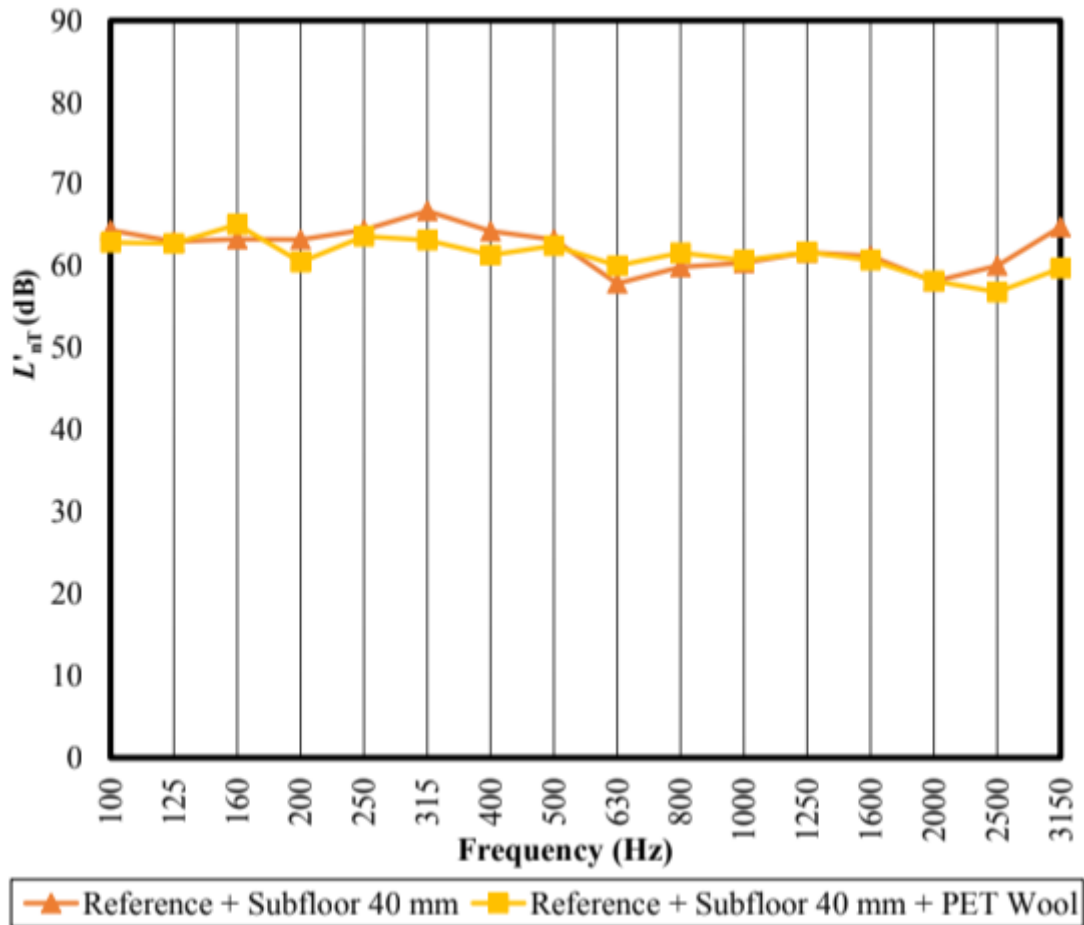


Figure 12: Test results for reference flooring systems with the subfloor

Source: The authors.

It was noticed that the use of 50 mm of thickness PET wool like CF+PB in the ceiling improved up to 3 dB (with PET wool in the plenum) in the impact noise insulation, because it mainly absorbs noise in the high-frequency bands. When the floor covering was mechanically

decoupled, the PET wool absorbed the high frequencies but did not change the final performance value. Figure 13 presents the experimental results for different compositions, according to the designation of Table 6. The graphs contain the L'_{nT} values by third-octave frequency band.

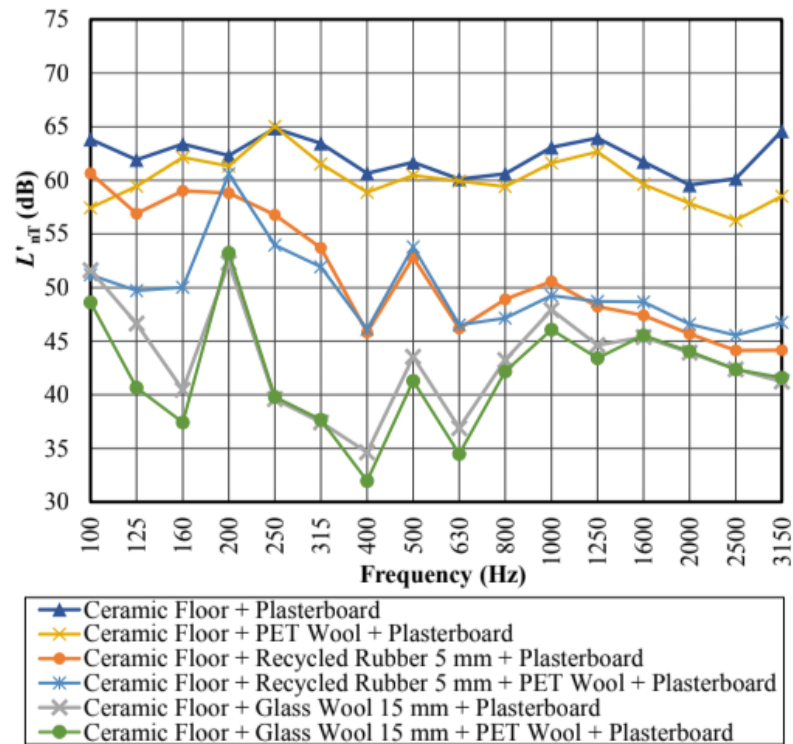


Figure 13: L'_{nT} values by third-octave frequency band in tests for ceramic floor systems

Source: The authors.

Installing resilient material among the linings modified the spectrum of the L'_{nT} values measured for the floor system without resilient material (CF+PW+PB), changing the system's behavior considerably. This occurred, especially for band frequencies below 250 Hz and above 1250 Hz.

On the other hand, for systems that are mechanically decoupled like those as CF+RR5+PW+PB and CF+GW15+PW+PB, the installation of PET wool in the plenum provided greater sound insulation for band frequencies of below 160 Hz and, also, 400 Hz e 630 Hz. Another important observation is that decoupling with rubber generated the most significant differences with and without PET wool, although the final weighted result did not change.

Despite the PET wool in the plenum modifying the frequency spectrum, significant changes in impact noise insulation are perceived with the improvement in the mechanical decoupling system, and not with the addition of plasterboard ceiling. Figure 14 presents the impact noise performance rating of the ceramic tile flooring systems studied in this research.

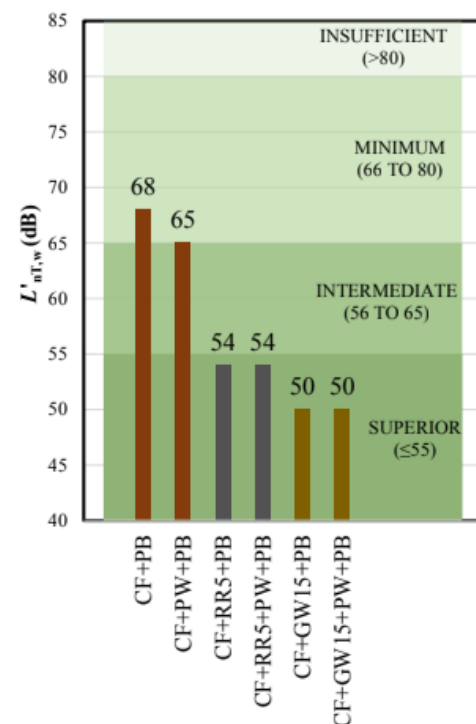


Figure 14: Performance of ceramic floor and ceiling systems as separating elements of autonomous housing units over bedrooms

Source: The authors.

In the first case (CF+PB), the addition of plasterboard lining brought the flooring system from minimum to intermediate (CF+PW+PB). These combinations of materials that promote mechanical decoupling from the floor can be classified as a superior level of performance according to NBR 15.575-3 (ABNT, 2021).

When it was inserted as a resilient material into the compositions of the floor system, the installation of PET wool in the plenum did not improve impact noise performance, as

seen in $L'_{nt,w}$ values. For the CF+RR5+PB and the CF+GW15+PB systems, when adding PET wool, the $L'_{nt,w}$ results kept the same performance at 54 and 50 dB, respectively.

Installing sound-absorbing material in the ceiling modified the curve of L'_{nt} values measured for the floor system without resilient material (VF+PW+PB). Except for the 200 Hz frequency, the addition of PET wool to the system attenuated the noise in the sound spectrum. Figure 15 demonstrates the L'_{nt} values for samples using vinyl floors.

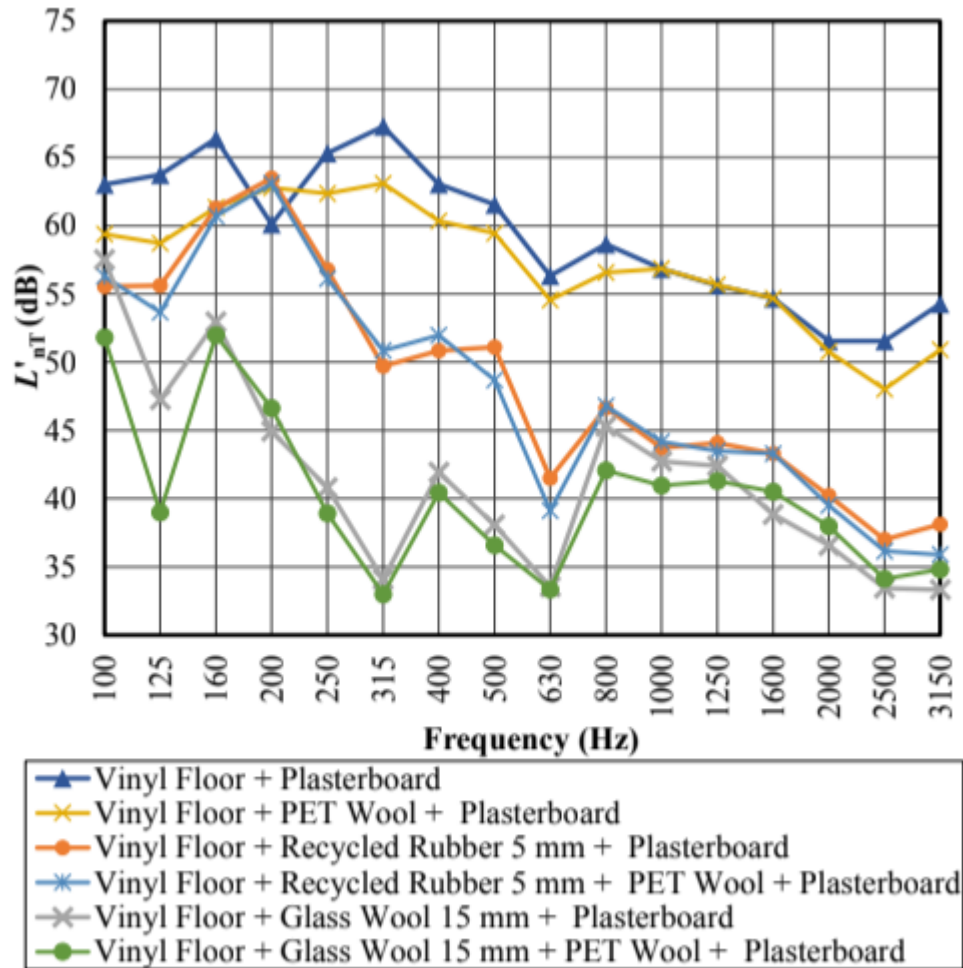


Figure 15: L'_{nt} values by third-octave frequency band in tests for vinyl flooring systems

Source: The authors.

With the mechanical decoupling of the subfloor with a recycled rubber pad (VF+RR5+PW+PB), it was noted that the installation of PET wool in the ceiling provided greater sound insulation for a frequency of 125 Hz (attenuation of 2 dB) and 630 Hz (attenuation of 3 dB). However, for compositions with recycled rubber pads (VF+GW15+PB and VF+GW15+PW+PB), the installation of PET wool in the interlining did not show significant differences in impact sound insulation. That is, the values of the L'_{nt} spectrum were close to each other. Figure 16 shows the impact noise performance classification of vinyl floor systems as separating elements of autonomous housing units over bedrooms.

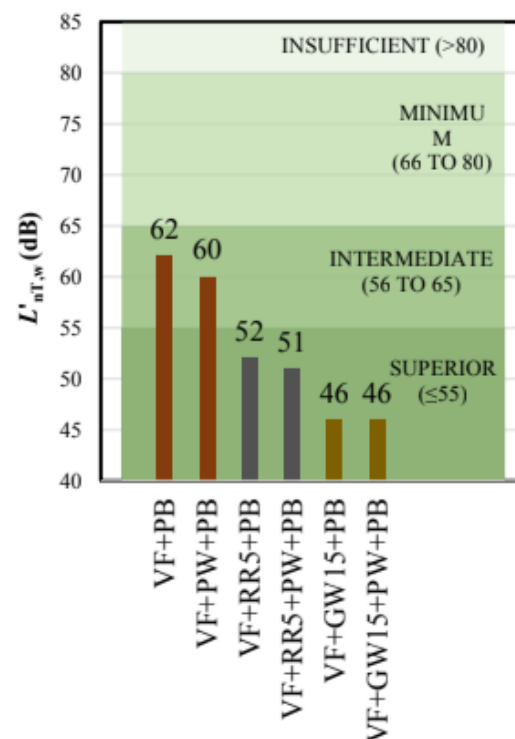


Figure 16: Performance of vinyl flooring and ceiling systems as separating elements of autonomous housing units over bedrooms

Source: The authors.

The same performance level of floor systems remained for vinyl floor compositions with PET wool in the plenum. Although the placement of PET wool in the system's interlining resulted in a 2 dB improvement in the impact noise insulation of the flooring system without resilient materials (VF+PW+PB), the system's performance level was maintained (intermediate). The VF+RR5+PB system resulted in a performance of $L'_{nt,w} = 52$ dB, and the addition of PET wool improved the impact noise insulation by 1 dB. However, both systems rank in the NBR as superior.

Regarding laminated wood floor, the results show that the application of PET wool in the ceiling caused a different behavior to the other types of coating, showing greater sound insulation in the frequency bands below 2000

Hz, as can be visualized in Figure 17. In addition to changes in the surface density of floor coverings, laminated wood floors have a polypropylene layer for laying, corroborating different behaviors in the frequency spectrum for sound insulation. Also, the system that had the most significant influence on the application of PET wool was LW+RR5+PB. There was an improvement of 9 dB in L'_{nt} for the 100 Hz frequency band and 5 dB for 500 Hz.

Thus, the PET wool improved the insulation regarding impact noise, mainly at low and medium frequencies. The results of the tests of the compositions with laminated wood cladding in the interlining are shown in Figure 17, whose graph contains the L'_{nt} values per third-octave frequency band.

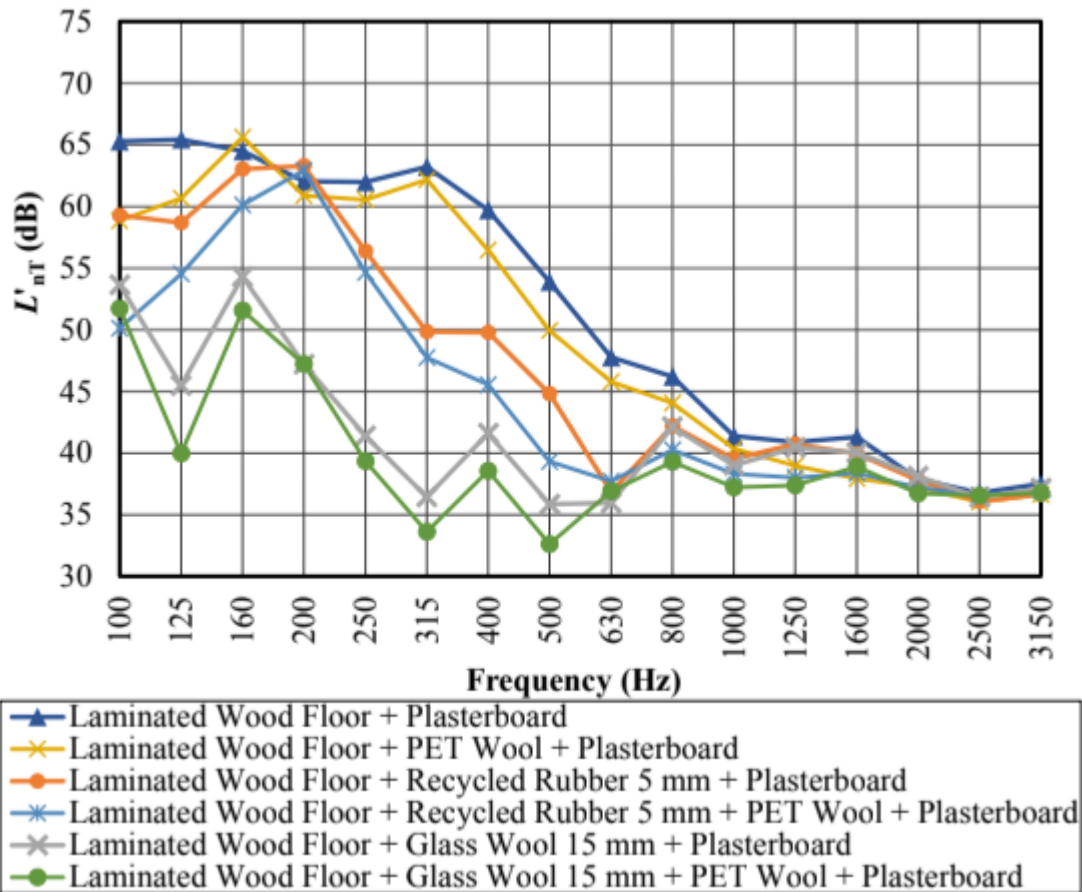


Figure 17: L'_{nT} values by third-octave frequency band in tests for wood laminate flooring systems

Source: The authors.

Figure 18 presents the impact noise performance rating of wood laminate floor systems. PET wool in the plenum and wood laminate flooring proved the most efficient ($L'_{nT,w} = 46$ dB). In addition, the placement of PET wool in the interlining of the flooring system without resilient material (LW+PW+PB) allowed it to reach a higher level of performance, improving $L'_{nT,w}$ by 2 dB.

In this case, without the pet wool, the performance was intermediate ($L'_{nT,w} = 57$ dB), and with the addition, the system reached superior performance ($L'_{nT,w} = 55$ dB). Thus, the superior level of performance provided for in NBR 15.575-3 (ABNT, 2021) was reached.

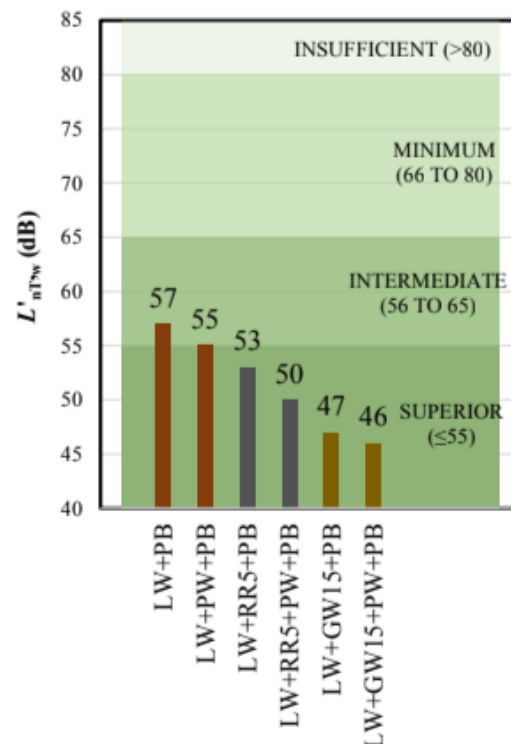


Figure 18: Performance of wood laminate flooring and ceiling systems as separating elements of autonomous housing units over bedrooms

Source: The authors.

Therefore, adopting wood laminate flooring in conjunction with the plaster lining with PET wool in the interlining results in higher performance ($L'_{nT,w} = 46$ dB). However, the results with PET wool did not test the performance of the samples. Thus, it is important to make the structural system compatible with techniques aiming for good acoustic performance.

From the above, the performances were better when the lining had an additional insulation layer. The use of PET wool evidences an absorption at high frequencies, which suggests its applicability in cases of insulation for airborne noise, and not for impact noise, as tested in this research. Furthermore, it is confirmed that other studies indicate that different strategies can be used to improve acoustic performance regarding impact noise. For example, the adoption of resilient materials in floating screeds, the use of suspended ceilings, and other alternatives that promote the discontinuity of the structure to attenuate the acoustic bridges (HAAS et al., 2022.; OLIVEIRA et al., 2021.; PARK; YOON; CHO, 2020).

The results indicate that placing absorbent material in the ceiling improves the impact noise insulation performance of flooring systems at low frequencies, as was concluded in different flooring systems (MEDEIROS, 2003.; RYU; SONG; KIM, 2018). However, Medeiros (2003) concluded that the rock wool placed in the ceiling had little influence on the impact noise insulation of a massive reinforced concrete slab.

5. CONCLUSIONS

The placement of a 50 mm thick PET wool in the plenum of the plasterboard ceiling system, installed under the prefabricated slab of prestressed joists and ceramic tiles analyzed, improved up to 3 dB in the noise insulation of impact. Two situations reached a higher performance level, considering the performance levels provided for in Brazilian standard NBR 15.575-3 (ABNT 2021), but which are linked to the mechanical decoupling of the subfloor, and not due to the addition of PET wool in the plenum. Notably, the acoustic performance of floor systems varies according to the geometry, volumes, execution details, and the unions between the building systems.

The results showed that PET wool significantly influenced the reduction of L'_{nT} at low frequencies in some mechanical decoupling systems, as in samples of laminated wood and vinyl flooring. In the reference samples, PET wool in the plenum resulted in up to a 3 dB improvement

in impact noise insulation. In the samples of ceramic flooring, the use does not show improvement, in the case of vinyl floors, this increase in sound insulation is in the order of 2 dB, as well as in laminated wood floors. The improvement of the PET wool occurs only when there is no mechanical decoupling, and there is no influence on the wool when the subfloor is uncoupled.

It is noted that the better the impact noise insulation of the flooring system without PET wool in the plenum, the less efficient the placement of this fibrous material. Also, the use of PET wool in the interlining is more efficient when combined with the use of laminated wood cladding. Using a resilient blanket on the slab and a 50 mm thick PET wool in the plenum proved ineffective in insulating impact noise for the systems with vinyl and ceramic coatings tested.

In future research, computer simulations will be used to compare the simulation with that obtained in the laboratory to encourage the use of these constructive systems in projects. In addition, new insulation materials will be tested in the ceiling and other ceiling systems to optimize this system's acoustic performance.

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STRATEGIC DECISIONS: A SUPPORT MODEL FOR PRIORITIZING PROJECTS IN THE BRAZILIAN TRANSPORT INFRASTRUCTURE

DECISÕES ESTRATÉGICAS: UM MODELO DE APOIO À PRIORIZAÇÃO DE PROJETOS NA INFRAESTRUTURA DE TRANSPORTES BRASILEIRA

DECISIONES ESTRATÉGICAS: UN MODELO DE APOYO A LA PRIORIZACIÓN DE PROYECTOS EN LA INFRAESTRUTURA DE TRANSPORTE DE BRASIL

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ABSTRACT

Efficient transportation infrastructure is essential for development but faces challenges such as resource demands, environmental impacts, and vulnerability to climate change. This study proposes an innovative action model for Brazil's transportation infrastructure, prioritizing financial viability, socioeconomic benefits, environmental sustainability, and resilience to climate impacts. The model focuses on optimizing resources, fostering adaptability, and promoting equitable development while addressing critical aspects like risk assessment, climate resilience, stakeholder involvement, and transparency. By integrating sustainability and climate adaptation, the study offers a holistic framework to enhance Brazil's transportation sector and ensure long-term resilience.

KEYWORDS

Brazilian transport infrastructure; Environmental sustainability; Climate change adaptation; Risk management; Resilience.

RESUMO

Infraestruturas de transporte eficientes são essenciais para o desenvolvimento, mas enfrentam desafios como alta demanda por recursos, impactos ambientais e vulnerabilidade às mudanças climáticas. Este estudo propõe um modelo de ação inovador para a infraestrutura de transporte no Brasil, priorizando a viabilidade financeira, os benefícios socioeconômicos, a sustentabilidade ambiental e a resiliência aos impactos climáticos. O modelo foca na otimização de recursos, na promoção da adaptabilidade e no incentivo ao desenvolvimento equitativo, abordando aspectos críticos como avaliação de riscos, resiliência climática, envolvimento de stakeholders e transparência. Ao integrar sustentabilidade e adaptação às mudanças climáticas, o estudo oferece uma estrutura holística para aprimorar o setor de transporte no Brasil e garantir sua resiliência a longo prazo.

PALAVRAS-CHAVE

Infraestrutura de transporte brasileira; Sustentabilidade ambiental; Adaptação às mudanças climáticas; Gestão de riscos; Resiliência.

RESUMEN

Las infraestructuras de transporte eficientes son esenciales para el desarrollo, pero enfrentan desafíos como la alta demanda de recursos, los impactos ambientales y la vulnerabilidad al cambio climático. Este estudio propone un modelo



de acción innovador para la infraestructura de transporte en Brasil, priorizando la viabilidad financiera, los beneficios socioeconómicos, la sostenibilidad ambiental y la resiliencia ante los impactos climáticos. El modelo se centra en la optimización de recursos, la promoción de la adaptabilidad y el impulso del desarrollo equitativo, abordando aspectos críticos como la evaluación de riesgos, la resiliencia climática, la participación de los stakeholders y la transparencia. Al integrar la sostenibilidad y la adaptación al cambio climático, el estudio ofrece un marco holístico para mejorar el sector del transporte en Brasil y garantizar su resiliencia a largo plazo.

PALABRAS CLAVE

Infraestructura de transporte brasileña; Sostenibilidad ambiental; Adaptación a los cambios climáticos; Gestión de riesgos; Resiliencia.

1. INTRODUCTION

An efficient and functional transportation infrastructure is vital for the smooth running of the economy and society (ERDOGAN, 2020; SANTOS *et al.*, 2021). However, its operation requires significant financial and spatial resources and is often associated with negative impacts (BRONIEWICZ & OGRODNIK, 2020).

From an environmental point of view, transport infrastructure has a wide-ranging impact on the environment (AMIRIL *et al.*, 2014; ASHER, GARG & NOVOSAD, 2020; DA COSTA *et al.*, 2022), affecting everything from obvious aspects such as the loss of local ecosystems and changes to the landscape, to emissions of air pollutants and greenhouse gases, noise and disturbances to the quality of ecosystems, as well as interference in hydrological processes (BRONIEWICZ & OGRODNIK, 2020; ASHER, GARG & NOVOSAD, 2020).

Attempts to integrate sustainability into the decision-making process for transportation infrastructure projects continue to gain momentum (BUENO, VASSALLO & CHEUNG, 2015; PAPP *et al.*, 2022). Transportation infrastructure projects often suffer from cost overruns and schedule delays, problems that persist despite the extensive research carried out in the field of transportation and planning over the past three decades. Unfortunately, progress in improving the performance of these projects has been limited (LOVE *et al.*, 2015).

The development and maintenance of an efficient and resilient transportation infrastructure plays a key role in the economic growth of any nation (DE ABREU *et al.*, 2022b; BAYOUMI *et al.*, 2022). In Brazil, a country with vast geographical dimensions and diverse transportation needs, making strategic decisions about infrastructure projects becomes crucial (DE ABREU *et al.*, 2023b). Transportation infrastructure projects generally involve large amounts of resources, long-term investments (AMIRIL *et al.*, 2014).

Therefore, the urgent need to develop an efficient and sustainable transport infrastructure is recognized, with a focus on cities that are more resilient to natural disasters and climate change, in line with the 2030 Agenda. This study proposes a model for action, considering financial viability, socioeconomic and environmental impact. In doing so, it aims not only to optimize the use of limited resources, but also to drive the equitable and sustainable development of

the country's transport system, since in 2023 there was a 3.2% increase in emissions from the transport sector, reaching an all-time high of 224 megatons of carbon dioxide equivalent (SEEG, 2024). In this context, this study proposes an innovative approach by presenting a model designed to facilitate decision-making in the prioritization of projects within Brazil's transport infrastructure.

2. METHODOLOGY

The development and implementation of the Brazilian transport infrastructure project prioritization model involved a careful and comprehensive methodological approach. This section describes the main steps and components used in the methodological process.

- **Definition of Objectives** - Initially, the model's objectives were defined, which include facilitating strategic decision-making in the prioritization of transport infrastructure projects, considering economic, socio-environmental and strategic aspects;
- **Literature Review** - An extensive literature review was carried out to understand the best practices, approaches and challenges faced when prioritizing transport infrastructure projects. This included academic studies, government reports and analysis by specialized consultancies;
- **Stakeholder Identification** - The main stakeholders relevant to the process of prioritizing transport infrastructure projects were identified and involved, including government representatives, private sector companies, non-governmental organizations and local communities;
- **Definition of Prioritization Criteria** - Based on the literature review and discussions with stakeholders, the criteria that would be considered when prioritizing projects were established. This included factors such as economic impact, financial viability, environmental sustainability, regional needs and long-term strategies;
- **Model development** - The prioritization model was developed using a multidisciplinary approach, integrating concepts from economics, engineering, social and environmental sciences. Quantitative and qualitative tools were used to evaluate and classify the projects according to the established criteria;
- **Model validation** - The model underwent a validation process, in which experts in the field of transport

infrastructure reviewed and tested its effectiveness. Adjustments and refinements were made based on the feedback received during this phase;

- Pilot Implementation - A pilot implementation of the model was conducted on a representative sample of transportation infrastructure projects in Brazil. This made it possible to assess its practical applicability and identify any challenges or limitations that needed to be addressed;
- Documentation and Dissemination - Finally, the model was comprehensively documented, including all stages of the methodological process, prioritization criteria and results obtained. In addition, efforts were made to disseminate the model among decision-makers, academic institutions and other stakeholders in the field of transportation infrastructure.

This comprehensive and participatory methodology ensured the robustness and relevance of the prioritization model developed, providing an effective tool for guiding strategic decisions in Brazilian transport infrastructure.

3. MODEL

The implementation of a project prioritization model in the Brazilian transport infrastructure is of paramount importance to optimize limited resources and face the growing challenges in this sector (DE ABREU *et al.*, 2023b). With Brazil's vast territorial extension and complex transportation needs, it is crucial to identify and select the most critical and strategic projects to promote economic and social development (SANTOS *et al.*, 2021). An effective prioritization model can consider various criteria, such as economic impact, current and future demand, environmental sustainability and technical feasibility, ensuring that investments are directed intelligently and in line with the country's long-term objectives (TRAN, YANG & HUANG, 2021). In addition, by providing a transparent and data-based framework for decision-making, this model contributes to increasing investor confidence, streamlining licensing processes and mitigating risks associated with the execution of large-scale projects (TSYGANOV, 2021).

Currently, in Brazil, the National Logistics Plan 2035 (PNL), developed by the Logistics Planning Company (EPL), and the General Guide for Socioeconomic Cost-Benefit Analysis of Infrastructure Investment Projects, published by the Ministry of Economy, can be cited as examples

of instruments for planning and evaluating transport infrastructure projects. The former addresses topics such as logistics efficiency and improvements in multimodal connectivity, mentioning aspects like energy efficiency and the reduction of greenhouse gas emissions only as byproducts of improved logistics efficiency. The latter focuses on assessing the economic feasibility of projects, estimating the socioeconomic impacts of infrastructure throughout its lifecycle, among other factors, mentioning emission reductions in the context of impact mitigation but not in terms of resilience.

Adopting a prioritization model can also catalyze the modernization and integration of transport infrastructure, promoting synergies between different modes and regions of the country. By identifying projects that complement and strengthen existing infrastructure, it is possible to create a more efficient and resilient network, capable of supporting economic growth and promoting national and international connectivity (PRUS & SIKORA, 2021). Furthermore, by prioritizing initiatives that encourage innovation and the adoption of disruptive technologies, such as intelligent transport systems and clean energy, the prioritization model can boost countries' competitiveness on the global stage and position the country as a leader in sustainable mobility solutions (DMYTRIIEVA, 2020).

It is essential to emphasize the importance of promoting studies aimed at increasing the resilience of transportation infrastructure to climate change, considering both soft adaptations and hard adaptations (DE ABREU, SANTOS & MONTEIRO, 2022). Soft adaptations encompass political, social, and educational measures that seek to foster adaptation through changes in behavior, public policies, regulations, technical training, and societal awareness. Examples of these actions include awareness campaigns, integrating climate resilience into city master plans, and creating incentives for sustainable practices in the transportation sector (DE ABREU *et al.*, 2023a).

On the other hand, hard adaptations refer to structural and technological measures focused on the design, construction, and modernization of physical infrastructure to make it more resistant to climate impacts (DE ABREU *et al.*, 2022a). Examples include elevating roads in flood-prone areas, using more durable materials adapted to extreme temperature variations, implementing more efficient drainage systems, and constructing barriers against natural disasters such as storms and landslides (DE ABREU, SANTOS & MONTEIRO, 2022).

By integrating these two approaches in a complementary manner, it is possible to promote a more

comprehensive and effective adaptation, balancing preventive and corrective actions. Investing in the combination of social and structural measures not only strengthens the resilience of transportation infrastructure but also contributes to the development of cities and systems that are more adaptable, safe, and sustainable, aligning with the challenges posed by climate change and the objectives of the 2030 Agenda (DE ABREU *et al.*, 2024b).

A good transport infrastructure model should focus on several key aspects as shown in Figure 1. First, it must prioritize projects efficiently by developing a systematic

approach that considers strategic factors, economic impact, and regional needs (TSAMBOULAS, 2007). Additionally, resource allocation optimization is essential, requiring a model that ensures the proper use of financial, technological, and human capital to guarantee successful project execution, as suggested by De Assis *et al.* (2022a; 2022b). Another crucial factor is the identification and mitigation of challenges and risks associated with each project, incorporating strategies for adaptation in the decision-making process (DE ABREU, SANTOS & MONTEIRO, 2022; ROKICKI & OSTASZEWSKI, 2022).



Figure 1: Aspects that should be considered in a transportation infrastructure model with a focus on sustainability.

Source: Made by the authors.

The model must also be aligned with broader national goals, policies, and long-term strategies for transport and infrastructure development, as highlighted by De Assis *et al.* (2022a; 2022b). Furthermore, it is important to involve stakeholders, including government agencies, private sector entities, and local communities, to enhance the inclusiveness and acceptance of the model (KOPPENJAN, 2005). Finally, adaptability and scalability are vital; the model should be flexible to adjust to changing circumstances and scalable for implementation at different government levels, accounting for geographic and demographic diversity (De Abreu, Santos & Monteiro, 2022).

The support model incorporates a comprehensive, multifaceted methodology that blends quantitative

and qualitative factors to enhance the decision-making process for transport infrastructure projects as shown in Figure 2. One of its core components is data analysis. By using in-depth data analysis, the model assesses the feasibility of projects, taking into account their potential impact on regional development and their compliance with environmental sustainability goals. This approach ensures that each project aligns with broader objectives, such as fostering regional growth while adhering to sustainability criteria, as emphasized by De Abreu, Santos & Monteiro (2022).

Another significant component is cost-benefit analysis. This rigorous evaluation method helps determine the economic viability of each project by considering both

short-term and long-term returns on investment. Through this analysis, the model ensures that resources are allocated efficiently, maximizing the economic impact of transport infrastructure projects (De Assis et al., 2022a; 2022b).

Risk assessment also plays a critical role in the support model. By conducting a thorough analysis of potential risks, obstacles, and challenges that may

arise during the project's lifecycle, the model provides valuable insights that contribute to more effective risk management. This proactive identification of risks helps to mitigate issues before they become significant problems, improving project outcomes and reducing unforeseen costs (De Abreu, Santos & Monteiro, 2022; Rokicki & Ostaszewski, 2022).



Figure 2: Key components to be considered in a sustainability-focused transport infrastructure model.
Source: Made by the authors.

Scenario planning further enhances the model's robustness by anticipating future changes in technology, population dynamics, and economic conditions (DE ABREU, 2024). By developing flexible scenarios, the model can adapt to shifting conditions in dynamic environments, ensuring that transport infrastructure projects remain resilient and relevant over time. This forward-thinking approach allows decision-makers to adjust plans based on future uncertainties, improving the longevity and sustainability of infrastructure investments.

Another vital element is contingency budgeting, which addresses the common issue of cost and schedule overruns in transport infrastructure projects (DE ABREU et al., 2024a). During the contract award phase, a construction contingency budget is typically established to accommodate unplanned events, such as changes in project scope. This financial cushion allows projects to stay on track despite unexpected developments, as

highlighted by Love et al. (2014) and Locatelli et al. (2017). The inclusion of this budget minimizes disruptions and ensures that project timelines and financial plans are better managed.

Lastly, public-private collaboration is essential for the successful execution of prioritized projects. The model encourages active collaboration between the public and private sectors, drawing on the strengths of both entities. Public-private partnerships allow for the pooling of knowledge, funding, and innovation, leading to more effective and efficient project implementation. By leveraging the expertise and resources of both sectors, infrastructure projects can be completed with greater speed, cost-efficiency, and innovation, ultimately contributing to the broader development of transport infrastructure systems.

The urgency of developing efficient and sustainable transport infrastructure, aligned with urban resilience to

natural disasters and climate change, is evident due to the increasing challenges posed by these phenomena (DE ABREU *et al.*, 2022a; DOS SANTOS *et al.*, 2024). Although initiatives such as the National Logistics Plan 2035 (PNL), developed by the Logistics Planning Company (EPL), and the General Guide for Socioeconomic Cost-Benefit Analysis of Infrastructure Investment Projects, published by the Ministry of Economy, are valuable instruments, the need to create a robust and integrated action model goes beyond their scope.

The PNL provides strategic guidelines and projections for Brazil's logistical development, while the General Guide establishes technical and methodological criteria for assessing the socioeconomic feasibility of projects. However, these initiatives need to be complemented by an action model that systematically integrates sustainability and urban resilience aspects, ensuring that projects are planned not only to meet current demands but also to mitigate the future impacts of extreme climate events and promote more adaptable cities.

The development of an action model is crucial because it can bring together:

- **Multisectoral Integration:** Incorporating environmental, social, and economic variables for a holistic approach that the PNL and the Guide, individually, do not fully address.
- **Preventive Planning:** Focusing on resilience by considering future climate change scenarios, thereby reducing cities' vulnerability to natural disasters.
- **Alignment with the 2030 Agenda:** Prioritizing the Sustainable Development Goals (SDGs), especially those related to infrastructure, sustainability, and resilience.
- **Local Focus:** Customizing solutions to address the specific needs of each region or city, recognizing Brazil's significant geographical and socioeconomic diversity.

Thus, an efficient action model will enable existing instruments to be enhanced, transforming current planning and evaluation efforts into more effective public policies aligned with the contemporary demands of sustainable development and resilient urban areas (DE ABREU *et al.*, 2024).

4. ATTENTION TO CRITICAL POINTS

A good transport infrastructure model must ensure efficient prioritization of projects, considering both their

strategic importance and their economic impact and regional needs (BUENO, VASSALLO & CHEUNG, 2015; ZERJAV, MCARTHUR & EDKINS, 2021). The optimized allocation of resources is key to ensuring the successful execution of these projects, involving the effective management of financial, technological and human capital (PRUS & SIKORA, 2021). Estimating the economic impacts of transportation investment is a fundamental phase for the public policy process at all levels (HOLL, 2006). In addition, it is essential to identify and mitigate potential challenges in each project, integrating adaptation and risk management strategies from the outset of the decision-making process.

A statistical study conducted by Flyvbjerg *et al.* (2004), for example, reveals important causes for cost increases in transportation infrastructure projects, based on a sample of 258 projects worth US\$90 billion. It found that cost increases are significantly linked to the duration of the implementation phase, suggesting that delays can result in substantial costs. In addition, larger projects, especially bridges and tunnels, tend to face more significant cost increases. Surprisingly, public ownership is not necessarily more problematic compared to private ownership in containing cost increases; instead, the type of responsibility seems to be a more important factor. These findings have significant policy implications, highlighting the need to effectively manage the duration of the implementation phase and consider the type of liability in transportation infrastructure projects.

Aligned with national goals, the model should ensure that projects contribute to the country's broader development objectives, while involving all relevant stakeholders, including government bodies, the private sector and local communities, to ensure inclusiveness and acceptance (PRUS & SIKORA, 2021; DE ASSIS *et al.*, 2022a; 2022b). In addition, the model should be designed with adaptability and scalability in mind, allowing for adjustments as circumstances change and for application at different government levels and geographical contexts (SANTOS *et al.*, 2021; DE ABREU, SANTOS & MONTEIRO, 2022). It is also vital that the supporting model integrates data analysis, rigorous cost-benefit analysis, comprehensive risk assessments and scenario planning to provide a solid basis for informed decision-making and effective collaboration between the public and private sectors (DE ABREU, RIBEIRO & SANTOS, 2022).

In this regard, Rokicki & Ostaszewski (2022) presented an innovative methodology based on the modified actuarial credibility approach. This approach

makes it possible to adjust initial cost estimates for public infrastructure projects by taking into account the additional risk/uncertainty factor. It therefore offers an interesting alternative to other existing forecasting methods. Through a real case application, the authors demonstrate that, despite its simplicity, the actuarial credibility approach can provide accurate cost estimates compared to more complex methods such as regression analysis (OLS) or machine learning (LASSO). In particular, they show that although forecast accuracy varies between different project categories, actuarial credibility outperforms other forecasting approaches in most cases. As a result, they argue that actuarial credibility should be considered as a relatively simple tool with very modest data requirements that can be easily applied by investors and policymakers to improve project planning and avoid cost overruns.

Policy decisions on investments in transport infrastructure often require an understanding of the welfare effects generated by the use of these infrastructures at a detailed regional level (BRÖCKER, KORZHENEVYCH & SCHÜRMANN, 2010; PRUS & SIKORA, 2021). This is because managing large-scale transportation infrastructure projects is difficult due to frequent misinformation about costs, which results in large cost overruns that often threaten the overall viability of the project (CANTARELLI *et al.*, 2013).

In addition to the points mentioned above, it is crucial that a transportation infrastructure model also takes environmental and social sustainability into account (AMIRIL *et al.*, 2014). This involves assessing the impact of projects on the environment as well as on local communities, ensuring the mitigation of any adverse effects and promoting practices that contribute to long-term sustainable development (GHAREHBAGHI, MCMANUS & ROBSON, 2019). The planning, construction and operation of transportation infrastructure are associated with a number of adverse effects on the environment. The Strategic Environmental Assessment (SEA) and the Environmental Impact Assessment (EIA) are important legal instruments of global environmental policy that make it possible to identify, predict, prevent and mitigate and/or compensate for these adverse effects (BRONIEWICZ & OGRODNIK, 2020).

Another fundamental aspect is technological innovation (RUDSKOY, ILIN & PROKHOROV, 2021). The model must be prepared to incorporate technological advances that can improve the efficiency, safety and sustainability of transportation systems. This includes not

only established technologies such as electric vehicles, but also emerging solutions such as artificial intelligence for traffic management and autonomous transportation systems. In this way, the model becomes adaptable and resilient in the face of technological transformations, ensuring its long-term relevance and effectiveness.

In addition, resilience to extreme events and climate change is a critical factor to consider (WANG *et al.*, 2020; DOMANESCHI *et al.*, 2024). The model must ensure that infrastructure projects are designed taking into account the possible impacts of natural disasters and climate events, as well as population growth and urbanization patterns that may affect transport demand (DE ABREU *et al.*, 2023b; SANTAMARIA-ARIZA *et al.*, 2023). Adaptation can be defined as the process of adjusting the system to actual or expected climate change and its effects. These adjustments can be both structural, i.e. rigid adaptations, and political, educational and social, i.e. flexible adaptations (DE ABREU *et al.*, 2023b).

In human systems, adaptation seeks to moderate or avoid damage or exploit beneficial opportunities (SUN, BOCCHINI & DAVISON, 2020). Adaptation measures should be linked to current and future risk reduction practices and management initiatives to increase transportation resilience and reduce the impacts of extreme weather events. In addition, these adaptation alternatives and solutions must be compatible with mitigation strategies (i.e. they need to have synergy) to avoid a drastic increase in GHG emissions (DE ABREU, SANTOS & MONTEIRO, 2022).

To further increase transparency and accountability, a series of comprehensive measures need to be implemented. This includes not only ensuring that decision-making processes are transparent and accessible, but also ensuring that relevant information is available in a clear and understandable way to the general public. In addition, it is essential to establish robust monitoring and evaluation mechanisms to track the performance and results of the policies and initiatives implemented.

This will not only allow for more effective accountability, but will also help to identify areas for improvement and take corrective action when necessary. In addition, it is important to promote a culture of responsibility, where decision-makers are held accountable for their actions and decisions, and citizens are encouraged and empowered to actively participate in the decision-making process at all levels. This will not only increase the trust and legitimacy of the model, but will also promote more inclusive and accountable governance, thus contributing to the well-being and progress of society as a whole.

5. FINAL CONSIDERATIONS

The development of an efficient, sustainable and resilient transportation infrastructure is crucial for the economic and social growth of any nation, and Brazil is no exception. This study proposed an innovative action model to prioritize projects within the country's complex transport infrastructure, considering not only financial viability, but also socio-economic and environmental impact. Throughout this research, significant challenges faced by transportation infrastructure projects were identified, including cost overruns, schedule delays and negative impacts on the environment and local communities. The model developed in this study seeks to address these challenges by offering a comprehensive framework that integrates multiple factors and considers sustainability at all stages of the decision-making process.

One of the main contributions of this study is the careful and participatory methodology adopted in developing the prioritization model. Involving key stakeholders from the outset of the process ensured that their concerns and perspectives were adequately considered, increasing the model's acceptance and effectiveness. In addition, the proposed model incorporates a number of key elements, such as comprehensive data analysis, risk assessment, scenario planning and public-private collaboration, which are fundamental to ensuring the effectiveness and long-term sustainability of transport infrastructure projects.

However, it is recognized that there are still challenges to overcome. Integrating technological innovations, adapting to climate change and ensuring transparency and accountability remain important areas of focus for future research and development. Ultimately, this study offers a significant contribution to advancing the field of transport infrastructure in Brazil by providing a holistic and action-oriented approach to prioritizing projects and promoting the sustainable development of the country's transport system. It is hoped that this model can serve as a valuable guide for decision-makers, academic institutions and other stakeholders in the field, helping to shape a more resilient and equitable future for Brazil's transportation infrastructure.

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RISK ASSESSMENT OF A POTENTIAL EXTERNAL AND INTERNAL SULFATE ATTACK IN POZZOLANIC CEMENTITIOUS MATRICES

AValiação DO POTENCIAL DE OCORRÊNCIA DO ATAQUE POR SULFATOS EXTERNO E INTERNO EM MATRIZES CIMENTÍCIAS POZOLÂNICAS

EVALUACIÓN DE RIESGO DE UN POTENCIAL ATAQUE POR SULFATOS EXTERNO E INTERNO EN MATRICES CEMENTICIAS PUZOLÁNICAS

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ABSTRACT

This work evaluated the behavior of cementitious composites against internal and external attack by sulfates (ISA and ESA, respectively) over time, as well as the mitigating potential of Brazilian cements considered pozzolanic. Three pozzolanic cements called sulfate resistant according to Brazilian standards were evaluated, coming from three regions of Brazil, in addition to a reference cement, with high initial resistance. Based on evaluations by Brazilian (ABNT) and American (ASTM) standardization, it was found that the use of pozzolanic additions to cement brings mainly mechanical and durability improvements in relation to external sulfate attack, however, depending on the standardization adopted, it is not possible to say whether it contributed to the mitigation of this attack. In relation to ISA assessments, no cement proved to be effective. Therefore, among the four cements tested, considering the criteria adopted in the study, no cement could be considered to mitigate expansions caused by both sulfate attacks, external - (ESA) and internal - (ISA).

KEYWORDS

Internal sulfate attack (ISA). External attack by sulfates (ESA). Delayed ettringite formation (DEF). Pozzolanic cement.

RESUMO

Este trabalho avaliou o comportamento de compósitos cimentícios frente ao ataque interno e externo por sulfatos (ISA e ESA, respectivamente) ao longo do tempo, bem como o potencial mitigador de cimentos brasileiros considerados pozolânicos. Foram avaliados três cimentos pozolânicos denominados resistentes aos sulfatos de acordo com a normalização brasileira, oriundos de três regiões do Brasil, além de um cimento de referência, de alta resistência inicial. A partir de avaliações pela normalização brasileira (ABNT) e americana (ASTM), verificou-se que o emprego de adições pozolânicas ao cimento traz melhorias principalmente mecânicas e de durabilidade em relação ao ataque externo de sulfatos, porém dependendo da normalização adotada, não é possível dizer se colaborou com a mitigação desse ataque. Em relação às avaliações de ISA nenhum cimento mostrou-se efetivo. Sendo assim, entre os quatro cimentos testados, considerando os critérios adotados no estudo, nenhum cimento pôde ser considerado mitigador das expansões causadas por ambos os ataques por sulfatos, externo - (ESA) e interno - (ISA).

PALAVRAS-CHAVE



Ataque interno por sulfatos (ISA). Ataque externo por sulfatos (ESA). Formação de etringita tardia (DEF). Cimento Pozolânico.

RESUMEN

Este estudio evaluó el comportamiento de compuestos cementicios frente al ataque por sulfatos, tanto interno (ISA) como externo (ESA), a lo largo del tiempo, así como el potencial mitigador de cementos brasileños con características puzolánicas. Se analizaron tres cementos puzolánicos, clasificados como resistentes a los sulfatos según la normativa brasileña, procedentes de tres regiones de Brasil, además de un cemento de referencia de alta resistencia inicial. A partir de evaluaciones basadas en las normativas brasileña (ABNT) y estadounidense (ASTM), se verificó que la incorporación de adiciones puzolánicas en el cemento mejora principalmente las propiedades mecánicas y la durabilidad frente al ataque externo por sulfatos. No obstante, según la normativa adoptada, no se pudo determinar con certeza si estas adiciones contribuyen a mitigar dicho ataque. En cuanto a las evaluaciones del ISA, ningún cemento demostró ser efectivo. Por lo tanto, considerando los criterios de este estudio, ninguno de los cuatro cementos analizados pudo ser clasificado como mitigador de las expansiones provocadas por el ataque de sulfatos, ya sea externo (ESA) o interno (ISA).

PALABRAS CLAVE

Ataque interno por sulfatos (ISA), ataque externo por sulfatos (ESA), formação de etringita tardia (DEF), cimento pozolânico.

1. INTRODUCTION

With the aim of increasing durability and improving construction material procurement, there has been a growing concern with pathological manifestations in concrete structures both in Brazil and worldwide, as is the case with expansive reactions, particularly those involving sulfate ions.

When compared with other chemical reactions, those involving sulfates are the most harmful to concrete, because they bring about the formation of expansive products, which in turn leads to matrix tensioning and concrete cracking (NEVILLE, 2015). Sulfates are commonly found in environments where concrete structures are exposed, such as contaminated soils, infiltration water, industrial settings, and sanitation-related construction works. This type of chemical degradation is referred to as an external sulfate attack (ESA) and this type of chemical attack is known as an external sulfate attack (ESA) (TAYLOR; FAMY; SCRIVENER, 2001; SCHIAVINI, 2018).

The deterioration of concrete caused by chemical reactions between cement and sulfate ions from external sources depends on the concentration of these ions and the composition of the cement paste. This attack often manifests cracking and expansion, which increase permeability and allow aggressive water penetration, ultimately accelerating the degradation process (MEHTA and MONTEIRO, 2014).

In addition to sulfates from the external environment, concrete is also subject to internal sulfate attacks (ISA), which lead to the formation of delayed ettringite, or DEF (Delayed Ettringite Formation). The formation of secondary or late ettringite is a complex process which is characterized by the non-formation or thermal decomposition of primary ettringite, and reprecipitation of its crystals in already hardened cementitious matrices. That phenomenon occurs over time, and generates expansions, when the recrystallization of the ettringite (BRYANT, 2011; THIEBAUT *et al.*, 2018). An internal attack can occur when the source is not in the environment but originates from either i) aggregates contaminated with gypsum and/or sulfides, ii) the cement itself, or iii) the thermal decomposition of the primary ettringite. The latter is related to DEF and is linked to concrete that has been subjected to high curing temperatures, usually above 60°C (HASPARYK; KUPERMAN, 2019; PORTTELLA *et al.*, 2021; HASPARYK *et al.*, 2022). The chemical reaction involving internal sulfates has the potential to cause high expansions, premature degradation of concrete

and damage to all its properties, directly impacting the durability and longevity of structures (MARTIN *et al.*, 2012; KCHAKECH *et al.*, 2016; HASPARYK, KUPERMAN, 2019).

With regard to preventive measures for ESA, the NBR 16697:2018 standard recommends that sulfate-resistant Portland cements should be used, which are cements that contain 15% to 50% of pozzolanic material in their composition. Since they contain pozzolans in their composition, RS cements provide stability when combined with reactive aggregates (which cause the alkali-silica reaction – RAS). Moreover, in acid attack environments - essentially those involving an “external” sulfate attack. Those materials can also reduce heat of hydration, which makes them suitable for mass placement of concrete at elevated temperatures.

The first recorded occurrence of DEF was in 1987 in Finland, in pre-cast concrete that had been subjected to inadequate heat treatment and exposed to humidity. Following this initial record, other countries around the world also reported the phenomenon in different types of precast elements (LCPC, 2009). In addition to prefabricated components, DEF was also documented as prematurely damaging several bridges in Great Britain, with reports of damage occurring 8 to 20 years after construction. In France, the first cases attributed to DEF were reported in the 1990s in structures aged 5 to 10 years (GODART, 2017).

In addition to those already mentioned, several structures made with cementitious materials have deteriorated due to sulfate attack, as documented. In Switzerland, Romer *et al.* (2003) report damage to tunnel structures in contact with groundwater containing sulfates. In the United Kingdom, Crammond (2002) cites sulfate wear in a variety of constructions, ranging from residential foundations and road bridges to tunnel linings and port staircases. In Germany, Bellmann *et al.* (2012) discuss 20 different cases, including the foundations and structural walls of bridges, tunnel linings, water channels, water reservoirs, mining wastewater processing basins, and sewage manholes.

ISA/DEF is a pathological manifestation that originates from the characteristics of the Portland cement. Mineral admixtures, when incorporated into cement in its grinding process, lead to an improvement in the properties and durability of the composites. Some laboratory studies in Brazil have already examined the advantages of pozzolanic Portland cement (CP IV), - when compared with high early strength Portland cement (CP V-ARI) - for mitigating the problem of DEF (SCHOVANZ,

2019; BRONHOLO, 2020; LANGOSKI, 2021; MELO, 2021 HASPARYK *et al.*, 2022). However, although there was an improvement in the behavior of concrete and reduction of its expansion, a complete mitigation of DEF was not achieved in the more advanced ages.

Another factor that affects the occurrence of DEF is the rise in temperature in the first hours of cement hydration and an increase in the C₃A content (ODLER, 2007; BRYANT, 2011). In light of this, many authors have stated that the use of pozzolans can reduce the heat of hydration (MEHTA; MONTEIRO, 2014; AMINE *et al.*, 2017; NGUYEN *et al.*, 2019).

So far, there have been no preventive standardization procedures with regard to DEF just as there are no efficient corrective measures after it has first emerged, which means that it is essential either to prevent or control the factors that cause it (SCHOVANZ, 2019; ZHANG *et al.*, 2021; MELO, 2021; HASPARYK *et al.*, 2022). The only established means of ensuring the avoidance of DEF, is to control the high internal temperatures, resulting from hydration heat of cement in concrete structures (HASPARYK, KUPERMAN, 2019, HASPARYK *et al.*, 2022; HASPARYK *et al.*, 2023)).

It should be borne in mind that some studies have demonstrated the long-term inefficiency of fly ash as a means of mitigating DEF (SCHOVANZ *et al.*, 2021; LANGOSKI, 2021; MELO, 2021; MELO *et al.*, 2023; HASPARYK *et al.*, 2023) for temperatures above 60-85 °C.

This research aims to correlate the behavior of sulfate-resistant cements produced with pozzolanic materials, including fly ash from various sources, with the occurrence of delayed ettringite formation (DEF) and their ability to mitigate both external and internal sulfate attacks.

2. MATERIALS AND METHODS

For the purposes of this study, a specific mixture was prepared with a ratio of 1:2.75 (cement: sand), based on ASTM C-012 (2019), which adopts a water-cement ratio (w/c) of 0.485.

For the evaluation of ISA, cylindrical specimens of (5 x 10) cm were cast for the mechanical tests, following the recommendations of NBR 7215 (ABNT, 2019) which were subjected to thermal curing throughout the period, and prismatic test specimens, measuring (2.5 x 2.5 x 28.5) cm for estimating expansions, in accordance with NBR 13583 (ABNT, 2014), which were also subjected to thermal curing. The ESA evaluation considered prismatic specimens of (2.5 x 2.5 x 28.5) cm to measure expansions

in accordance with procedures by NBR 13583 (ABNT, 2014) and ASTM C-1012: 2019). During the research, two types of curing methods were devised, which can be classified as: “thermal cure” and “cure under sodium sulfate solution”. These healing combinations can be seen in Table 1.

Type of Attack	Cement	Curing	Specimens
ISA-DEF	(3) CP IV32 - RS (1) CP V-ARI	Thermal curing	Cylindrical & Prismatic
ESA 1	(3) CP IV32 - RS (1) CP V-ARI	Sodium sulfate solution NBR 13583 (2014)	Prismatic
ESA 2	(3) CP IV32 - RS (1) CP V-ARI	Solution of Sodium sulfate ASM C-1012 (2019)	Cubic & Prismatic

Table 1: Conditions of testing

ISA: Internal sulfate attack; **ESA 1 and 2:** External sulfate attacks.

2.1 Materials

The experimental investigations included the following materials: **Binders:** 3 cements, called CP IV-32 RS, sulfate-resistant pozzolanic cements, with several mineral admixtures, but without fly ash. These can be described as follows: a) those with calcined clay (PC-PCC), b) those with acid slag (PC-AS) and, finally, c) cement with incorporation of volcanic material (PC-VO) and 1 cement, called CP IV-ARI reference cement called (PC). **Fine aggregate:** from granitic rock, (Pedreira Anhanguera, Goiânia - GO), innocuous with regard to the alkali-silica reaction - RAS (in order to avoid the occurrence of a couple attack - DEF and RAS, and then only isolate DEF). The aggregate used for the production of mortars has a maximum size of 4.8 mm and a fineness modulus of 2.42. **Potable water:** from the water supply network of the town of Passo Fundo/RS.

With regard to the chemical properties of the studied cements, the loss on ignition was above the standard limit for the PC-AS cement content, which was 6.63 and the norm has a limit of < 6.5, but the other characteristics were within the limits. Regarding the physical properties, all the cements met the standard requirements.

Identification	Cement	Heat of hydration	
		41 h	72 h
PC	CP V-ARI	297.90	306.70
PC-PCC	CP IV-32-RS	163.10	166.66
PC-AS	CP IV-32-RS	156.60	174.60
PC-VO	CP IV-32-RS	173.20	200.50

Table 2: Heat of hydration of cements.

Table 3 shows the results of the pozzolanic activity of each cement. However, when measured at the age of 8 days, as recommended by the standard NBR 5753 (ABNT, 2016), two cements, (PC-AS and PC-VO), did not show pozzolanicity, and had to be measured at a later age, which suggests a slower pozzolanicity. It is significant that the PC cement is a CP V-ARI cement with no admixture, and thus, considered to be a non-pozzolanic material.

Cement type	Cement type	PA 8 days	PA 15 days
PC	CP V-ARI	NP	NP
PC-PCC	CP IV-32-RS	P	P
PC-AS	CP IV-32-RS	NP	P
PC-VO	CP IV-32-RS	NP	P

Table 3: Pozzolanic activity (PA) at 8 and 15 days.

2.2 Methods

2.2.1. Induction of the ESA

External attacks were assessed in two ways, one following the Brazilian standard requirements (ABNT (Brazilian National Standards) NBR 13583:2014) and the other, in accordance with the American international organization - ASTM (American Standard for Testing and Materials) C-1012:2019.

The main differences between the standards discussed in this study are the trace elements, solution concentration, test temperature, and total analysis time. NBR 13583 (ABNT, 2014) provides faster results on the behavior of cementitious materials in a laboratory environment, with a shorter exposure time to sodium sulfates (42 days). In contrast, ASTM C-1012:2019 tests simulate natural exposure conditions more accurately, with an extended exposure period of 365 days.

The 3 stages of curing in which the mortar bars were subjected to the procedure described in NBR 13583 (ABNT, 2014), are as follows: **1) Initial wet curing:** While still in the molds, the test specimens were taken to the moist chamber for 48 h. After this period, the specimens were demoulded. **2) Intermediate Curing:** The specimens

were immersed in water saturated with lime for 12 days at a temperature of $(23 \pm 2) ^\circ\text{C}$. **3) Final curing:** The specimens were placed in a container containing a sodium sulfate solution (Na_2SO_4), with a concentration of 10%, in accordance with the specifications from NBR 13583 (ABNT, 2014), under a constant temperature of $(40 \pm 2) ^\circ\text{C}$ throughout the test period.

Curing was also conducted by following the procedure described in ASTM C-1012, which comprised 3 stages: **1) Initial wet curing:** The specimens were immersed in water at $(35 \pm 3) ^\circ\text{C}$ for 24 h. After this period, they were demolded, and stage 2 began. **2) Intermediate Curing:** The specimens were immersed in water saturated with lime, until it reached a compressive strength of 20 MPa at a temperature of $(23 \pm 2) ^\circ\text{C}$. **3) Final curing:** The specimens were placed in a container containing a sodium sulfate solution (Na_2SO_4), with a concentration of 5%, which was prepared in accordance with the ASTM C-1012 specifications, under $(23 \pm 2) ^\circ\text{C}$ during the entire period.

The specimens were submerged in a Na_2SO_4 solution and the dimensional variation was monitored for 180 days, by ASTM C-1012, and for 42 days, by NBR 13583, the latter estimate being extended to the age of 98 days since no stabilization had occurred. The external attack was assessed in two ways – one in compliance with the Brazilian standards (ABNT NBR 13583:2014) and the other in accordance with the American standard (ASTM C-1012:2019).

2.2.2. Induction of the ISA (DEF)

When assessing the internal attack by sulfates, the thermal cycle adopted for thermal curing of the test specimens, called the Brazilian method (HASPARYK *et al.*, 2020; 2022), was employed to induce the occurrence of DEF in the laboratory. This procedure was developed based on a number of works in the literature: (FU, 1997; KCHAKECH *et al.*, 2016; GODART, 2017; MARTIN *et al.*, 2017; RASHIDI *et al.*, 2017; ZHANG *et al.*, 2017; SANCHEZ *et al.*, 2018; GIANNINI *et al.*, 2018; SCHOVANZ, 2019; BRONHOLO, 2020; LANGOSKI, 2021). The only adjustment made for the present study was a change in the type of cement composite, from concrete to mortar. Trials were carried out up to the mortar age of 1 year.

After the CPs had been cast, the mortars went through the stages shown in Figure 1. It should be noted that exposure over time occurs in immersion in water at $38 ^\circ\text{C}$ after thermal curing.

- 1°. Specimens remained at room temperature for 6 hours;
- 2°. Specimens were stored in a tank with water at an initial temperature of 25 °C;
- 3°. The heating rate of the water in the tank adopted was 10°/h, until it reached 85 °C, which was a period that lasted 6 hours;
- 4°. The samples remained for 12 h at a temperature of 85 °C;
- 5°. After this period, the water in the tank was cooled at the same rate (10 °C/h), and up to 38 °C;
- 6°. Specimens remained in this condition (immersed in water, at 38 °C (± 2 °C)) throughout the established ages for concrete testing i.e., for twelve months.

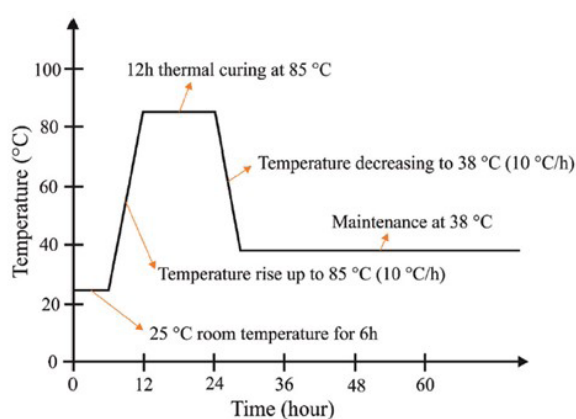


Figure 1: Procedure of DEF induction at laboratory.

Source: Hasparyk *et al.* (2020).

2.2.3. Assessment methods

When assessing the occurrence of ISA in the mortars, the linear dimensional change was determined, by following the recommendations set out in NBR 13583 (ABNT, 2014), although with a prolonged exposure time (1 year). Six prismatic mortar specimens were made for each cement, measuring (2.5 x 2.5 x 28.5) cm. Dimensional assessment was assessed every 7 days in the first 3 ages and, after 28 days of age, every 15 days, up to 1 year. To the measurements were made using a measuring device equipped with a dial indicator with 0.001mm resolution. Readings were performed with the samples positioned vertically, and always with the same face facing up. The readings were carried out in a controlled temperature environment of (23 $\pm$ 2) °C. The linear dimensional variation (expansion or retraction) of individual bars is given by the difference between the value measured at the corresponding exposure time and the initial reading, divided by its effective length, in percentage. The results

individual results obtained are rounded to the nearest thousandth and the final result average obtained from the 6 individual bars, rounded to the nearest hundredth. It should be noted that all CPs were molded from a single production, in a mechanical mixer, for each condition under study, in order to guarantee the homogeneity of the composites.

As for the evaluation of ESA by the Brazilian standard, the determination dimensional assessment took up to 98 days and by the American standard, up to 180 days. Six prismatic mortar specimens were molded for each cement also, measuring (2.5 x 2.5 x 28.5) cm. Measurements were assessed every 7 days until 28 days of mortar age, and then, every 15 days, up to the respective ages indicated by each standard. The measuring device, procedure, environment and test tolerance followed the same format as the ISA assessment.

In the evaluation of the internal attack (ISA), the mechanical properties of the mortars were also determined in cylindrical PCs (5 x 10) cm), at the ages of 7, 28, 56, 84, 168, 252 and 365 days. The axial compressive strength was determined in accordance with NBR 7215 (ABNT, 2019), while the tensile strength through diametral compression, in accordance with NBR 7222 (ABNT, 2011), by adapting the size of the specimen to the dimensions of (5 x 10) cm. The equipment used for these tests was a PC 200C press, from the EMIC brand, with capacity of 2000 kN and accuracy of approximately 1% of the applied load. They were used 4 specimens at each test age.

3. RESULTS

3.1. Evaluation of mortars subject to the required conditions for the development of the ESA

The expansions determined in mortars by applying the Brazilian method as set out in NBR 13583 (ABNT, 2014) are shown in Figure 2 (up to the age of 98 days).

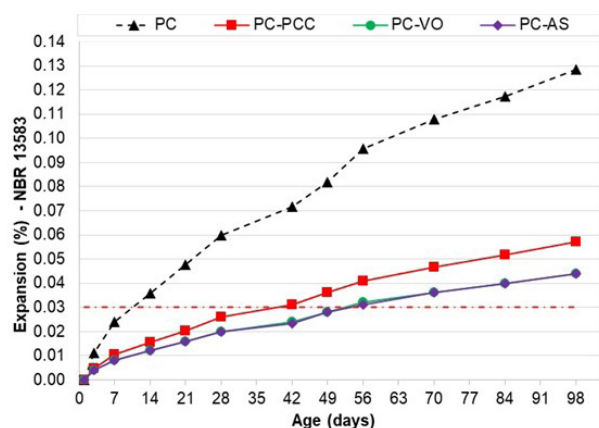


Figure 2: ESA: Expansions according to Brazilian standard NBR 13583 up to 98 days.

The mortars produced and analyzed at the age of 42 days did not exceed the maximum expansion stipulated by the standard, which is 0.03%, except for the PC-PCC and PC mortars, the latter being produced with CP V-ARI cement. However, if the analysis had been conducted after 2 weeks, at 56 days, all the cements would have shown expansions above this limit, which raises concerns about their potential resistance to sulfate ions.

The mortars have a similar behavioral pattern among themselves, in particular PC-AS and PC-VO, which have average expansions that ranged from 0.02% to 0.03% in 28 days, followed by an almost linear pattern of behavior, reaching values between 0.04% and 0.06%, in 98 days. The PC mortar reaches 0.06% expansion after 28 days and 0.13% after 98 days.

When the test time was extended to 98 days, there was no stabilization for any of the three cements assessed. Thus, on the basis of this research study, it can be stated that even if the test extends beyond 42 days, the CP IV-32-RS cements would not be able to prevent the expansions resulting from the external attack of sulfates.

In general, several studies have shown that pozzolanic admixtures are efficient in mitigating the external attack by sulfates (OUYANG *et al.*, 2014; HOPPE FILHO *et al.*, 2015). Hoppe Filho *et al.* (2015) analyzed the influence of various materials, (both inert and active), with regard to these kinds of attacks. The authors found that the reference mortar (with no admixture) obtained an expansion rate of approximately 0.05%; the mineral admixture that achieved the greatest influence on mitigating the attack was silica fume (10% in mass replacement), reducing the expansion to approximately 0.01%, at 42 days. According to the researchers, this positive result was due to the pozzolanic effect of the addition, which reduces the availability of CH that is able to react with sulfate ions, as well as altering

the distribution of pores and the interconnectivity of the capillary network; however, studies in this area have not advanced beyond 42 days.

The expansions monitored over a period time, and resulting from the mortars that were subjected to the exposure conditions set out by ASTM C-1012, over 180 days of testing, are shown in Figure 3. The highest rate of growth and expansions was observed for CP cement V-ARI (PC Blend), which reached 0.085% in the last age.

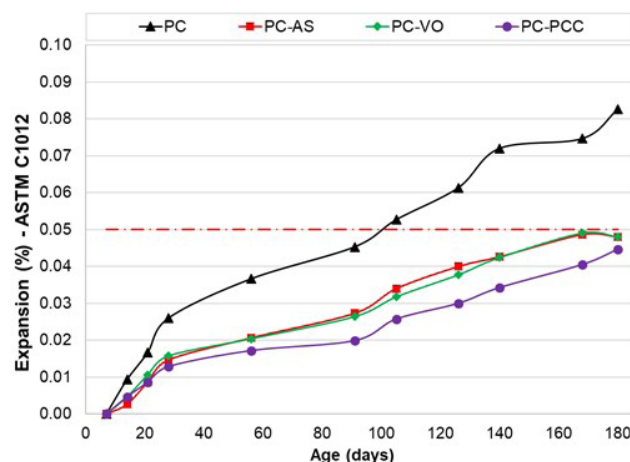


Figure 3: ESA: Expansions according to American standard ASTM C-1012 up to 180 days.

Up to the age of 30 days, there is an important expansion growth rate, followed by a lower rate of acceleration for up to 90 days; then the growth rates increase again up to 6 months of mortar age for all the cements assessed. The highest growth rates and expansions were observed for PC-AS and PC-VO cements, from the pozzolanic cement group, which again have a very similar behavioral pattern. At the end of the tests (180 days) it was found that, with the exception of the PC-PCC mixture, the other two mortars (PC-AS and PC-VO), reached the maximum limit of the American standard, which is 0.05% of expansion, and is a high degree of aggressiveness, as recommended by ASTM C-150:2021. The PC-PCC mixture was close behind, at around 0.45%. The PC mixture with cement, CP V-ARI, reached the standard limit after 100 days, and at the end of the test its expansion was 0.08%.

3.2. Evaluation of mortars induced for ISA

3.2.1. ISA Expansion monitoring

The average expansions obtained in the mortars exposed to the conditions that might result in an ISA, can be observed in Figure 4, and are classified for each evaluated cement.

According to the dimensional variation of the mortar prisms, it was possible to confirm that the PC-VO and PC-AS mortars had the highest expansions at the same age when compared with the PC-PCC mixture, since they were 0.19% and 0.18%, respectively. The expansions were measured in a period of up to 1 year and did not cease, which suggests their potential for continuity over time. The PC mortar, produced with CP V-ARI cement, achieved an expansion rate of 0.43% in the last age, more than double that of the other impressions in the same concrete age.

The observed pattern of behavior shows the occurrence of DEF, since, at first, the crystals fill the pores of the matrix and, afterwards, start to cause internal tensions and thus lead to expansions. There are still no parameters to constrain the DEF expansion rate in mortars, by means of the employed method. The only benchmark with regard to attacks by sulfates, (of external origin), is NBR 16697 (ABNT, 2018), which determines that for a cement to be resistant to sulfates (in the case of an external attack) its expansion rate in mortar must be less than, or equal to, 0.03%, at 42 days of age, when tested through the established method in compliance with NBR 13583 (ABNT, 2014). If this limit were used for the DEF, none of these impressions would have expansions below the limit at 42 days and, at the final age of evaluation (1 year). Moreover, all the cements evaluated would reach a rate that is well above 0.03% expansion, with no stabilizing patterns in time.

It should be noted, however, that the CP IV-32-RS type cements that were assessed had a delaying effect on the deleterious expansive process of the DEF, when compared with the CP V-ARI, although the degree of efficiency fluctuated between them. In this study, the most efficient cement with regard to expansion, was the one with calcined clay (PC-PCC), followed by acid slag (PC-AS) and, finally, cement with volcanic material (PC-VO).

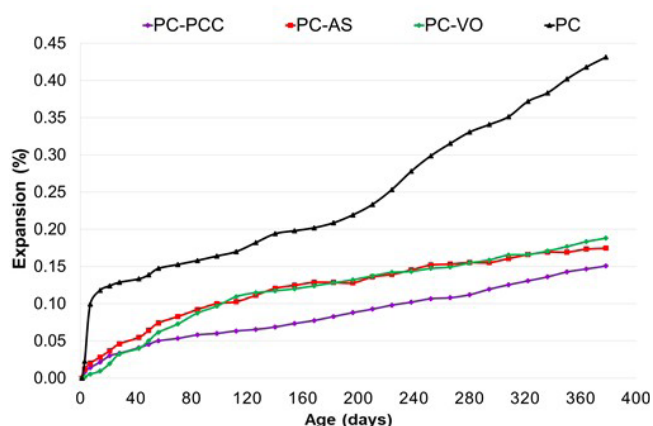


Figure 4: DEF: Mortar expansions over time and up to 400 days.

3.2.2. Monitoring tensile strength

The results displayed in Figure 5 show greater total losses of tensile strength for the PC mortar, which are around 40%, followed by the PC-VO mortar, with falls of around 35% at the age of 1 year, which can be taken as the peak of its strength. The PC-PCC and PC-AS and PC-VO mixtures suffered losses in this property of about 20% and 15%, respectively, at the age of 1 year.

According to Sanchez *et al.* (2018), in the case of concretes that are affected by DEF with expansion levels (ranging from 0.05% to 0.12%), the reduction in tensile strength can reach around 65%. With regard to higher expansion levels ($\geq 0.20\%$), the reduction rate reaches around 70-80%. In studies conducted by Hasparyk *et al.* (2022) for expansion levels between 0.20% and 0.40%, the reduction in tensile strength was close to 40%.

Langoski *et al.* (2022) showed that expansions above 0.45% promote damages to mechanical properties is very significant, with reductions of around 50%. Furthermore, for expansions of the order of 0.10% there are already clear signs of a beginning of DEF deterioration, since the tensile strength is reduced by around 10% in one year. In the case of the pozzolanic cement in this aforementioned research project with fly ash, the behavioral pattern was different in terms of tensile strength. Expansions above 0.14% involved a decrease of around 18%.

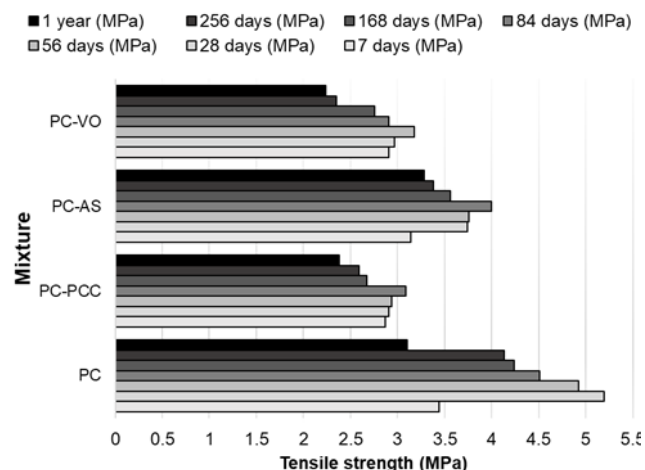


Figure 5: Splitting tensile strength.

3.2.3. Compressive strength

With regard to compressive strength, Figure 6 shows that the mortars that had the biggest fall were those with CP V-ARI (PC), and the PC-PCC mixture, with reductions of

around 40%. These mortars reached expansions of 0.15% at the final age of 1 year. The PC-AS and PC-VO mixtures, on the other hand, suffered decreases of around 15%. According to Taylor *et al.* (2001), the microcracking generated by DEF starts in the interfacial transition zone (ITZ), and leads to significant reductions in compressive strength, unlike other expansive reactions, particularly in mixtures containing pozzolanic admixtures.

Tiecher, Langoski and Hasparyk (2022) found intense microcracks, filled pores and massive formations of ettringite in cement paste and in the ITZ, after assessing mortars without mineral admixtures over a period of 1 year.

Current research indicates that DEF modifies the mechanical characteristics of concrete, reducing compressive and tensile strength, in addition to reducing the modulus of elasticity (SCHOVANZ *et al.*, 2021; HASPARYK *et al.*, 2022).

Drops on compressive strength continued over time and, from 6 months to 1 year, with lower reduction rates. It was not possible to determine a unique pattern of behavior in the tested mixtures, but, as the expansions increase, there is a corresponding reduction in compressive strength.

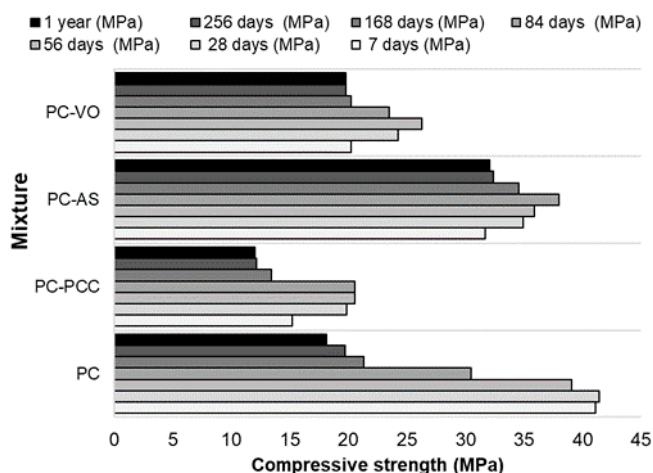


Figure 6: Compressive strength.

In a study with concrete test specimens Pichelin *et al.* (2020) concluded that the compressive strength begins to suffer signs of a decrease when the expansions reach values of 0.17% and 0.25%, during the deterioration stage of the acceleration phase. In this interval the compressive strength may undergo a reduction of the order of 30%,

and then stabilize at the end of the acceleration period.

3.3 Relationship between cement characteristics and expansions for ESA and ISA

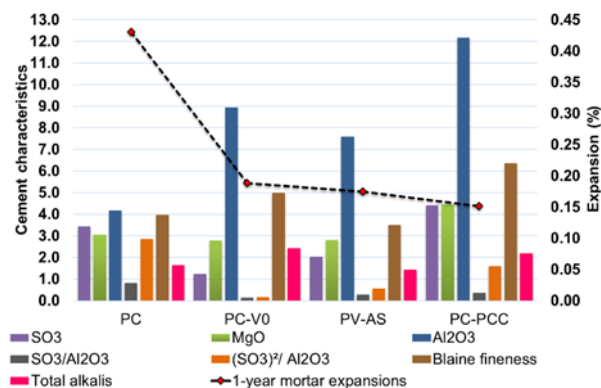


Figure 7: DEF: Properties of cements versus expansion of mortars over time.

Figure 7 shows the relationship between the main chemical parameters of the cements and the expansions obtained in the research.

It can be confirmed that, in general, Al₂O₃ elements above 12% led to smaller expansions by DEF. In addition, as can be seen, the PC-PCC cement had the highest Al₂O₃ content and the PC cement had the lowest, which resulted in the greatest expansion in the study. The same phenomenon occurred for SO₃ and MgO, where the PC-PCC cement had the highest content of these compounds, (4.42% and 4.47%, respectively). Although both ratios involving SO₃ and Al₂O₃ were higher, their values are lower than those mentioned in the literature to determine DEF risks (0.5 and 2.0, respectively), according to Bauer *et al.* (2006).

According to Schmalz (2018), the amount of SO₃, MgO and cement fineness, directly influences DEF and the rate of expansions. Cements with SO₃ content above 2.6% are cited as propensity for the occurrence of DEF is likely, and important levels of MgO, above 1%. The results of the present study demonstrate that all cements contain MgO values well above 1%.

With regard to SO₃, PC and PC-PCC cements had amounts higher than 2.6%, with maximum expansions of 0.43% and 0.15%, respectively, after 1 year of monitoring. The PC impression, which can be considered as the most expansive impression in the study, was made with CP V-ARI cement, and whereas the PC-PCC impression, with the lowest expansion, was produced with CP IV-32-RS cement, its behavior was probably influenced by the use

of a pozzolanic cement, with the content of about 25% of calcined clay. This means that an individual analysis of only a single parameter is not enough.

According to Taylor *et al.* (2001), Zhang *et al.* (2002), Bauer *et al.* (2006) and Tosun (2006), the closer the $\text{SO}_3/\text{Al}_2\text{O}_3$ ratio is to 1, the greater its propensity for DEF development. As can be seen, CP V-ARI cement (PC molding) has the highest $\text{SO}_3/\text{Al}_2\text{O}_3$ ratio (0.83) and the highest rate of expansion caused by DEF (0.43%). In the case of the other pozzolanic cements, the ratios found are much lower, (always below 0.40), with no clear behavioral pattern between these cements.

Bauer *et al.* (2006) state another ratio $(\text{SO}_3)^2/\text{Al}_2\text{O}_3$. For values greater than 2, there is susceptibility to DEF occurrence. The impressions that have this high ratio, and are close to 2, are PC and PC-PCC. In the case of pozzolanic cements (with the exception of PC-PCC), the ratios found are much lower, with contents below 0.55 (Figure 7).

Another point that needs to be analyzed in Figure 7 is the fineness that affects the expansions, because it influences the porosity of the paste microstructure in the early ages and over time. According to Tosun (2006), in the initial ages the fineness of the cement facilitates the proliferation of the expansions due to the rapid formation of ettringite on the surface of non-hydrated cement particles with high permeability. In the more advanced ages, the rate of DEF formation tends to slow down since it is difficult for the water to penetrate the deeper regions of the non-hydrated cement. Despite the above, no clear pattern of behavior could be observed for this parameter.

In summary, based on the tests and acknowledging that expansive chemical reactions can persist for years, none of the Brazilian cements tested in this study were found to be resistant to sulfate ions, whether of internal or external origin. Sulphate resistant cements should guarantee at least resistance to external sulfate attack; however, this was not observed in the present research.

4. GLOBAL ANALYSIS

Regarding the DEF, the results obtained show that there was a growth of expansions over time for all the tested cements, with high values achieved, as well as damage caused to the mechanical properties

The mechanical properties were prematurely affected for mortar with cement (PC), and experienced high levels of damage when there were significant expansions. As for the tested mortars (PC-PCC; PC-AS and PC - VO), only a

delay in the expansion process and deterioration caused by DEF were noted, owing to the presence of admixtures.

In the evaluation of the external attack by sulfates, a comparison between the Brazilian and American standards, showed an incompatibility in the results and behaviors. However, when the timeline for the analysis of the expansions was extended, by employing the NBR method, the expansions did not cease for the pozzolanic cements, which suggests that there was only a slower development of the expansive behavior by DEF.

Under the terms of the Brazilian regulatory standards the expansive behavior of mortars for the ESA must be assessed at an early stage (at the mortar age of 42 days), while the ASTM believes it can be better delineated in time through an assessment of more advanced ages. If the NBR method is applied for the ESA, it is recommended that the analysis time should be extended to at least 3 months, as, in this way, the method will provide more consistent results and be compatible with those of the ASTM. Moreover, if the same NBR limit was adopted for the ASTM, no cement would be regarded as resistant to sulfates.

Another point of observation was that the SO_3 content and the SO_3 and Al_2O_3 ratios had the greatest influences on the expansions in both the ISA and ESA studies. The MgO content of all cements remained above 1%, which shows a propensity for the occurrence of DEF for all the tested mixtures.

In short, since it is well-known that expansive chemical reactions can last for years, Table 4 was devised on the basis of a global analysis of the results. This clearly shows that none of the cements evaluated in this research can be considered to be resistant to sulfate ions, whether of external or internal origin. Cements with the suffix -RS (sulfate resistant) should, at least, ensure resistance against external sulfate attacks, (although this was not

Cement	ISA / DEF	ESA ASTM (0.05% ¹)	ESA NBR (98 days ²)	Final Conclusion ESA & ISA
PC	NR	NR	NR	NR
PC-PCC	NR	R	NR	NR
PC-AS	NR	NR	NR	NR
PC-VO	NR	NR	NR	NR

Table 04: Global analysis - ISA & ESA

1 - Limit by ASTM (age: 180 days); 2 - Suggested age of evaluation by this manuscript keeping the same limit of 0.03% from NBR; R - Resistant for sulfates; NR - Nonresistant.

observed), largely owing to the extension of the deadline adopted by the Brazilian standard, NBR 13583 (ABNT, 2014), as well as the reduction of the limit for ASTM C -1012.

5. CONCLUSION

On the basis of the results obtained from the ESA evaluation, it can be concluded that there are differences in the behavior of the mortars, depending on the cement type and the mineral admixture used, as well as between the assessment methodologies. Nonetheless, some of the results between the two tested methods (NBR and ASTM) in the evaluation of the external attack, were found to be incompatible.

Regarding the ESA, according to the ASTM criteria, three of the four cements surpassed the 0.05% limit for extremely aggressive environments, which suggests that they are not resistant to sulfates caused by an external attack. If the limit of 0.03% were also applied to this method, none of the cements would demonstrate resistance. It is noteworthy that the expansions did not cease for any of the mixtures evaluated during the period of assessment, in either of the methods.

Distinct levels of expansion were measured for the ISA and in the case of the PC mixture (CP V-ARI) the expansions were higher, (in the order of 0.43%). The mortars produced with pozzolanic cements (CP IV-32-RS), containing various admixture types, only experienced a delay in the expansion and deterioration process. The expansions did not cease until the last evaluated age, and ranged from 0.15 to 0.19%; in addition, they suffered serious mechanical losses, from which it can be concluded there was damage caused by DEF.

Thus, it was confirmed that the measured mechanical properties were impaired. In terms of tensile strength, decreases of the order of 20 to 40% were found. In the case of compressive strength, there were reductions of up to 40% for CP V-ARI (PC), and with regard to the PC-PCC mixture, the other mixtures had reductions of around 15%. In other words, the tested pozzolanic cements have the potential to reduce the expansions when compared to a cement without any pozzolan (CP V-ARI). However, the incorporation of pozzolanic mineral admixtures at the contents used by the factory, were not enough to mitigate attacks.

Another point to note is that losses of up to 30% in compressive strength are unacceptable, as well as comparable drops in tensile strength. This situation already shows a high degree of aggressiveness and deterioration.

Hence, there is evidence to show that when based

on the methods employed and the boundary conditions and constraints adopted, none of the three pozzolanic cements tested, proved to be resistant to sulfates, either in the ESA or ISA/DEF study.

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LIFE CYCLE INVENTORY (LCI) OF A MECHANICAL GEARBOX MANUFACTURING PROCESS

INVENTÁRIO DE CICLO DE VIDA (ICV) DE UM PROCESSO DE FABRICAÇÃO DE CAIXA DE TRANSMISSÃO MECÂNICA

INVENTARIO DEL CICLO DE VIDA (ICV) DE UN PROCESO DE FABRICACIÓN DE UNA CAJA DE TRANSMISIÓN MECÁNICA

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ABSTRACT

The metal-mechanical industry bears an environmental responsibility with respect to the proper use of natural resources. This translates into constant efforts to develop processes and products with optimum use of raw materials, incorporate clean technologies and reduce waste generation. A life cycle assessment (LCA) is an environmental resource management tool that evaluates all stages in the life cycle of a product or process. In this study, a simplified LCA was applied to the manufacturing process of a mechanical gearbox. Primary data from a life cycle inventory (LCI) were used to determine the mass balance of solid metallic waste per functional unit (FU) and energy balance. The energy balance was of 56.96kWh/FU, acquired through free market supply. Thus, the LCI was able to identify possible environmental aspects and impacts which could be used as future guidelines.

KEYWORDS

LCI, block diagram, mechanical gearbox

RESUMO

A indústria metalmecânica possui uma responsabilidade ambiental na utilização dos recursos naturais, estando em constante busca do desenvolvimento dos processos e produtos visando a otimização do uso de matérias-primas, emprego de tecnologias limpas, e a minimização da geração de resíduos. A ACV é uma ferramenta de gestão ambiental que avalia todas as etapas do ciclo de vida de um produto ou processo, e diante deste cenário a pesquisa aplicou a metodologia de ACV simplificada no processo de fabricação de uma caixa de transmissão mecânica. Com os dados primários do ICV foram elaborados o balanço mássico dos resíduos sólidos metálicos por unidade funcional (UF) e o balanço energético. Através dos resultados obtidos foram propostas melhorias através da aplicação de P+L em parte do processo. O balanço energético resultou em 56,96kWh/UF, em que foi utilizada energia de aquisição pelo mercado livre de energia. Com os resultados do ICV foram identificados os possíveis aspectos e impactos ambientais do processo pesquisado, os dados que auxiliam na tomada de decisões futuras.

PALAVRAS-CHAVE

ICV, diagrama de blocos, caixa de transmissão mecânica

RESUMEN

La industria metalmecánica mantiene una responsabilidad ambiental en la utilización de los recursos naturales y busca constantemente desarrollar procesos y productos con vistas a optimizar el uso de materias primas, emplear tecnologías



limpias y minimizar la generación de residuos. La ACV es una herramienta de gestión ambiental que evalúa todas las etapas del ciclo de vida de un producto o proceso, y ante este escenario, la investigación aplicó la metodología de ACV simplificada en el proceso de fabricación de una caja de transmisión mecánica. A partir de los datos primarios del ICV se elaboró el balance de masa de residuos sólidos metálicos por unidad funcional (UF) y el balance energético. A través de los resultados obtenidos se propusieron mejoras mediante la aplicación de P+L en parte del proceso. El balance energético arrojó 56,96kWh/UF, que utilizó energía adquirida a través del mercado libre de energía. Con los resultados del ICV se identificaron los posibles aspectos e impactos ambientales del proceso investigado, datos que ayudan en la toma de decisiones futuras.

PALABRAS CLAVE

ICV, Diagrama de bloques, Caja de transmisión mecánica

1. INTRODUCTION

The constant evolution of the manufacturing sector and unbounded consumption of natural resources results in environmental, economic and social impacts (Jamwal *et al.*, 2021b; Priarone *et al.*, 2021). Additionally, Industry 4.0 initiatives promote the efficient use of resources and large scale production with automation and smart systems (Jamwal *et al.*, 2021a; Manuguerra *et al.*, 2023). These combined demands bring the need to evaluate manufacturing processes and develop solutions with significant effects on productivity and sustainability (Reis *et al.*, 2023). This has additional consequences since sustainability concerns are a considerable challenge to industry and affects its competitiveness (Siltori, 2020; Vrchota *et al.*, 2020).

The manufacturing sector in the state of Rio Grande do Sul is the 2nd largest in Brazil both in terms of plants and employment (Rio Grande Do Sul, 2021). Consequently, it carries substantial environmental responsibilities in conservation, handling and use of natural resources. This requires the development of processes and products that optimize the consumption of raw materials, applies clean technologies and minimizes waste generation (Potrich; Teixeira; Finotti, 2007). To this end, a life cycle analysis (LCA) is one of the most appropriate methodologies since it encompasses the entire life cycle of a process or product (Guinée *et al.*, 2011). The analysis starts at the extraction and processing of raw materials, followed by manufacturing, packing, transportation, distribution, use, re-cycling or re-use until final destination (Fernandes *et al.*, 2019; Hinz; Valentina; Franco, 2006).

Life cycle concepts have been promoted over the past decades through policies and government agencies (Guinée *et al.*, 2011). Some examples were the National Policy on Solid Wastes (PNRS) which determined shared responsibility on the life cycle of products, Sustainable Public Acquisition Guidelines (GCPS) which promoted labels based on LCA that attest to sustainable products and services and the Brazilian Life Cycle Assessment Program (PBACV) developed jointly by Associação Brasileira de Ciclo de Vida (ABCV), Instituto Brasileiro de Informação em Ciência e Tecnologia (IBICT) and

Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO) (Cherubini; Ribeiro, 2015).

An LCA is a complex methodology covered in Brazilian standards NBR ABNT ISO 14040, 14041, 14042 and 14043. It evaluates a production system through inflows and outflows. Inflows are the raw materials and energy consumption of the system while outflows are emissions, wastes, co-products and environmental discharges (Barros *et al.*, 2019). An LCA allows an industrial segment to identify opportunities of improved environmental performance at several stages along the life cycle of a product. Additional benefits would be positive marketing engagement (Cherubini; Ribeiro, 2015) and project design with realistic sustainable solutions (Selhorst; Alves; Nobre, 2020).

Alvarenga *et al.* (2012) presented a simplified LCA which was less complex than a detailed LCA and did not fully comply with all guidelines from ISO standards. However, this simplified LCA could be applied as qualitative, quantitative or semi-quantitative analysis. Life cycle inventory (LCI) results can allow to identify the environmental aspects and impacts of the manufacturing process, in the present case, the mechanical gearbox. These methodologies contribute to the continuous investment in innovation of the industrial sector as it aligns itself with environmental responsibilities (Oliveira; Matos; Pereira, 2017). The objective of this study was to carry out a Life cycle inventory (LCI) of the product system within the boundaries of the manufacturer, e.g., gate-to-gate. This was conducted with primary data collection and block diagram methodology.

2. METHODOLOGY

The simplified LCA used in this study was based on established methodologies and contained the 4 stages defined in standards NBR ISO 14040 (ABNT, 2014a) and 14044 (ABNT, 2014b). These were goal and scope definition, inventory analysis and interpretation of results as shown in Figure 01.

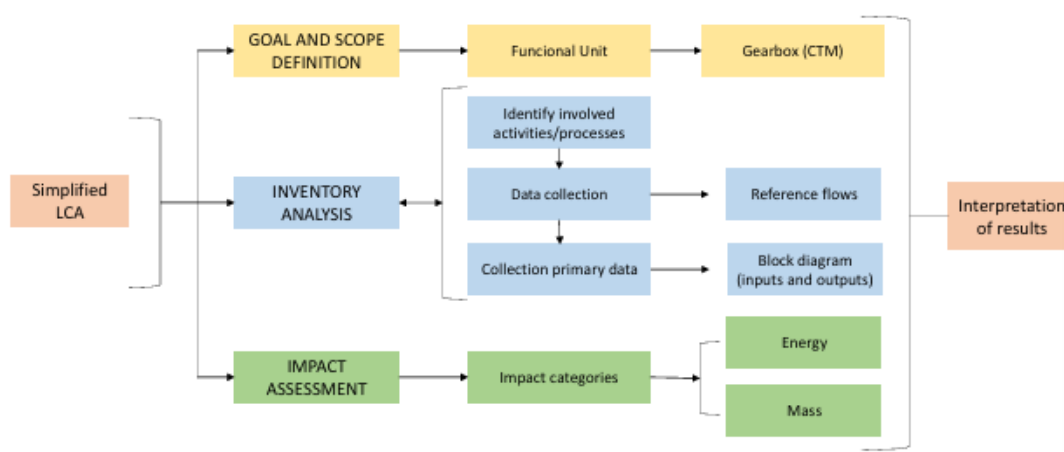


Figure 1: Methodology applied in the experimental program.

Source: The authors

2.1. Simplified LCA Stages

2.1.1. Goal and Scope Definition

The objective of this study was to conduct a simplified LCA of a mechanical gearbox used primarily in agricultural equipment. The manufacturer was a metal-mechanic business specialized in machinery and related equipment, henceforth referred to as Business A.

The functional unit (FU) of the study was a mechanical gearbox (MG) and the scope was its manufacturing process at Business A. The MG has commercial applications in farm equipment such as spreaders, distributors and seeders. It has a mass of approximately 6.5 kg and can be used either as a multiplier or redactor with an input rotation of 540 rpm or 1,000 rpm.

The system boundaries of this study were mechanical components manufactured in-house, gate-to-gate, by Business A for the mechanical gearbox. These were the housing, gears, axles and the assembly process of the gearbox.

auxiliary items. Outflows were co-products and wastes. Water, oil, lubricants and hydraulic fluids used in the manufacture of an FU were also considered.

The methodology broke down the production system of an FU into separate processes. Each process was based on specific items manufactured in this process, which were: housing, crown gear, pinion gear, axle 1, axle 2 and assembly.

Based on data collected, reference flows were determined for the manufacturing process of a mechanical gearbox. These flows made use of symbols that allowed easy identification and understanding of the primary processes for all members of the study. Furthermore, they allowed block diagrams to be drawn up for the entire manufacturing process.

Flowcharts were produced for each process based on in loco knowledge shared through diagrams and manufacturing invoices (MFG) of each item. Due to non-disclosure agreements, these were not presented or referenced in this study.

The live cycle inventory (LCI) was determined from collected data and process flows. From it, block diagrams were created for the entire MG product system. Table 01 shows a sample block diagram based on Excel® spreadsheet software.

2.1.2. Life Cycle Inventory analysis (LCI)

Data collection was conducted in loco within the boundaries of the system. Inflows considered were energy, raw materials and

Product Sistem	Functional unit			Intermediate product	Functional unit part			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification check	Elementary process	Elementary outflow	Quantity	Units	Classification check

Table 1: Sample table for compiling data into inventory block diagrams of process inflows and outflows.

Source: The authors.

Mass balances in the block diagrams were calculated for an FU from total monthly data collected from production management software used by Business A, namely, Codi® and Tecnicon®.

Elementary outflow of contaminated waste from the machining process was calculated in the LCI through the net flow of soluble oil and hydraulic oil. Solid metallic waste generation was calculated from the weight difference of the part before and after machining. Induction heating was used for forging and cooling made use of a closed-system cooling tower. This use of a natural, renewable resource promoted conservation and decreased environmental impact. Heat produced by the induction process

was quantified from occupational hazard guidelines, which was part of Business A waste management program (WMP). Again, due to non-disclosure agreements, the WMP was not presented in this study. However, the environmental heat tolerance limit was listed in Regulation Standard 15 from Ministério do Trabalho (BRASIL, 2022b).

Elementary inflows included inserts, broaches and hobbing tools used in machining. Hobbing of the gear teeth made use of a Gleason Pentac gear cutting system. These tools were not included in elementary outflows of metallic waste since they were reused within the manufacturing process or returned to suppliers. For example, all edges of hard metal inserts containing tungsten

carbide were used up to their useful lifespan limit and returned to the supplier, which in turn reincorporated them in their manufacturing process as a co-product. This procedure prevented the disposal of hard metals in industrial landfills. The hobbing Gleason Pentac system was sharpened in-house after each use as were the broaches until the end of their useful lifespan.

Energy balances in the block diagram were calculated from electrical consumption by applying Eq. (1) to all equipment used in the manufacturing process of an FU. Nominal power consumptions (P_e) were taken from technical specifications of each equipment and operational times (t) were measured in loco with Tecnicon® software.

$$EE = P_e t \quad (1)$$

Validation of LCI data was necessary to ensure quality and identify faults. This was conducted by first confirming that all MG manufacturing data were included in the LCI by comparing it to written process descriptions and work instructions provided by Business A with ISO 9001:2015 certification.

Data trustworthiness was evaluated with the methodology of Kappler et al. (2018) at the inventory stage as seen in Figure 02. This methodology separated data sources individually and converted each into a mass fraction of an FU. Data for each material could be classified in up to 5 levels, which could be multiplied by their corresponding process to yield a final value between 1 and 25. Results are shown in Table 02 with lowest classification values indicating higher trustworthiness.

Classification	Description
1	Checked measured data
2	Unchecked measured data
3	Unchecked data partially taken from measureme
4	Qualified estimates
5	Unqualified estimates

Table 2: Data trustworthiness classification for LCI data

Source: Adapted from Kappler et al. (2018).

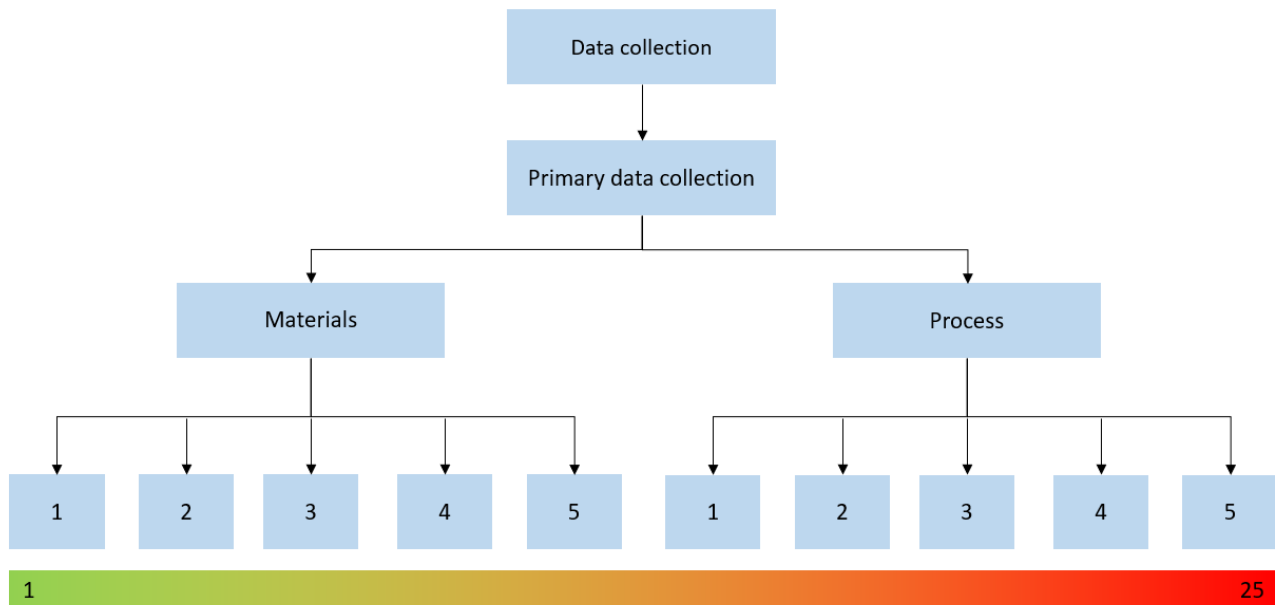


Figure 2: Evaluation flowchart for data trustworthiness of the LCI of this study.

Source: Adapted from Kappler et al. (2018).

2.2 Evaluation of the Environmental Aspects and Impacts

After the LCI accounted for all inflows and outflows of the manufacturing process of an FU, an environmental aspects and impacts could be conducted. To this end, the ReCiPe methodology was applied which made use of 18 midpoint indicators associated with 3 endpoint indicators:

- Damage to human health (in DALY – disability-adjusted life year): this included climate change, ozone depletion, human toxicity, photo-chemical formation, particulate matter and ionizing radiation;
- Damage to ecosystems (in species/year): this included ecosystem climate change, terrestrial acidification, fresh water eutrophication,

terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, land use transformation and agricultural and urban land occupation;
c) Damage to resource availability (in monetary \$ units): this included mineral resources and fossil resources.

Several studies have applied the ReCiPe methodology. The LCA of Maheshwari et al. (2023) applied ReCiPe to compare 2 manufacturing processes of Inconel alloy 625. Kokare et al. (2023) applied all 18 midpoint indicators to two additive manufacturing processes of a marine propeller: wire arc additive manufacturing (WAAM) and selective laser melting (SLM) compared to conventional computer numerical control (CNC) hobbing. Lastly, Landi et al. (2022) also applied all 18 midpoints to compare the lifecycle of straight gears manufactured with additive laser manufacturing or conventional techniques.

It should be noted that, as an LCA progresses, it might be necessary to include/exclude categories based on environmental impacts identified upon completion of the LCI. In this study, the LCI was used to classify aspects and impacts of the manufacturing process of both intermediate products and the FU into relevant categories. However, no specific LCA software was used for the calculations.

3. RESULTS AND DISCUSSION

3.1. Functional Unit and System Boundaries

The functional unit (FU) of this study was a mechanical gearbox (MG) while system boundaries were items manufactured internally by Business A as seen in Figure 3, these were the housing, crown gear, pinion gear, axle 1 and axle 2.

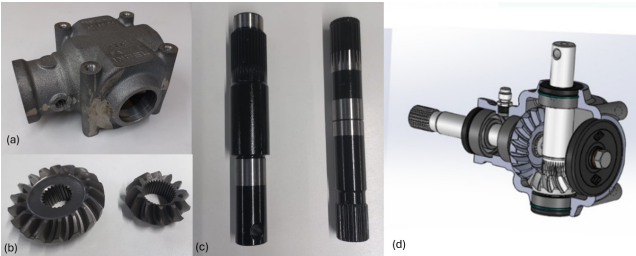


Figure 3: Items manufactured internally for the mechanical gearbox and FU: (a) housing; (b) crown gear and pinion gear; (c) axle 1 and axle 2 and (d) FU.
Source: The authors.

3.2. Reference Flow

Reference flows were determined from data collected in loco at Business A. For the assembly of the MG, other items that make up the FU were also manufactured in-house. The resulting manufacturing process flowcharts are shown in Figures 4 through Figure 7.

The manufacturing process for the housing started by separating smelted steel parts from raw material supplies. This material was sourced from outside system boundaries. The part was machined in a machining cell in 3 steps as shown in Figure 04. After washing, the part underwent quality control and sent to storage

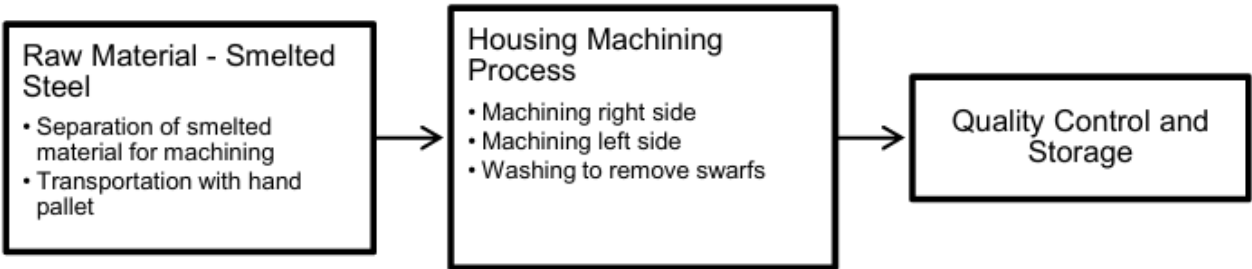


Figure 4: Manufacturing process flowchart of the housing used in the FU of this study.
Source: The authors.

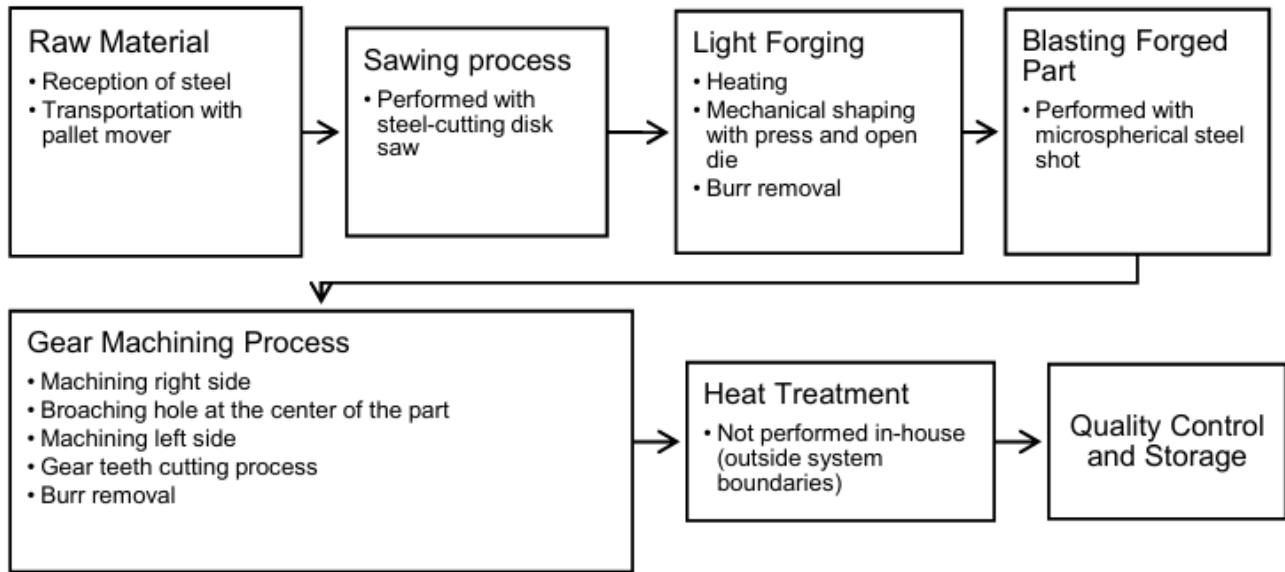


Figure 5: Manufacturing process flowchart of the crown gear or pinion gear used in the FU of this study
Source: The authors.

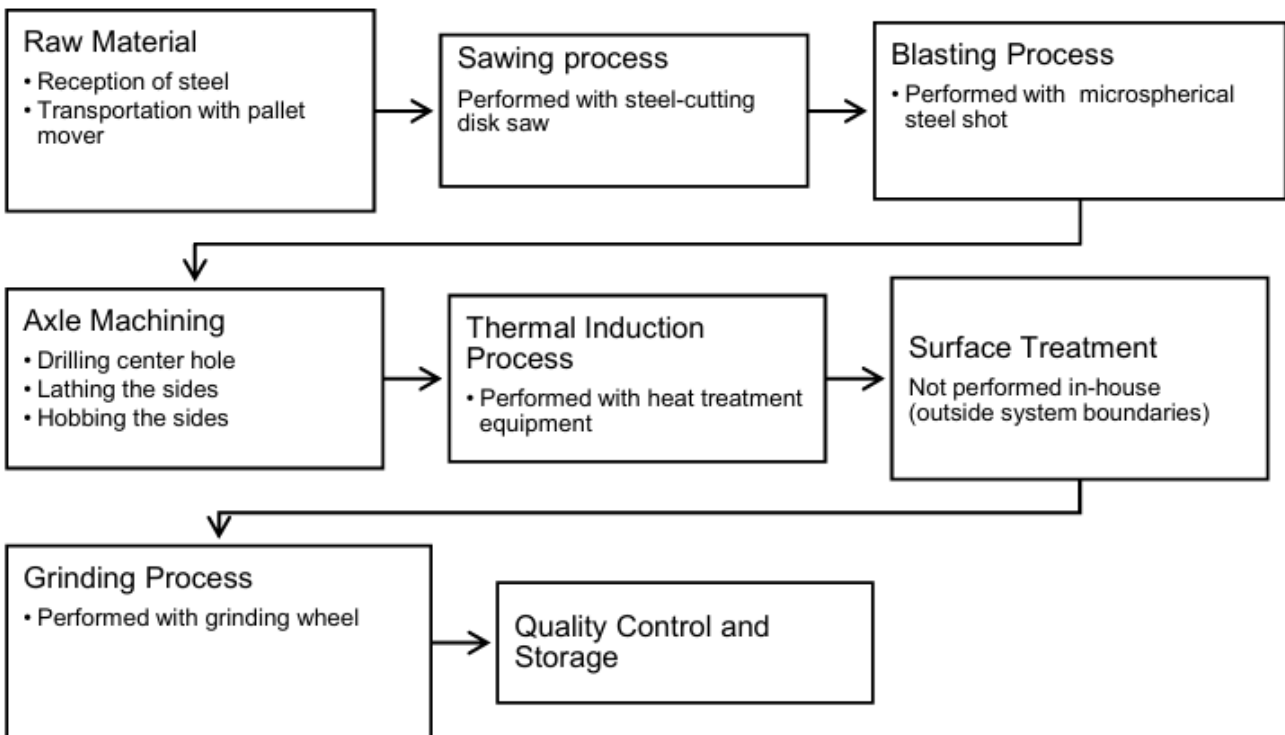


Figure 6: Manufacturing process flowchart of Axle 1 and Axle 2 used in the FU of this study.
Source: The authors.

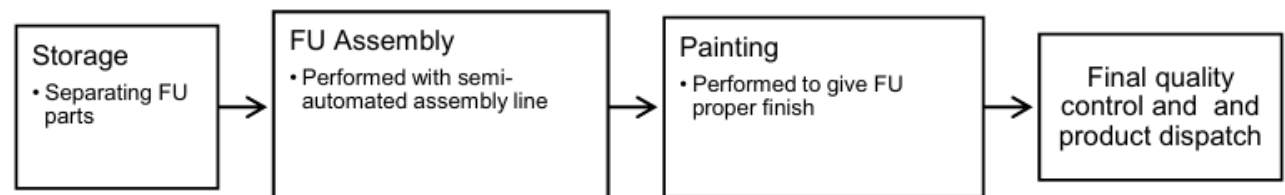


Figure 7: Manufacturing process flowchart of FU assembly for this study.
Source: The authors.

The manufacturing process of gears and axles started with a common first step of reception of steel bars. These materials were accompanied by a manufacturing invoice (MFG). Although not included in the references, this document contained specifications regarding the chemical composition of the steel, dimensions of the parts etc. The second common step in the manufacturing process was cutting with circular saws down to the dimensions required for each part.

Following cutting of the raw material, crown gears and pinion gears underwent a forging process consisting of heating under induction, shaping with an open die in an eccentric press and burr removal. After forging, blasting with micro-spherical steel shot was conducted to remove scales. Gears were machined in a gear machining cell in 5 steps as shown in Figure 05. The resulting conical helicoid gears were heat treated by a 3rd party contractor outside system boundaries. Upon return, the parts were checked for quality control and sent to storage.

Following cutting of the raw material, the manufacturing process of Axle 1 and Axle 2 consisted of blasting followed by machining. Machining was conducted in an axle machining cell in 3 steps as shown in Figure 06. The axles were tempered by induction heating followed by quenching to increase surface hardness. Surface treatment, which consisted of painting, was conducted outside system boundaries. Upon return, a grinding process was performed to adjust dimensions in accordance to design requirements. Finally, the axles were inspected for quality control and sent to storage.

The FU assembly process flowchart is shown in Figure 07. The process started with the separation of parts from storage. This step included items that were manufactured outside system boundaries. Parts were fed to an automated assembly line for assembly of the FU. The completed FU was sent to a painting line and finished its manufacturing process with quality control and delivery to dispatch.

3.3. Evaluation of the Environmental Aspects and Impacts

The Environmental Aspects and Impacts was conducted with data collected in loco and the manufacturing flowcharts presented in Section 3.2. The resulting block diagrams of the manufacturing process of the MG were developed on Excel® spreadsheet software and are presented in Annex 1.

Business A had a waste management program (WMP) in accordance to the national PNRS (BRASIL, 2010). The PNRS

listed types and amounts of solid wastes and their corresponding proper environmental separation, collection, storage, transport, recycling, destination and final disposal.

In accordance to environmental license regulations, effluents from the elementary outflow of machining processes were sent for external treatment at another business located in the state of Rio Grande do Sul. Treatment consisted of separation of oil and water through a physical process of evaporation under controlled temperature. Metallic waste destination started with in loco collection on a conveyor belt to a waste trolley. The collected waste was stored in a designated solid waste storage area (SWSA) where separation occurred in accordance to the WMP of Business A. Separated waste was then sold to licensed recycling businesses. The LCA conducted by Garbin et al. (2023) obtained environmental gains from recycling metallic waste associated with global warming (GWP 100a), acidity, human toxicity (air, water and soil) and ozone layer destruction. However, recycling associated with other categories had a negative gains due to high energy consumption requirements. Swarf from machining contained a degree of waste oil contamination. Business A separated the oil prior to swarf recycling by placing the waste on a perforated screen over a collection basin. Accumulated oil over 2 days was drained from the bottom of the basin, filtered and fed back to the machining cell equipment. Simon et al. (2017) evaluated this procedure as highly eco-efficient.

Class I solid waste generated were abrasive particles from blasting, scales from grinding and paint-contaminated waste from painting. These were sent to a specialized business licensed to handle Class I and II waste. Waste with significant energy content was converted into fuel while non-energetic wastes were forwarded for thermal disposal or used as replacement material in the production of cement. Araujo (2020) noted that the co-processing of waste in the cement industry was a suitable option for sustainability since it encompassed social, economic and environmental aspects. However, the LCA of Garbin et al. (2023) pointed out potentially negative environmental impacts in the incineration of dangerous wastes which were generated in all impact categories of this study.

3.3.1. Mass Balance

Table 04 presents the resulting inflow and outflow mass balances of intermediate products used in the FU. The mass balance identified that the larger proportion of solid metallic

waste were generated from the manufacture of crown gear (35 %) and pinion gear (59 %) intermediate products.

Intermediate product	Raw material (kg)	Solid metallic waste (kg)	%
Housing	3.9090	0.4560	12%
Pinion gear	0.4830	0.2870	59%
Crown gear	0.816	0.2896	35%
Axle 1	1.130	0.2800	25%
Axle 2	0.800	0.17	21%

Table 4: Mass balance of intermediate products of the FU.

Source: The authors.

The detailed individual mass balance of the pinion gear presented in Table 05 breaks down the elementary processes that make up the 59 % metallic solid waste generated from the machining process. Table 05 shows

that 23 % of the waste originated from machining the right side, which involved drilling through the center of the gear. Table 05 also shows that the crown gear generated less waste when compared to the pinion gear even though both parts had the same elementary processes. This was due to the crown gear geometry having final dimensions close to the location where gear teeth were hobbled. Consequently, gear hobbing accounted for 16% of waste for the crown gear but 26% for the pinion gear.

As shown in Table 05, the open die forging technique currently used generated 25% and 8% of solid waste for the crown and pinion gears, respectively. As noted by Flausino (2010), shaping provided by a close die offered improved control over the inflow of raw materials and reduced or eliminated swarf. Consequently, replacing the open die with a closed one with a shape in accordance with the final part would directly decrease the consumption of raw materials and waste generation.

Elementary Process	Raw Material (kg)	Solid metallic Residue (kg)	%
Crown Gear			
Steel cutting process	0.8161	0.0001	0%
Mechanical shaping with press and open die	0.8160	0.0000	0%
Light forging and swarf removal	0.8160	0.0723	25%
Right side machining	0.7437	0.0973	34%
Broaching center hole	0.6464	0.0085	3%
Left side machining	0.6379	0.0663	23%
Gear hobbing process	0.5716	0.0451	16%
Pinion Gear			
Steel cutting process	0.4831	0.0001	0%
Mechanical shaping with press and open die	0.4830	0.0000	0%
Light forging and swarf removal	0.4830	0.0392	8%
Right side machining	0.4438	0.1034	23%
Broaching center hole	0.3404	0.0107	3%
Left side machining	0.3297	0.0646	20%
Gear hobbing process	0.2652	0.0691	26%

Table 5: Break down of crown gear and pinion gear mass balance.

Source: The authors.

3.3.2. Energy Balance

Table 06 presents inflow and outflow energy balances of the manufacturing processes of the intermediate products used in the FU of this study. As shown in Table 06, the manufacture of a single FU of this study consumed 59.967 kWh of electricity. The energy balance of intermediate products identified that gear manufacture consumed the most energy due to the nominal power of the equipment. In comparison, axle manufacturing, while operating over the same length of time, consumed less energy.

Business A sought to decrease the environmental impact of energy consumption by acquiring its monthly electricity demand of 0.4 MW, which accounted for all manufacturing processes, from the free energy market

since 2018. This switch to the free market model could favor renewable energy sources since suppliers were free to acquire energy from federal auctions and provide service to their customers at variable rates (CEEE, 2022).

The industrial sector in Brazil accounted for 34.1 % of total consumption in 2021 as noted by the Atlas da Eficiência Energética (BRASIL, 2022b). The main energy sources for the industrial sector in 2020 were reported as sugarcane bagasse (22 %), electricity (21 %) and coal and derivatives (14 %) (BRASIL, 2021). In the case of Business A, its energy consumption and characteristic floor area suggested a possible change in energy matrix from a traditional model to photovoltaic, pending a detailed economic and environmental investment evaluation.

Intermediate Product	Nominal Power (kW)	Operating Time/FU (h)	Energy Consumption / FU (kWh)
Housing	42.240	0.1000	4.224
Pinion gear	431.748	0.0333	14.392
Crown gear	431.748	0.0333	14.392
Axle 1	290.208	0.0333	9.674
Axle 2	290.208	0.0333	9.674
Assembly	59.300	0.0778	4.612
Total energy consumed / FU (kWh)			56.967

Table 6: Energy balance of intermediate products for the FU of this study.

Source: The authors.

3.4. Evaluation of the Environmental Aspects and Impacts

Table 07 presents the aspects and impacts of the manufacturing process of the FU based on the inventory analysis of inflows and outflows. Business A belonged to the metal-mechanical sector and its manufacturing processes mostly consisted of machining. Consequently, as shown in Table 07, aspects and impacts were repeated in all processes. Impact categories for LCIA were related to Damages to Resource Availability in the ReCiPe methodology, although no specialized software was used in the analysis.

Regarding the use of steel and its contribution to the decrease in natural resources, it was concluded that the small quantities used in the production of the FU posed no probability of resource depletion. The steel used as raw material for gears and axles were imported from overseas suppliers due to economic reasons and

laid outside system boundaries. Thus the only possible opportunities for reducing environmental impact were the ones presented in Sec. 3.3.1.

Electricity consumption also presented an impact of decrease in natural resources. This was directly related to the Brazilian energy generation matrix, which was 72 % hydroelectric, 12. 9% wind power and 9.9 % thermoelectric (ONS, 2023). Business A currently acquired electricity from free market suppliers and the LCIA recommended investing in photovoltaic power generation if further studies confirmed its viability.

Process	Aspect	Impact	LCIA	
			Impact Category	Indicator
Housing, pinion gear, crown gear, Axle 1 and Axle 2	Materials consumed in small quantities and no probability of natural resource depletion. Raw material: steel	Decrease in Natural Resources	Resource Consumption	kg per FU
	Materials consumed in small quantities with probability of natural resource depletion. Used in inserts: rare metals	Decrease in Natural Resources	Resource Consumption	kg per FU
	Use of natural resource: water	Decrease in Natural Resources	Resource Consumption	L per FU
	Electricity consumption	Decrease in Natural Resources	Resource Consumption	kWh per FU
	Noise emissions	Sound Pollution	-	-
	Atmospheric emissions	Changes in air quality	-	-
	Solid waste generation	Changes in soil and water quality	Resource Consumption	kg per FU
	Contaminated effluent emissions	Changes in soil and water quality	Resource Consumption	L per FU
Assembly	Chemical products consumed in small quantities: non-halogenated solvents and paints	Decrease in Natural Resources	Resource Consumption	L per FU
	Noise emissions	Sound Pollution	-	-
	Electricity consumption	Decrease in Natural Resources	Resource Consumption	kWh per FU
	Solid waste generation	Changes in soil and water quality	Resource Consumption	kg per FU

Table 7: Processes Aspects and Impacts on FU production.

Source: The authors.

Changes in soil and water quality were impacts related to Class I solid waste generation from the manufacturing process and contaminated effluents from machinery cleaning processes. Steps taken by Business A to mitigate environmental impacts and use of industrial landfills were to send Class I waste for co-processing and effluents for treatment at outside businesses, as required by environmental legislation. Thus, no direct environmental onus was laid at Business A.

Regarding noise emissions from operating machinery, impacts and mitigating steps were evaluated in accordance with directives from regulating agencies and reported as required for environmental operating licenses. Atmospheric emissions from oil and paint spray associated with changes in air quality were mitigated by monitoring and replacing exhaust filters as recommended by suppliers.

Overall, the identified environmental impacts associated with the production of the FU and current adopted

mitigating steps demonstrated that Business A was concerned with environmental issues and compliant with environmental legislation.

4. CONCLUSIONS

Currently, while the industrial sector continuously invests in improvements to manufacturing processes, customers also demand attention from businesses and products to environmental concerns. An LCA methodology can attend to both issues since it can identify opportunities in manufacturing processes that improve environmental performance of a product along its life cycle. The resulting efforts could be further used in the production of public relation materials with positive marketing potential.

This study applied a simplified LCA to the manufacturing process of a mechanical gearbox through mass

and energy balances and block diagram methodology. System boundaries were defined as items manufactured in-house. The goal and scope were the life cycle of a single mechanical gearbox FU through manufacturing process flows. Primary data collected in loco were used as base to construct inventory inflow and outflow through block diagrams.

The inventory inflow and outflow allowed the calculation of mass balances of metallic solid waste in the manufacturing process of an FU both globally as well as for individual intermediate products. For example, the pinion gear intermediate product accounted for 59 % solid waste generation. A breakdown of the elementary processes of the pinion gear identified that machining the right side and gear hobbing accounted for 23 % and 26 % of solid waste generated, respectively.

The evaluation of the environmental aspects and impacts of the mechanical gearbox FU manufacturing process identified the decrease of natural resources as the major impact affecting all processes, followed by changes to soil and water quality. Data collected in 2021 demonstrated that Business A already engaged in environmentally conscious practices. It was concluded that the use of a simplified LCA as an environmental management tool could aid in directing future initiatives to further mitigate environmental impacts.

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ANNEX 1

Product System	Mechanical Gearbox (MG)			Intermediate Product	Housing			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Smelted steel	3.9090	kg	1	Transport on hand pallet	Smelted steel	3.9090	kg	1
LPG (gas)	0.0001	m³	4		Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party service				Hydraulic oil (used)	3rd party service		
Smelted steel	3.9090	kg	1	Right side machining	Housing machining – right side	3.7700	kg	1
Inserts	0.0046	un	1		Solid waste (metal)	0.1390	kg	1
Electricity	1.6	kWh	4		Inserts (used)	0.0046	un	1
Soluble oil	0.0042	L	4		Contaminated effluent	0.0050	L	4
Hydraulic oil	0.0008	L	4		Atmospheric emissions	Undetermined		
Housing machining – right side	3.77	kg	1	Left side machining	Housing	3.4530	kg	1
Inserts	0.0066	un	1		Solid waste (metal)	0.3170	kg	1
Electricity	1.5	kWh	4		Inserts (used)	0.0066	un	1
Soluble oil	0.0042	L	4		Contaminated effluent	0.0050	L	4
Hydraulic oil	0.0008	L	4		Atmospheric emissions	Undetermined		
Housing	3.453	kg	1	Washer	Housing	3.4530	kg	1
Water	0.0083	L	5		Contaminated effluent	0.0249	L	5
Electricity	1.1	kWh	4		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0166	L	1					
Housing	3.4530	kg	1	Transport on pallet carrier	Housing	3.4530	kg	1
Electricity	0.0240	kWh	4					

Table 3: Inventory inflows and outflows for the manufacture of the housing used in the FU of this study.

Source: The authors.

Product System	Mechanical Gearbox (MG)			Intermediate Product	Pinion gear			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	26.947	kg	1	Transport by hoist	Steel bar	26.947	kg	1
Electricity	0.0111	kWh	4					
Steel bar	26.947	kg	1	Steel cutting with disk saw	Saw 1	0.483	kg	1
Disk saw	0.0005	un	1		Solid waste (metal)	0.0001	kg	1
Electricity	0.1042	kWh	4		Disk saw waste	0.0005	un	1
Cutting oil	0.0013	L	1		Contaminated effluent	0.0025	L	1
Hydraulic oil	0.0012	L	1		Atmospheric emissions	Undetermined		
Saw 1	0.4830	kg	1		Part heating	Heated saw 1	0.4830	kg
Electricity	1.6667	kWh	4	Heat		26.8	°C	1
Cooling system (water)	200.00	L	4	Cooling system (water)		200.00	L	4
Heated saw 1	0.4830	kg	1	Shaping with press and open die	Forged part 1	0.4830	kg	1
Electricity	0.6214	kWh	4		Contaminated effluent	0.0057	L	1
Demolder	0.0057	L	1					
Forged part 1	0.4830	kg	1	Scale removal	Forged part 1	0.4438	kg	1
Electricity	0.1022	kWh	4		Solid waste (metal)	0.0392	kg	1
Forged part 1	0.4438	kg	1	Transport by pallet carrier	Forged part 1	0.4438	kg	1
LPG (gas)	0.0001	m³	4		Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party service							
Forged part	0.4438	kg	1	Blasting	Pinion gear	0.4438	kg	1
Blasting steel material	0.0053	kg	1		Solid waste (Class I)	0.0053	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		
Air filter	0.0003	un	1		Solid waste (Class I)	0.0003	un	1

Pinion gear	0.4438	kg	1	Rights side machining	Pinion gear	0.3404	kg	1
Inserts	0.0048	un	1		Solid waste (metal)	0.1034	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0031	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0048		1
Hydraulic oil	0.0019	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.3404	kg	1	Broaching center of the part	Pinion gear	0.3297	kg	1
Broach	0.0004	un	1		Solid waste (metal)	0.0107	kg	1
Electricity	0.7333	kWh	4		Contaminated effluent	0.0023	L	1
Soluble oil	0.0012	L	1		Broach (used)	0.0004	un	1
Hydraulic oil	0.0010	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.3297	kg	1	Machining	Pinion gear	0.2652	kg	1
Inserts	0.0031	un	1		Solid waste (metal)	0.0646	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0021	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0031	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.2652	kg	1	Gear teeth cutting	Pinion gear	0.1961	kg	1
Pentac cutter	1.0000	un	1		Solid waste (metal)	0.0691	kg	1
Electricity	2.7667	kWh	4		Pentac cutter (used)	1.0000	un	1
Soluble oil	0.00176	L	1		Contaminated effluent	0.0176	L	1
Water	0.0158	L	1		Atmospheric emissions	Undetermined		
Pinion gear	0.1961	kg	1	Swarf removal	Pinion gear	0.1961	kg	1
Disk saw	0.0010	un	1		Solid waste (metal)	0.0000	kg	1
Electricity	0.0667	kWh	4		Disk saw (used)	0.0010	un	1
Lubricant oil	0.0007	L	1		Atmospheric emissions	Undetermined		
					Contaminated effluent	0.0007	L	1
Pinion gear	0.1961	kg	1	Transport by pallet carrier to storage	Pinion gear	0.1961	kg	1
Electricity	0.0240	kWh	4					

Table 4: Inventory inflows and outflows for the manufacture of the pinion gear used in the FU of this study.

Source: The authors.

Product System	Mechanical Gearbox (MG)			Intermediate Product	Crown gear			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	26.947	kg	1	Transport by hoist	Steel bar	26.947	kg	1
Electricity	0.0111	kWh	4					
Steel bar	26.947	kg	1	Steel cutting with saw disk	Saw 2	0.8160	kg	1
Saw disk	0.0005	un	1		Solid waste (metal)	0.0001	kg	1
Electricity	0.1042	kWh	4		Contaminated effluent	0.0025	L	1
Cutting oil	0.0013	L	1		Saw disk (used)	0.0005	un	1
Hydraulic oil	0.0012	L	1		Atmospheric emissions	Undetermined		
Saw 2	0.8160	kg	1		Part heating	Heated saw 2	0.8160	kg
Electricity	1.6667	kWh	4	Heat		26.8	°C	1
Cooling system (water)	200.00	L	4	Cooling system (water)		200.00	L	4
Heated saw 2	0.8160	kg	1	Shaping with press and open die	Forged part 2	0.8160	kg	1
Electricity	0.6214	kWh	4		Contaminated effluent	0.0057	L	1
Demolder	0.0057	L	1					
Forged part 2	0.8160	kg	1	Scale removal	Forged part 2	0.7437	kg	1
Electricity	0.1022	kWh	4		Solid waste (metal)	0.0723	kg	1
Forged part 2	0.7437	kg	1	Transport by pallet carrier	Forged part 2	0.7437	kg	1
LPG (gas)	0.0001	m³	4		Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party maintenance							
Forged part 2	0.7437	kg	1	Blasting	Crown gear	0.7437	kg	1
Blasting material	0.0057	kg	1		Solid waste (Class I)	0.0057	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		

Table 5: Inventory inflows and outflows for the manufacture of the crown gear used in the FU of this study.

Source: The authors.

Crown gear	0.7437	kg	1	Matching right side	Crown gear - right side	0.6464	kg	1
Inserts	0.0048	un	1		Solid waste (metal)	0.0973	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0031	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0048	un	1
Hydraulic oil	0.0019	L	1		Atmospheric emissions	Undetermined		
Crown gear - right side	0.6464	kg	1	Broaching center of the part	Crown gear right side broach	0.6379	kg	1
Broach	0.0004	un	1		Solid waste (metal)	0.0085	kg	1
Electricity	0.7333	kWh	4		Contaminated effluent	0.0023	L	1
Soluble oil	0.0012	L	1		Broach (used)	0.0004	un	1
Hydraulic oil	0.0010	L	1		Atmospheric emissions	Undetermined		
Crown gear - right side broach	0.6379	kg	1	Machining	Crown gear	0.5716	kg	1
Inserts	0.0031	un	1		Solid waste (metal)	0.0663	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0021	L	1
Soluble oil	0.0012	L	1		Inserts (used)	0.0031	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Crown gear	0.5716	kg	1	Gear teeth cutting	Crown gear	0.5265	kg	1
Pentac cutter	1.0000	un	1		Solid waste (metal)	0.0451	kg	1
Electricity	2.7667	kWh	4		Atmospheric emissions	Undetermined		
Soluble oil	0.0018	L	1		Contaminated effluent	0.0176	L	1
Water	0.0158	L	1		Pentac cutter (used)	1.0000	un	1
Crown gear	0.5265	kg	1	Swarf removal	Crown gear	0.5265	kg	1
Saw disk	0.0010	un	1		Saw disk (used)	0.0010	un	1
					Solid waste (metal)	0.0000	kg	1
Electricity	0.0667	kWh	4		Atmospheric emissions	Undetermined		
Lubricating oil	0.0007	L	1		Contaminated effluent	0.0007	L	1
Crown gear	0.5265	kg	1	Transport by pallet carrier to storage	Crown gear	0.5265	kg	1
Electricity	0.0240	kWh	4					

Table 5: Inventory inflows and outflows for the manufacture of the crown gear used in the FU of this study (cont.)

Source: The authors.

Product System	Mechanical Gearbox (MG)			Intermediate Product	Axle 1			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	37.2910	kg	1	Transport by hoist	Steel bar	37.2910	kg	1
Electricity	0.0111	kWh	4					
Steel bar	37.2910	kg	1	Steel cutting with disk saw	Saw 3	1.1300	kg	1
Saw disk	0.0005	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.0613	kWh	4		Contaminated effluent	0.0626	L	1
Cutting oil	0.0013	L	1		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0012	L	1		Saw disk (used)	0.0005	un	1
Saw 3	1.1300	kg	1		Saw 3	1.1300	kg	1
LPG (gas)	0.0001	m³	4	Transport by pallet carrier	Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party maintenance				Hydraulic oil	3rd party maintenance		
Saw 3	1.1300	kg	1	Blasting	Axle 1	1.1300	kg	1
Blasting steel material	0.0057	kg	1		Solid waste (Class I)	0.0057	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		
Air filter	0.0003	un	1					
Axle 1	1.1300	kg	1	Drilling center of part	Axle 1 - center drilling	1.1000	kg	1
Inserts	0.0012	un	1		Solid waste (metal)	0.0300	kg	1
Electricity	0.5000	kWh	4		Contaminated effluent	0.0028	L	1
Soluble oil	0.0020	L	1		Inserts (used)	0.0012	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Axle 1 - center drilling	1.1000	kg	1					
Inserts	0.0078	un	1	Lathing	Axle 1	0.8900	kg	1
Electricity	0.9194	kWh	4		Solid waste (metal)	0.2100	kg	1
Soluble oil	0.0020	L	1		Contaminated effluent	0.0028	L	1
Hydraulic oil	0.0008	L	1		Inserts (used)	0.0078	un	1
					Atmospheric emissions	Undetermined		

Table 6: Inventory inflows and for the manufacture of the Axle 1 used in the FU of this study.

Source: The authors.

Axle 1	0.8900	kg	1	Hobbing the sides	Axle 1	0.8700	kg	1
Inserts	0.0003	un	1		Solid waste (metal)	0.0200	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0030	L	1
Soluble oil	0.0004	L	1		Inserts (used)	0.0003	un	1
Hydraulic oil	0.0028	L	1		Atmospheric emissions	Undetermined		
Axle 1	0.8700	kg	1	Thermal induction treatment	Axle 1	0.8700	kg	1
Soluble oil	0.0020	L	1		Contaminated effluent	0.0031	L	1
Electricity	5.0000	kWh	4		Atmospheric emissions	Undetermined		
Lubricating oil	0.0009	L	1					
Soluble oil	0.0001	L	1					
Axle 1	0.8700	kg	1	Grinding	Axle 1	0.8600	kg	1
Grinder	0.0001	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.8667	kWh	4		Contaminated effluent	0.0015	L	1
Lubricating oil	0.0002	L	1		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0012	L	1		Solid waste (Class I)	0.0001	un	1
Axle 1	0.8600	kg	1	Transport by pallet carrier to storage	Axle 1	0.8600	kg	1
Electricity	0.0240	m ³	4					

Table 6: Inventory inflows and for the manufacture of the Axle 1 used in the FU of this study (cont.)

Source: The authors.

Product System	Mechanical Gearbox (MG)			Intermediate Product	Axle 1			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Steel bar	26.9470	kg	1	Transport by hoist	Steel bar	26.9470	kg	1
Electricity	0.0111	kWh	4					
Steel bar	26.9470	kg	1	Steel cutting with disk saw	Saw 4	0.8000	kg	1
Saw disk	0.0005	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.0613	kWh	4		Contaminated effluent	0.0626	L	1
Cutting oil	0.0013	L	1		Saw disk (used)	0.0005	un	1
Hydraulic oil	0.0012	L	1		Atmospheric emissions	Undetermined		

Table 7: Inventory inflows and outflows for the manufacture of the Axle 2 used in the FU of this study.

Source: The authors.

Saw 4	0.8000	kg		Transport by pallet carrier	Saw 4	0.8000	kg	
LPG (gas)	0.0001	m³			Atmospheric emissions	Undetermined		
Hydraulic oil	3rd party maintenance				Hydraulic oil	3rd party maintenance		
Saw 4	0.8000	kg	1	Blasting	Axle 2	0.8000	kg	1
Blasting steel material	0.0057	kg	1		Solid waste (Class I)	0.0057	kg	1
Electricity	0.1144	kWh	4		Atmospheric emissions	Undetermined		
Air filter	0.0003	un	1					
Axle 2	0.8000	kg	1	Center hole drilling	Axle 2 - center drilling	0.7900	kg	1
Inserts	0.0012	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.5000	kWh	4		Contaminated effluent	0.0028	L	1
Soluble oil	0.0020	L	1		Inserts (used)	0.0012	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Axle 2 - center hole	0.7900	kg	1	Lathing	Axle 2	0.6700	kg	1
Inserts	0.0078	un	1		Solid waste (metal)	0.1200	kg	1
Electricity	0.9194	kWh	4		Contaminated effluent	0.0028	L	1
Soluble oil	0.0020	L	1		Inserts (used)	0.0078	un	1
Hydraulic oil	0.0008	L	1		Atmospheric emissions	Undetermined		
Axle 2	0.6700	kg	1	Hobbing	Axle 2	0.6500	kg	1
Inserts	0.0003	un	1		Solid waste (metal)	0.0200	kg	1
Electricity	1.2667	kWh	4		Contaminated effluent	0.0030	L	1
Soluble oil	0.0004	L	1		Inserts (used)	0.0003	un	1
Hydraulic oil	0.0028	L	1		Atmospheric emissions	Undetermined		
Axle 2	0.6500	kg	1	Induction heat treatment	Axle 2	0.6500	kg	1
Soluble oil	0.0020	L	1		Contaminated effluent	0.0031	L	1
Electricity	5.0000	kWh	4		Atmospheric emissions	Undetermined		
Lubricating oil	0.0009	L	1					
Soluble oil	0.0001	L	1					

Table 7: Inventory inflows and outflows for the manufacture of the Axle 2 used in the FU of this study (cont.)

Source: The authors.

Axle 2	0.6500	kg	1	Grinding	Axle 2	0.6400	kg	1
Grindstone	0.0001	un	1		Solid waste (metal)	0.0100	kg	1
Electricity	0.8667	kWh	4		Contaminated effluent	0.0015	L	1
Lubricating oil	0.0002	L	1		Atmospheric emissions	Undetermined		
Hydraulic oil	0.0012	L	1		Solid waste (Class I)	0.0001	un	1
Axle 2	0.6400	kg	1	Transport by pallet carrier to storage	Axle 2	0.6400	kg	1
Electricity	0.0240	m ³	4					

Table 7: Inventory inflows and outflows for the manufacture of the Axle 2 used in the FU of this study (cont.)

Source: The authors.

Product System	Mechanical Gearbox (MG)			Intermediate Product	Assembly			
Inflow				Stage	Outflow			
Elementary inflow	Quantity	Units	Classification	Elementary process	Elementary outflow	Quantity	Units	Classification
Housing	3.4530	kg	1	Semi-automated FU assembly	MG	6.3500	kg	1
Pinion gear	0.1961	kg	1					
Crown gear	0.5264	kg	1					
Axle 1	0.8600	kg	1					
Axle 2	0.6400	kg	1					
Oil	0.2500	L	1					
Miscellaneous parts	0.6744	kg	1					
Electricity	0.2567	kWh	4					
MG	6.3500	kg	1	Painting and Finishing	MG	6.3500	kg	1
Paint	0.007	L	1		Non-halogenated solvent effluent	0.003	L	1
Electricity	4.556	kWh	4		Solid waste (Class I)	0.002	un	1
Air filter	0.002	un	1		Atmospheric emissions	Undetermined		
Solvent	0.003	L	1					

Table 7: Inventory inflows and outflows for the assembly of the FU of this study.

Source: The authors.

SUSTAINABLE MAINTENANCE OF AGING REINFORCED CONCRETE STRUCTURES: EVALUATING DIAGNOSTIC TECHNIQUES FOR EARLY DETECTION OF REINFORCEMENT CORROSION

MANUTENÇÃO SUSTENTÁVEL DE ESTRUTURAS DE CONCRETO ARMADO ENVELHECIDAS: AVALIAÇÃO DE TÉCNICAS DE DIAGNÓSTICO PARA DETECÇÃO PRECOCE DA CORROSÃO DAS ARMADURAS

MANTENIMIENTO SOSTENIBLE DE ESTRUCTURAS DE HORMIGÓN ARMADO ENVEJECIDAS: EVALUACIÓN DE TÉCNICAS DE DIAGNÓSTICO PARA LA DETECCIÓN TEMPRANA DE LA CORROSIÓN DE LOS REFUERZOS

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ABSTRACT

Reinforcement corrosion is a critical issue affecting the durability of reinforced concrete structures, particularly in Brazilian urban buildings now 40 to 50 years old. Sustainable management of these aging structures is essential to extend their service life and reduce the environmental impact of demolition and reconstruction. Repairing these structures, rather than demolishing them, significantly lowers the consumption of raw materials and construction waste, aligning with sustainability principles. Early corrosion detection is crucial for timely maintenance, helping preserve structural integrity and avoid unnecessary replacements, further minimizing environmental impacts. This study, part of a doctoral thesis, evaluates diagnostic techniques based on corrosion potential measurements to support sustainable infrastructure management. Full-scale reinforced concrete beams were subjected to induced corrosion using the Modified Immersion Accelerated Corrosion (CAIM) method, targeting 5%, 10%, and 15% mass loss levels. The results showed significant uncertainty in corrosion potential diagnostics at 5% and 10% mass loss, making early-stage assessments inconclusive. However, at 15% mass loss, the method produced satisfactory results, indicating its reliability at more advanced stages. The study highlights the need for more accurate diagnostic tools for early corrosion detection to promote sustainable maintenance and reduce environmental and economic costs from structural failure and replacement.

KEYWORDS

Sustainable Maintenance; Corrosion; Diagnosis; Corrosion Potential; Corrosion Acceleration.

RESUMO

A corrosão das armaduras é um problema crítico que afeta a durabilidade de estruturas de concreto armado, particularmente em edifícios urbanos brasileiros agora com 40 a 50 anos de idade. A gestão sustentável dessas estruturas envelhecidas é essencial para estender sua vida útil e reduzir o impacto ambiental da demolição e reconstrução. Reparar



essas estruturas, em vez de demolir, diminui significativamente o consumo de matérias-primas e os resíduos de construção, alinhando-se aos princípios de sustentabilidade. A detecção precoce da corrosão é crucial para a manutenção oportuna, ajudando a preservar a integridade estrutural e evitar substituições desnecessárias, minimizando ainda mais os impactos ambientais. Este estudo, parte de uma tese de doutorado, avalia técnicas de diagnóstico baseadas em medições de potencial de corrosão para apoiar o gerenciamento sustentável de infraestrutura. Vigas de concreto armado em escala real foram submetidas à corrosão induzida pelo Método de Corrosão Acelerada por Imersão Modificada (CAIM), visando níveis de perda de massa de 5%, 10% e 15%. Os resultados mostraram incerteza significativa nos diagnósticos de potencial de corrosão em 5% e 10% de perda de massa, tornando as avaliações em estágio inicial inconclusivas. Contudo, com 15% de perda de massa, o método apresentou resultados satisfatórios, indicando sua confiabilidade em estágios mais avançados. O estudo ressalta a necessidade de ferramentas diagnósticas mais precisas para a detecção precoce da corrosão, a fim de promover a manutenção sustentável e reduzir os custos ambientais e econômicos decorrentes de falhas estruturais e substituições.

PALAVRAS-CHAVE

Manutenção Sustentável; Corrosão; Diagnóstico; Potencial de Corrosão; Aceleração da Corrosão

RESUMEN

La corrosión de los refuerzos es un problema crítico que afecta la durabilidad de las estructuras de hormigón armado, particularmente en edificios urbanos brasileños de 40 a 50 años de antigüedad. La gestión sostenible de estas estructuras envejecidas es esencial para prolongar su vida útil y reducir el impacto ambiental de la demolición y reconstrucción. Reparar estas estructuras, en lugar de demolerlas, reduce significativamente el consumo de materias primas y los residuos de construcción, alineándose con los principios de sostenibilidad. La detección temprana de la corrosión es fundamental para realizar un mantenimiento oportuno, preservando la integridad estructural y evitando reemplazos innecesarios, minimizando así los impactos ambientales. Este estudio, parte de una tesis doctoral, evalúa técnicas de diagnóstico basadas en mediciones de potencial de corrosión para respaldar la gestión sostenible de infraestructuras. Vigas de hormigón armado a escala real fueron sometidas a corrosión inducida mediante el Método de Inmersión Acelerada Modificada (CAIM), con niveles de pérdida de masa del 5%, 10% y 15%. Los resultados mostraron una incertidumbre significativa en los diagnósticos de potencial de corrosión con pérdidas de masa del 5% y 10%, haciendo que las evaluaciones en etapas tempranas fueran inconclusas. Sin embargo, con una pérdida de masa del 15%, el método produjo resultados satisfactorios, indicando su fiabilidad en etapas más avanzadas. El estudio subraya la necesidad de herramientas diagnósticas más precisas para la detección temprana de la corrosión, con el fin de promover el mantenimiento sostenible y reducir los costes ambientales y económicos derivados de fallos estructurales y reemplazos.

PALABRAS CLAVE

Mantenimiento Sostenible; Corrosión; Diagnóstico; Potencial de Corrosión; Aceleración de la Corrosión

1. INTRODUCTION

In the early years of the twentieth century, civil construction underwent a significant paradigm shift. Traditional construction methods at the time predominantly relied on self-supporting masonry and metallic structures. However, the introduction of reinforced concrete brought about a transformative change. This innovative material combined the versatility and availability of concrete with the high strength of steel, offering new possibilities for construction. As a result, reinforced concrete technologies began to rise in prominence, marking the beginning of a new era in construction that started in the early decades of the last century.

Reinforced concrete structures, including buildings and bridges, are designed for longevity. Bridge structures often have a design life of 100 years or more. When the correct concrete cover is used with an appropriate mix design, the concrete typically provides adequate corrosion protection for the embedded steel reinforcement bars, Donadio, Capacho, Santander (2023).

A significant portion of this growth occurred because, in the early days, it was believed that reinforced concrete structures possessed unlimited durability and required little to no maintenance. As a result, reinforced concrete was initially heralded as a material with indefinite longevity. However, it is now understood that no construction material has such characteristics, as all materials degrade and deteriorate over time.

It is widely acknowledged that when properly designed, executed, and mixed, reinforced concrete can have a substantial lifespan. However, this longevity depends on carefully evaluating several factors, including environmental exposure conditions, protective measures, and ongoing maintenance.

The pursuit of understanding the behavior of reinforced concrete throughout its lifespan has led to numerous studies aimed at comprehending the underlying mechanisms of structural degradation. Among the various degradation processes that compromise the performance of reinforced concrete structures, reinforcement corrosion stands out as the most critical due to its frequent occurrence and severity. Corrosion of the reinforcement must be carefully monitored, as it can alter fundamental structural parameters, leading to several detrimental effects, including a reduction in the cross-sectional

area of the reinforcement, concrete cracking due to the tensile stress caused by corrosion products, displacement of the concrete cover; the reduced bond between the reinforcement and concrete; and a decrease in the flexibility of the steel.

However, the phenomenological mechanism of corrosion is inherently slow, making natural observation of the process impractical for timely experimental evaluation. This has led to developing methods to accelerate the corrosion process for research purposes. One of the most widely used methods is the Modified Immersion Corrosion technique. This method accelerates the corrosion process, allowing for the experimental evaluation of its effects on reinforced concrete structures. To ensure that the results are consistent with the natural phenomenon, specific parameters are adopted to minimize discrepancies.

Reinforcement corrosion is one of the main challenges faced by Civil Engineering. According to El-Reedy (2018), this type of pathological manifestation incurs billions of dollars in worldwide costs. A concerning factor, as noted by Cascudo (1997) and Ribeiro (2018), is that a significant portion of buildings and infrastructure in Brazilian urban centers were constructed during the 1970s and 1980s. As a result, many of these structures are now between 40 and 50 years old and are reaching a stage where repairs and maintenance are becoming routine. Consequently, issues related to reinforcement corrosion are expected to become more pronounced in the coming years.

The preservation and maintenance required to prevent the deterioration of the built environment involve substantial costs due to the complexity of the technologies and processes involved in rehabilitation and repair. Buildings and infrastructure are critical components of developed societies, and ensuring their usability while maintaining the highest safety standards is an indisputable priority (Andrade, 2019). Therefore, there is a growing need to evaluate corrosion at various levels of degradation, establish correlations with diagnostic techniques such as corrosion potential, and support the detection of corrosion in structures.

2. CORROSION IN REINFORCED CONCRETE STRUCTURES: EFFECTS ON STRUCTURAL BEHAVIOR

The study of corrosion in reinforced concrete is a prominent research focus within the Structural Models Testing Lab Research Group (LEME) and the Graduate School Program

in Civil Engineering (PPGEC) at the Federal University of Rio Grande do Sul (UFRGS). This chapter briefly reviews the effects of corrosion on reinforced concrete structures, particularly concerning their structural behavior.

Reflecting on the history of PPGEC/UFRGS, several comprehensive works have delved into the topic of corrosion, including studies by Andrade (1992), Andrade (2001), Adamatti (2016), Caetano (2008), Graeff (2007), and Stein (2019). Beyond these contributions, there exists an extensive bibliography on the subject, featuring works by Cascudo (1997), Helene (1993), Helene (1986), Meira (2017), Mehta and Monteiro (2014), Ribeiro and Cunha (2014), Tuutti (1982), among others.

2.1 Corrosion Degree in Reinforced Concrete Structures: General Considerations

Research conducted by Apostolopoulos (2007), Caprili and Salvatore (2015), Fernandez *et al.* (2015), Gehlen and Weirich (2016), and Kashani *et al.* (2015) has evaluated the influence of corrosion on reinforcement bars in steel structures, both embedded in and separate from concrete. The findings consistently confirm that corrosion adversely affects the mechanical properties of steel. Specifically, corrosion directly reduces the tensile strength of steel while simultaneously causing fragmentation, which in turn leads to reduced flexibility. From a structural behavior perspective, flexibility is highly desirable, as its absence can result in brittle failure and, often, unpredictability. In reinforced concrete structures, where steel is responsible for ensuring flexibility, corrosion levels are expressed as mass loss exceeding 5%, impacting strength and flexibility significantly. These adverse effects become more pronounced when corrosion levels surpass 10%.

It is important to note that these effects have been observed in studies focusing solely on the impact of corrosion on isolated steel bars. However, the effects of corrosion in reinforced concrete structures tend to be more severe due to the additional reduction in bond strength between the reinforcement and the concrete. Almusallam *et al.* (2001), Graeff (2007), and Caetano (2008) have reported that bond strength decreases sharply when corrosion levels reach or exceed 10%, whereas, at lower levels (1.5% to 4.0%), there may be an increase in bond strength between the two materials.

When analyzing corrosion in reinforced concrete structures, particularly in elements subjected to bending, such as beams, a similar pattern of behavior is observed.

Even at a corrosion level of 5%, there is a noticeable reduction in the structural performance of these elements. However, the decrease in structural performance becomes significantly more severe when corrosion levels exceed 10%. This intensified effect can be attributed to the reduction of steel's mechanical properties and the loss of bond strength between the concrete and steel

2.2 Corrosion Mechanism in Reinforced Concrete Structures

Tuutti (1982) proposed a phenomenological model for the corrosion mechanism in reinforced concrete reinforcements, dividing the process into two stages: start and propagation. According to Cascudo (1997), the development of corrosion requires the rupture of the steel's passive layer. Andrade (2001) defines the start process as the time for aggressive agents, such as carbon dioxide or chlorides, to penetrate the concrete cover and break the reinforcement's passive layer.

Once the passive layer is breached, the reinforcement becomes vulnerable to corrosion, marking the beginning of the propagation stage (Cascudo, 1997). During this phase, as noted by Meira (2017), the corrosion process advances, leading to the kinetics of corrosion. This stage is where the harmful effects of corrosion manifest. Based on studies conducted within this research, which focus on the propagation stage, the primary harmful effects of corrosion in reinforced concrete structures are introduced and discussed.

The effects of corrosion in reinforced concrete structures can be categorized into three main consequences: the mechanical properties of the reinforcements, the bond between the reinforcements and the concrete, and the fissuring of the concrete. A key concern in the literature is the loss of monolithic behavior in the structure, which reduces its load-bearing capacity.

Additionally, the weakening of steel during the corrosive process is frequently discussed, as it diminishes the steel's ability to deform under load. Consequently, the relative impact of corrosion on the structural behavior of reinforced concrete is primarily developed around the themes of the mechanical properties of the reinforcements and the loss of bond strength between the concrete and the reinforcement (Reginato, 2020).

Reinforcement plays a crucial role in reinforced concrete structures. The amount of reinforcement is determined through often complex calculations

and is typically expressed in terms of the necessary reinforcement area. Thus, the reinforcement area is one of the most critical parameters in reinforced concrete structures (Graeff, 2007).

During the corrosion propagation stage, corrosion products (such as oxides and iron hydroxides) form, consuming the reinforcement's mass. This results in material loss and a consequent reduction in the reinforcement's cross-sectional area.

Corrosion can significantly impact the tensile strength and flexibility of the reinforcements. These properties are essential for structural performance, affecting the structure's load-bearing capacity and failure mode (Meira, 2017).

3. NONDESTRUCTIVE METHODS FOR THE EVALUATION OF CORROSION

Over the past few decades, the application of Nondestructive Testing (NDT) in Civil Engineering has garnered significant interest in many countries (Lorenzi *et al.*, 2015). The use of NDT in this field is closely tied to the reliability of the methods, the understanding of their application, and their economic viability (Beutel *et al.*, 2006).

Since corrosion is one of the most common degradation mechanisms in reinforced concrete structures, various NDT techniques have been developed to evaluate it. Notable among these are the corrosion potential technique, resistivity measurements, and corrosion rate assessments.

3.1. Corrosion Potential

The measurement of reinforcement corrosion potential involves recording the voltage difference between the reinforcement and a reference electrode, which is in contact with the concrete surface. This is primarily a qualitative technique that provides information about the likelihood of corrosion occurring in the analyzed reinforcement. The testing procedure is guided by ASTM C-876 (2015), the Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete. This standard establishes a correlation between potential difference intervals relative to a Cu/CuSO₄ (Copper/Copper Sulfate) reference electrode and the probability of corrosion, as shown in Table 1.

Potential Difference (p.d.)	Corrosion Probability
p.d. > -200 mV	Corrosion probability smaller than 10%
-200 mV ≤ p.d. ≤ -350 mV	Uncertain corrosion probability 50%
p.d. < -350 mV	Corrosion probability greater than 90%

Table 1: Correlation Between Potential Difference Values and Corrosion Probability.

Source: Adapted from ASTM C-876, 2015.

3.2. Resistivity

Concrete resistivity is a critical parameter in the corrosion of reinforced concrete structures. High resistivity concrete significantly reduces the likelihood of reinforcement corrosion. Electrical resistivity is determined by measuring the potential differences on the concrete surface caused by applying a small current (Mehta e Monteiro, 2014).

Table 2 presents the recommendations of the Comité Euro-International du Béton, as outlined in CEB 192 (1988), which relate concrete resistivity to the probable corrosion rate.

Several techniques are available for evaluating resistivity, including the external electrode method. This method involves placing a disc-shaped metallic electrode on the concrete surface and connecting it to the reinforcement bar. The resistivity is then measured between the disc and the steel bar. This method follows the RILEM TC 154 recommendation (Elsener *et al.*, 2003).

Concrete's Resistivity (Ω.m)	Probable Corrosion Rate
> 200	Negligible corrosion probability
100 a 200	Low corrosion probability
50 a 100	High corrosion probability
< 50	Very high corrosion probability

Table 2: Correlation Between Resistivity Values and Corrosion Probability.

Source: Adapted from CEB 192, 1988.

3.3. Corrosion rate

Quantitative information regarding the steel corrosion rate is crucial for evaluating repair methods, predicting lifespan, and assessing the structural integrity of elements affected

by corrosion. One of the few techniques for this purpose is the polarization resistance method (Bertolini *et al.*, 2004). The RILEM TC 154-EMC recommendation outlines the testing procedure for determining the corrosion rate of reinforcement in reinforced concrete structures through polarization resistance (Andrade, 2001).

This method provides two critical characteristics related to corrosion: the instantaneous corrosion current density (I_{corr}) and the corrosion rate (V_{corr}). Both metrics are essential for evaluating the risk of corrosion. The current density (I_{corr}) is typically expressed in $\mu A/cm^2$, where values below 0.1 indicate negligible corrosion, while values greater than 1.0 suggest a high risk of corrosion.

The corrosion rate (V_{corr}) represents the volumetric loss of steel per unit area and time, usually expressed in mm/year. This value is derived from the current density (I_{corr}) using Faraday's Law. The corrosion rate for an I_{corr} of 1 $\mu A/cm^2$ is approximately 0.0116 mm/year, assuming uniform corrosion. This value can also be correlated with a specific degree of corrosion (Bertolini *et al.*, 2004).

Table 3 presents the detailed relationship between current density and corrosion rate, as detailed in Andrade *et al.* (2004).

Current's density - I_{corr} ($\mu A/cm^2$)	Corrosion's speed - V_{corr} (mm/year)	Degree of corrosion
$\leq 0,1$	$\leq 0,001$	negligible
0,1 a 0,5	0,001 a 0,005	low
0,5 a 1,0	0,005 a 0,010	moderate
$> 1,0$	$> 0,010$	high

Table 3: Correlation Ranges of Current Density and Corrosion Rate Values Relative to Armature Service Life Significance.

Source: Adapted from ASTM C-876, 2015.

4. EXPERIMENTAL PROGRAM

The experimental program is organized into three phases: molding, corrosion acceleration, and evaluation through NDT testing. The study is designed around a comparative analysis of the effects of corrosion on entire structural elements, explicitly comparing those that did not experience any harmful effects of corrosion. The detailed structure of the experimental program is

illustrated in Figure 1, which outlines the different steps undertaken in the study.

Table 4 presents the terminology of the beams used throughout the experimental study, aligning with its development phases. Two beams were utilized for each combination.

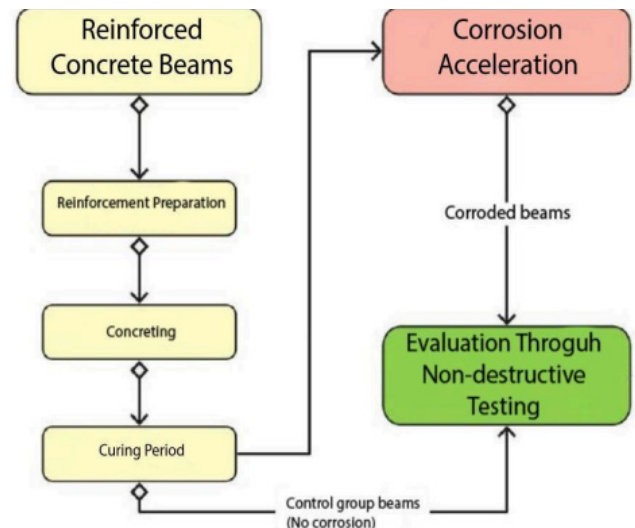


Figure 1: Experimental program's detailing.

Source: The authors.

Degree of Corrosion	Nomenclature*
0% (Reference)	COR-0-V1
	COR-0-V2
5%	COR-5-V1
	COR-5-V2
10%	COR-10-V1
	COR-10-V2
15%	COR-15-V1
	COR-15-V2

* V1 and V2 refer to samples 1 and 2 for each nomenclature

Table 4: Combinations and beam nomenclature.

Source: The authors.

4.1. Structural Design of Reinforced Concrete Beams

To approximate the study conditions to those of actual urban constructions and coastal environments, concrete with a characteristic compressive strength of 30 MPa was selected. This strength level is the minimum NBR 6118 (2014) required for Environmental Aggressiveness Class III (CAAIII). This choice reflects the common usage of concrete with compressive strengths between 20 and 30 MPa in general building construction. Additionally, concrete with higher compressive strength is less susceptible to reinforcement corrosion.

This is due to its lower porosity, which impedes the transport of oxygen and moisture, thereby reducing the passage of electrical current and slowing the corrosion process, Caetano (, 2008); Graeff (2007), Stein (2019).

Regarding the geometry, the dimensions were determined based on important considerations, as discussed in Almusallam (2001). All beams have a cross-sectional area of 15 cm (width) x 30 cm (height) and a length of 300 cm. The lower longitudinal reinforcement

consists of two CA-50 steel bars, each with a diameter of 12.5 mm, anchored with hooks at the ends. The upper reinforcement also uses CA-50 steel, with a diameter of 6.3 mm. The transverse reinforcement consists of stirrups with a diameter of 6.3 mm, spaced uniformly at 7 cm intervals. The reinforcement has a concrete cover of 1.5 cm. The detailed design of the reinforced concrete beams is illustrated in Figure 2

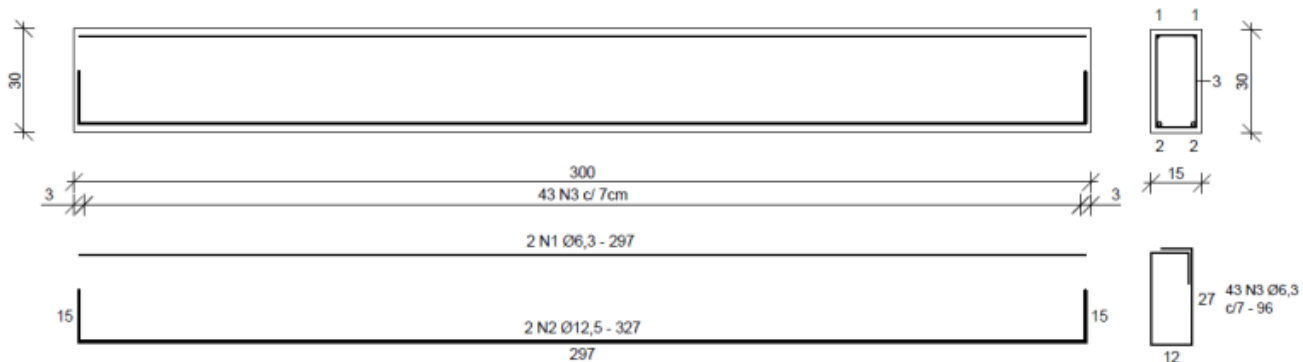


Figure 2: Reinforcement Detailing of Reinforced Concrete Beams.

Source: The authors.

4.2 Materials

The company responsible for producing the reinforced concrete beams provided the materials used in this research. The following materials were employed: Portland cement CPV-ARI, natural sand (fine and medium), basaltic gravel (types 1 and 0), and a superplasticizer additive.

The beams were concretized at a precast factory in Porto Alegre, RS. For this purpose, a computerized concrete batching plant with mass dosing was utilized. All beams were cast using concrete from a single batch, ensuring consistency in the mix composition. Table 5 details the concrete mix composition used in this study.

Cement (kg/m ³)	Thin sand (kg/m ³)	Medium sand (kg/m ³)	Gravel 0 (kg/m ³)	Gravel 1 (kg/m ³)	Water(kg/m ³)	Additive (l/m ³)	Relation a/c
271	280	654	231	692	185	0.8	0.68

Table 5: Description of the Concrete Mix Used in the Execution of Reinforced Concrete Beams.

Source: The authors.

The beams were analyzed at 502 days of age, exhibiting an average compressive strength of 32.4 MPa and an elasticity modulus of 34.8 GPa. This analysis was selected to eliminate the influence of compressive strength variation on the experimental results. This criterion was necessary because different degrees of corrosion required varying acceleration periods (ranging from 10 to 45 days). Stabilizing compressive strength was crucial to ensure that the analyses exclusively reflected the effects of corrosion on structural performance.

The steel used for both positive and negative reinforcement was CA-50. For the positive reinforcement, with a diameter of 12.5 mm, the average yield stress was 670 MPa, and the tensile strength was 770 MPa. The negative reinforcement, with a diameter of 6.3 mm, showed an average yield stress of 650 MPa and a tensile strength of 765 MPa.

4.3. Accelerated Corrosion

As mentioned, the corrosion acceleration method was adopted as the CAIM (Modified Immersion Accelerated Corrosion) testing. Lima [34] developed the CAIM method, building on the studies of Varela and Espinosa (1988). Many researchers have successfully employed it at LEME, such as Adamatti (2016), Caetano (2008), Graeff (2007), Stein (2019), Kirchheim *et al.* (2005), Marchesan *et al.* (1997), Selistre *et al.* (1997), and Torres (2006).

This method induces corrosion through electrochemical stimulation by applying a potential difference (p.d.) or current (i) in a chloride-rich environment. Based on the studies by Graeff (2007) and the discussions presented by Caetano (2008), the decision was made to use a constant current stimulus for electrochemical induction.

One of the critical parameters influencing this method is the current density used to accelerate corrosion. El Maaddawy and Soudki (2003) suggest that specific current density ranges are more appropriate for accelerating corrosion in reinforced concrete reinforcements. High corrosion current densities (above $500 \mu\text{A}/\text{cm}^2$) can distort the corrosion mechanism (Graeff, 2007). When the current density is too high, corrosion products do not have sufficient time to settle into the concrete's pores, leading to increased tension levels that cause fissuring inconsistent with naturally occurring phenomena in structures.

In the CAIM method, chlorides are introduced into the immersion water. To simulate natural conditions, sodium chloride was dissolved in the immersion water at a concentration of 35 g/l, creating a saline solution with a chloride concentration similar to that of the Atlantic Ocean, which borders the Brazilian coast, Adamatti (2016), Caetano (2008), Graeff (2007), and Stein (2019).

To ensure the presence of oxygen and moisture, essential for developing the corrosive process, the reinforced concrete beam is submerged up to the lower face of the longitudinal reinforcement, as shown in Figure 3. In the solution, both a negative and a positive electrode, made of stiff copper wire with a diameter of 2.5 mm, are placed. The positive electrode is positioned 3 mm above the longitudinal reinforcement. To prevent contact between the electrode and the reinforcement, the electrode is encased in a U-shaped butyl rubber sheath, as illustrated in Figure 3.

Since the current rate is proportional to the corroded surface area of the reinforcement, both the longitudinal reinforcements and a portion of the transverse

reinforcements were considered. The longitudinal reinforcement was accounted for (297 cm long), with an additional 2.5 cm for each anchoring hook—equivalent to twice the reinforcement's diameter. The transverse reinforcement was considered in two portions: one below the longitudinal reinforcement and another extending 2.5 cm above the longitudinal reinforcement, equivalent to twice the longitudinal reinforcement's diameter.

Finally, the reinforcement intended for corrosion had a mass of 7,800 g and a surface area of $3,878 \text{ cm}^2$ exposed to the corrosive process, considering both the longitudinal and a portion of the transverse reinforcement. Using power supplies, each beam's current of 1.94 A was applied based on a current density of $500 \mu\text{A}/\text{cm}^2$.

Each power supply featured two outputs capable of providing either constant current or voltage, with current ranging from 0 to 3 A and voltage ranging from 0 to 30 V.

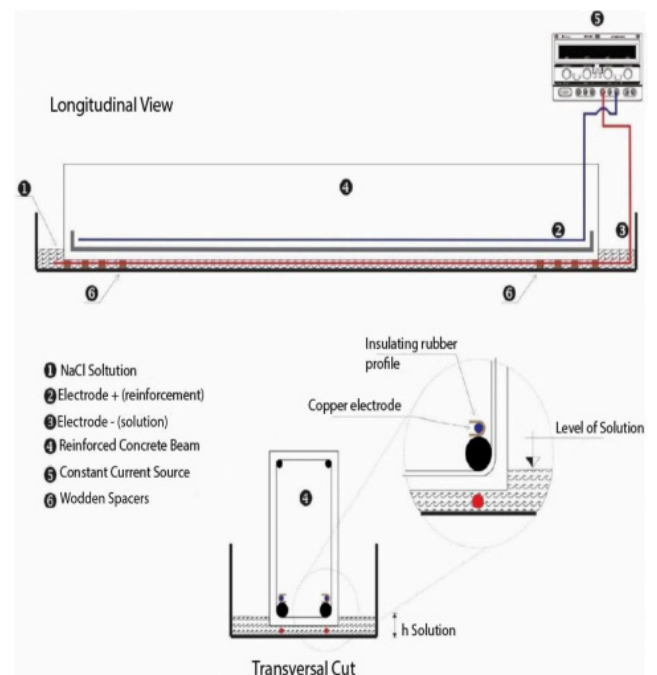


Figure 3: Layout Adapted for Corrosion Acceleration.

Source: The authors.

To achieve the desired degrees of corrosion, a theoretical approach based on Faraday's Laws was employed to predict mass loss and, consequently, the degree of corrosion.

This theory has been utilized by various authors such as Helene (1997), Adamatti (2016), Caetano (2008), Graeff (2007), and Stein (2019). The degree of corrosion predicted by Faraday's Law corresponds to the area under the curve of current versus time. In cases where corrosion is accelerated by applying a constant current, this area can be approximated as a rectangle.

Thus, the degree of corrosion is calculated by determining the mass loss using Faraday's Law, as expressed in equation (1):

$$\Delta m = \frac{M \times I \times t}{z \times F} \quad (1)$$

Where Δm = mass of consumed steel (g); M = metal's atomic weight (56 Fe); I = current applied (A); t = corrosion acceleration time (s); z = ionic charge (= 2); F = Faraday's constant (=96500A/s).

As the researchers describe, extended test times are necessary to achieve the desired degrees of corrosion beyond those predicted by the simple application of Faraday's Law. Due to this, the methodology proposed by Graeff [10] is applied for calibrating the corrosion degrees, and the values presented by Stein [11] are utilized.

Therefore, using equation (2), the predicted time required for corrosion is determined based on the mass loss necessary to reach the intended degree of corrosion:

$$tc = \left[\left(\frac{\Delta m \cdot z \cdot F}{M \cdot I} \right) 1,1778 \right] + 357825 \quad (2)$$

Where tc = time of corrosion (s).

4.4. Corrosion Potential

First, it is essential to locate the reinforcement bars to determine the corrosion potential. This was achieved using a cover meter detection device, specifically the PROFOMETER 600 model, as shown in Figure 4.

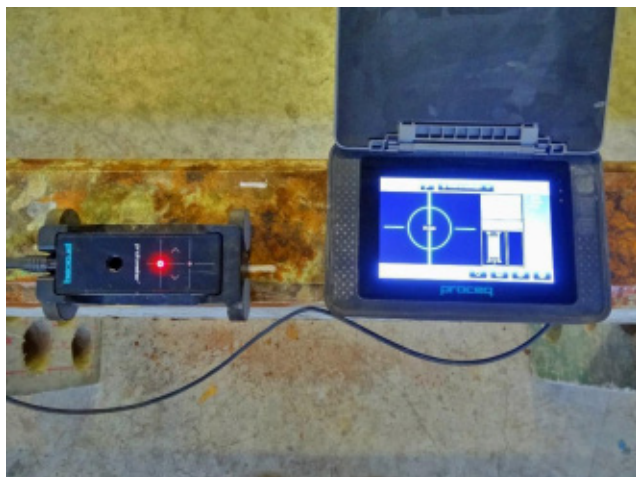


Figure 4: Locating reinforcements through a cover meter and marking the reading grid for NDT evaluation.

Source: The authors.

The corrosion potential testing procedure follows ASTM C-876 [28], which establishes a correlation between potential difference intervals measured against a reference electrode made of Cu/CuSO₄ (Copper/Copper Sulfate) and the probability of corrosion.

The GECOR 8 equipment, equipped with a Cu/CuSO₄ reference electrode, was used to conduct the test. The negative pole of the device is connected to the electrode. In contrast, the positive pole is connected to the reinforcement bar via a copper wire attached to the reinforcement before concreting.

The electrode is then positioned on the concrete surface, ensuring an electrical connection with the reinforcement bar. Figure 5 illustrates the method's application and the equipment setup.

The evaluation was conducted by mapping the corrosion potential for each analyzed beam. Measurements were taken along the longitudinal reinforcement bars, with a 25 cm spacing between each reading point.

4.5. Evaluation of the Degree of Corrosion

The beam reinforcements were extracted, as shown in Figure 6. The region near the support was chosen for this retrieval. Reinforcements were extracted from all beams, including those that did not undergo a corrosive process, to serve as a control group for determining the degree of corrosion.



Figure 5: Determining the corrosion potential with the GECOR 8 equipment.

Source: The authors.

After the beam reinforcements were retrieved, the concrete adhered to the bars was removed. The reinforcements were then immersed in a solution of 3.5 g hexamethylenetetramine, diluted in a mixture of hydrochloric acid (500 ml) and distilled water (500 ml).

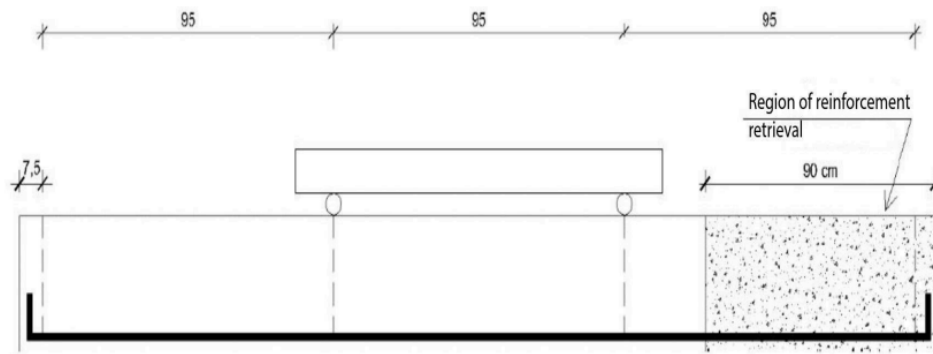


Figure 6: Region of beam reinforcement retrieval, distances in centimeters.
Source: The authors.

This procedure follows the ASTM G1-03 standard (2017). The bars were kept in the solution for 40 minutes to remove the corrosion products. Afterward, they were rinsed in running water to remove residual hydrochloric acid. Following the cleaning, the bars were placed in an oven set at 30°C until all moisture was removed. Once dry, the mass and length of each bar were measured to determine the linear mass. The degree of corrosion, expressed as mass loss, was calculated using Equation (3).

The reference linear mass was taken as the average of the non-corroded reinforcements.

$$GC = \frac{(m_{ref} - m_{cor})}{m_{cor}} \times 100 \quad (3)$$

Where GC = Degree of corrosion, expressed in mass loss; m_{ref} = average linear mass of non-corroded reinforcement; m_{cor} = individual linear mass to corroded reinforcement.

5. RESULTS AND DISCUSSIONS

5.1. Accelerated corrosion

The accelerated corrosion was conducted following the parameters and methodology described in Section 4. All beams that underwent corrosion during the acceleration process exhibited the following behavior. As the corrosion process progressed—using an electrical circuit formed between the solution and the corrosion electrode, powered by a constant current—it was observed that the current did not remain constant. The current decreased early in the acceleration process (within the first 3 to 5 days). Then, it returned to its initial level after 1 to 2 days, remaining constant for the tests.

This behavior is related to the kinetics of the corrosive process, a phenomenon known as concrete pore clogging.

After the tests, the longitudinal reinforcement bars were extracted from each beam to determine the actual degree of corrosion, following the procedure outlined in ASTM G1-03 (2017).

Due to possible differences between theoretical and actual corrosion, the results were evaluated within various variations. The adopted ranges reflect the practical evaluation of corrosion. The mass loss percentage was determined using average values, with two reinforcement bars analyzed for each beam. Table 6 shows the actual degree of corrosion for one of the beams.

According to Table 6, the actual corrosion values were close to the predicted values established in the experimental program when comparing the average values for each group of corroded beams. The exception was at 5%; the corrosion was 1.27% below the predicted outcome. This discrepancy may be attributed to concrete pore clogging, which occurs early in the corrosion acceleration process, requiring an adaptation period for the expected corrosion level to be reached.

5.2. Corrosion diagnosis through non-destructive methods: Corrosion potential

The measurement of corrosion potential is a widely used qualitative technique that provides data on the likelihood of corrosion in the analyzed reinforcement. The testing procedure was conducted following ASTM C-876 (2015). The corrosion potential values in Table 7 represent the average for each beam and the corresponding standard deviation. These parameters are also related to the probability of corrosion for each level of corrosion (beam group).

As expected, a decrease in corrosion potential was observed as the level of corrosion increased. When comparing the acquired data with the value ranges

specified in ASTM C-876 (2015), it was found that for the control group (COR-0), the probability of corrosion was below 10%. The results were uncertain for the corroded beams at the 5% and 10% levels (COR-5 and COR-10). However, for the 15% corrosion level (COR-15), the probability of corrosion was greater than 90%.

It was noted that the corrosion measurements using the corrosion potential technique for the 5% and 10% levels were uncertain. At both levels, the corrosion potential remained within the same reading range and was classified with a 50% chance of corrosion occurrence.

Nevertheless, despite the uncertainty, corrosion was confirmed by measuring reinforcement mass loss, even if it was not visually apparent.

Therefore, the evaluation of corrosion using the corrosion potential method showed limited efficacy in diagnosing corrosion for levels up to 10%. However, it was more reliable for levels around 15%. Despite these findings, the corrosion potential test did not consistently produce safe results. It suggests that while it can be used for diagnosing corrosion, it should be applied cautiously as it may yield potentially unreliable outcomes.

In addition to the statistical data on corrosion potential presented in Table 7, a potential mapping for each beam was conducted, as shown in Figure 7. This mapping was created by elaborating hypsometric curves using data interpolation with the minimum curve technique.

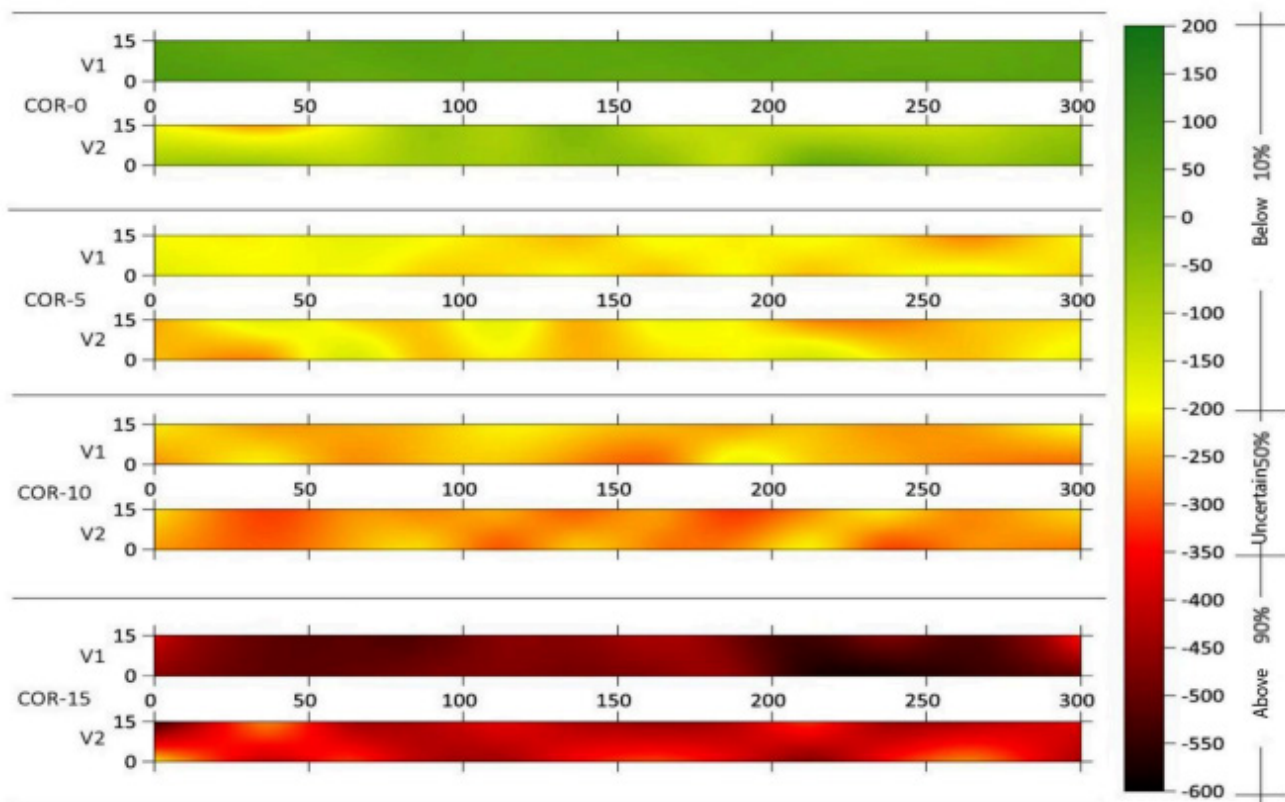


Figure 7: Corrosion potential mapping, distance in centimeters.

Source: The authors.

This interpolation technique utilizes a polynomial to create a surface that minimizes curvature. This results in a smoother surface that passes through the sampled points, accurately reproducing the variable values. The interpolation and mapping were generated using image processing software (Andriotti, 2009).

The scale used for the mapping was based on ASTM C-876 (2015) parameters, which express corrosion potential in millivolts (mV) and relate these values to the

probability of corrosion. The corrosion potential mapping, illustrated in Figure 7, provides a global visualization rather than just a numerical parameter. It was observed that the potential was uniform for each of the analyzed beams and that there was a consistent relationship between potential and the beam groups. This mapping graphically demonstrates that corrosion potential decreases as the corrosion level increases—the higher the level of corrosion, the lower the corrosion potential.

6. CONCLUSIONS

This research assessed potential corrosion techniques to diagnose corrosion in reinforced concrete beams, focusing on sustainability in materials durability and long-term structural integrity. The key findings regarding the corrosion acceleration process are summarized as follows:

a) The accelerated corrosion technique, applied to reinforced concrete beams through CAIM testing, effectively advancing the corrosion process sustainably and efficiently.

b) The average corrosion degree closely matched the theoretical values outlined during the experimental program design, ensuring accurate and predictable outcomes supporting sustainable infrastructure maintenance.

CAIM testing confirmed the efficacy of the accelerated corrosion technique in reinforced concrete beams. By adjusting corrosion time using the methodology proposed by Graeff (2007) and integrating values from Stein (11), a strong correlation was established between the theoretical and empirically obtained degrees of corrosion. This highlights that the corrosion acceleration procedure used in this research was adequate and sustainable, effectively optimizing time and resources.

Regarding the corrosion diagnosis technique using non-destructive testing (NDT) through corrosion potential, the study revealed uncertainties in the measurement at 5% and 10% corrosion levels. Both levels had similar corrosion potentials, with a 50% probability of corrosion occurrence, indicating limitations in precision for lower corrosion rates. The corrosion potential method, however, proved effective at diagnosing corrosion at the 15% level, where sustainable monitoring practices can be more reliably implemented.

In conclusion, while corrosion potential testing may not consistently deliver consistent results, it remains a viable diagnostic tool when applied cautiously in sustainable practices. For enhanced accuracy, especially for corrosion levels with a mass loss between 5% and 10%, it is recommended that additional diagnostic techniques be employed simultaneously to ensure the long-term durability and sustainability of reinforced concrete structures.

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ANNEX 1

Beam	Theoric corrosion degree	Real corrosion degree	Average corrosion degree	Intended corrosion degree
COR-5-V1	5,03%	3,49%	3,73%	5%
COR-5-V2	5,09%	3,97%		
COR-10-V1	10,17%	9,97%	10,05%	10%
COR-10-V2	10,14%	10,13%		
COR-15-V1	15,65%	14,20%	13,87%	15%
COR-15-V2	15,46%	13,55%		

Table 6: Actual Corrosion Degree Obtained Empirically Compared to Theoretical Values.
Source: The authors.

Beam Group	Beam	Av. (mV)	SD (mV)	Group Av. (mV)	Group SD (mV)	Corrosion Probability
COR-0	V1	28,84	7,45	-30,78	25,24	Below 10%
	V2	-90,40	43,03			
COR-5	V1	-298,22	21,34	-257,57	22,59	Uncertain 50%
	V2	-216,92	23,85			
COR-10	V1	-240,96	17,95	-252,99	19,71	Uncertain 50%
	V2	-265,03	21,47			
COR-15	V1	-494,11	32,94	-438,42	33,01	Above 90%
	V2	-382,72	33,08			

Table 7: Average and Standard Deviation of Corrosion Potential for the Control Group and Corroded Beams.
Source: The authors.

SOUNDSCAPE AND NOISE MAP OF A HOSPITAL AREA IN A SMALL CITY

PAISAGEM SONORA E MAPA DE RUÍDO DE ÁREA HOSPITALAR EM UMA CIDADE DE PEQUENO PORTE

PAISAJE SONORO Y MAPA DE RUIDO DE UN ÁREA HOSPITALARIA EN UNA CIUDAD PEQUEÑA

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ABSTRACT

This article investigates noise pollution in hospital areas, focusing on the Hospital de Caridade e Beneficência (HCB) in Cachoeira do Sul, Rio Grande do Sul. Through field measurements and simulations using the iNoise software, sound pressure levels around the hospital and the local population's perception of noise impact were analyzed. The results indicate that noise levels exceed the limits established by NBR 10.151, with values reaching up to 61.7 dB, while the allowed limit for residential and hospital areas is 50 dB. The main noise-generating factors are vehicular traffic and machinery. Despite the high noise levels, respondents' perceptions revealed an adaptation to the noise, with many considering the environment calm. It is concluded that, even in smaller cities, noise pollution affects sensitive areas such as hospitals, making it necessary to implement acoustic mitigation measures to ensure user comfort.

KEYWORDS

Noise Pollution; Acoustic map; Hospitals; Sound pressure levels

RESUMO

Este artigo investiga a poluição sonora em áreas hospitalares, com foco no Hospital de Caridade e Beneficência (HCB) de Cachoeira do Sul, Rio Grande do Sul. Através de medições de campo e simulações com o software iNoise, foram analisados os níveis de pressão sonora no entorno do hospital e a percepção da população local sobre o impacto do ruído. Os resultados indicam que os níveis de ruído ultrapassam os limites estabelecidos pela NBR 10.151, com valores de até 61,7 dB, enquanto o limite permitido para áreas residenciais e hospitalares é de 50 dB. Os principais fatores geradores de ruído são o tráfego veicular e máquinas. Apesar dos altos níveis de ruído, a percepção dos entrevistados revelou adaptação ao barulho, com muitos considerando o ambiente tranquilo. Conclui-se que, mesmo em cidades menores, a poluição sonora afeta áreas sensíveis, como hospitais, sendo necessária a implementação de medidas de mitigação acústica para garantir o conforto dos usuários.

PALAVRAS-CHAVE

Poluição sonora; Mapa acústico; Hospitais; Níveis de pressão sonora



RESUMEN

Este artículo investiga la contaminación acústica en áreas hospitalarias, centrándose en el Hospital de Caridade e Beneficência (HCB) en Cachoeira do Sul, Rio Grande do Sul. Mediante mediciones de campo y simulaciones con el software iNoise, se analizaron los niveles de presión sonora en el entorno hospitalario y la percepción de la población local sobre el impacto del ruido. Los resultados indican que los niveles de ruido superan los límites establecidos por la NBR 10.151, con valores de hasta 61,7 dB, mientras que el límite permitido para áreas residenciales y hospitalarias es de 50 dB. Los principales factores generadores de ruido son el tráfico vehicular y la maquinaria. A pesar de los altos niveles de ruido, la percepción de los entrevistados reveló adaptación al ruido, y muchos consideraron que el ambiente era tranquilo. Se concluye que, incluso en ciudades más pequeñas, la contaminación acústica afecta a zonas sensibles, como los hospitales, siendo necesario implementar medidas de mitigación acústica para garantizar el confort de los usuarios.

PALABRAS CLAVE

Contaminación Acústica; Mapa Acústico; Hospitales; Niveles de Presión Sonora

1. INTRODUCTION

Noise pollution, a pressing issue that significantly impacts people's quality of life, has now surpassed water pollution, ranking second in the list of major causes of diseases (PERIS, 2020; WHO, 2011). The primary culprit is traffic, which generates intense noise in urban areas. The rapid urban growth further exacerbates this issue, making it crucial to conduct acoustic mapping studies to address this pressing issue.

Noise is a public health issue, according to the European Environment Agency (AEMA), there are 12,000 premature deaths and 48,000 unprecedented cases of ischemic heart disease per year in Europe, due to the degradation of environmental quality in people's lives (PERIS, 2020). Thus, Europe established the need for a noise map for cities with more than 100 thousand inhabitants. Meanwhile, other countries carry out this in limited locations, with potential noise sources, such as educational and urban centers, airports and railways, and roads with a large flow of cars.

In hospital areas, noise pollution becomes an even more pronounced obstacle, significantly impacting the health and well-being of patients, visitors, and employees. The hospital environment, already naturally stressful and anxious for many, can be further disrupted by additional noise, making it difficult for patients to rest and recover and interfering with communication between healthcare professionals and patients. The lack of research in this area, particularly in acoustic mapping, is a significant gap that urgently needs to be addressed (ANDRADE et al., 2021).

In this context, it is possible to verify that it is crucial to carry out studies that evaluate nighttime, daytime, internal, and external sound pressure levels by NBR 10.151 (ABNT, 2021). This paper evaluates sound pressure levels in hospital areas in a small city, Cachoeira do Sul, in Rio Grande do Sul, Brazil. The intention is to evaluate the different conditions of the soundscape surrounding hospitals in this city, questioning users, taking sound pressure level measurements and simulating them using the iNoise software and creating noise maps of these contexts.

2. BIBLIOGRAPHIC REVIEW

Considering the devaluation of acoustic mapping studies in hospital areas, comparing case studies

in different locations where similar conclusions were reached was possible. The study at Hospital Rocha Faria in Campo Grande, Rio de Janeiro, revealed the urgent need to control urban noise in the region.

Intense vehicle traffic, disorderly growth, and a lack of road safety contribute to excessive noise levels exceeding recommended limits. Infrastructure improvements, driver awareness, and public policies are essential to mitigate noise and promote a safer and quieter environment around the hospital (SILVA; TORRES, 2023).

External measurements of hospitals in the municipality of Sorocaba show that noise levels exceed the limits recommended by NBR 10151 and the WHO, both day and night. Acoustic maps confirm high noise levels on facades, even on streets with less traffic. Combined actions are necessary to reduce noise levels and meet recommended standards (ANDRADE, 2022).

At the National Institute of Traumatology and Orthopedics in Rio de Janeiro, after noise simulations, traffic data collection, and field measurements, it was found that noise levels in the daytime and afternoon periods around the hospital are far above those standards of NBR 10.151 (ABNT, 2019), with minimums of 70.1 dB, more than 20 dB above recommended. These high levels can cause discomfort and worsen health problems. Strategies to reduce external and internal noise in the hospital are necessary, given the proximity to busy roads (CRUZ, 2022).

In Santa Maria, in Rio Grande do Sul, the soundscape surrounding the Hospital de Caridade Astrogildo de Azevedo (HCAA) was characterized, revealing sound pressure levels above the 50 dB recommended by ABNT NBR 10.151 and municipal legislation, mainly due to vehicular flow. The sound map and parameter evaluation highlighted the negative impact of noise in the hospital area (FERREIRA, 2021).

Passers-by found the sounds of traffic and machines unpleasant, while natural and human sounds were seen as calmer. Familiarization with noise is worrying, as the adverse effects are cumulative. However, the results showed that the nuisance is not very significant, possibly because people have become accustomed to the noise, which is worrying due to the cumulative adverse effects of noise (FERREIRA, 2021).

Finally, two cases were compared in the neighborhoods of João Pessoa, Paraíba. The first, carried out in the Jardim Oceania neighborhood, concludes that the noise map is crucial for managing noise pollution. It is useful both for public administration in urban planning and for designers at the building level. This study focused

on the Jardim Oceania neighborhood, reveals a worrying scenario of noise pollution due to vehicular traffic.

Mapping allows a visual noise propagation analysis, highlighting the need for public policies for the neighborhood's growing population. This work expands the debate on urban noise in João Pessoa and seeks improvements to citizens' environmental quality and quality of life (MORAIS; SANTOS, 2023).

In the Tambaú neighborhood, using the SoundPLAN software, it was revealed that all the points studied are out of compliance with NBR 10151, with 62.5% exceeding the daytime limit by more than 10 dB. Using the maps, he analyzed the excess noise in the collector roads, indicating potential harmful exposure to health (ARAÚJO; MENESES; MORAIS, 2023).

3. METHODOLOGY

The methodology used in this research follows the following steps: (I) Preparation of the soundscape questionnaire and approval by the Human Research Ethics Committee (CEP); (II) Sound pressure level measurements in the hospital area of Cachoeira do Sul in conjunction with the application of the questionnaire; (III) Simulation in iNoise software for noise maps; (IV) Preparation of the data obtained.

When analyzing the particularities of each location studied in this work, a series of factors that cause frequent noise were noticeable, among which the following can be listed: sounds coming from vehicles, pedestrians, children on the playground, construction machinery, and occasional natural sounds. Questionnaires were applied to the surrounding population to understand better the sound agents that influence the study spaces. Perception can be subjective for each individual. Therefore, repetition in the questionnaire responses helped to consider the most relevant items.

Finally, an in-depth analysis relating the results obtained through objective and subjective methods was carried out.

Figure 1 shows the flowchart with the study steps, detailed below.

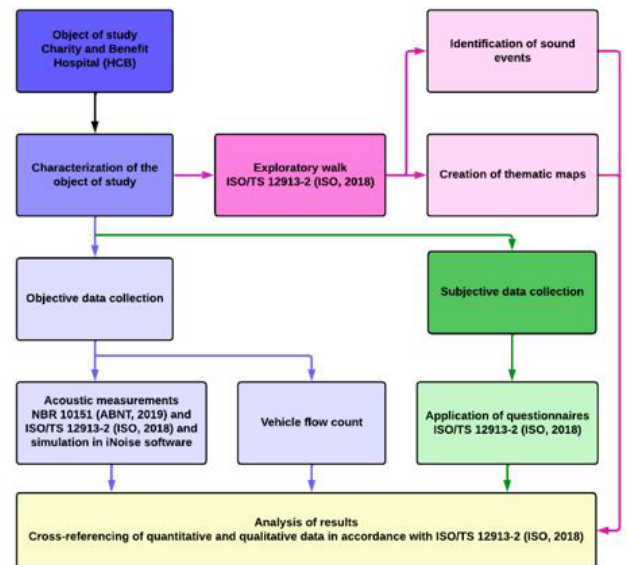


Figure 1: Flowchart with study stages.

Source: The authors (2024).

3.1. Object of study and its characterization

The study was conducted in the cities of Cachoeira do Sul, located in the center of Rio Grande do Sul. The object of study was taken in the southern region of the city of Cachoeira do Sul, the roads in front of the Charity and Charity Hospital (30° 03' 07" S 52° 53' 24" W), which can be viewed on the map shown in Figure 2.



Figure 2: Location of the study area.

Source: The authors (2024).

Road traffic noise, especially when the flow is high density, easily spreads throughout the city and can even affect areas sensitive to excessive noise levels, such as schools, hospitals, and residential areas. Therefore, this study analyzes a sensitive building (hospital) located in a

predominantly commercial use and occupation zone, as classified in the Brazilian standard NBR 10151 (ABNT, 2021).

The study site is located in the commercial area, according to the Master Plan of Cachoeira do Sul (CACHOEIRA DO SUL, 2024), Rua Saldanha Marinho has commercial use, Via Tuiuti has a residential area. Tiradentes Street has a high vehicular flow, with public transport and bus stops. Furthermore, the bus stop on the corner of the hospital is the starting and ending point of the urban vehicular line where these buses are often parked there, with the engine running, generating constant noise throughout the day.

As for the road hierarchy, the Hospital de Caridade e Beneficência (HCB) area is located on a corner plot, with the influence of noise on three of its facades, Rua Tiradentes and Tuiuti are local roads. At the same time, Saldanha Marinho and 7 de Setembro are collector streets, according to the Cachoeira do Sul Master Plan. The measurement points are shown in Figure 3, and the views of the roads are shown in Figure 4.



Figure 3: Thematic map with the demarcation of the HCB sound measurement points.
Source: GOOGLE EARTH (2024).



Figure 4: Views of the HCB study area.
Source: GOOGLE MAPS (2024).

To characterize the object of study, data, and information on urban morphology were collected, as well as a description of the users of the environments. The concepts of Bistafa (2018) on sound propagation and Kohlsdorf (1996) for urban morphology were used to support the characterization. According to the two

authors mentioned, each element considered relevant for studying the soundscape within the environment is indicated in the flowchart in Table 1.

Characterization of the environment		
Demographic profile	Characterize the profile of each environment user (age, gender, education...) This information is part of the context, which is intrinsically linked to the analysis of the soundscape	
Urban morphology	Road network	Where sound pressure level measurements were carried out by NBR 10151 (ABNT, 2019) and ISO/TS 12913-2 (ISO, 2018)
	Green areas	Dense areas of vegetation in the urban environment can influence the soundscape, promoting sound absorption and scattering (BISTAFA, 2018).
	Built density	This analysis is essential for constructing the sound map, as it identifies the interference of the built environment in the sound landscape due to sound propagation, absorption, reflection, and diffusion.
	Vehicle flow	Counting vehicle flow is essential for creating sound maps and understanding the SPL (sound pressure level) generated by this linear source.

Table 1: Elements of characterization of the study environment.

Source: Adapted from FERREIRA (2021).

3.1.1. Preparation of the questionnaire on soundscape and approval by the human research committee (CEP)

The development of a questionnaire to be applied to users and passers-by of the locations evaluated in the research aims to capture subjective impressions about the local soundscape, equipment, or noisy points. In this way, the questionnaire was organized starting with respondents' identification questions - gender, age group, and education; followed by questions related to the use of the locations - frequency, motivation, and satisfaction; and, finally, it addresses specific questions about local noise - main sources and which noises are considered unpleasant. The last two questions followed a 5-point Likert scale pattern, based on what is recommended by ISO 12913-2 (ISO - INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018), with ranges between 0 (very calm) and 5 (very noisy).

Before being applied, the questionnaire was submitted to the CEP (Ethics and Research Council on

Human Beings of UFSM), which approved it through the substantiated opinion CAAE: 67621823.0.0000.5346. It is presented in full in "Annex A."

Through the population of the neighborhood in which the HCB is located. 25,194 (IBGE, 2020), the sample size was calculated for a confidence level of 90% and a margin of error of 12%, in this way, the sample should be 48 interviewees, the SurveyMonkey platform was used for this definition. In the time allocated for the questionnaire, 49 people were willing to answer the questions, whether local or not.

To calculate the probabilistic sample analyzed, equation (1), established by Santos (2018), was followed, being:

$$Sample = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1 + \left(\frac{z^2 \times p(1-p)}{e^2 N} \right)} \quad (1)$$

In which the variables correspond:

p = proportion expected to meet

N = population size = margin of error

z = number of standard deviations between proportion and mean

3.2. Field measurements and vehicle counting

Sound pressure level measurements and vehicle counts were carried out on a weekday (Monday) and during daytime hours of peak vehicle flow in August 2023. Peak vehicle hours were defined as 4 p.m. to 6 p.m. A noise measurement was recorded for each measurement point, with signal recordings over 15 minutes with integration time every 1 second.

The A-weighted equivalent total continuous sound pressure level, integrated over a time interval T, in dB, is calculated according to Equation 2, where N is the number of samples in the reference time interval and $L_{Aeq,T}$ is each reading (per second) of the sound pressure level in dB (ABNT, 2021).

$$L_{(Total),Aeq,T} = 10 \log \left[\frac{1}{N} \sum_{i=1}^N 10^{\frac{(L_{Aeq,T})_i}{10}} \right] \quad (2)$$

To begin the measurements, meteorological conditions were measured to carry out sound pressure level measurements. Data collection is not recommended on days of precipitation and high wind

intensity, as they interfere with the results obtained (RENTERGHM; BOTTELDOOREN, 2010).

Vehicle counting was carried out using manual counters, separating motorcycles and light and heavy vehicles (two axles, three axles, or more). The vehicle count was carried out simultaneously with the noise measurements. Five (5) individuals were involved in this process, carrying out both sound level measurements and vehicle counts. For each measurement point, the sound level meter, coupled to the tripod, was positioned 1.5 meters above the ground by NBR 10151 (ABNT, 2019) and ISO 12913-2 (ISO, 2018), referring to the height of the average human ear.

The equipment used in all measurements were three SLM, Class 1 Type-2270 (Brüel & Kjær) [37]; three 1/2" free-field microphones, Type 4189 (Brüel & Kjær); three SLM calibrators, Type-4231 (Brüel & Kjær); three 1.50 m high tripods (Brüel & Kjær); three windscreens, Type-UA-1650 (Brüel & Kjær); a thermo-hygrometer; five manual numeric counters; and a GPS to record the UTM coordinates of the measurement points. All equipment had a calibration certificate, valid during the measurement campaign.

3.3. Noise map simulation in iNoise

The iNoise software was used to model the road traffic noise map for the acoustic indicator Lday. Horizontal maps were performed at 1.50 m from the ground level, the same height as the SLM. To represent and analyze the objectives of this study, the horizontal grid size for the map was 10 m × 10 m.

ISO 9613-2 (ISO, 2024) was used to calculate traffic noise. To characterize traffic noise as a linear noise source, iNoise was configured for source power per frequency band dB/(A).

Table 4: Combinations and beam nomenclature.

Source: The authors.

The simulation area was imported using shapefiles obtained from the city's planning department, which contained information on the heights of buildings, topography, street layout, blocks and type of paving that make up the study area. The collection point was located approximately in the middle of the stretch, on the side of one of the avenue's lanes, away from intersections.

Within this calculation area (Grid), iNoise generated a grid of receiving points, the spacing between which was defined based on accuracy and calculation time. For the maps, a spacing of 10.00 m was adopted, since this is an urban region (GUEDES; BERTOLI; ZANNIN, 2011; FIEDLER,

2013). The height of the calculation plane was defined as 1.20 m, corresponding to the position of the sound level meter in relation to ground level.

To validate the proposed acoustic model, the sound level calculated by the iNoise software was compared with the value measured at the reference point. For this purpose, the logarithmic mean of all the equivalent continuous sound levels (L_{Aeq}) measured was adopted. Directive 2002/49/EC (EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2002) stipulates this descriptor as the basis for the sound level indicator – day (L_{day}), which is determined by the acoustic simulation software.

3.4. Thematic map

The thematic map that integrates the methodology of this work was created from GOOGLE EARTH maps (2024) to illustrate the measurement points within the environment, facilitating the visualization of the quantitative data collection milestones. The decision-making of the sound measurement points was made through the exploratory walk-in by ISO 12913-2 (ISO, 2018). Walks were carried out around the environment, aiming to identify sound events. After the entire accessible area had been analyzed, the measurement points were defined in certain places by filling in Table 2 to identify each sound event.

Points	Sounds events	Predominant sound	Sensation
P. 1 e 2	Intense traffic, people walking and talking	Traffic sounds: acceleration, deceleration and horn	Discomfort, difficulty listening and talking
P. 3 e 4	Intense traffic; machines and equipment; people walking and talking; barely perceptible natural sounds	Traffic sounds: acceleration, deceleration and horn	Discomfort, difficulty listening and talking

Table 2: Identification of sound events at each HCB measurement point.

Source: The authors (2024).

4. ANALYSIS AND DISCUSSION OF RESULTS

Firstly, the results obtained when describing the soundscape of the environment being analyzed are

discussed. Initially, the data collected through surveys (demographic profile, sound perception, quality, and tranquility) is presented descriptively, accompanied by quantitative graphs. We then explored the correlations between the responses obtained.

4.1. Results of sound pressure level measurements and noise maps

Table 3 describes the vehicle count at each measurement point. Analyzing the study area, the streets with the most significant impact in this section are Tiradentes and Sete de Setembro, as they have a greater flow of vehicles than the remaining, mainly due to the continuity of these roads. Despite Saldanha Marinho's great directional importance in the city, the analysis section ends at the end of the study block. Therefore, there is not much vehicular flow there.

Figure 5 presents the noise map calibrated from sound pressure level measurements at the highlighted points, demonstrated by colors, from 0 to 100 dB.

Vehicle flow count - HCB			
	Heavy	Light	Motorcycles
Point 1	7	51	2
Point 2	2	58	2
Point 3	0	38	3
Point 4	1	10	1

Table 3: Vehicle flow count of measurement points.

Source: The authors (2024).

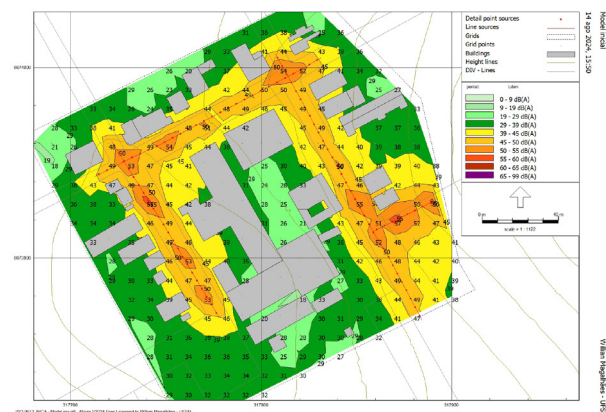


Figure 5: Noise map of the HCB hospital area.

Source: The authors (2024).

Table 4 presents the Average L_{Aeq} and the L_{Aeq} values per frequency band of the measurement points and is demonstrated in Annex B.

The noisemap shows that the highest noise concentration comes from the roads, especially Rua Tiradentes, 7 de Setembro, and Saldanha Marinho. Notably, levels lower than 50 dB were measured in the frequency range.

According to the criteria of NBR 10151:2019 (ABNT, 2019), the maximum level allowed for strictly urban residential areas, hospitals, or schools during the daytime is 50 dB (ABNT, 2019). Therefore, the recorded noise levels are beyond the limits established by the standard, especially when highlighting the average values of $L_{Aeq15min}$.

Point 1 is Rua Saldanha Marinho. This measurement location presented an $L_{Aeq15min}$ of 60.6 dB. The main noise source in this location was vehicular traffic, which can be seen by recording the highest sound pressure levels relating to medium frequencies. This road is the main route for users from the center to the hospital (arrival).

Point 2 is measured on Rua Tiradentes, which presented the highest value for $L_{Aeq15min}$ 61.7 dB. The street is the main facade of the hospital building, and the bus stop for public transport is on site. The sound events that result in higher sound pressure levels are the accelerations and decelerations of the public transport fleet at the bus stop, in addition to the engine noise itself, shown in Figure 6.

Considering the measured and simulated values, it is possible to estimate the response of users in this area to the sound level to which they are exposed, as shown in Table 5.

Value at which the corrected sound level exceeds the criterion level [dB(A)]	Estimated Community Response	
	Category	Description
0	None	No reaction observed
5	Little	Sporadic complaints
10	Average	Generalized complaints
15	Energetic	Community action
20	Very energetic	Vigorous community action

Table 5: Estimated Community Response.

Source: ISO 1996:1 (ISO, 2016).



Figure 6: 3D noise map of the HCB hospital area.

Source: The authors (2024).

Measuring point 3, on Rua 7 de Setembro, on the side of the hospital, presented an $L_{Aeq15min}$ of 60.2 dB. Notably, the last two measurement points presented lower values, a fact that is directly related to the lower vehicular flow in the surrounding area. However, the difference does not become so significant as these roads do not have asphalt paving; the friction noise tire pavement contributes to raising the measured sound pressure levels.

Measuring point 4, on Rua Tuiuti, presented lower sound pressure levels than the other points due to its location further away from the main roads. Sound pressure levels attenuate as the distance from the main roads increases as vehicular flow is reduced.

On the noise map, orange represents the highest noise values, ranging between 50 and 60 dB. These noisier areas are mainly concentrated along the Saldanha Marinho and Tiradentes roads, where traffic is heaviest. According to NBR 10152: 2017, reference values for internal hospital environments must be a maximum of 40 dB for uses such as nurseries, surgical centers, offices, and individual rooms (ABNT, 2017).

Considering that Saldanha Marinho and Tiradentes streets have $L_{Aeq15min}$ of 60.6 and 61.7 dB, respectively, sound insulation strategies on the facades must be implemented so that the hospital's internal environments can achieve the acoustic comfort values required by regulations, attenuating at least 22 dB. Implementing acoustic barriers and improvements to window seals can help reduce internal noise levels, ensuring patient comfort and compliance with current acoustic standards.

When comparing the measured and simulated sound pressure levels, we can see the difference between them in Table 6. Although the difference of + 4.7 dB(A) exceeds the uncertainty of +/- 4.0 dB(A), established by WG - AEN (2006) for noise maps in urban areas, it was adopted as acceptable, given the simplifications made to the acoustic model and the main objective of this paper.

Period	Simulated sound level [dB(A)]	Measured sound level [dB(A)]	Difference [dB(A)]
Afternoon	55	61,7	+ 6,7

Table 6: Measured and simulated sound pressures levels.

Source: The authors (2024).

4.2. Perception of the sound landscape by users

The questionnaires were administered around the Hospital de Caridade e Beneficência de Cachoeira do Sul on August 14, 2023, from 4:00 pm to 6:00 pm. Covering profiles of different users of the location through questions aimed at interpreting sound perceptions of places close to the location.

Of the 49 respondents, 63.3% were female, and 3.7% were male (Figure 7). Furthermore, the entire questionnaire is available in Annex A: Questionnaire applied in the research.

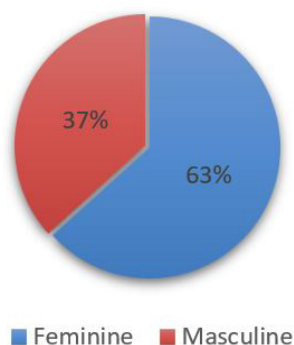


Figure 7: Gender of respondents.

Source: The authors (2024).

The most significant number of respondents were women, representing more than half of the responses. Notably, at the bus stop, most hospital staff were women. When walking on the sidewalks, females also showed greater interest in participating and answering the questionnaire. These data highlight a significant participation of women in the research, both as interviewees and as active participants in the areas observed.

The ages of the participants who responded to the questionnaire, shown in Figure 8, range from under 20 to over 81, with all interviewees over 18. Notably, the 20 to 35-year-old age group records the highest frequency of responses, followed by the 36 to 50-year-old age group

and the 51 to 65-year-old age group. As it is an area with a bus stop, it is common to observe employees from the surrounding area gather in this location. Furthermore, it was noted that people who accompany family members in the hospital tend to be older, especially the partners of the person undergoing treatment.

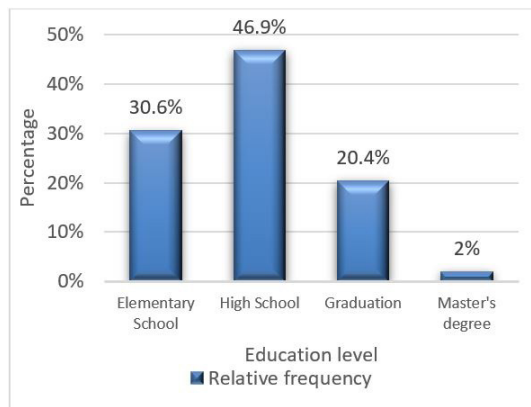


Figure 8: Age of respondents.

Source: The authors (2024).

Figure 9 shows the respondents' education level. The highest percentage (46.9%) corresponds to people who have completed secondary education, followed by those who have only completed primary education. Thirdly, there is a significant representation of people in the process of graduating or who have already completed their degree. This distribution reflects educational diversity in the sample, with a notable concentration at the high school level.

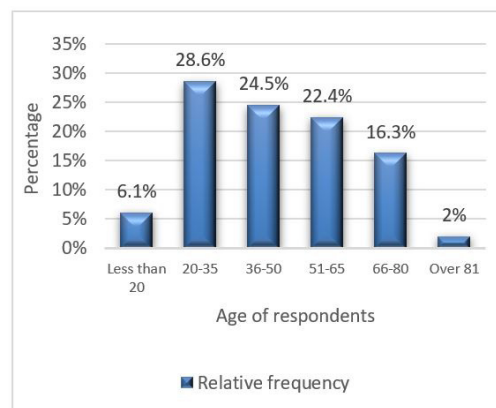


Figure 9: Educational level of respondents.

Source: The authors (2024).

The frequency of visits to the site is predominantly five times a week, which suggests the regular presence of users in the surrounding area. On the other hand, visiting once a week or at most once a month is more common among hospital patients. This can be attributed to many

of these patients coming from other cities and visiting Cachoeira do Sul only when they need to return for medical appointments. These data can be seen in Figure 10.

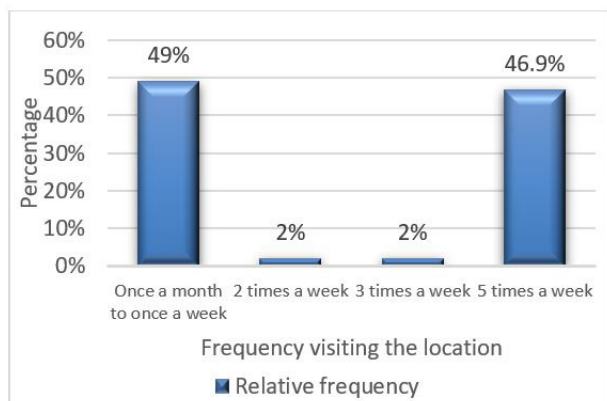


Figure 10: Regularity of visits to the respondents' location.

Source: The authors (2024).

The main motivation for being there is commerce and services (Figure 11). This trend is observed among surrounding residents and in the responses of individuals at the bus stop working in the area. Secondly, health-related motivation, due to the presence of the hospital, is mentioned as a significant reason for people to be there.

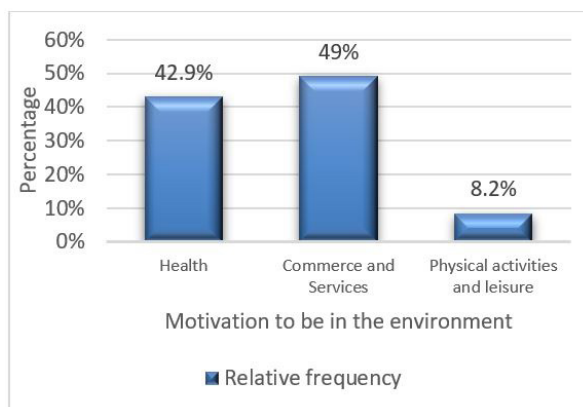


Figure 11: Motivation inherent to presence in the environment.

Source: The authors (2024).

Among the responses about satisfaction with the infrastructure at the location (Figure 12), a significant number of participants indicated that they were satisfied, followed by those who declared themselves very satisfied. Furthermore, another portion expressed a neutral position. These responses suggest that most respondents perceive the area as well cared for. Notably, many people from other cities compared their places of origin, concluding that Cachoeira do Sul has better care and infrastructural conditions.

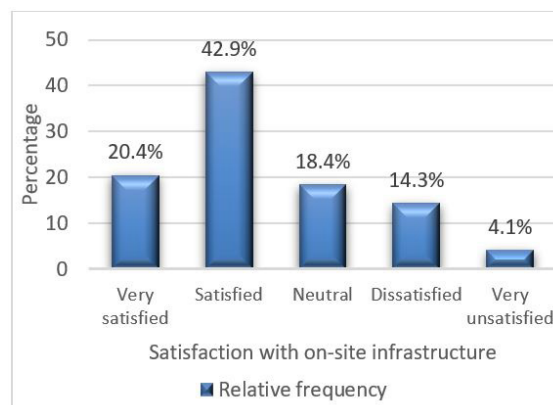


Figure 12: Satisfaction regarding environmental infrastructure conditions.

Source: The authors (2024).

Regarding satisfaction about the aesthetics of the surroundings, the responses indicate that the highest percentages are from people who declared themselves satisfied and neutral. Collecting responses on-site made it possible to note that many participants could not provide a clear opinion on this aspect, suggesting a lack of concern or specific attention regarding the area's aesthetics. This can be seen in Figure 13.

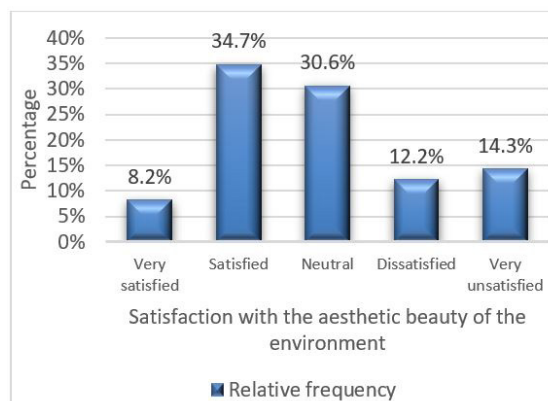


Figure 13: Respondents' satisfaction with the aesthetics of the environment.

Source: The authors (2024).

People often mentioned vehicle traffic, including trucks, when asked about the main noise source. Also, they pointed out machinery that uses the roads as a route to the industrial region close to the river. The responses relating to the main noise sources are shown in Figure 14.

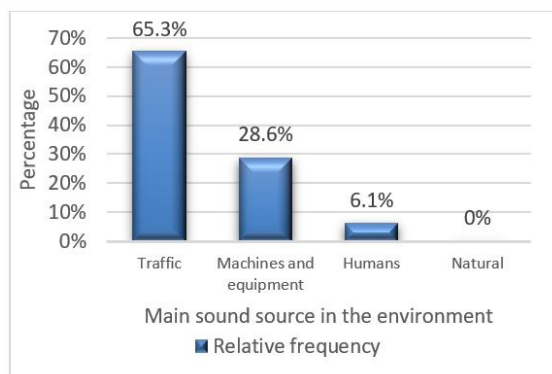


Figure 14: Responses regarding the main sound source of noise in the environment.
Source: The authors (2024).

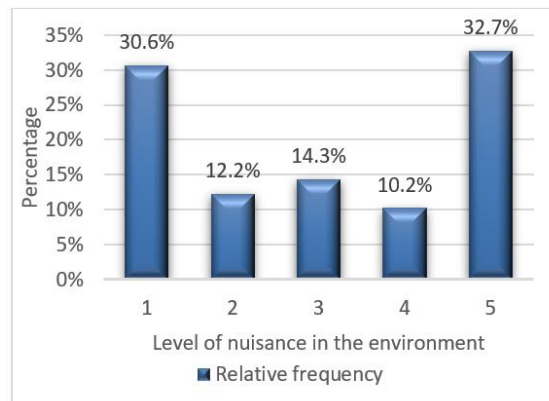


Figure 16: Responses regarding the nuisance of noise generated in the surroundings.
Source: The authors (2024).

When asked about the noises that bothered them most (Figure 15), most responded that they came from vehicle traffic, especially trucks, followed by machinery and equipment. Surprisingly, many people said they were not bothered by the noise. When asked why they did not feel uncomfortable, even though they noticed the surrounding noise, many explained that this was because they did not stay in the area long. It is also estimated that the population has normalized sound pressure levels, reducing discomfort.

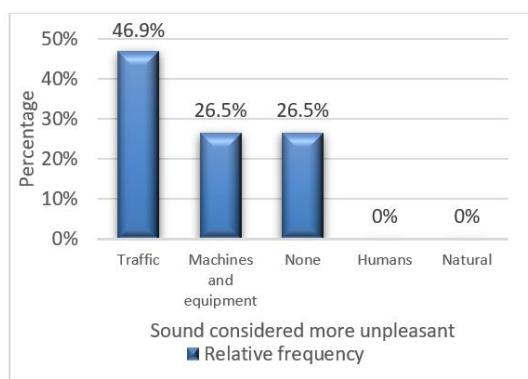


Figure 15: Responses regarding the most unpleasant sound elements.
Source: The authors (2024).

A significant value disparity was observed when asking people to rate their level of noise annoyance on a scale of 1 to 5. The most significant percentage assigned the maximum nuisance level (5), followed by a portion that indicated the lowest nuisance value (1), and an intermediate group that chose levels 3, 2, and 4. This significant variation in responses highlights the diversity of perceptions and sensitivities about the noise present in the area, showing how relative it can be between users. The responses related to the level of discomfort are shown in Figure 16.

Regarding the level of tranquility in the environment (Figure 17), the most common response was attributed to the maximum level (5), indicating that people consider the area calm. Secondly, a significant choice was observed for intermediate levels 3 and 2. This distribution of responses suggests a predominant perception of tranquility in the region.

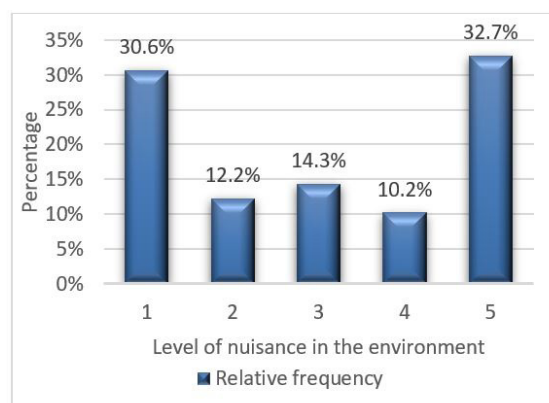


Figure 17: Responses regarding the level of tranquility in the environment.
Source: The authors (2024).

5. CONCLUSIONS

This research demonstrates that, even though it is a small city with a total population of around 80 thousand inhabitants, the urban environment can still present sound pressure levels above the values allowed by standard 10,151 (ABNT, 2019). From this perspective, urban centers are constantly intrinsic to noise pollution.

Furthermore, hospital environments, which, due to their use, should protect the recovery of patients, are affected by sound pressure levels like any other regions of cities, which further demonstrates the need to devise strategies to achieve values lower than 50 dB during

daytime periods and 45 dB during nighttime periods, as determined by NBR 10.151 (ABNT, 2019).

None of the four measurement points obtained values below 50 dB. When dealing with roads with a greater flow of cars, these values exceeded 61 dB, as demonstrated in point 2, which added the noise from vehicular traffic with the acceleration and deceleration of public transport at the bus stop.

Furthermore, the questionnaires demonstrated that the population still considers the environment peaceful. Some perspectives can be drawn from the regularity of visits to the site, the majority of respondents are HCB employees, and in addition, users consider the aesthetics of the environment to be very pleasant, these factors can corroborate results that tend to get used to noise pollution.

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WML: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project management, resources, supervision, validation, visualization, writing - original draft and writing - review & editing.

BCG: data curation, formal analysis, investigation, methodology and writing - original draft.

AFB: data curation, formal analysis, investigation, methodology and writing - original draft.

GM: conceptualization, funding acquisition, methodology, resources and writing - original draft.

MJS: funding acquisition, methodology, resources, writing - original draft and writing - review & editing.

Conflict declaration: nothing to declare.

ANNEX 1 - QUESTIONNAIRE ASSIGNED IN THE RESEARCH

Questionnaire			Relative frequency (%)	Absolute frequency
1	What is your gender?	Feminine	63,3	31
		Masculine	36,7	18
2	What is your age?	Less than 20	18	3
		20-35	28,6	14
		36-50	24,5	12
		51-65	22,4	11
		66-80	16,3	8
		Over 81	2	1
3	What is your education level?	Elementary school	30,6	15
		High school	46,9	23
		Graduation	20,4	10
		Master degree	2	1
4	What is the motivation for being in the environment?	Once a month to once a week	49	24
		Two times a week	2	1
		Three times a week	2	1
		Five times a week	46,9	23
5	How satisfied are you with the on-site infrastructure?	Health	42,9	21
		Commerce and services	49	24
		Physical activities and leisure	8,2	4
6	How satisfied are you with the on-site infrastructure?	Very unsatisfied	4,1	2
		Dissatisfied	14,3	7
		Neutral	18,4	9
		Satisfied	42,9	21
		Very satisfied	20,4	10
7	Regarding satisfaction with the aesthetic beauty of the environment?	Very unsatisfied	8,2	4
		Dissatisfied	12,2	6
		Neutral	30,6	15
		Satisfied	34,7	17
		Very satisfied	14,3	7
8	What is the main sound source in the environment?	Traffic	65,3	32
		Machines and equipments	28,6	14
		Humans	6,1	3
		Natural	-	-
9	What is the most unpleasant sound?	Traffic	46,9	23
		Machines and equipments	26,5	13
		Humans	-	-
		Natural	-	-
		None	26,5	13

10	What is the level of discomfort in the environment?	1	30,6	15
		2	12,2	6
		3	14,3	7
		4	10,2	5
		5	32,7	16
11	What is the level of tranquility in the environment?	1	8,2	4
		2	16,3	8
		3	16,3	8
		4	14,3	7
		5	44,9	22

Table 7: Questionnaire assigned in the research.

Source: The authors.

ANNEX 2

Point 1 - $L_{Aeq15min}$ 60,6 dB									
Frequency (Hertz)	31	63	125	250	500	1000	2000	4000	8000
L_{Aeq} (dB)	55,9	56,9	57,2	58,5	60,4	65,1	63,8	62,1	57
Point 2 - $L_{Aeq15min}$ 61,7 dB									
Frequency (Hertz)	31	63	125	250	500	1000	2000	4000	800
L_{Aeq} (dB)	59,1	59,9	60,3	60,5	63,5	67,1	64,9	64	62,7
Point 3 - $L_{Aeq15min}$ 60,2 dB									
Frequency (Hertz)	31	63	125	250	500	1000	2000	4000	8000
L_{Aeq} (dB)	58,1	58,9	59,6	59,8	62,2	66	64,5	63,2	60,1
Point 4 - $L_{Aeq15min}$ 56,1 dB									
Frequency (Hertz)	31	63	125	250	500	1000	2000	4000	8000
L_{Aeq} (dB)	50,5	53,2	54,1	54,2	56,3	58,1	55,6	54,2	51,2

Table 4: Sound pressure levels measured around the HCB.

Source: The authors.

ANALYSIS OF THE APPLICATION OF LIMESTONE WASTE IN CEMENTITIOUS SYSTEMS BASED ON A SYSTEMATIC LITERATURE REVIEW

ANÁLISE DA APLICAÇÃO DO RESÍDUO DE CALCÁRIO EM SISTEMAS CIMENTÍCIOS A PARTIR DE UMA REVISÃO SISTEMÁTICA DE LITERATURA

ANÁLISIS DE LA APLICACIÓN DE RESIDUOS DE CALIZA EN SISTEMAS CEMENTICIOS A PARTIR DE UNA REVISIÓN SISTEMÁTICA DE LA LITERATURA

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ABSTRACT

Limestone is a sedimentary rock composed mainly of calcite and aragonite, both composed of CaCO_3 , and may contain magnesium (dolomite). Its mining causes environmental problems due to the inadequate disposal of the waste generated. This study aims to identify the applicability of limestone residue from rocks in cementitious systems and to evaluate the techniques used to analyze these residues and their products. The method used was bibliographic research with Systematic Literature Review (SLR) as a tool. Limestone waste is generally calcitic and originates from quarries that extract carbonate rocks. Chemical and/or mineralogical analysis of the residue is not always performed, and there is no predominance of characterization regarding particle size, shape, and texture. Furthermore, most studies do not describe the state of the residue at the collection site and do not detail the preparation of the residue for use. Limestone waste has generally been applied in the form of a filler, partially replacing fine aggregate or cement in mortars. Its use in mortar production is viable and beneficial and can maximize new research on the use of waste, as well as help reduce the extraction of non-renewable natural resources.

KEYWORDS

Limestone waste; cementitious systems; characterization techniques; limestone filler; carbonate rocks

RESUMO

O calcário é uma rocha sedimentar composta principalmente por calcita e aragonita, ambas compostas por CaCO_3 , podendo conter magnésio (dolomita). A sua mineração traz problemas ambientais devido a deposição inadequada dos resíduos gerados. Esse trabalho objetiva identificar a aplicabilidade do resíduo de calcário proveniente de rochas em sistemas cimentícios e avaliar a partir de quais técnicas esses resíduos e seus produtos vêm sendo analisados. Utilizou-se como método a pesquisa bibliográfica com Revisão Sistemática de Literatura (RSL) como ferramenta. O resíduo de calcário geralmente é calcítico e originado de pedreiras que fazem a extração de rochas carbonáticas. A análise química e/ou mineralógica dos resíduos nem sempre é realizada, bem como não há predominância de caracterização quanto à granulometria, forma e textura das partículas. Além disso, a maioria dos estudos não descrevem o estado do resíduo no local de coleta e não detalham a preparação do resíduo para uso. O resíduo de calcário vem sendo aplicado geralmente na forma de fíler, substituindo parcialmente o agregado miúdo ou cimento em argamassas. O seu uso na produção de argamassa é viável e benéfico, podendo maximizar novas pesquisas sobre o uso do rejeito, bem como auxiliar na redução da extração de recursos naturais não renováveis.



PALAVRAS-CHAVE

Resíduo de calcário; sistemas cimentícios; técnicas de caracterização; filer calcário; rochas carbonáticas

RESUMEN

La caliza es una roca sedimentaria compuesta principalmente de calcita y aragonito, ambas compuestas de CaCO_3 , y puede contener magnesio (dolomita). Su extracción ocasiona problemas ambientales debido a la inadecuada disposición de los residuos generados. Este trabajo tiene como objetivo identificar la aplicabilidad de residuos calizos de rocas en sistemas cementosos y evaluar las técnicas utilizadas para analizar estos residuos y sus productos. El método utilizado fue la investigación bibliográfica teniendo como herramienta la Revisión Sistemática de Literatura (RSL). Los residuos de piedra caliza son generalmente calcíticos y proceden de canteras que extraen rocas carbonatadas. No siempre se realizan análisis químico y/o mineralógico de los residuos, no existiendo predominio de caracterización en cuanto a tamaño de partícula, forma y textura. Además, la mayoría de los estudios no describen la condición de los residuos en el lugar de recolección ni detallan la preparación de los residuos para su uso. Los residuos de piedra caliza se aplican generalmente en forma de relleno, sustituyendo parcialmente al agregado fino o al cemento en los morteros. Su uso en la producción de mortero es viable y beneficioso, y puede maximizar nuevas investigaciones sobre el uso de residuos, además de ayudar a reducir la extracción de recursos naturales no renovables.

PALABRAS CLAVE

Residuos de caliza; Sistemas cementicios; Técnicas de caracterización; Relleno de caliza; Rocas carbonatadas

1. INTRODUCTION

The use of mineral waste has been gaining ground in the replacement and manufacture of construction materials and components to contribute to their proper final disposal, as well as to reduce the environmental impacts generated by their extraction.

Thus, countries have been adopting policies aimed at optimizing the use of local materials for several reasons, and this may be due to the housing deficit or the scarcity of component materials for agglomerated mixtures in certain regions (BÉDÉRINA et al., 2005). In addition, the increase in construction activity has led to a huge demand for good quality construction and building materials, leading to a considerable increase in the mining rate of natural fine aggregates and the consequent generation of large amounts of solid and powder waste (CHOUHAN et al., 2019, 2020). In addition, other industries in various segments benefit from their use, such as paper, plastics, soil conditioner for agriculture, animal feed supplements, toothpaste, medicines and cosmetics (HALDAR, 2020).

Limestone is one of the most prominent and commonly available rocks found worldwide; It has bright colors and a smooth surface and is used for decorative purposes in the form of ornaments, tiles, and flooring in buildings and monuments around the world (CHOUHAN et al., 2020). In addition to availability, Haldar (2020) states that sedimentary rocks are relatively easy to cut into blocks and are long-lasting, making them commonly used in architecture, sculptures, historical monuments and buildings around the world.

Limestone is a sedimentary rock composed mainly of calcite (trigonal crystal system) and aragonite (orthorhombic crystal system), both composed of calcium carbonate - CaCO_3 (BARROS et al., 2020), and may contain magnesium in its composition, which can be characterized as dolomitic (HALDAR, 2020).

Mining activity brings serious environmental problems due to the inadequate disposal of the waste generated, generally in open areas (TAMMAM; UYSAL; CANPOLAT, 2022), landfills or other inadequate disposal sites (BARROS et al., 2020), such as soil waterproofing, closing of river courses, partial degradation of the environment, contamination of rivers and soil, among others. Barros et al. (2020) point out that such waste can be in the form of solids, resulting from tailings in mines or processing units, or

sludge, generated as a semi-liquid substance composed of particles from sawing and polishing processes.

Despite the discussions that have taken place in recent decades, there is still a search to mitigate the increase in the amount of waste (TAHER et al., 2021). Jamshidi (2024) reiterates that a solution to this problem still lies in recycling limestone waste to produce materials for various applications in construction projects, such as concrete, artificial stones and cement, and points out that such a measure leads to sustainable development through the added value of extraction and job creation.

Limestone waste has been studied timidly, but research indicates that it can be beneficially used in cementitious/agglomerated systems, partially replacing components of mixtures. Thus, initiatives to evaluate the appropriate disposal of this waste as construction material are presented as a viable alternative.

To study and analyze aspects related to the composition and structure of components in cementitious systems, it is necessary to use available characterization techniques that help understand their behavior when subjected to different experimental projects, which can range from the analysis of replacement of components in the mixture to its response when subjected to environmental adversities. Generally, the techniques are accompanied by instruments that provide data related to the analyzed material and, often, accompanied by analysis software. The results obtained can help in the discussion about the usability of a given material, as well as point out efficiency and durability criteria.

The main objective of this work is to identify the applicability of limestone residue from rocks in cementitious systems and to evaluate the techniques used to analyze these residues and their products, as well as to verify the importance of these techniques in their characterization.

2. METHODOLOGY

This study used bibliographic research as a strategy with Systematic Literature Review (SLR) as a tool. SLR is a type of scientific research that has gained recognition in different international scientific scenarios due to its high level of evidence (GALVÃO; RICARTE, 2019). The authors also define that to ensure the quality of the review, it is necessary to comply with its development stages, which are:

- a) delimitation of the issue to be addressed in the review;
- b) selection of bibliographic databases for consultation and collection of material;

- c) development of strategies for advanced search;
- d) selection of texts and systematization of information found.

In SLR, it is essential to record all research stages, both for the sake of reproducibility in other research, and to show that the process follows all previously defined stages (RAMOS; FARIA; FARIA, 2014). Figure 01 outlines the stages for the present study.

The databases used were Periódicos Capes and Science Direct due to the researchers' familiarity with the platforms and availability of institutional use, as well as these being widely used in materials, concentrating renowned journals at an international level.

To begin the search process, keywords in English were discussed that would direct to studies that met the objective of the study, that is, studies that addressed limestone waste and the characterization tests generally used, such as X-ray Fluorescence and Diffraction (XRF and XRD), Scanning Electron Microscopy (SEM), Thermogravimetric Analysis (TG/DTG) and BET surface area (BET), for example. It was assumed that studies that used XRD, XRF, SEM, TG and BET techniques could perform and present other characterization techniques and, if the use and relevance of other techniques were found, these would be included in the discussions.

The definition of Boolean operators was also an important step, since these, if used appropriately, optimize

the search, helping to identify and/or eliminate papers according to their relevance to the research, but their use is quantitatively limited in a single search in Science Direct (eight, maximum). Thus, the following keywords and Boolean operators were defined in Periódicos Capes: "limestone waste" AND (cement OR paste OR mortar OR concrete) AND (XRD OR XRF OR EDX OR SEM OR TG OR BET). In Science Direct, two sets of keywords were used due to the limitation of Boolean operators and were: "limestone waste" AND (cement OR paste OR mortar OR concrete) AND (XRD OR XRF OR EDX) and "limestone waste" AND (cement OR paste OR mortar OR concrete) AND (SEM OR TG OR BET).

To direct the authors to relevant works on the topic, it was determined that these should be present in the title, abstract or keywords. To this end, the search was performed in the advanced search field of the Science Direct platform; the Periódicos Capes platform automatically performs this search in the main field. Eight and two articles were found in Periódicos Capes and Science Direct, respectively, but there was an overlap between them, totaling eight distinct articles published in the last 17 years. Considering the reasonable number of articles, as well as the relevance of the journals responsible for the publications, the eight articles were considered suitable for analysis.

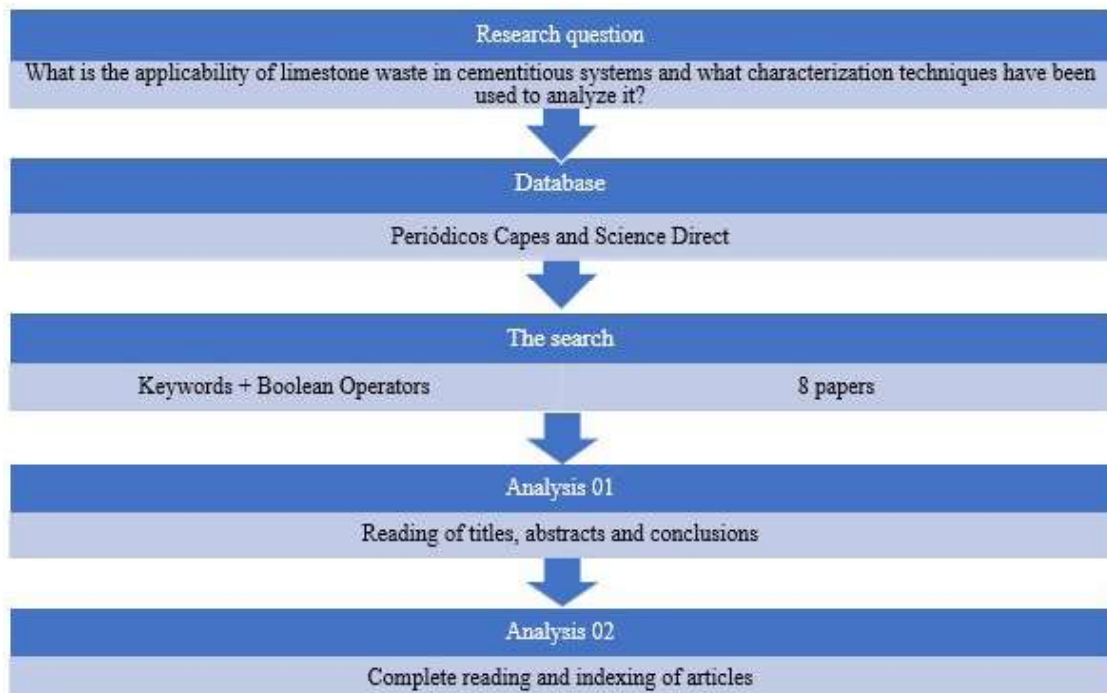


Figure 1: Research design.

Source: The authors.

Table 01 lists the identified works in chronological order of publication, indicating the title, source, database and application of limestone residue.

Although the study by Barros et al. (2020) is not necessarily about limestone residue in an agglomerated system, its characterization results proved to be relevant to the discussions.

No.	Title	Source/ authorship	Periódicos Capes	Science Direct	Application of residue
1	Use of limestone obtained from waste of the mussel cannery industry for the production of mortars	Ballester et al. (2007)	X		Mortar
2	Encapsulation of limestone waste in concrete after arsenic removal from drinking water	Chintalapat et al. (2009)	X		Concrete
3	Gainful utilization of dimensional limestone waste as fine aggregate in cement mortar mixes	Chouhan et al. (2019)	X	X	Mortar
4	Ecological bricks from dimension stone waste and polyester resin	Barros et al. (2020)	X	X	Ecological brick
5	Investigating use of dimensional limestone slurry waste as fine aggregate in mortar	Chouhan et al. (2020)	X		Mortar
6	The Influence of Crystalline Admixtures on the Properties and Microstructure of Mortar Containing By-Products	Hodul; Žižková; Borg (2020)	X		Mortar
7	Effects of alternative ecological fillers on the mechanical, durability, and microstructure of fly ash-based geopolymer mortar	Tammam; Uysal; Canpolat (2022)	X		Mortar
8	Effect of Waste Filler Materials and Recycled Waste Aggregates on the Production of Geopolymer Composites	Tammam et al. (2023)	X		Mortar

Table 1: Data from the articles analyzed.

Source: The authors.

3. RESULTS AND DISCUSSIONS

To aid in understanding the discussions that follow, Appendix 1 is presented at the end of this paper, summarizing: the objectives and conclusions of the articles analyzed; the origin, form of use and preparation of the residue, as well as the details of the characterization techniques used. Next, the results of the characterizations of the limestone residue and the products generated from its application are compared and discussed. Such discussion is relevant to understanding the objective of each technique, as well as pointing out familiarity, or not, in its use.

3.1 Chemical composition and physical properties

The chemical composition, when determined and presented, was performed using XRF. Table 02 presents a

summary of the chemical compositions of the limestone residues studied, as well as specific physical properties. The residues are calcitic (magnesium content below 5%). The results also show that the limestone residues used have calcium oxide (CaO) as the main component, followed by quartz (SiO₂). To analyze the mineralogy of the residue, XRD tests were performed.

The studies by Barros et al. (2020) and Hodul et al. (2020) used XRD (Figure 02) to analyze the mineralogy of limestone residue. Figure 02, in the upper part, shows predominant peaks of calcite (1 - CaCO₃), dolomite (2 - CaMg(CO₃)₂), quartz (3 - SiO₂) and kaolinite (4 - Al₂O₃). In the lower part, the diffractogram also shows a limestone with a predominantly calcite composition (C - CaCO₃) with smaller peaks of quartz (Q - SiO₂). The peaks of greatest intensity are located at similar 2θ angles. The mineralogies can be correlated with the chemical compositions presented in Table 02.

Source/ author- ship	Chemical composition (%)							Physical properties				
	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	P ₂ O ₅	K ₂ O	Specific Gravity	Density (g/cm ³)	Fineness modulus	Water absorption (%)	Blaine (cm ² /g)
Ballester et al. (2007)	-	-	-	-	-	-	-	-	-	-	-	-
Chintalapati et al. (2009)	-	-	-	-	-	-	-	-	-	-	-	-
Chouhan et al. (2019)	37,85	23,5	3,1	1,94	-	-	-	2,70	0,96-1,29	1,29-1,99	3,50-8,80	
Barros et al. (2020)	89,49	1,08	-	0,48	2,6	0,1	0,07	-	2,76	-	-	-
Chouhan et al. (2020)	-	-	-	-	-	-	-	2,59	0,96	1,29	8,77	
Hodul; Žižková; Borg (2020)	-	-	-	-	-	-	-	-	-	-	-	-
Tammam; Uysal; Canpolat (2022)	51,97	4,93	0,82	0,58	0,58	-	-	2,79	-	-	-	2500
Tammam et al. (2023)	51,97	4,93	0,82	0,58	0,58	-	-	2,70			4,60	2500

Table 2: Chemical compositions and physical properties of waste.

Source: The authors.

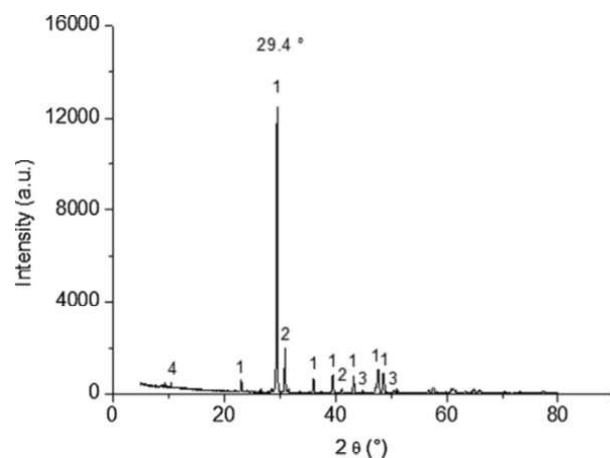


Figure 2 (top): X-ray diffraction pattern of limestone residue.

Source: Barros et al. (2020).

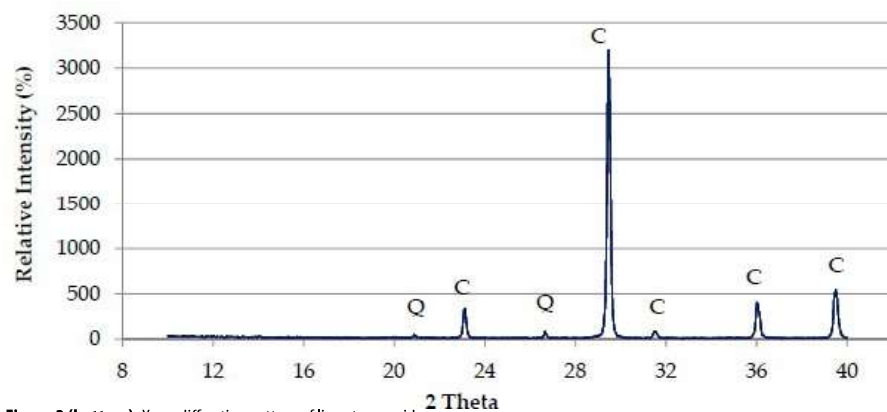


Figure 2 (bottom): X-ray diffraction pattern of limestone residue.

Source: Hodul; Žižková; Borg (2020).

The limestone residue was used in different ways, both in terms of its granulometry and its replacement function. Although Chintalapati et al. (2009) do not indicate the method for defining granulometry, the authors state that the limestone had particle dimensions of 0.5 to 1 mm, consistent with the granulometric range for sand according to the American standard.

Figure 03 shows the granulometric distribution of the aggregates used by Ballester et al. (2007) (top) and Chouhan

et al. (2019) (bottom), characterizing the use of the residue in the form of filler. Ballester et al. (2007) detail that the granulometry was determined using a laser analyzer.

Chouhan et al. (2020) presented more details on the granulometry of residues from limestone sludge (DLSW), where 36.4% of the particles were smaller than 0.15 μm , appearing finer in relation to river sand, of which only 6.3% of the particles were smaller than 6.3 μm .

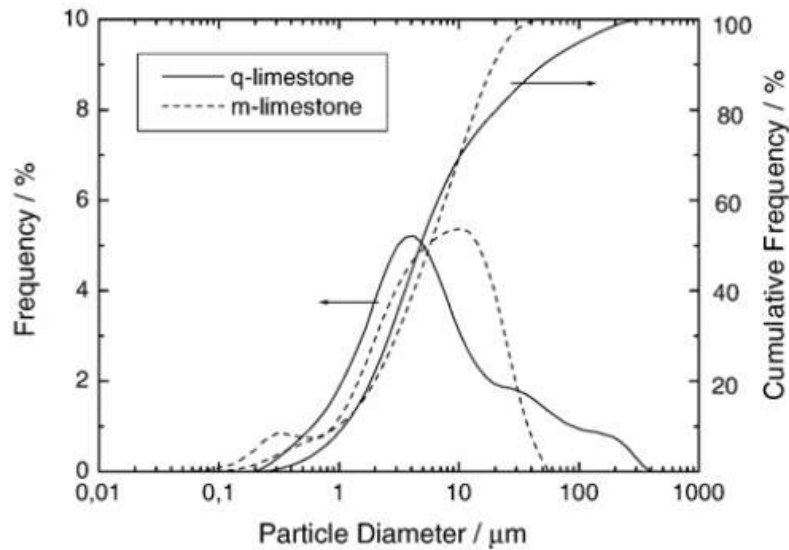


Figure 3 (top): Granulometric distribution of limestone residues.
Source: Ballester et al. (2007).

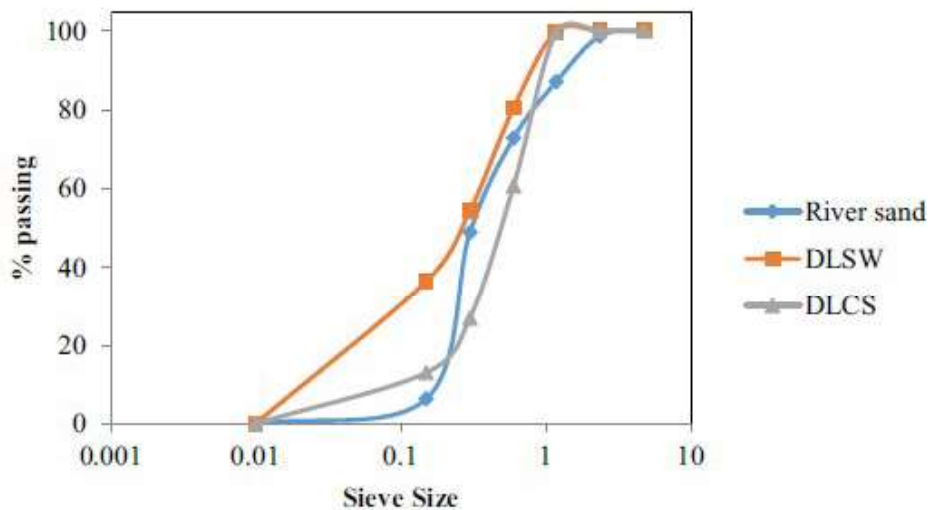


Figure 3 (bottom): Granulometric distribution of limestone residues.
Source: Chouhan et al. (2019)..

The beams were analyzed at 502 days of age, exhibiting an average compressive strength of 32.4 MPa and an elasticity modulus of 34.8 GPa. This analysis was selected to eliminate the influence of compressive strength variation on the experimental results. This criterion was necessary because different degrees of corrosion required varying acceleration periods (ranging from 10 to 45 days). Stabilizing compressive strength was crucial to ensure that the analyses exclusively reflected the effects of corrosion on structural performance.

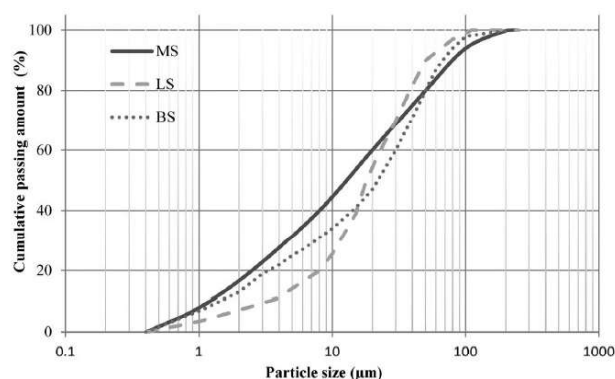


Figure 4: Granulometric distribution of limestone residues (LS).

Source: Tammam et al. (2022).

Thus, regarding the granulometry defined for the waste from the analyzed works, this is presented in different ranges depending on the applicability of the waste, but generally in the format of:

- a) limestone sand partially replacing fine aggregate (BALLESTER et al., 2007);
- b) limestone filler partially replacing fine aggregate (CHINTALAPATI et al., 2009; CHOUHAN et al., 2019, 2020; TAMMAM et al., 2023; TAMMAM; UYSAL; CANPOLAT, 2022);
- c) limestone filler partially replacing cement (HODUL; ŽIŽKOVÁ; BORG, 2020);
- d) limestone filler with only the addition of resin (BARROS et al., 2020).

3.2. Microstructure

SEM was the technique used to analyze the morphology of the limestone residues. Figure 5 shows the microstructure of the two limestone residues studied by Ballester et al. (2007), where it is possible to observe different particle sizes and shapes. The quarry limestone (top) has rounded

particles ranging in size from 2 to 6 μm , and, in turn, the mussel limestone (bottom), not the focus of this study, has prismatic particles up to 14 μm in length and a small fraction of particles smaller than 1 μm , which is confirmed by the distribution of particle sizes. The authors justify the gain in strength precisely by the intercrossing of particles with prismatic morphology, a characteristic of mussel limestone, which can result in the formation of a network where the cement particles strongly bind to the aggregates after the solidification of the cement paste, thus increasing the strength of the mortar.

This result was also confirmed by Tammam et al. (2023), in which as the replacement rate of fine aggregate by limestone filler residues increased, there was also an improvement in compressive, tensile and flexural strengths due to the higher limestone content (up to 75%) increasing the reactive phase and reducing water absorption. Another relevant observation was that such different granular characteristics between limestones influenced the consistency of the mortars produced, where limestone with prismatic particles led to more workable mortars.

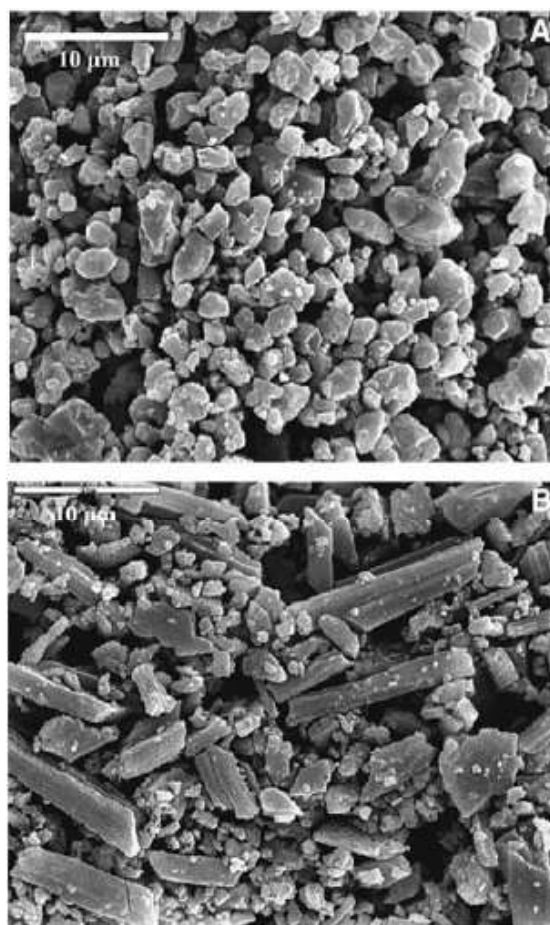


Figure 5: SEM images of limestone residues: (A) quarry limestone and (B) mussel limestone.

Source: Ballester et al. (2007).

Chouhan et al. (2019), when evaluating two residual forms of limestone (Figure 06), limestone slurry (DLSW) and crushed limestone sand (DLCs), identified that both have an irregular shape and rough texture, especially when compared to conventional river sand (RS), which has a smooth surface and rounded shape (CHOUHAN et al., 2019, 2020).

Corroborating the morphologies presented previously, the residues from Barros et al. (2020) and Hodul et al.

(2020) have an irregular shape (Figure 07), probably related to calcium carbonate grains. Both studies used residues from quarries, from the cutting of limestone rocks. Tammam et al. (2023) also presented the SEM result for the limestone filler studied, with no discussions about its shape; however, according to Figure 07, the residue also has an irregular shape.

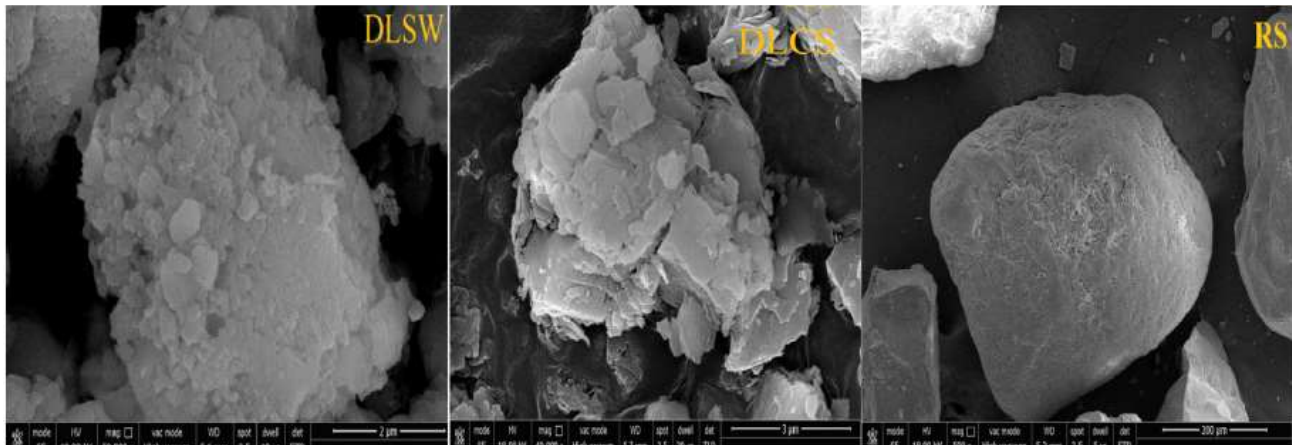


Figure 6: SEM images of limestone slurry residue (left), crushed limestone sand (center) and conventional river sand (right).

Source: Chouhan et al. (2019).

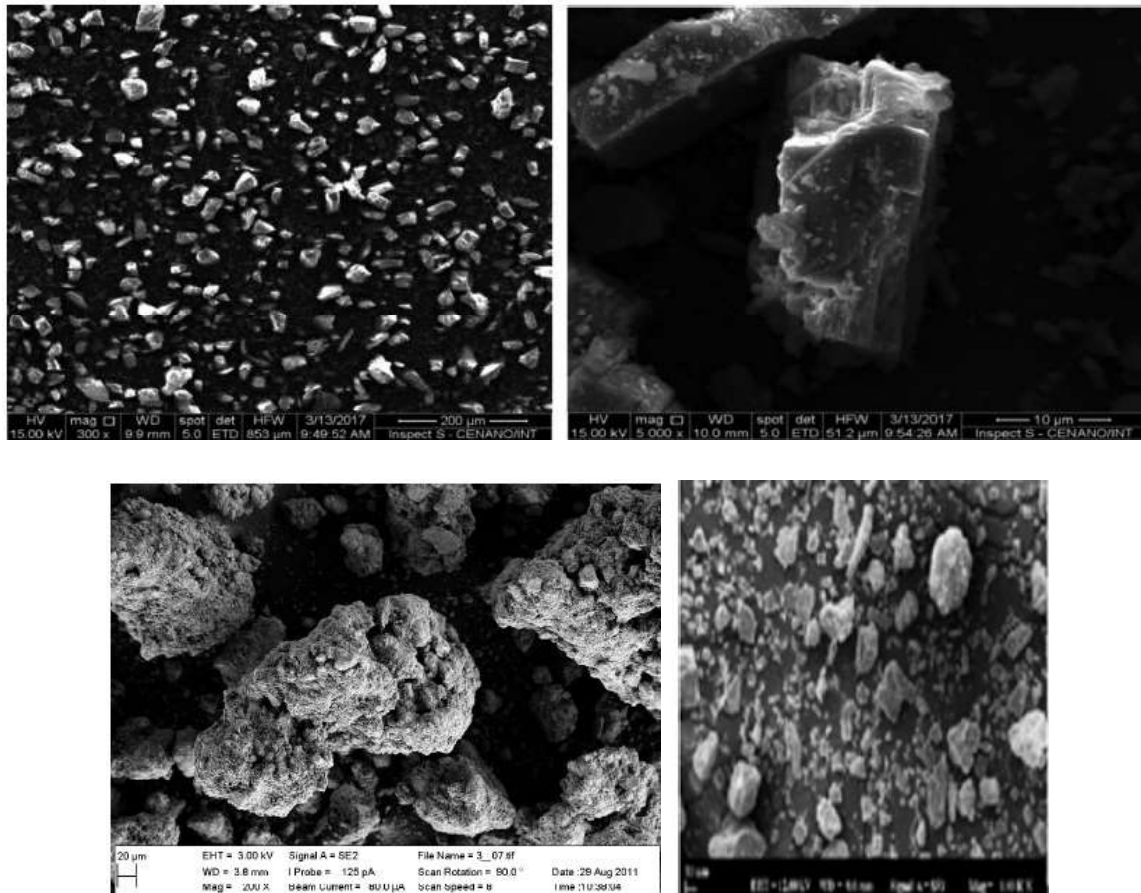


Figure 7: SEM images of limestone residues.

Source: top: Barros et al. (2020); bottom left: Hodul; Žižková; Borg (2020); bottom right: Tammam et al. (2023).

When combined, XRD and SEM can be useful for analyzing changes in the mineralogy of cementitious products after different levels of component replacement. Thus, SEM was also used to evaluate the microstructure of the products generated in the studies. Ballester et al. (2007) identified that a rounded morphology (Figure 08) in the aggregate should prevent the formation of the interconnected system that helps to bind the different components as cement hydration progresses.

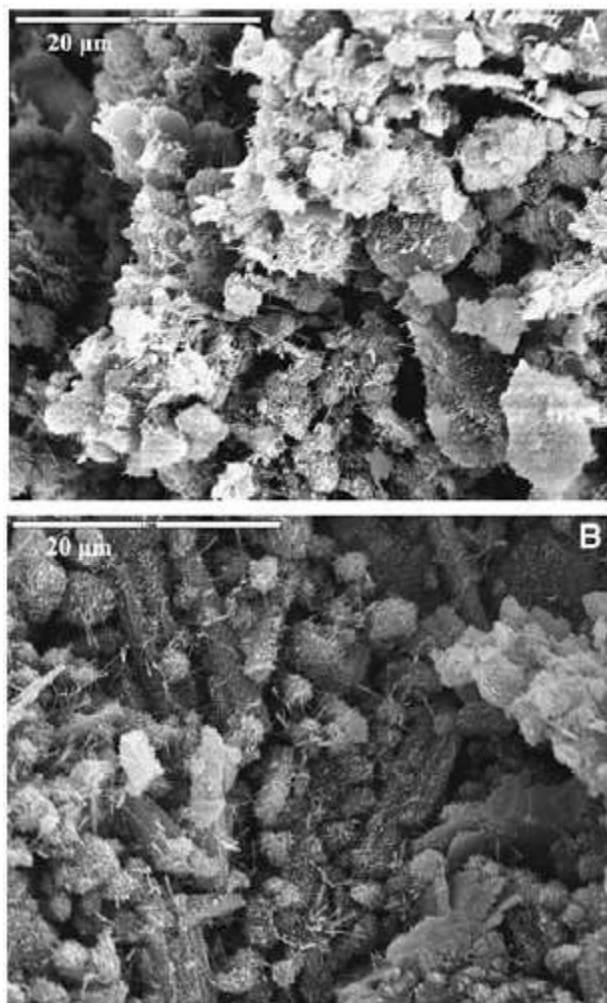


Figure 8: SEM images of limestone residues: (A) quarry limestone and (B) mussel limestone.
Source: Ballester et al. (2007).

Chouhan et al. (2020), in turn, analyzed the interfacial transition zone (ITZ), ettringite, calcium silicate hydrate (C-S-H) and the pores present in the microstructure of the mortar with dry limestone mud residues (Figure 09), concluding that as the replacement level increases, a more packed structure with dense formation of C-S-H emerges and results in increased strength. Chouhan et al. (2019) add that, for this reason, the mortar with the residue formed a

denser and more compact structure and that, above 60% replacement, internal cracks can be observed.

In the case of Tammam et al. (2022) and Tammam et al. (2023), it was observed that the mortars had a compact, homogeneous structure, without cracks and a good degree of bonding with the matrix components (Figure 10). Thus, they concluded that the limestone residue particle fills the pores between the hydration products, reduces the porosity in the matrix, improves the degree of hydration of the binder and generates more hydration products.

3.3. THERMAL ANALYSIS

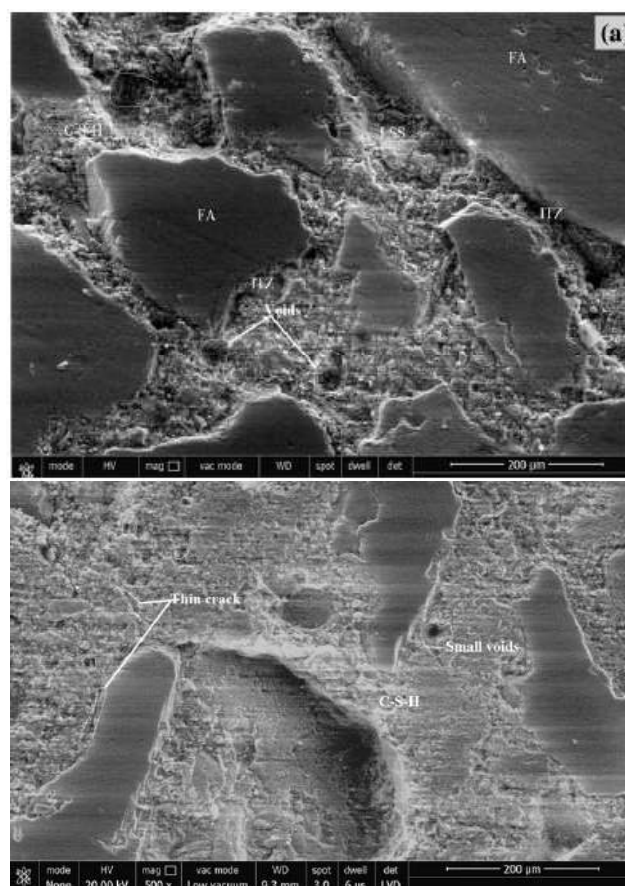


Figure 9: SEM images of the sample without residue (top) and with 40% replacement (bottom).
Source: Ballester et al. (2007).

The thermal analysis test, when used in the studies, was the Thermogravimetric Analysis (TG/TGA). Barros et al. (2020) were the only researchers who performed the analysis on the limestone residue, presenting TG and DTG curves (Figure 11), with an initial mass loss temperature around 700°C and a final one around 810°C, with a peak

in the DTG curve at around 783.4°C and a residual mass of 6.52%, typical of the decomposition of CaCO_3 into CaO releasing CO_2 .

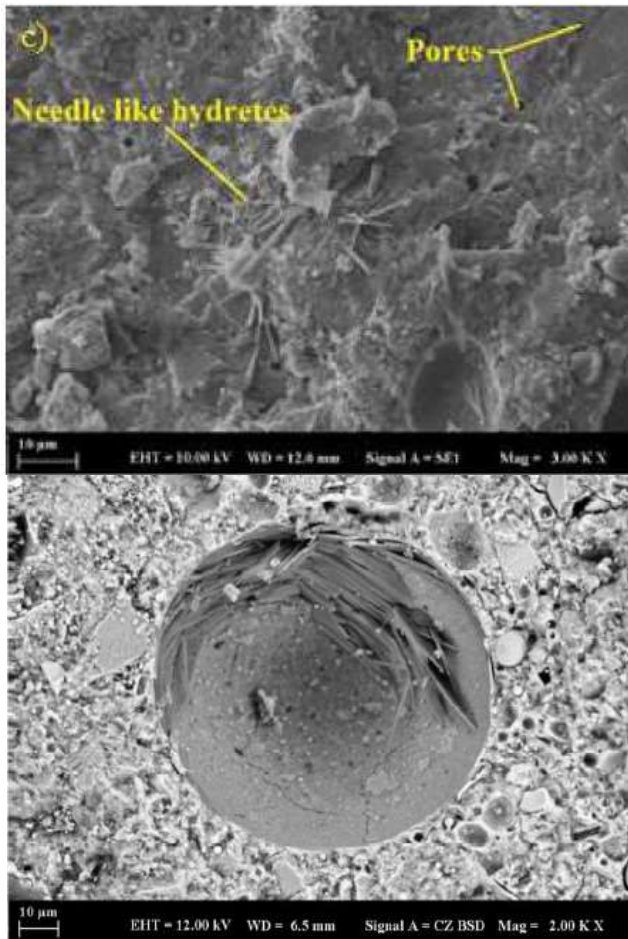


Figure 10: SEM images of mortars with limestone residue.

Source: top: Tamam; Uysal; Canpolat (2022); bottom: Tamam et al. (2023).

Other studies that used thermal analysis did so on the cementitious products produced. Ballester et al. (2007) used the technique to interpret the correlation observed between limestone aggregates and the strength of mortars, comparing the mass loss at each stage of the different curing periods and, thus, identifying the influence of the aggregate on the development of the setting process. The authors were able to identify four phases associated with different physicochemical processes: (i) weight loss due to adsorbed water (25-120°C); (ii) loss of chemically bound water (120-450°C); (iii) weight loss associated with the dehydroxylation of $\text{Ca}(\text{OH})_2$ (450-490°C); and (iv) loss of CO_2 due to the decomposition of carbonates.

Chouhan et al. (2020) also identified four temperature ranges (Figure 12): (i) between 30 and 300°C, the curve trend showed a gradual decrease indicating moisture

evaporation; (ii) between 300 and 450°C a gradual loss of 4% was observed for the control mixture and 5-6% for the mixtures with substitution attributed to the dehydroxylation of $\text{Ca}(\text{OH})_2$; (iii) between 450 and 600°C there was a constant drop in the curve, indicating a weight loss of around 5% for the control mixture and 6-7.5% for the mixtures with substitution, which indicates the beginning of the phase transition or decomposition of calcite into CaO ; (iv) between 600 and 800°C a sharp drop in the curve was observed, with a weight loss in the control curve of 6.5%, with the curves of the mixtures with substitution indicating a loss of 14.5% to 31% depending on the increase in the substitution content, justified by the decomposition of CaCO_3 into calcium oxide and release of CO_2 .

3.4. POROSITY

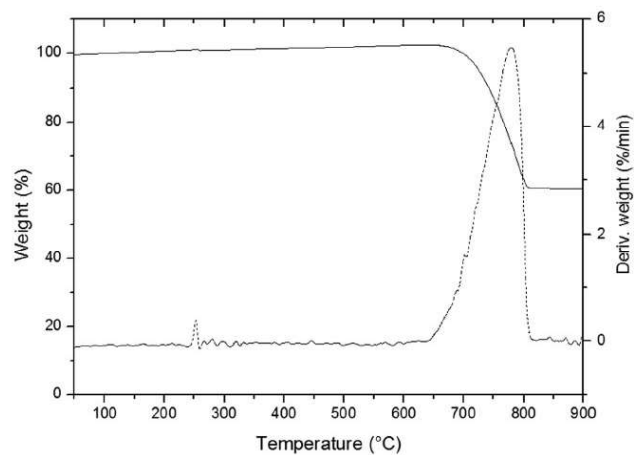


Figure 11: TG (-) and DTG (---) curves of limestone residue.

Source: Barros et al. (2020).

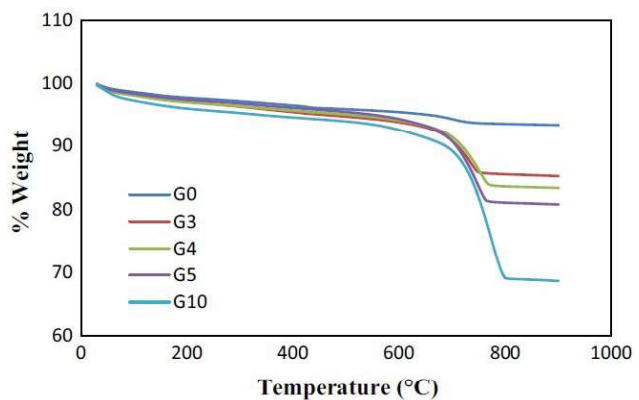


Figure 12: TGA curves for mortars with 0, 30, 40, 50 and 100% replacement of limestone residue.

Source: Chouhan et al. (2020).

Mercury injection porosimetry (MIP) was the technique used to analyze the porosity of the products. For Ballester et al. (2007), MIP revealed the presence of smaller pores in mortars based on prismatic particle limestone (mussel limestone), consistent with a more efficient filling of the pores and responsible for the increase in compressive strength.

On the other hand, Chouhan et al. (2020) concluded that with substitution of up to 40% (G4, in Figure 13), the results were comparable to the control sample, and, above this limit, the mortars presented high porosity, indicating a reduction in compaction efficiency due to finer particles. Figure 13 illustrates the mercury intrusion rate in relation to pore size.

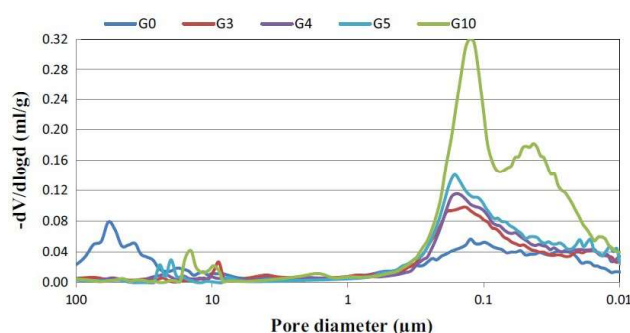


Figure 13: Mercury intrusion rate versus pore size.

Source: Chouhan et al. (2020).

4. CONCLUSION

The main objective of this study was to evaluate the usability of limestone residue in cementitious systems and, in addition, to list the main techniques that have been used to evaluate the raw materials and products generated. For this, the bibliographic review was used as a method with the Systematic Literature Review (SLR) as a tool.

It was found that limestone residue commonly originates from quarries that extract carbonate rocks. However, other sources have been explored, such as the mussel canning industry.

Quantitatively, the compositions of the limestone can be different depending on the type, source/location of generation and degree of contamination by other components. Despite the general knowledge that limestone is composed mainly of Calcium Oxide (CaO), it is possible to conclude that there is no consensus, in the studies analyzed, that the chemical and/or mineralogical analysis of the residues is presented as an indispensable

preliminary analysis, since some of the studies do not perform it or do not present it. However, the limestones identified here are calcitic, which corroborates the literature that identifies that calcitic limestones as a component present better performance in rheological characteristics and mechanical properties (ISAIA; RIZZATTI, 2020).

The residue generally has an irregular shape and rough texture. Despite this, it is worth noting that there is no predominance of a complete characterization regarding the granulometry, shape and texture of the particles. The lack of this information contributes to the non-reproducibility of characterization tests, as well as not providing an enrichment of the literature on the characterization of solid waste from rocks.

Limestone waste has generally been applied in the form of a filler, partially replacing fine aggregate or cement in mortars. Even when combined with other components, studies show that the partial replacement of fine aggregate with limestone filler can improve the mechanical properties of mortars. It was noted that, as the replacement rate of fine aggregate with limestone filler residue increased, there was also an improvement in compressive, tensile and flexural strengths due to the higher limestone content increasing the reactive phase, increasing the density of the samples and reducing water absorption. That is, the beneficial characteristics are present when the residues are finely ground, with a smaller particle size than the replacement components, since they act as filler material, increasing the degree of packing in the mixtures.

Studies on limestone waste have shown that its use in mortar production is viable and beneficial and can maximize new studies on the use of waste, as well as help reduce the extraction of non-renewable natural resources. On the other hand, barriers can still be found in the use of waste, ranging from concerns about the performance of the products generated to contamination of the material due to different exposures and the lack of regulations that direct its use.

Regarding characterization techniques, XRF and XRD are used to identify the chemical and mineralogical composition of limestone residue, respectively. XRF is used only on the raw material, i.e., before application to the cement product, to identify the chemical composition. XRD, however, can be used in both phases, i.e., both for mineralogical definition and for analysis of the interaction of the residue in the product.

Regarding the physical characterization of the materials, data on density, fineness modulus and water absorption, Blaine surface area and granulometry are described, but

without further details on the method/standard used. To define the granulometry, only one study indicates the laser analyzer as the equipment used, while the others do not provide details, but describe the data that indicate the use of traditional sieving as equipment.

In the case of morphological analysis of residues and cementitious products, all the research analyzed here used SEM as a technique, which can be used on raw materials, generated products, or both. SEM was mainly used to identify the shape and texture of limestone. However, confirmation of particle size distribution, as well as analysis of the interaction of materials as products, were performed thanks to the use of SEM. This reflects and justifies the power and popularity of the technique within the research of cement materials in the analysis of microstructure.

Thermal analysis, using TGA, and porosimetry, using MIP, were also techniques identified in some studies. When used on limestone, TG helped confirm the mineral due to the observed decomposition phases and, when used on mortar, allowed a better understanding of its mechanical behavior. MIP, in turn, was applied to analyze the porosity of mortars produced with limestone partially replacing fine aggregate, also helping in discussions about mechanical behavior.

Finally, regarding characterization techniques, the timid use of the FTIR technique (Fourier Transform Infrared Spectroscopy) was identified. FTIR allows the identification and analysis of chemical changes and composition variations (AZEER; SHENBAGARAMAN, 2025). When used only on limestone, FTIR confirmed its mineralogical origin and, when used on mortar, it served as a parameter in the analysis of mechanical behavior, thus proving to be a complementary technique.

Despite the predominance observed in detailing data on equipment and procedures, such as manufacturer, parameters, software, sample preparation, among others, some studies did not do so, which can make comparisons between results from different studies difficult, as well as reproducibility in new research. In addition, most studies do not describe the state of the waste at the collection site (sludge, pieces of rock or sawdust powder, for example), nor do they address the form of waste preparation, such as drying, transportation and comminution.

In future, it is suggested that investigations be carried out into the other components (aggregates, additives, additions, etc.) of the mixtures that may also influence the results obtained, since the studies analyzed here use different compositions in the mortar mixes produced. In addition, a new analysis of the characterization of the

limestone residue used as filler can be carried out, finding it in literature as limestone powder or dust, which generally come from industries that process and commercialize it.

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FIRST STEPS TO N95: LOW-TECH AND ADAPTED EQUIPMENT FOR THE AUTONOMOUS DEVELOPMENT OF PLASTIC MICROFIBERS FOR MASK FILTRATION

PRIMEIROS PASSOS PARA O N95: EQUIPAMENTO DE BAIXA TECNOLOGIA E ADAPTADO PARA O DESENVOLVIMENTO AUTÔNOMO DE MICROFIBRAS PLÁSTICAS PARA FILTRAÇÃO DE MÁSCARAS

PRIMEROS PASOS HACIA EL N95: EQUIPOS DE BAJA TECNOLOGÍA Y ADAPTADOS PARA EL DESARROLLO AUTÓNOMO DE MICROFIBRAS PLÁSTICAS PARA LA FILTRACIÓN DE MASCARILLAS

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ABSTRACT

The pandemic has brought unprecedented obstacles. One of the critical challenges was the shortage of Personal Protective Equipment (PPE). Additive manufacturing has emerged as a viable solution to address the PPE shortage. Developed 3D-printed masks were a way to combat market shortages, but producing the filter element remains an obstacle. This study documents research into the feasibility of applying the plastic casting technique using centrifugal melt spinning, a possible way to replicate existing processes. The concept is simple and similar to how cotton candy is made. The aim is to propose possible ways of using distributed manufacturing, recycling, and adapting local infrastructure to manufacture viable filters, comparing them with those produced using traditional methods.

KEYWORDS

Cotton Candy; Melt Spinning; Filter.

RESUMO

A pandemia trouxe obstáculos sem precedentes. Um dos desafios críticos foi a escassez de Equipamentos de Proteção Individual (EPI). A manufatura aditiva emergiu como uma solução viável para enfrentar essa carência de EPIs. Máscaras desenvolvidas por impressão 3D foram uma forma de combater a escassez no mercado, mas a produção do elemento filtrante permanece um obstáculo. Este estudo documenta a pesquisa sobre a viabilidade da aplicação da técnica de moldagem de plástico por centrifugação de fusão ("centrifugal melt spinning"), uma possível maneira de replicar processos existentes. O conceito é simples e assemelha-se ao modo de fabricação do algodão-doce. O objetivo é propor formas de empregar manufatura distribuída, reciclagem e adaptação da infraestrutura local para produzir filtros viáveis, comparando-os com aqueles obtidos por métodos tradicionais.

PALAVRAS-CHAVE



Algodão-Doce; Fiação por Fusão; Filtro

RESUMEN

La pandemia ha presentado obstáculos sin precedentes. Uno de los desafíos críticos fue la escasez de Equipos de Protección Personal (EPP). La fabricación aditiva ha surgido como una solución viable para abordar esta falta de EPP. Las mascarillas desarrolladas mediante impresión 3D fueron una forma de combatir la escasez en el mercado, pero la producción del elemento filtrante sigue siendo un obstáculo. Este estudio documenta la investigación sobre la viabilidad de aplicar la técnica de moldeo de plástico mediante hilado centrífugo fundido ("centrifugal melt spinning"), una posible manera de replicar procesos existentes. El concepto es sencillo y es similar al modo en que se produce el algodón de azúcar. El objetivo es proponer vías para emplear fabricación distribuida, reciclaje y adaptación de la infraestructura local para fabricar filtros viables, comparándolos con los obtenidos mediante métodos tradicionales.

PALABRAS CLAVE

Algodón de Azúcar; Hilado por Fusión; Filtro

1. INTRODUCTION

The COVID-19 pandemic, caused by the SARS-CoV-2 coronavirus, has triggered an unprecedented global public health crisis, affecting nearly every aspect of human life. With easy transmission and initially unknown transmission routes, the number of hospital cases rose sharply, creating demand for PPE that exceeded available stocks. PPE such as masks, gloves, aprons, and face shields became vital in preventing virus transmission, protecting users, and mitigating community spread. Governments faced shortages of this equipment, including N95 respirators, due to increased global demand that strained supply chains and created challenges in meeting healthcare workers' needs (Ehrlich et al., 2020).

The limited availability of PPE not only endangered frontline personnel but also hindered effective COVID-19 patient management, highlighting the critical importance of ensuring a stable and sufficient supply of protective equipment during health crises (Valdez et al., 2022). In response to PPE shortages, designers and institutions implemented innovative solutions, research, and strategies to address supply gaps and protect healthcare staff. Some hospitals resorted to reusing masks or improvising with adapted resources to cope with limited equipment availability (Grossman et al., 2020). Additionally, initiatives such as disinfecting N95 respirators using vaporized hydrogen peroxide were introduced to extend PPE usability and optimize resource utilization during the pandemic (Fram et al., 2020). The challenges presented by PPE shortages underscored the need for efficient acquisition, distribution, and use of protective equipment to safeguard healthcare professionals (Schmidt et al., 2021).

PPE shortages during the pandemic had far-reaching consequences for healthcare workers, requiring alternative approaches and concerted efforts to address supply chain disruptions and ensure universal safety. The challenges highlighted the importance of proactive planning, resource allocation, and decentralized production alternatives to mitigate shortages and protect populations during public health emergencies.

With this increased demand, new manufacturing techniques played a key role. The use of additive manufacturing technology emerged as a viable

solution to resolve the severe equipment shortages during the COVID-19 pandemic. By leveraging 3D printing capabilities, communities could quickly produce essential PPE in response to supply shortages (Amir & Amir, 2022). Custom 3D-printed face masks were also developed to address the lack of commercially available FFP2/3 masks by offering personalized solutions tailored to specific needs (Swennen et al., 2020). These masks typically consisted of reusable 3D-printed components combined with filter elements, providing an alternative production approach during epidemic crises (Swennen et al., 2020).

2. THE RESEARCH

Researchers at BioDesign at PUC-Rio are developing new PPE, such as filtering mask models that use surgical mask fabric as the filtering element (Yamaki et al., 2022 - Figure 1). The use of surgical masks as filters was based on laboratory breathability tests, which indicated that surgical masks were highly permeable and comfortable for breathing. This, combined with their effective filtration, led to research into respiratory masks aimed at solving the problem of facial sealing, eliminating unfiltered air leakage.

Although using surgical masks satisfied researchers' air filtration requirements during mask development, progress remains incomplete regarding the goal of producing respiratory masks entirely independent of conventional production chains. Designing filter manufacturing methods represents an important step.

The introduction of filter manufacturing could enable complete mask production. There are many techniques for developing air filters by controlling air passage through fabrics, whether woven or non-woven, composed of synthetic or natural fibers. One method for producing synthetic fibers is centrifugal plastic melt spinning, where fibers are made into fabric and electrically charged to enhance effectiveness.

When implementing centrifugal melt spinning (Bandi, 2020) on a smaller scale, specialized machines are unnecessary due to its conceptual simplicity. This technique, already implemented and published, involves melting and casting plastic, similar to the cotton candy process. Instead of fine sugar fibers, researchers can create plastic polymer fibers.

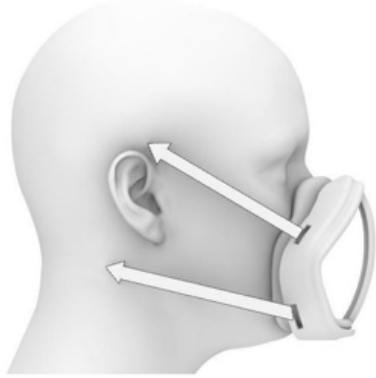


Figure 1: Mask made by additive manufacturing using a surgical mask as filtering media.
Source: Yamaki et al., 2020.

3. EMERGENCY FILTER MANUFACTURING

Bandi (2020) explores applying the cotton candy technique to create electrostatically charged filter meshes compared with commercially available masks. The study presents the experimental method of electrocharging mask filters using corona discharge treatment (CDT) (Bandi et al., 2021). By subjecting these locally manufactured materials to electrical discharges, the research aims to enhance the filtration performance of full-face respirators, increasing their protective capabilities against airborne particles and pathogens.

Molina (2020) also examines implementing centrifugal melt spinning to manufacture filters comparable to N95 masks. The study focuses on developing and applying the fiber production technique using modified cotton candy machines. It demonstrates the feasibility of distributed manufacturing using everyday materials to meet growing demand for respiratory protective equipment. The author also discusses this approach's advantages, such as scalability, sustainability, and cost-effectiveness.

Building on these authors' developments, this study investigates the feasibility of applying the plastic casting technique through the cotton candy manufacturing method to produce protective mask filters. The objective is to propose ways of using distributed manufacturing, recycling, and adapting local infrastructure to manufacture viable filter elements, comparing them with those produced by traditional methods.

4. MATERIALS AND METHODS

4.1. Research through Design

The research uses the "Research through Design" (RtD) method, a systematization that integrates research and

design processes to create new knowledge and solutions. It comprises iterative analysis, design, development, and implementation of products in authentic contexts, leading to the creation of contextually sensitive design principles and theories (Basballe & Halskov, 2012). This approach is closely related to research through practice, where the creation of objects drives knowledge generation.

RtD uses praxis and design thinking as a methodology and research model in product creation. Unlike conventional design practice focusing on commercially successful products, design researchers use RtD to create artifacts intended to answer specific research questions (Zimmerman et al., 2007). It involves prototyping, testing, and refining solutions to solve complex problems or develop new products. This methodology emphasizes integrating design thinking, experimentation, and analysis to generate new knowledge and practical outcomes.

The value of RtD lies in its ability to bridge the gap between research and design, as emphasized in studies about research through design dynamics (Basballe & Halskov, 2012). RtD involves creating objects while developing protocols, descriptions, and guidelines to ensure process reliability, repeatability, and validity (Reeves, 2015). RtD is a multifaceted methodology that promotes innovation and practical solution development. By integrating diverse research methods, purposeful sampling strategies, and interdisciplinary collaboration, researchers can address complex problems and generate contextually relevant solutions.

4.2. Cotton candy method

The central idea, explored in the works of Bandi (2020) and Molina (2020), is to repurpose standard equipment by adapting it for alternative uses, adjusting specifications to pandemic realities. When detailing necessary adaptations for cotton candy machines, Bandi suggests component replacements if original machines are unavailable. According to the study, small commercial cotton candy machines typically use electric heating elements, while larger ones are gas-powered. Most operate at 160-175°C, below the required 280-340°C range for generating pure PP or PP-PS yarn (the thermoplastics used in his experiment). He recommends modifying the machine's heating circuits to achieve higher temperatures.

For custom-built machines, developing an adjustable electric heating element is preferable if technical knowledge is available. A simpler alternative uses a gas

torch, adjusting flame distance from the emitter cup while monitoring temperature with a kitchen thermometer. Regarding motors, commercial machines reach 3000-4500 rpm - sufficient for fiber formation - but Bandi suggests upgrading to 15,000 rpm for optimal results.

4.3. Machine components



Figure 2: Typical cotton candy machine available in Brazil.
Source: INOVAMAQ, 2024.

The traditional cotton candy machine contains these key elements: a central motor rotating a perforated emitter cup with a heating element (Figure 2). When activated, the cup rotates at high speed, melting its contents, which extrude through holes as strands that accumulate on the surrounding container walls. Based on author recommendations and researcher adaptations, the modified machine incorporated these substitutions:

4.3.1. Motor

The standard cotton candy machine motor operates at 4500 rpm – the minimum speed required for fiber production. However, Bandi (2020) recommends achieving up to 15,000 rpm for optimal results. To meet this specification, researchers employed an 830W angle grinder capable of reaching 11,000 rpm, nearing the upper range suggested in the study. A dimmer was integrated into the system to precisely regulate speed by adjusting voltage and controlling grinder rotations (Figure 3).



Figure 3: Skill 830W grinder and voltage controller Dimmer used on the machine.
Source: Ritec e Loja EliteNet, 2024.

4.3.2. Central emitter cup

The emitter cup is mounted and rotates on the motor shaft, containing the material (sugar for conventional machines or plastic in this application) that melts to form fibers. While Bandi (2020) suggests using a halved soda can as an emitter, initial tests revealed this couldn't withstand the grinder's rotational speeds (up to 11,000 rpm). We initially substituted it with a halved powdered milk can due to its more rigid metal structure, but this also proved insufficient. The final solution employed a 300ml steel mug cut in half, providing greater thickness and structural integrity through its seamless deep-drawn construction.

For secure attachment, a 2.5mm-thick diamond cutting disc was used to mount the emitter cup to the grinder shaft. This disc features 12 concentric holes (plus the central axis) that allow screw-fastening to the cup, significantly improving assembly stability (Figure 4).



Figure 4: 4.3/4\"/>

4.3.3. Temperature control

Following methodological recommendations from the literature, temperature was monitored using an infrared (laser) culinary thermometer. This instrument was selected for its combination of practicality, accessibility, and precision – critical factors for experimental work.

The non-contact laser thermometer not only enabled accurate real-time temperature measurements but also ensured reliable, reproducible results, thereby enhancing the overall data accuracy (Figure 5).



Figure 5: Digital laser thermometer and 2000W thermal blower used to assemble the machine.
Source: Maquinbal e Loja do Mecânico, 2024.

4.3.4. Emission drilling

Bandi's (2020) publication documents the use of an 87-gauge drill (0.254mm diameter holes) while suggesting that smaller perforations could yield superior results. In our initial prototype, we drilled 2mm diameter holes in a powdered milk can. For the second iteration, we created 15mm diameter holes in the can wall and installed a three-layer folded mesh from commercial cornmeal sieves - the finest available option. These sieves typically feature 16-mesh steel screens composed of 0.45mm diameter wires with 1.13mm openings. While this configuration served as our primary solution with the steel mug emitter, we ultimately implemented an even finer mesh as originally intended.

4.3.5. External recipient

For fiber collection, researchers employed a 40-liter aluminum pan with the following dimensions: 22 cm base diameter, 32 cm mouth diameter and 15 cm height. A central hole was drilled in the pan's base to accommodate the grinder's rotating axis. The assembly was mounted on a 43 cm x 28 cm MDF baseboard (20 mm thickness), with both the aluminum pan and grinder securely affixed to this platform (Figure 6).



Figure 6: Cornmeal sieve and 40-liter aluminum pan.
Source: Tegape Telas, 2024.

4.4. Used Materials



Figure 7: Recycled 4mm polypropylene pellets and leftover PLA filament.
Source: The authors.

For the experiments, researchers utilized both recycled polypropylene pellets and PLA filament scraps from previous 3D printing jobs (Figure 7). While polypropylene remains the recommended polymer for filter production, PLA was included in this study phase due to high availability from laboratory waste streams (including failed prints and support structures) and potential applications in textile manufacturing through fiber spinning. The use of PLA waste aligns with broader material recycling initiatives beyond just filter production.

5. EXPERIMENTS

The initial prototype iterations served dual purposes: they provided valuable methodological insights into machinery adaptation while highlighting critical safety considerations when repurposing tools beyond their intended design specifications. During these tests, researchers exercised extreme caution - a necessary precaution when modifying equipment for unanticipated applications, as manufacturers cannot guarantee performance under such conditions.

The first configuration used a modified powdered milk can, with researchers initially confident that its welded seams could withstand the grinder's high rotational speeds (Figure 8). While preliminary tests proved successful, subsequent operation revealed structural limitations: during one trial, the can's soldered joint failed catastrophically. The base separated from the sidewall (remaining attached to the mounting disc), propelling metal fragments outward at high velocity (Figure 9). Strict adherence to safety protocols - including mandatory use of the protective enclosure and personal protective equipment - prevented injuries during this incident.



Figure 8: Emitter cup used in the first tests. Researchers manufactured the first two attempts using powdered milk cans, first making small holes in the can itself with a drill (left) and then making larger holes and using a cornmeal sieve as a screen to disperse the threads.

Source: The authors.

Therefore, these safety protocols remain in effect: The equipment must only be operated with the reinforced safety lid properly secured. Operators are required to wear full personal protective equipment (PPE), including (1) a NIOSH-approved N95 respiratory mask to filter airborne plastic particles, (2) hearing protection to mitigate loud engine noise, (3) safety goggles combined with a face shield for complete facial protection, and (4) heat-resistant gloves when handling high-temperature materials.



Figure 9: An accident occurred with the use of a can. Only the bottom of the can remained fixed to the cutting disc.

Source: The authors.



Figure 10: Detail - the space between the bottom of the cup, the base disc (left), and the stove used to help melt the plastic (right).

Source: The authors.

The initial experiments using only the thermal air blower proved unsuccessful. Researchers mounted the can using spacer nuts between its base and the disc to maintain the grinder shaft's functionality as the emitter. However, during rotation, the emitter cup created air vortices that disrupted the hot airflow, preventing proper plastic melting. To address this, an electric stove was implemented as an additional heat source, with its heating element positioned above the emitter cup to radiate heat downward (Figure 10).

This modified approach ultimately failed to produce satisfactory results, as it generated excessively high temperatures with no means of precise temperature regulation or directional heat control (Figure 14). The plastic became overly fluid, causing it to eject prematurely when the machine was activated. Instead of forming the desired fibers, the molten material simply accumulated on the walls of the collection container (Figure 11).

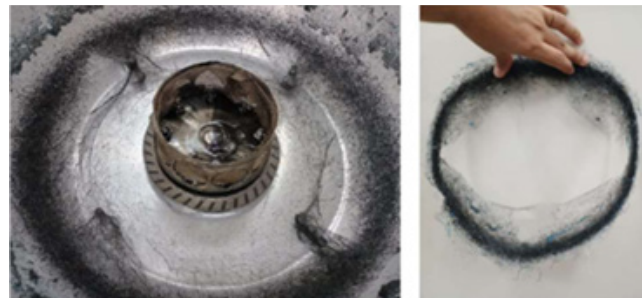


Figure 11: The high temperature melted the plastic, leaving it very fluid, leaving a solid residue on the container wall.

Source: The authors.



Figure 12: Detail of the base assembly.

Source: The authors.

To provide stability while maintaining portability, researchers used a 20 mm thick MDF sheet as a base, incorporating a cut-out carry handle (Figure 12). Due to significant engine vibration, the team strongly recommends permanently securing the machine to a workbench using clamps during operation. The grinder was mounted using a perforated steel band along with two angle brackets, all securely screwed to both the tool body and base. While the primary design utilized 3D-printed custom components through additive

manufacturing to ensure perfect horizontal alignment, the study confirms that traditional wooden bases can serve the same purpose.

Figure 13 illustrates the complete assembly of the first prototype, with components listed in descending order: the 2000W heat gun (or hot air blower), followed by the 3mm MDF plate lid, electric burner, fixing nuts, modified powdered milk can (cut and perforated), spacer nuts, cutting disk, and finally the fixing screws.



Figure 13: Exploded view of the first construction of the machine.
Source: The authors.

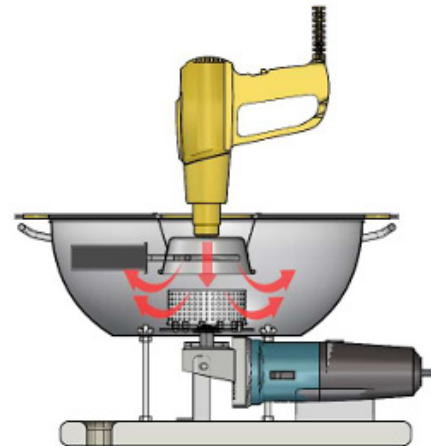


Figure 14: Section of the machine's first attempt. The red arrows indicate the hot air flow.

Source: The authors.



Figure 15: Mini pudding mold used to channel air. A hole was made in the central part for air passage.

Source: The authors.

Based on these findings, researchers determined the emitter cup must be mounted directly to the disc without spacer elements. Additionally, the air stream from the blower required proper channeling to minimize energy losses. An inverted aluminum pudding mold (10.5 cm top diameter, 7.5 cm base diameter, 5 cm height) was installed immediately above the emitter cup (Figures 14 and 15) to optimize airflow direction. This modification successfully directed the heated air stream

into the plastic material within the cup, enabling proper extrusion through the mesh screens and achieving the intended fiber formation (Figure 18).

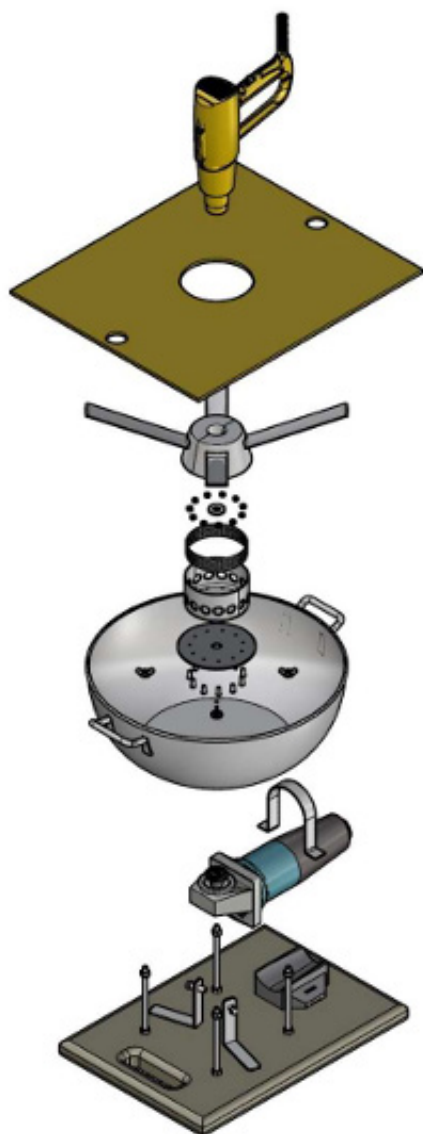


Figure 16: Exploded view of the construction of the new cotton candy machine.

Source: The authors.

The adapted cotton candy machine's complete assembly is shown in Figure 16, displaying all components in descending order from top to bottom. The configuration consists of: a 2000W heat gun (or hot air blower), followed by a 3mm MDF plate lid, an inverted pudding cup, the emitter cup fixing nuts and grinder center axle nut, the emitter cup itself, the cutting disk, the cup fixing screws, a 40-liter aluminum collection pot, the grinder fastener, an 830W angle grinder, the grinder base, a 20mm MDF board base, and finally the threaded bar used for pan fastening.

For proper assembly, the aluminum pot and grinder must first be securely anchored to the base. The modified emitter cup, which already incorporates the sieve screen, should then be attached to the cutting disc before mounting the complete assembly onto the machine's rotating shaft. The pudding mold requires connection to the pot walls using sheet steel strips that are permanently secured with rivets.

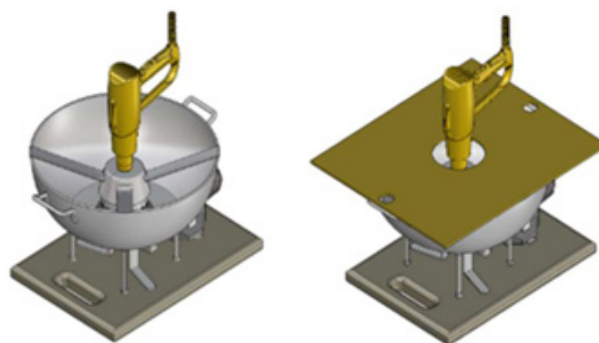


Figure 17: Final assembly of the machine without cover (left) and with cover (right).

Source: The authors.

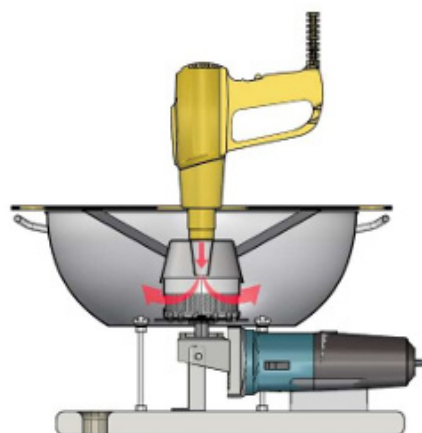


Figure 18: Hot air flow indicated by red arrows.

Source: The authors.

Through experimentation, the research team established the proper operating procedure: the motor should be activated only when the emitter cup contains plastic material. Preheating is strongly recommended to ensure the plastic melts properly and prevents premature ejection upon startup. Once prepared, the operator must securely close the lid (Figure 17) and position the blower vertically downward, directing airflow from the pudding mold (which is permanently affixed to the pan walls) into the rotating emitter cup. When operating at full speed, this configuration creates an efficient airflow pattern

where heated air enters through the top of the cup and escapes through the side perforations, successfully generating the desired polymer fibers.

6. PRELIMINARY RESULTS

Polypropylene served as the initial test material during machine development. Using unprocessed PP pellets, researchers produced a preliminary fleece containing partially fused plastic fragments. During this early prototype phase (prior to implementing the airflow-optimizing pudding mold), material heating relied solely on an electric stove. This uncontrolled heating method led to inconsistent melting – while some polymer formed fibrous structures, excess heat liquefied portions of the material, causing uncontrolled ejection rather than proper fiber formation (Figure 19).

In subsequent tests using PLA filament after implementing directed airflow, fleece quality improved significantly. With its lower melting temperature (145°C), PLA demonstrated easier processing characteristics and more consistent fiber production, yielding promising preliminary results.



Figure 19: Fleece obtained with recycled polypropylene pellets (blue) and recycled PLA fleeces in black, white, and orange.

Source: The authors.

For preliminary analysis, the PLA fiber samples were examined under a digital microscope at 1000x magnification to measure their diameters, with direct comparison to fibers collected from an N95 mask filter (Figures 20 and 21).

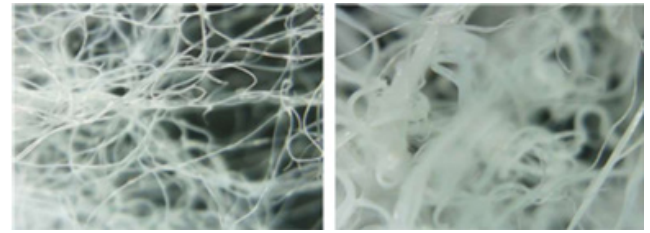


Figure 20: Magnification (x1000) of the media from the N95 mask used as control (left) and white PLA threads manufactured on the machine.

Source: The authors.

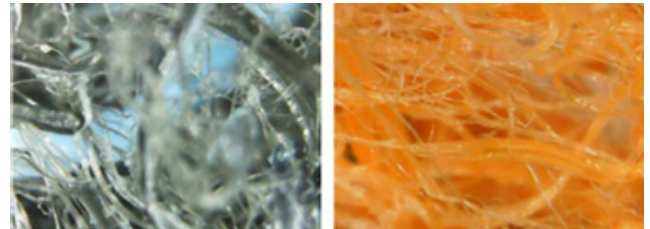


Figure 21: Magnification (x1000) of the PLA wires manufactured on the machine, black (left) and orange (right).

Source: The authors.

The initial visual analysis reveals that at identical magnification, the machine-produced PLA fibers demonstrate inconsistent uniformity and thickness compared to the polypropylene fibers from the N95 reference mask. While some PLA fibers approach the control sample's dimensions, others exhibit significantly larger diameters. This variation was anticipated, as the PLA samples represent preliminary production trials using different materials and screen hole diameters, manufactured without precise process control.

These findings confirm the need for further research refinement. However, this comprehensive documentation of early-stage experimentation proves valuable for identifying system limitations and guiding subsequent design improvements.

6.1. FILTER MANUFACTURING TRIALS

Despite not achieving optimal fleece quality, preliminary filter production trials were conducted with the available material. Importantly, while physical structure validation remains crucial, the final filters will require additional electrostatic charge enhancement via air ionizer treatment. Bandi (2020) specifically recommends exposing the polymeric fabric to isothermal loading for 10 minutes at a 1 cm distance from a domestic air ionizer – a process to be implemented once the filters meet preliminary specifications. Given the current limitations,

research has focused on perfecting SMS fabric welding techniques for interim filter production.

The use of adapted welding equipment serves dual purposes: it functions as both a prototyping tool and a case study for distributed manufacturing solutions in resource-limited settings. Compared to specialized ultrasonic sewing machines (which are cost-prohibitive and scarce outside urban PPE factories), these adaptations can maintain higher PPE efficacy than conventional sewing methods.

The sublimation hot press emerges as the most viable option among tested equipment. More affordable and

widely available in garment factories across diverse regions, these presses are typically used for customized textile printing (promotional items, sportswear, and fashion products). Their precise temperature and time controls enable accurate SMS welding without material degradation. Extensive testing has validated their application for various PPE components, including N95-style masks, 3D-printed mask filters, and surgical gowns (Figure 22). These experiments identified critical parameter dependencies for successful welding outcomes.



Figure 22: Welding studies using sublimation hot presses carried out on different personal protective equipment with filtering needs.

Source: The authors.

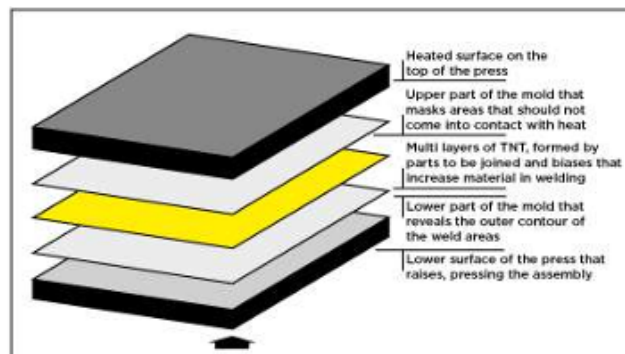


Figure 23: Schematic image of the layers to be organized for hot pressing in the sublimation press to weld the SMS.

Source: The authors.

Pure polypropylene (without additives) has a melting point of 170°C, though this can increase beyond 200°C with additives. Notably, the welding process requires lower temperatures than typical industrial processing methods - unlike extrusion or injection molding which operate between 210-270°C. Through systematic testing, researchers identified 175°C as the optimal pressing temperature, providing the best control within the evaluated 160-190°C range for the developed components.

It is important to note a temperature variation on the press's heated surface in your area. The intensity and uniformity of heat can vary from equipment to equipment, so calibration tests must be carried out based on the variation in the model and equipment used.

An important consideration is the inherent temperature variation across the press's heating surface. Heat intensity and distribution uniformity vary significantly between equipment models, necessitating device-specific calibration tests. The required pressing time depends directly on the set temperature and material thickness - as more layers require longer duration for complete heat penetration to achieve proper melting. This temperature-time relationship follows an inverse

proportionality: higher temperatures permit shorter pressing times to prevent weld defects.

Excessive duration risks material degradation, causing holes and imperfections in both the weld zone and surrounding areas. Conversely, insufficient time prevents complete heat penetration, resulting in either partial melting of layers or failed bonding. Optimal parameters must account for both material properties and equipment characteristics. For the experimental trials, researchers employed 65-70 second cycles for smaller weld areas ($\leq 25 \text{ cm}^2$) and 75-80 seconds for larger surfaces ($> 25 \text{ cm}^2$), establishing these as baseline values for the tested configurations.

Sublimation presses generate heat exclusively from their upper surface, requiring specialized molds to achieve localized heat application. Research findings indicate these molds must be constructed from rigid, thermally insulating materials and precisely cut to expose only targeted heating areas. Proper implementation involves alternating material layers with the mold during pressing, while ensuring thermal insulation through non-stick surfaces.

Optimal mold design incorporates a bleeding zone extending beyond the primary heat application area - a feature implemented in the final prototypes with 2cm bleed margins on all sides. For prototype development, researchers utilized 3mm MDF boards, laser-cut according to vector designs derived from the cutting templates (Figure 24).

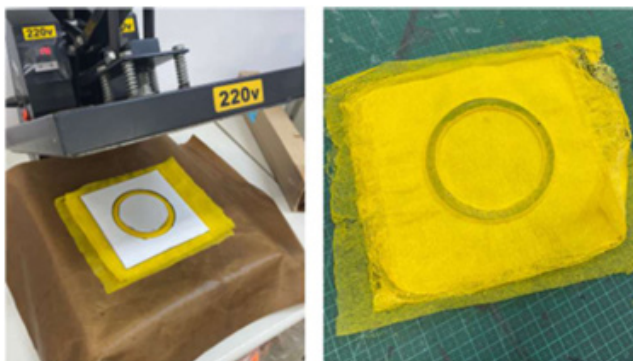


Figure 24: Sublimation press with layers of TNT, fleece, and MDF assembled (left) and the pressed result (right).

Source: The authors.

Both the mold and press surfaces require non-stick coatings to prevent molten SMS material from adhering, particularly to porous mold surfaces. In the experimental setup, Teflon foil was applied to both the upper and lower press surfaces, while the molds were lined with repurposed adhesive insulating material - a

readily available resource in PUC-Rio's printing workshop. Alternative non-stick solutions like wax and oils were also evaluated, though their effectiveness proved dependent on multiple factors including application thickness, operating temperature, and the base material's porosity.

Simple components require relatively straightforward molds, needing only properly stacked SMS layers in the appropriate configuration (Figure 24). More complex parts may demand multiple pressing cycles. For the mask prototype, two pressings proved sufficient: the first creates the filtered layer with edge seals, while the second joins the upper and lower sections to complete assembly.

The filters were specifically designed for compatibility with an additively manufactured mask model featuring an FDM-printed TPE shell and ABS front rim. This integrated design approach allows for complete local production of both mask and filter components (Figure 25), representing a promising direction for ongoing research and development.

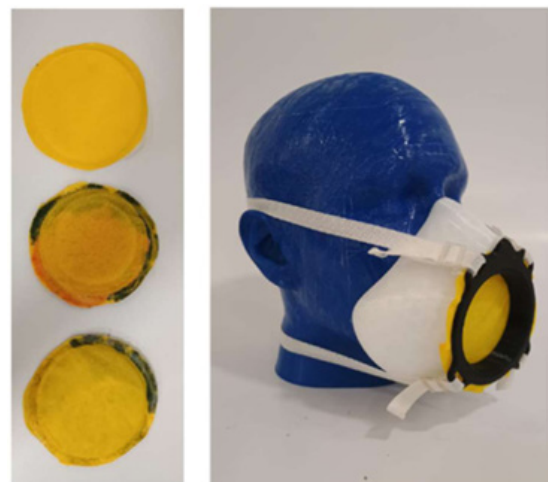


Figure 25: Three tests were carried out using the different fleeces formed by the cotton candy machine (left). On the right the A01V16 mask with the integrated concept filter.

Source: The authors.

7. CONCLUSION

The adaptation of cotton candy machine principles for respiratory mask filter production represents an innovative approach to address the increasing demand for protective equipment. This method enables the creation of electrostatically charged polymeric fibrous membranes, allowing rapid scaling of filter manufacturing during public health emergencies (Wibisono et al., 2020). As demonstrated during the

COVID-19 pandemic, this unconventional technique offers both cost efficiency and manufacturing flexibility in crisis situations (Wibisono et al., 2020).

Building on this concept, the current study presents a further simplified device design for mask filter production, potentially offering a more accessible and economical alternative to conventional methods that requires no specialized expertise. Through strategic repurposing and functional redesign of standard tools, this research aims to advance both technological accessibility and safety standards in personal protective equipment.

The adapted machine developed for prototyping and research applications demonstrates potential beyond filter manufacturing, serving as an effective plastic-to-fiber recycling system. This technique holds particular promise for the design and fashion industries, where it could transform recycled plastics into raw fibrous material suitable for producing textiles, cushioning, and foam products.

The combined use of the modified cotton candy machine and sublimation hot press for filter production highlights the innovative approaches required to mitigate supply chain vulnerabilities in critical protective equipment. This methodology, which repurposes existing tools and develops alternative manufacturing processes, enables decentralized production facilities to supplement traditional filtration element manufacturing. Such solutions prove particularly valuable when addressing global challenges like the recent pandemic. While further refinements are necessary, current research continues to optimize and simplify the filter media production process.

8. FUTURE WORK

Building upon published studies demonstrating the feasibility of producing mask filters with commercial-grade quality and safety standards - particularly Bandi (2020) and Molina (2020) - this research outlines four key development areas:

1. **Production Process Optimization:** Refine the cotton candy-inspired plastic casting method to establish optimal parameters including material selection, melting temperatures (160-200°C range), extrusion speeds (3000-15000 rpm), and fiber diameter control (targeting 0.5-5µm), while implementing electrostatic charging protocols from literature.

2. **Material Characterization:** Conduct comprehensive analysis of fiber morphology using SEM imaging, diameter distribution via laser diffraction, and spatial arrangement within the filter matrix.
3. **Performance Validation:** Evaluate filtration efficiency against NIOSH standards, measuring both particulate retention (for 0.3µm particles) and airflow resistance (<350 Pa at 85L/min).
4. **Economic Assessment:** Compare production costs against conventional methods, analyzing scalability potential for decentralized manufacturing using repurposed tools, with particular focus on sustainability metrics.

This integrated approach aims to develop a novel filter manufacturing methodology that combines accessible tools with optimized processes to achieve scalable, cost-effective production without compromising performance standards.

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PTAC: conceptualization, data curation, formal analysis, investigation, writing - original draft and writing - review & editing.

RPV: conceptualization, formal analysis and investigation.

GREEN CREATIVE DESIGN FOSTERING A SUSTAINABLE MENTAL MODEL

DESIGN CRIATIVO VERDE: IMPULSIONANDO UM MODELO MENTAL SUSTENTÁVEL

EL DISEÑO ECOLÓGICO CREATIVO PROMUEVE UN MODELO MENTAL SOSTENIBLE

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ABSTRACT

Green creativity has emerged as a vital field in sustainability research, emphasizing the integration of creative processes with environmental responsibility. Literature on green creativity highlights its role in generating eco-innovations and fostering awareness of sustainable practices through design. Engagement in sustainability initiatives often depends on such creativity-driven approaches, which encourage individuals to view sustainability as part of their core values and social identity. This study explores how a creative framework based on green creativity and design techniques can effectively promote sustainable engagement. The method involved adapting a Creative Framework for the “Cidades pelo Clima” project (CpC), to engage participants in sustainable issues. It helped establish shared values and collective goals, empowering participants to actively contribute to environmental solutions. Results demonstrate that green creativity not only enhances team cohesion and motivation but also embeds sustainability into participants' mental models, fostering long-term commitment to eco-conscious behaviors. The research contributes to the field of sustainable design by showcasing how creativity can serve as a catalyst for promoting long-term engagement and fostering sustainable mental models.

KEYWORDS

Creativity; Design Thinking; Green Creativity; Mental Models; Green Commitment.

RESUMO

A criatividade verde emergiu como um campo vital na pesquisa em sustentabilidade, enfatizando a integração de processos criativos com responsabilidade ambiental. A literatura sobre criatividade verde destaca seu papel na geração de eco-inovações e na promoção da conscientização sobre práticas sustentáveis por meio do design. O engajamento em iniciativas de sustentabilidade frequentemente depende de abordagens orientadas pela criatividade, que incentivam os indivíduos a enxergar a sustentabilidade como parte de seus valores centrais e de sua identidade social. Este estudo explora como um framework criativo baseado em criatividade verde e técnicas de design pode promover efetivamente o engajamento sustentável. O método envolveu a adaptação de um Framework Criativo para o projeto “Cidades pelo Clima” (CpC), com o objetivo de envolver os participantes em questões sustentáveis. Esse framework ajudou a estabelecer valores compartilhados e metas coletivas, capacitando os participantes a contribuir ativamente para soluções ambientais. Os resultados demonstram que a criatividade verde não apenas potencializa a coesão e a motivação das equipes, mas também incorpora a sustentabilidade nos modelos mentais dos participantes, promovendo um compromisso de longo prazo com comportamentos ecoconscientes. A pesquisa contribui para o campo do design sustentável ao mostrar como a criatividade pode servir de catalisador para fomentar o engajamento duradouro e o desenvolvimento de modelos mentais sustentáveis.



PALAVRAS-CHAVE

Criatividade; Design Thinking; Criatividade Verde; Modelos Mentais; Compromisso Verde.

RESUMEN

La creatividad verde ha surgido como un campo vital en la investigación sobre sostenibilidad, que hace hincapié en la integración de los procesos creativos con la responsabilidad medioambiental. La literatura sobre creatividad verde hace hincapié en su papel a la hora de generar ecoinnovaciones y promover la concienciación sobre prácticas sostenibles a través del diseño. El compromiso con las iniciativas de sostenibilidad depende a menudo de enfoques basados en la creatividad que animen a los individuos a ver la sostenibilidad como parte de sus valores fundamentales y de su identidad social. Este estudio explora cómo un marco creativo basado en la creatividad verde y las técnicas de diseño puede promover eficazmente el compromiso sostenible. El método consistió en adaptar un Marco Creativo al proyecto «Ciudades por el Clima» (CpC), con el objetivo de implicar a los participantes en cuestiones sostenibles. Este marco ayudó a establecer valores compartidos y objetivos colectivos, capacitando a los participantes para contribuir activamente a soluciones medioambientales. Los resultados muestran que la creatividad verde no sólo mejora la cohesión y la motivación de los equipos, sino que también incorpora la sostenibilidad a los modelos mentales de los participantes, promoviendo un compromiso a largo plazo con comportamiento eco-consciente.

PALABRAS CLAVE

Creatividad, Design Thinking, Creatividad Verde, Modelos Mentales, Compromiso Verde.

1. INTRODUCTION

Creativity is a fundamental factor in developing innovative solutions; therefore, it is also crucial in facing global sustainability challenges. It is an important ally in building a sustainable mindset and engaging people in teamwork, allowing a new perspective and approach to sustainability challenges. In this context, creativity becomes essential, as it challenges us to perceive the world in different ways and thus promotes questioning of old beliefs and habits, opening up space for ideas that consider the common good and care for the environment (Amabile, 1983).

This creative and reflective process contributes to the formation of a more sustainable set of values (sustainable mental models), enabling individuals and their groups to see and understand the world with a more conscious approach as a direct result of this type of creative practice. According to Jodi Summers et al. (2021), these mental models shape the way we think and act. Thus, creativity oriented towards perceiving different angles of specific problems allows individuals to see new connections and understand the impacts of their decisions.

In this context, engagement becomes more than a response to goals and objectives; it becomes "flow," a state of total immersion where individuals are fully involved and motivated in the activity they are developing (Csikszentmihalyi, 1996). In teams that value sustainability and creative thinking, this engagement becomes natural, as each member understands their role as essential in the search for solutions that can make a real difference. This collective awareness creates a sense of belonging and purpose, strengthening connections among members and fostering a genuine commitment to the group's goals.

Thus, creativity is seen not only as a tool for problem-solving but as a starting point for individuals and teams to become more committed and engaged in sustainable projects. By expanding individual horizons, creativity unites individual and collective purposes around a shared vision where sustainability is the central value. In this way, beyond generating innovative solutions, creativity can also be used to strengthen team relationships and cohesion, providing a more connected environment oriented toward a more sustainable future. According to Brown (2010), methodologies such as design thinking foster this practice by promoting empathy and collaboration,

which are essential for teams to not only share a sustainable vision but also unite around it.

In this sense, this work aims to analyze the efficacy of creativity and design tools as drivers to motivate environmental awareness, and then, promoting sustainable engagement of people. Bertella et al. (2021) shows examples of which frameworks were applied as a useful approach to promote innovation by a critical systemic thinking. Furthermore, this work sought to understand the follow issue: Can a creative design framework, exclusively developed to foster business models, guide creativity to play a crucial role to promote sustainable engagement of teams, raising confiança e espírito de equipe to support reliable decisions?

Our research sheds light on the creativity tools as an important approach to reach sustainable aims, as well as the impact of such tools on the development of espírito de equipe e identidade social among membros de equipes, serving as a guide force in sustainable projects to help managers. In the following sections, relevant work on creativity, green creativity, sustainable design, and design tools and engagement is reviewed and organized as follows. Section two, three and four we present a background on creativity and green creativity and their relationship with sustainable design, as well as creativity and design are taken into account to foster sustainable engagement. Section five we show the research method and approach of the case study. The section six we present the results and discussions, elaborating the implications sustainable projects. The paper ends with a presentation of conclusions and recommends future research.

2. CREATIVITY FOR SUSTAINABILITY

Creativity is a fundamental factor in the development of innovative solutions; therefore, it is also crucial in addressing the global challenges of sustainability, with its variables, dynamics, and complex interactions that make the sustainability problem even more challenging (Anderson et al., 2014; Martens, 2011). This chapter discusses the nature of creativity, its role in promoting and motivating sustainable practices, and, in particular, the importance of Green Creativity for generating ideas and developing solutions that focus on environmental responsibility in design and innovation processes.

2.1. GREEN CREATIVITY: fostering sustainable mental models

Creativity is a widely used term; however, its definition is quite broad throughout the specialized literature, reflecting the difficulty and ambiguity in defining a theory that provides an accurate conceptualization. This complexity is determined by a multitude of factors that can be analyzed from different perspectives (Sharma & Teper, 2008; Costa, 2006; Saleh & Brem, 2023). The difficulty in defining it makes creativity a topic studied by researchers from several fields.

Creativity is inherently subjective, making it challenging to study over time. Before the 17th century, creativity and creative actions were explained by genius or divine inspiration (Pinheiro & Cruz, 2009). Similarly, in Darwin's evolutionary perspective, creativity was also considered divine or a genetic evolution linked to genius (Pelaes, 2010; Wechsler, 2008). Guilford's pioneering research was among the first to treat creativity as a measurable and trainable skill. Today, research focuses more on understanding the components necessary to foster creativity (Mkhize & Ellis, 2020; Arslan et al., 2022).

Due to its multifaceted nature, many researchers approach creativity from different perspectives, defining it as the ability to produce original and useful ideas (Boden, 1994). From a neuroscience perspective, creativity is understood as an innate human response to problem-solving (Kandel et al., 2014; Sprugnoli et al., 2017). According to Csikszentmihalyi (1996), creativity is an idea or product that transforms existing knowledge, while for Plucker (2004), creativity is socially recognized for being not only new but also useful. Amabile (1983) views creativity as a process leading to creative outcomes. Many other definitions highlight its main characteristics as originality, flexibility, fluency, and elaboration (Torrance, 1972; Guilford, 1967). For Cropley (2000), its qualities are novelty, elegance, and applicability in different contexts. According to Gurteen (1998) and Lubart (2007), divergent thinking is at the core of creativity, generating new knowledge. For Newbigin (2010), creativity is the act of questioning paradigms, challenging existing beliefs and assumptions. Despite the wide variety of perspectives, there is a consensus to understand creativity as the generation of new ideas that, when useful, drive innovation (Bedani, 2012).

The development of creativity does not occur in isolation; rather, it is systemic and influenced by internal factors (e.g., intrinsic and extrinsic motivation) and

external factors, such as work environments and/or organizational policies (Gerhart, 2015). In organizations, creativity can be encouraged by management practices that promote an environment of experimentation and innovation. Research highlights that creativity is not just an individual skill but is also perceived and fostered in groups and organizations through collaborative processes and learning (Csikszentmihalyi, 2001).

Face current challenges, in the context of sustainability, creativity is the way to find innovative ideas for environmental, social, and economic problems, with solutions that can be applied in the medium and long term. Furthermore, new concepts of sustainability-oriented creativity emerge as an effective approach to increase awareness and creative engagement in sustainable solutions, such as "mindfulness" (Rodrigo, 2016). In this sense, in recent years, many researchers have sought to understand the role of creativity in sustainability, and different studies have focused on applying creative thinking in developing solutions to maximize the transition to sustainability (Brem & Puente-Díaz, 2020a; Kagan et al., 2020; Przychodzen et al., 2016; Sovacool et al., 2018). In this context, Shrivastava (2014) points to ways of integrating cognition and emotion in his research on sustainability, while Hensley (2020) and Mróz & Ocetkiewicz (2021) aim to understand how to incorporate creativity in education for sustainability. Luu (2021), Li et al. (2020), and Jiang et al. (2021) research approaches to promoting green creativity among employees in organizations (Rabab Saleh, 2023).

In this context, the concept of Green Creativity emerges, based on the need to integrate innovation processes with sustainable environmental practices. According to Chen and Chang (2013), Green Creativity can be defined as "the development of new ideas about green products, services, processes, or practices that are original, useful, and environmentally responsible". Thus, green creativity appears in the discourse of environmental management and organizational innovation as the ability to generate new ideas that are sustainable and beneficial for organizations, aligning innovation with social and environmental responsibility (Chen & Chang, 2016). Creativity is linked to innovation and problem-solving, making it fundamentally useful in tackling urgent sustainability challenges by generating solutions that reduce environmental impact while maintaining the economic viability of the products and services created.

According to (Shrivastava & Ivanova, 2015) Green creativity can transform prevailing mental models in society,

meaning it can alter current cognitive structures used by individuals to interpret and respond to the world around them. The current mental models in society prioritize financial gain based on intensive resource exploitation. However, these mental models are being replaced by models that prioritize sustainability, and in this sense, green creativity promotes the conditions necessary for this shift by incentivizing the generation and development of ideas and practices aligned with long-term sustainability rather than immediate economic returns.

For a long time, prevailing mental models have produced unsustainable behaviors, promoting growth without considering environmental impacts. Thus, green creativity challenges this mental mode, fostering new ways of thinking where social and environmental responsibility becomes the primary strategic objective of organizations (Kagan, 2011). The new mental models aim not only for innovation but also for behaviors and actions that reduce environmental impacts, relieving pressure on natural resources.

Green creativity acts simultaneously as a product and catalyst of sustainable mental models by generating cognitive structures that imply environmentally responsible behaviors, thus contributing to the development of responsible mental models. According to Shrivastava and Ivanova (2015), the transition to sustainable practices requires not only political changes or technological innovations but also a change in the mental models that guide decision-making. Therefore, green creativity provides the tools and processes necessary for society to reconsider its environmental impact, promoting sustainable approaches to problem-solving and thereby motivating more sustainable behaviors and transformation (Poldner, 2017).

Chen & Chang (2013) assigned that such sustainable changes require the courage to challenge conventional practices and adopt new, long-term sustainable mental models, implying systemic changes in organizations and their respective operational segments. An organization that adopts green creativity can trigger a ripple effect where green creativity becomes the norm rather than the exception, encouraging more innovation and sustainable mental models throughout the value chain (Renwick et al., 2013).

In sectors like fashion, architecture, and design, green creativity has already started to reshape the mental model (Jia, 2018). According to Poldner et al. (2016), the luxury brand Osklen has integrated sustainability into its business model, where green creativity enables

the integration of a sustainable mental model into its design process. In this way, it reduces its environmental impact and, more importantly, establishes a model to be followed on how creativity can be used to drive a shift toward sustainable practices (Poldner, 2017). In this sense, the definition of creativity, where originality and effectiveness are highlighted as main characteristics (Runco, 2012), aligns with the goals of sustainable design. A sustainable design project can be considered creative not only for presenting a new solution but also for considering environmental issues as guiding principles of the project. This integration of Green Creativity into design development processes can lead to the generation of innovative and sustainable solutions.

2.2. Integrating green creativity into sustainable design processes

In the design process, there are divergent stages dedicated to discussion and creation, where creativity represents the expression of new ideas, as well as convergent phases of definition and materialization, in which innovation brings these ideas into reality (Thaler, 2016). Thus, the concepts used in design are closely linked to creativity, as design itself can be seen as a capability for problem-solving, developing, and implementing ideas (Farias, 2022). Like creativity, the design process is based on individual cognitive processes and takes place within a social context involving multiple actors (Zavadil, 2016). In design, creativity manifests in various forms, shaped by each designer's unique characteristics (Iervolino, 20XX). Consequently, when we think of designers, we envision creative individuals with knowledge of human attributes and behavior, as well as technical skills, which translate creativity into the development of objects and/or services (Iervolino, 20XX; Thaler, 2016).

In the sustainability context, sustainable design and green creativity form a strong alliance to address the environmental challenges. Sustainable design focuses on reducing environmental impact, increasing resource efficiency, and promoting social responsibility through the development of products and services. On the other hand, green creativity promotes awareness and innovation in ways that prioritize socio-environmental sustainability. These concepts work to generate products and services that not only meet functional needs but also actively contribute to socio-environmental preservation. When integrated, sustainable design and green

creativity enable designers to generate impactful and innovative solutions that respect both current and future environmental limitations (Bozkurt & Tan, 2021).

Traditionally, design projects have primarily focused on market demand, profitability, and user convenience. However, sustainability has necessitated a paradigm shift toward more environmentally responsible design approaches (Kagan, 2011). Green Creativity facilitates this shift by incorporating environmental factors into the design process and encouraging designers to think beyond aesthetics or functionality in their creations (Rabab Saleh, 2023; Ramsha, 2022). Sustainable Design includes various techniques, such as Design Thinking with its iterative and human-centered approach, serving as a catalyst for the integration of sustainability and creativity (Malene, 2010). Furthermore, sustainable design emphasizes empathy, ideation, and prototyping, creating a method through which it is possible to develop solutions that meet practical requirements and stringent environmental goals, encouraging life-cycle thinking that considers the entire impact of a product, from creation to disposal (Ahmed, 2023).

In sustainable design, maximizing green creativity means considering environmental factors throughout the creative process, from ideation to final production (Empson, 2019). Green creativity in sustainable design goes beyond aesthetics or functionality; it prioritizes these values and guides designers to develop sustainable solutions and innovations, where novelty and environmental responsibility coexist (Lozano, 2014). This holistic vision aligns with Amabile's (1996) components of creativity, which empower designers to go beyond conventional problem-solving, allowing them to reimagine existing practices to achieve sustainable results. In this context, creative thinking becomes an essential driver of sustainable solutions, with design developing various techniques and tools that use structured methods to drive innovative ideas (Alves et al., 2024), ensuring alignment with environmental priorities. Thus, green creativity is maximized, reinforcing the use of sustainable practices that are efficient and resilient to environmental changes.

Among several techniques and tools, (Guaman-Quintanilla et al., 2023) indicates that incorporating design thinking into sustainable design practices encourages creative problem-solving, promoting innovative approaches that go beyond traditional product development. Ivano and Louis (2021) note that one of the strengths of design thinking is its ability to bring together different perspectives, thus fostering a comprehensive understanding of the needs of both users and the

environment. Furthermore, design thinking is aligned with sustainability due to its focus on empathy with users, which allows it to extend empathy to environmental impacts through techniques that promote a deeper understanding of the user's role within environmental systems (Xia, 2021). As design thinking gains popularity, its role as a guide for sustainable innovation also increases, allowing a generation of designers to address sustainability challenges with heightened creativity and purpose (Ivano and Louis, 2021).

The design thinking collaborates to achieve a balance between divergent and convergent thinking, essential for creating innovative solutions. Divergent thinking supports the generation of a wide range of creative ideas, promoting an open approach that is crucial for exploring new concepts and challenging assumptions. Convergent thinking, on the other hand, plays a critical role in refining these ideas, evaluating their feasibility, and selecting the most viable solutions (Xia 2021). This balance ensures that the creative processes in sustainable design result in innovative and implementable solutions. Alves (2024) points out that the duality between divergent and convergent thinking is fundamental to guiding designers in structured creative processes. Additionally, ideation techniques in sustainable design rely on both logical and intuitive approaches to problem-solving. Methods such as TRIZ (Theory of Inventive Problem Solving) and SCAMPER (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse) provide systematic approaches that allow for both the expansion of ideas and the critical evaluation needed to ensure sustainability (Alves, 2024).

Integrated within the green creativity framework, divergent and convergent thinking provide designers with the necessary flexibility to develop solutions for complex sustainability challenges while also meeting traditional project requirements (Bertella et al., 2021). Thus, Green creativity serves as a guide for designers to push the boundaries of conventional solutions. Finally, through approaches such as Design Thinking, it is possible to raise awareness among different stakeholders about sustainability challenges, fostering strong engagement with environmental issues.

3. DESIGN TOOLS AND CREATIVITY PROMOTING GREEN ENGAGEMENT

Faced with various environmental challenges, the concept of sustainability has been integrated into global discourse.

In this context, green creativity and design tools emerge as fundamental approaches to encourage individuals and communities toward sustainable behaviors, transforming abstract environmental principles into real-life activities (Charlie Wilson, 2018; Elina et al., 2018). By enabling people's emotional connection to sustainability, green creativity fosters a cultural shift oriented toward environmental responsibility (Sandile Mkhize & Ellis, 2020; Hussain et al., 2019). Meanwhile, design tools provide a structured framework, helping people develop sustainable solutions in a tangible and practical way (Phillips et al., 2020; Leon Cruickshanka et al., 2017). Together, green creativity and design tools foster awareness and action, motivating people to contribute to socio-environmental well-being (Saima Hussain et al., 2019; Anke Buhl et al., 2019).

Studies indicate that sustainability initiatives are successful when aligned with personal values, making environmental responsibility part of individual and social identity (Sophia Becker et al., 2021; Elisabeth van de Grift et al., 2020), encouraging people to view sustainable behavior as inherent to their identity and community (Charlie Wilson, 2018; Najla Mouchrek, 2017). In this sense, green creativity combines sustainability with creative processes to promote pro-environmental behaviors in a personal and engaging way (Elisabeth van de Grift et al., 2020; Sandile Mkhize & Ellis, 2020). Through methods that simplify complex topics, green creativity seeks to make tangible environmental issues, promoting long-term socio-environmental commitments (Elina Narvanen et al., 2018; Charlie Wilson, 2018).

According to Sandile Mkhize & Ellis (2020) and Elina Narvanen et al. (2018), when based on playful and community activities, green creativity makes sustainability enjoyable. Gamified initiatives thus engage people by reducing potential inconveniences associated with a sustainable lifestyle. This more pleasant approach generates a sense of shared sustainable purpose (Saima et al., 2019; Leon Cruickshanka et al., 2017). On the other hand, design tools act as instruments to translate sustainability concepts into concrete actions. Through organized structures like workshops, participants can perceive sustainability from multiple perspectives, gaining systemic understanding and practical experience (Bertella et al., 2021; Phillips et al., 2020). Workshops incorporating design tools encourage participants to co-create solutions, making the learning process dynamic and meaningful (Anke Buhl et al., 2019; Augsten & Marzavan, 2017).

According to Najla Mouchrek (2017) and Bertella et al. (2021) the workshop approach effectively bridges

the "value-action gap," where pro-sustainability values don't always align with individuals' actions, providing opportunities for practical and experiential learning and helping participants incorporate sustainable practices into their lives (Phillips et al., 2020; Anke Buhl et al., 2019). This holistic approach promotes sustainable awareness, motivating individuals to take responsibility for their sustainability journey and reinforcing their confidence to experiment with new ideas (Augsten & Marzavan, 2017; Leon Cruickshanka et al., 2017).

Design tools make sustainability concepts accessible and tangible, for example, through eco-mapping and user journeys, enabling participants to create visual representations of sustainability goals, helping them see the impact of their actions (Phillips et al., 2019; Anke Buhl et al., 2019). Meanwhile, prototyping tools allow people to transform abstract ideas into physical models, breaking down complex environmental challenges into manageable and actionable steps (Leon Cruickshanka et al., 2017; Phillips et al., 2019). These techniques, followed by feedback cycles, empower participants to experiment and refine sustainable practices based on new environmental insights, reinforcing a dynamic environmental mindset (Phillips et al., 2020; Augsten & Marzavan, 2017). Other techniques, such as personas and empathy mapping, promote sustainable engagement by encouraging empathy, inclusion, and adaptability. They encourage people to consider the needs of different stakeholders, leading to inclusive and people-centered solutions (Mouchrek, 2017; Leon Cruickshanka et al., 2017). User-centered approaches ensure that sustainable practices align with participants' values, making sustainability personally relevant for engagement (Cruickshank et al., 2017; Phillips et al., 2020).

Buhl et al. (2019) and Bertella et al. (2021) highlight that these tools create a deep connection between people and the environment, transforming sustainability from an abstract concept into a lived and personal experience. Sophia Becker et al. (2021) and Elisabeth van de Grift et al. (2020) affirm that design tools strengthen sustainable commitment, inviting individuals to collaborate in the creation and development of solutions, enabling participants to embrace sustainability as an integral part of their social identity. Together, green creativity and design tools cultivate a shared and resilient responsibility, encouraging collective sustainable actions (Bertella et al., 2021; Anke Buhl et al., 2019). Facing urgent environmental challenges, the integration of green creativity and design tools offers a path to a sustainable future.

4. METHOD

Based on the background outlined previously, it is essential to understand whether and how creativity and design tools can contribute to fostering strong engagement with sustainable and environmental issues. In this sense, this work aims to analyze the efficacy of creativity and design tools as drivers to motivate environmental awareness and, consequently, to promote sustainable engagement. The theory and practice of Design Thinking illustrate examples of frameworks that have been applied as effective approaches to foster innovation through critical systemic thinking (Bertella et al., 2021). Furthermore, this study sought to address the following question: Can a creative design framework, exclusively developed to

foster business models, be capable of guiding creativity to play a crucial role in promoting sustainable team engagement, enhancing trust and team spirit to support reliable decision-making?

To achieve the aim of the work, after extensive theoretical research on the following themes — Creativity and Green Creativity, Creative Design Tools, and Engagement — a Creative Framework (Alves, 2024) was applied in the Portuguese project “Cidades pelo Clima” (CpC). This project is a network of 20 Portuguese cities aiming to achieve climate neutrality by 2030. Thus, in this research, the first stage of the Creative Framework was adapted and conducted with a group of 20 participants who were appointed by their respective cities to represent them in the CpC project. The participants were divided in 4 teams.

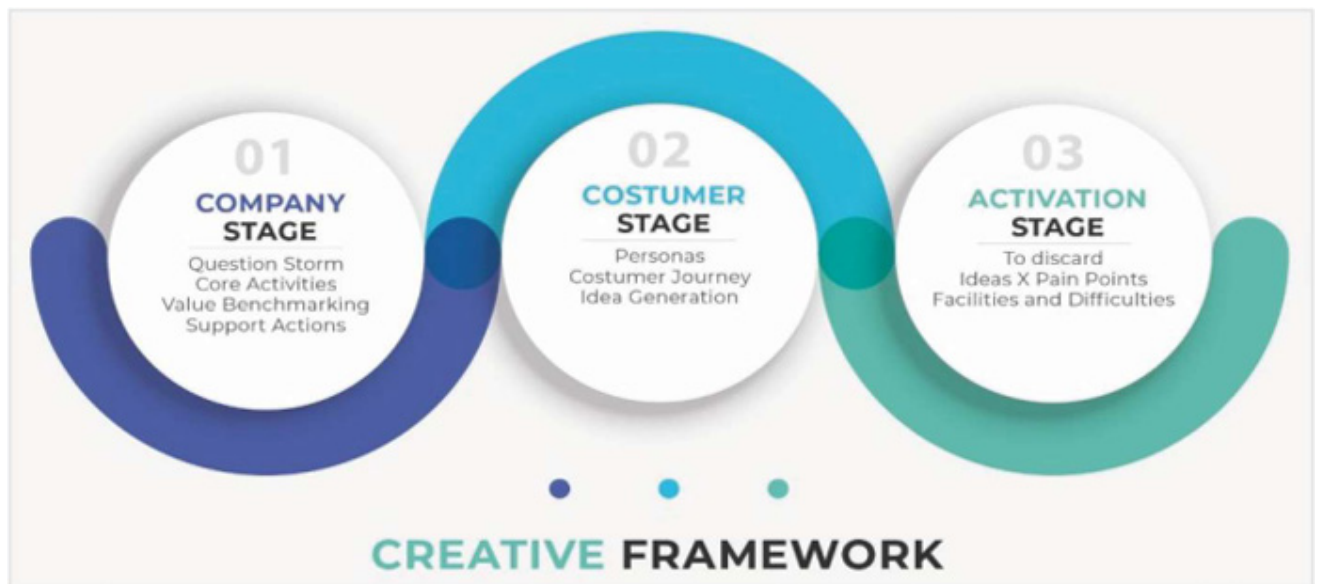


Figure 01: Creative Framework stages.

Source: The authors.

According to Alves et al. (2024), the Creative Framework (Figure 1) includes the following stages: Company Stage, Customers Stage and Activation Stage. For the purposes of this study, based on the literature review conducted, the Company Stage was adapted to create a sense of team and/or community, thereby enhancing participant engagement in the CpC.

sustainable projects. In this sense, by analyzing all ideas, propositions, and the collected data generated through the framework, it became possible to assess the results from each activity. This approach make possible to get a clearer understanding of the relationship between the activities analyzed and their performance, based on the prior theoretical review.

5. RESULTS AND DISCUSSIONS

The main aim of this study is to examine if the structure of the Creative Framework can mitivate a new mental model in individuals, thereby fostering their engagement in

5.1. ICEBREAKER

Focusing on the individual, the objective of this activity is to bring people closer by introducing them to one another in a way that allows them to get to know each

other beyond their technical and/or professional skills, getting to know each other's personal characteristics, feelings, and emotions as well. This approach helps participants feel more confident and comfortable with each other, fostering a sense of ease and commitment in group activities (Megan, 2020).

Activities		Tasks
Icebreaker	Company Stage (Business)	Team Stage (Engagement)
	1- Name the Group	1- Name the Group
	2- Introduce yourself (general information)	2- Introduce yourself (general information)
	3- Talk about a chosen personal object	3- Talk about a chosen personal object
	4- Share a personal failure	4- Share a personal failure
		5- Share what you expect from the project

Table 1: Business and Engagement: Icebreak activity and tasks.

Source: The authors.

Table 01 presents the tasks carried out in this activity, both in their original business-oriented configuration (Company Stage) and in the adapted version focused on engagement and team building (Team Stage). It is possible to see that in both versions, the first four tasks, which make up this activity, are identical and aim to develop creative confidence within the group (Kelley and Kelley, 2013). However, in its adapted version, task 5 was added with the goal of promoting the sharing of participants' expectations regarding the CpC as a sustainable project. Figure 02 shows the participants during the activity.



Figure 02: Icebreak activity section.

Source: The authors.

The participants were invited to individually express, through a word and/or a phrase, their expectation regarding the CpC. The technique used was Brainwriting because it is more anonymous than brainstorming, preventing participants from influencing each other and allowing everyone to be productive simultaneously (Thompson, 2003). After a 5 minute period for individual input, participants shared their expectations with the other members of their respective teams, enabling them to identify the first similarity within the team. The results show that, despite using different words and, primarily, representing various contexts and realities from their respective cities, all participants across the four teams have expectations that can be classified as shown in Figure 03.-

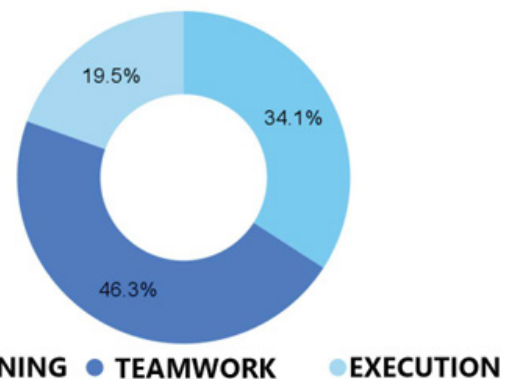


Figure 03: Expectations of participants about the project.

Source: The authors.

It is noticeable that nearly half of the participants (46.3%) indicate that their main expectation is teamwork, followed by training (34.1%) and execution (19.5%). Thus, it can be inferred that the participants hope to engage in a project that primarily promotes the opportunity to work as a team, along with the possibility of learning and acquiring new knowledge

with that team, and, finally, participants expect to see practical and tangible results being achieved. Figure

04 presents the pointed expectations that led to the main classification.

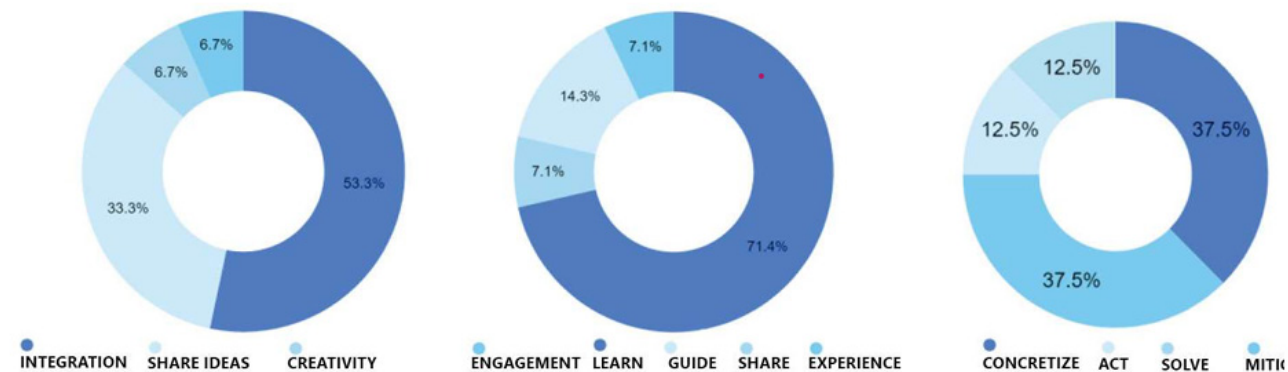


Figure 04: Raw words for main participants' expectations.
Source: The authors.

5.2. Questions Storm

In the original version of the Creative Framework, this activity aims to create (at least) three questions to better understand companies and their problems (Cralves, 2024),

while in its engagement version the focus is to obtain and understand, in a more in-depth way, the beliefs and biases that participants hold about sustainable projects and/or initiatives similar to CpC (Table 02).

Activity	Tasks	
	Company Stage (Business)	Team Stage (Engagement)
Question Storm	Creation of questions that enable viewing the company's problem from different perspectives	Identification of possible causes for failures in similar projects Understanding the causes and motivations that may have led such projects to failure

Table 2: Beliefs and Biases about Sustainable Projects.
Source: The authors.

In this activity, participants were encouraged to think about sustainable projects they had been involved in or were aware of that, for some reason, failed to achieve their objectives. In its engagement version, this activity takes place in two stages. In the first, similar to the previous activity, participants were invited to identify possible causes of these sustainable project failures through a word and/or a sentence (Brainwriting). To facilitate the reasoning process and identification of these causes, the following questions were presented to participants: Why did the projects not succeed? What prevented their success? What were the possible causes of their failure?

After a 10 minute for individual input, participants shared their beliefs withthe other members of their respective teams, once again allowing them to identify similarities among everyone. Then, as a team,

participants identified the top three main causes of failure. Thus, each team presented their chosen causes, and, once again, participants were surprised to see that the teams had identified similar beliefs. Finally, all teams discussed as a large group and defined the top three causes they believe led to the failure of previous sustainable projects: lack of participant engagement, lack of dedicated time for the project, and lack of objective and pragmatic actions to support the projects. Figure 05 shows a word cloud generated from individual inputs; it is possible to see that the words appearing most frequently indeed represent the three main causes defined by the entire participant group.



Figure 5: Word cloud from all inputs.

Source: The authors.

According to Berger, W. (2014), it is essential to value questioning, and among the important questions to be asked, "why?" is the one that allows the perception of a new reality. In this sense, in the second part of the activity,

participants were guided to think: Why did these defined causes occur? Why did a lack of participant engagement, dedicated time, and objective and concrete actions occur? What were their motivations?



Figure 6: Presentation of the teams' main motivations.

Source: The authors.

The participants, individually, identified their beliefs about the reasons that led to the causes of project failures and why. After 10 minutes, the participants shared their possible motivations with their teams, which then defined the top three motivations. Finally, each team shared their top three motivations that led to the emergence of the causes of sustainable project failures (Figure 06). Once again, participants were surprised to discover that the teams defined similar motivations, and finally, all teams engaged in a large group discussion to better understand their beliefs, biases, and challenges they would face in the CpC. Table X presents the words and/or phrases identified by the teams.

Similarities are observed among the teams (Table 03), and the recurring identification of these similarities fosters a sense of group/team among participants, allowing them to perceive connections with one another. This perception initiates a process of collective identity (Sophia Becker, 2021), bringing people closer together through the realization that they share the same problems, beliefs, and goals. In this way, an intrinsic motivation spontaneously arises (Amabile, 1997), leading to individual engagement that enhances participants' interest in being part of the whole to solve their problems.

Team	Main motivations/Reasons
01	Lack of technical and political domain definition Lack of priority criteria definition Lack of involvement and accountability
02	Different priorities No involvement because it does not generate votes Disorganized HR and organizational policies
03	Political objectives are usually short-term Lack of funding opportunities Different cultures/opinions involved
04	Cultural level misaligned with actual needs Lack of awareness of the importance of the theme Lack of funding and bureaucracy

Table 3: Main motivations of Project failures.

Source: The authors.

At the end of these activities, participants were able to get to know each other (both technically and emotionally) and, most importantly, realize that despite all their contextual differences, since they come from different cities and regions of Portugal, they share the same concerns and beliefs about sustainability-related projects and initiatives. Finally, participants were invited to share their perceptions of these two activities, and all of them assigned that it was highly valuable to share their expectations regarding the CpC and their beliefs about what could lead the CpC to failure, thus seeking common solutions for the whole group, given their shared opinions. This result aligns with Gaertner and Dovidio (2011), which states that situational context emphasizes the significance of categorical distinctions between groups, where contexts impact

social identity, as the latter is a concept that spans both social and individual experience (Upham et al., 2019). Individuals who share group beliefs and feelings tend to have a stronger intention to act consistently with those groups (Fielding et al., 2008).

5.3. Core activities and Value Benchmarking

Once the similarities that enable participants and their respective cities to work in harmony towards common goals are recognized and established, thus allowing for the formation of a group identity and behavior, this activity and those that follow focus on establishing rules that allow for group recognition. In other words, they aim at developing concepts that represent CpC—and

its participants—as a network of cities striving for climate neutrality. In this way, this activity aims to think about the concepts that represent the core of CpC as a

sustainable project (Table 04), in which each participant identifies the main words or sentences that represent essential values for CpC.

Activity	Tasks	
	Company Stage (Business)	Team Stage (Engagement)
Core activities	It aims to think about the core of the company, activities carried out by the company, those that add essential value to the business.	It aims to think about the concepts of the sustainable project that represent essential value of the project

Table 4: Business and Engagement: Core activities activity and tasks.

Source: The authors.

This activity is also performed through Brainwriting, writing ideas instead of speaking them eliminates the issue of productivity blocking, as participants do not need to wait for their turn to produce ideas (Thompson, 2003). In this divergent thinking activity, convergent thinking emerges in the analysis and selection of the best concept obtained. Each participant lists at least 20 essential concepts that could represent CpC within 20 minutes. After that each team must select, in 30 minutes,

four concepts from the total obtained, considering what is essential to represent the core value and what truly contributes to the social identity of CpC. Then, each team posts their defined concepts on a central board, and finally, everyone agrees on the four concepts they believe best represent CpC as a project focused on sustainability and climate neutrality for Portuguese cities. Figure 07 shows the moment of discussion and final concept selection.



Figure 7: Concepts discussion and definition.

Source: The authors.

As a result of the co-creation process involved in this activity, four concepts were defined that best represent CpC: Capacity Building, Sharing, Realization, and Credibility. It is noticeable that, except for the concept of Credibility, all other concepts reflect the expectations previously defined (Capacity Building, Teamwork, and Execution). This result can be explained by the fundamental role that expectations play in cortical conceptual processing, thus exerting significant influence on conceptual categorizations (Lane, P. 2019; Schubotz, R., I. 2015).

In line with the Value Benchmarking task outlined by the CoCreative Framework, participants conduct a web search to explore how the four core concepts have been addressed across various market sectors, whether through products or services. Through this analogical process, participants broaden their perspective on these concepts, engaging in discussions on how those market solutions might be adapted for the CpC context (Table 05).

Activity	Tasks	
	Company Stage (Business)	Team Stage (Engagement)
Value Benchmarking	The participants carry out a search to find and understand better the 4 core activities.	The participants carry out a search to find and understand better the 4 core.

Table 5: Business and Engagement: Value benchmarking activity and tasks.

Source: The authors.

5.4. Support actions and ideas generation

It is widely known that ideation processes and techniques are fundamental for generating innovative solutions (Ju Hyun Lee, 2022). Thus, utilizing all inputs generated in previous activities and through team-building and social identity development, enhanced by recognizing various similarities among participants and their different contexts, the final activities in this engagement-focused version are directed toward ideating solutions. In its business version,

these activities are conducted separately; however, in the engagement version, they have been combined to foster a better understanding of the objectives to be achieved. In this version, the objective of this activity is to guide participants to think about actions that can be implemented in the CpC to ensure that the defined concepts are effectively delivered, and mainly to develop action plans that prevent causes and motivations like those that led previous projects to failure (Table 06).

Activity	Tasks	
	Support Actions	Ideas Generation
Support Actions	It aims to guide participants to think about actions that support the 4 defined core activities.	It aims to guide participants to think and generate ideas about actions that support the 4 defined core concepts.
Ideas Generation	It aims to generate a huge quantity and diversity of ideas based on all repertoire achieved from previous activities.	

Table 6: Business and Engagement: Support Actions and Ideas Generation activity and tasks.

Source: The authors.

Support Actions aims to guide participants to think about actions that enable the implementation of the four defined core concepts, identifying actions that the project carries out and/or can implement. Meanwhile, Ideas Generation by Method 635 aims to generate a large quantity and diversity of ideas based on all the knowledge gained from previous activities oriented by CpC, its concepts, expectations, problems, and beliefs shared by participants. This method takes a total of 30 minutes, and once 635 is complete, all ideas must be analyzed and discussed among participants, selecting three ideas with the most potential to, in their activation, prevent and/or reduce the likelihood of failure due to the same causes and motivations encountered in other projects.

By the end of the activity, approximately 300 ideas were generated regarding preventive actions or procedures that could be implemented in the CpC to enhance its success. This outcome proved highly valuable and essential for the coordination of the CpC project, as it resulted in a substantial repository of actions that when analyzed and assessed for activation feasibility, these ideas, from collective teamwork, have significant potential for acceptance by the team. This collaborative generation of ideas supports the empowerment of participants, shifting them from passive actors subject to coordination decisions to active contributors in creating value and ensuring project success. Finally, participants were invited to share their experiences with all activities developed in this work.

Positive	Negative
The dynamics of the activities were very interesting; I really enjoyed them.	Nothing to point out
The team was very friendly, with accessible and clear language.	Very generic
Exceeded my expectations	Unclear conclusions
Excellent work session	Revision of some tasks
Important interaction with colleagues from municipalities and communities	Low participation from municipalities
Thank you very much to the whole team for the rich experience.	Using too much paper
I liked the dynamic, the sharing, and the teams	We didn't introduce ourselves individually
Good organization and work method	
I liked the dynamic and the shared information	
I really enjoyed this session; I learned new concepts	
I really liked the various methodologies used	
I enjoyed the informal and relaxed atmosphere of the session	
I appreciated the promotion of dialogue created between municipalities	
I liked the knowledge exchange and the interaction	
Different ways of thinking and working methods	
Informality in sharing ideas and experiences	
Communication, organization, teamwork, and sharing	
Dynamic activity, out-of-the-box, and multidisciplinary	
Motivation with clear and accessible speech	
Knowledge sharing with colleagues	
I liked the dynamic used	
Conversations among participants	
I enjoyed the methodology adopted for a future perspective of a network for sharing and implementing solutions to combat climate change	
Very positive session with a dynamic and creative model which created an ideal environment of comfort and relaxation for sharing ideas	
Relaxed and practical meeting atmosphere	
Moderator with high professionalism	
Good organization in the sequence of activities	
Sharing challenges from different municipalities	
New ideas to improve the CpC network	
Idea of sharing implemented projects on the CpC website	
Good discussion and positive attitude	
Interesting sharing and common/shared willingness	

Table 7: Participants' feedback.

Source: The authors.

The results (Table 7) show that the vast majority of participants rated all activities positively, highlighting the importance of this work in dynamically, engagingly, and uniquely fostering teamwork and allowing them to learn from the realities of other participants from various cities. It is important to note that the statements point out a perception of a social sense of team, in which the participants assigned a significant experience of sharing their knowledge, seeing a common goal towards sustainability,

fostering a new mental models about sustainable projects. Thus, it can be said that the engagement-adapted structure of the Creative Framework points its effectiveness in using creativity-related techniques and approaches to introduce a new way of perceiving sustainability. It also fostered a sense of unity and team cohesion, with participants working toward similar problem-solving goals, ultimately becoming facilitators and supporters of the project at hand.

6. CONCLUSIONS

The conclusion of this research highlights how a creative framework can effectively engage participants in sustainable projects. By integrating design techniques and green creativity, this approach nurtures sustainable mental models and fosters meaningful engagement. Activities such as Icebreakers, Question Storming, Core Activities, and Value Benchmarking revealed that when creativity is used to connect personal expectations, social values, and shared objectives, participants develop a deeper sense of community and commitment to sustainability goals.

This research demonstrates that a creative framework tailored for sustainability projects promotes a shift in participants' mental models, encouraging them to adopt long-term, environmentally responsible mindsets. Through structured creative exercises, participants not only shared common beliefs and concerns but also collectively generated actionable ideas. This collective ideation serves as a foundation for sustainable design, reinforcing each participant's role in achieving practical, eco-friendly solutions.

Furthermore, by making sustainability principles tangible and action-oriented, this study showcases the value of green creativity in sustainable design practices. It underlines that green creativity is not merely an abstract concept but a practical approach that fosters team cohesion, empathy, and a proactive stance on sustainability. Consequently, the research provides valuable insights into how creative frameworks can serve as powerful tools in shaping sustainable behaviors, thereby contributing to the broader field of sustainable design and environmental responsibility.

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PROPOSITION AND DISCUSSION ON LOW-CARBON BUILDING TECHNOLOGY - LCBT

PROPOSIÇÃO E DISCUSSÃO DE PRINCÍPIOS PARA TECNOLOGIA CONSTRUTIVA DE BAIXO CARBONO – TCBC

PROPUESTA Y DISCUSIÓN DE TECNOLOGÍAS CONSTRUCTIVAS BAJAS EN CARBONO - TCBC

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ABSTRACT

Society has faced the unique challenge of reducing CO₂ emissions associated with its productive activities. Such a goal is particularly relevant to the construction sector, which accounts for 37% of global greenhouse gas emissions. However, the initiatives undertaken in the sector have not yielded satisfactory results. This article proposes and discusses principles that contribute to the formulation and development of low-impact building technologies. The hypothesis is the organization – a central aspect of technology – of architectural production significantly contributes to its unsustainability. Logical argumentation supported by a literature review on technology, sustainability, and low-carbon practices was employed as a methodological approach and the outcome involved identification and characterization of seven principles, namely, permanent building, non-alienated labor, man-nature integration, less energy, self-determination, productive rationality, and popular empowerment. The principles define Low-Carbon Building Technology and suggest a framework for reorganizing production processes so that they become less carbon-intensive.

KEYWORDS

Building technology; Low-carbon; Concept; Modes of production; Civil construction.

RESUMO

A sociedade se encontra diante de um desafio ímpar: reduzir as emissões de CO₂ relacionadas às suas atividades produtivas. Trata-se de uma das metas da construção civil, a qual emite 37% do montante de gases de efeito estufa, globalmente. As ações empreendidas neste setor, contudo, não têm demonstrado resultados satisfatórios. O objetivo deste artigo é propor e discutir princípios que contribuam para a formulação e o desenvolvimento de tecnologias construtivas de menor impacto. Parte da hipótese de que a maneira como se organiza a produção da arquitetura é o que a torna mais insustentável, sendo esta organização um aspecto central da tecnologia. Como abordagem metodológica foi empregada a argumentação lógica, apoiada na revisão da literatura sobre tecnologia, sustentabilidade e baixo carbono. O resultado da pesquisa consiste na nomeação e caracterização de sete princípios denominados edificação permanente, trabalho desalienado, integração homem-natureza, menos energia, autocentrismo, racionalidade produtiva e poder popular. Em conjunto, delimitam Tecnologia Construtiva de Baixo Carbono e indicam uma forma de rearranjar os processos produtivos para torná-los menos intensivos em carbono.

PALAVRAS-CHAVE

Tecnologia construtiva; Baixo carbono; Conceito; Modo de produção; Construção civil.

RESUMEN

La sociedad se enfrenta a un desafío sin precedentes: reducir las emisiones de CO₂ derivadas de sus actividades productivas. Este es uno de los principales objetivos del sector de la construcción, responsable del 37 % de las emisiones globales de



gases de efecto invernadero. Sin embargo, las acciones llevadas a cabo en este sector no han producido resultados satisfactorios. Este artículo tiene como objetivo proponer y discutir principios que contribuyan a la formulación y al desarrollo de tecnologías constructivas de menor impacto ambiental. Parte de la hipótesis de que la forma en que se organiza la producción arquitectónica es lo que la hace más insostenible, siendo esta organización un aspecto central de la tecnología. Como enfoque metodológico, se empleó la argumentación lógica, respaldada por una revisión de la literatura sobre tecnología, sostenibilidad y bajo carbono. El resultado de la investigación consiste en la identificación y caracterización de siete principios denominados: edificación permanente, trabajo no enajenado, integración humano-naturaleza, menos energía, autocentrado, racionalidad productiva y poder popular. En conjunto, estos principios definen lo que se entiende por Tecnología de Construcción Baja en Carbono e indican una forma de reorganizar los procesos productivos para hacerlos menos intensivos en carbono.

PALABRAS CLAVE

Tecnologías constructivas; Bajo en carbono; Concepto; Modos de producción; Construcción civil.

1. INTRODUCTION

Rising temperatures, global warming, greenhouse gases (GHGs), climate adaptation plans, resilience, mitigation, and vulnerability have been widely disseminated by the media, gradually extending beyond the scientific domain due to climate change. In turn, there is growing consensus within the scientific community that the human development model is the primary cause of such changes (IPCC, 2022). Some scientists have even argued that human activity has been responsible for systemic transformations on a planetary scale, considered decisive for the beginning of a new geological epoch currently referred to as Anthropocene, Capitalocene, Corporatocene, or Plantationocene (Marras & Taddei, 2022).

Despite the different designations and interpretations regarding causes of the aforementioned situation, the crucial point is the disruption of the planet's climate balance directly affects the conditions that led to the current stage of human prosperity, threatening the physical, mental, and food security of society (IPCC, 2014) and existence of various species. The importance of discussing global warming lies in ensuring the minimum conditions for survival in a scenario where the limits of prudence have already been exceeded (Lowe, 2012; Marques, 2020). The issue is no longer on mitigating to preserve, but rather on adapting life to a diverse and increasingly unpredictable world.

The warning signs of this tension date back to the 1960s, when the first studies pointed to an environmental crisis defined by three main factors: a) humanity was consuming more resources than the environment could regenerate, with population growth continuously intensifying this pressure; b) waste generation exceeded the natural assimilation capacity; and c) a wide range of pollutants was being released into water, air, and soil from multiple sources (Saramago, 2023). Since then, collaborative efforts have been made to understand the consequences of environmental degradation for both the planet and humanity, leading to seminal works such as *Silent Spring* (Carson, 1962), *The Population Bomb* (Ehrlich, 1968), *The Tragedy of the Commons* (Hardin, 1968), and the reports *The Limits to Growth* (Meadows et al., 1972), *Only One Earth* (Ward & Dubos, 1973), and later *Our Common Future* (WCED, 1991), initially published in 1987 and also known as the Brundtland

Report. The Intergovernmental Panel on Climate Change (IPCC), established in 1987, was tasked with compiling studies aimed at clarifying the specific effects of rising greenhouse gas concentrations on Earth's systems, and has since published periodic reports on climate change.

Although an extensive body of data and scientific projections support that phenomenon, there has been significant resistance from society and its representative institutions to implementing actions truly capable of minimizing both causes and effects of global warming. The Kyoto Protocol has proved insufficient (Souza; Corazza, 2017) and it is now widely acknowledged that the Nationally Determined Contributions (NDCs) proposed by various countries under the Paris Agreement must be more ambitious if the goal is to limit the increase in global average temperature to no more than 1.5°C above pre-industrial levels (Tsai et al., 2024).

Such a lack of decisive action is due to, among other reasons, global warming challenging the economic system based on the logic of production growth, which serves as the reference for the definition of the Gross Domestic Product (GDP) of several countries and is the leading indicator of development and progress. Production growth is presented in the GDP framework as a mechanism for improving social well-being (If more is produced at a lower cost, more people will be able to have their essential needs met) and maintaining the system itself, ensuring social order and the international power structure (Latouche, 2009; Sachs, 1997). The "extract – transform – discard" motto is emblematic of contemporary society (EMF, 2015), even though not all cultures are based on that assumption.

Given our social division of labor, the productive system is essential for generating the goods necessary for human survival. However, while increasing production surpluses seemed crucial for centuries, production now threatens human security (Marques, 2020). It must be highlighted that the goods produced have not been distributed equally or fairly across society, as historically claimed, considering persistent social inequality, income concentration, poverty, and chronic hunger (Oxfam, 2017). Fundamentally, that is a distribution problem, since the proclaimed comfort and security are not based on meeting human needs and the most basic ones, such as adequate food, water, and housing are rather based on the consumer's purchasing power (Andrioli, 2009).

Even if equal consumption were ensured for the entire global population according to the standards of so-called developed countries, humans would face an

unavoidable problem of insufficiency of environmental resources (Boff, 2015; WWI, 2010), since physical and natural factors impose limits on economic growth. Economy fundamentally depends on both extraction and use of matter and energy supplied by nature and humans cannot produce any material goods without relying on those finite natural resources (Georgescu-Roegan, 2012). Rethinking the meaning of development and social progress has thus become a key factor in discussions on sustainability and climate change (Tavares; Chiletto; Ino, 2022). The rationalization of those resources has prevailed to date and, according to Georgescu-Roegan (2012), prolongs our existence as we know it, but does not exempt us from an imminent collapse.

2. CIVIL CONSTRUCTION, LOW CARBON, AND SUSTAINABILITY

Research on sustainability in civil construction is extensive and well established, with an increasing focus on carbon reduction. Energy, the central theme of the recent discourse, is the primary source of greenhouse gas (GHG) emissions globally due to its widespread use in various human activities such as goods production, building operation, transportation of people and goods, communication, food preservation, healthcare, among others. Consequently, energy efficiency and development and adoption of new energy sources have become pressing and tangible demands.

The following two relevant considerations must be highlighted: 1) social demand for energy continues to grow, and, to date, no energy source has been simultaneously economical, abundant, and highly efficient as fossil-based ones (Marques, 2020); and 2) energy demand, in its various forms and continuous growth, results from the way production, distribution, and consumption of human creations are organized. In other words, the conflict lies within a broader context, i.e., in the material reproduction of life, a human choice socially enacted by its representatives and those who hold decision-making power (currently, the owners of substantial financial resources invested in large corporations).

In that regard, focusing efforts solely on energy efficiency or altering the energy matrix enable the perpetuation of the economic system through the preservation of fundamental resources necessary for sustaining production and consumption (O'Connor, 2000), as in the rationalization of material and water use (Acsehrad,

2002). The approach is also supported by the Brundtland Report, which prescribes sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs (CMMAD, 1991). Under that framework, a false sense of proactivity in favor of the climate arises, resulting in little real progress given the continual increase in greenhouse gas emissions, when their levels should instead be decreasing. Moreover, loopholes open to label products or buildings as sustainable or low-carbon when they are not - a "status quo of sustainability" approach (Hopwood; O'Brien, 2005) often promoted through the management of environmental resources (Saramago; Lopes, 2023).

2.1. The need for a new approach

The construction sector plays a vital role in promoting social well-being, for it is responsible for the development of buildings and infrastructure. The transformation of natural resources through labor, materials, tools, and technical knowledge is achieved through various means, processes, and methodologies that create safe and functional spaces supporting human development and workforce renewal. Additionally, due to its extensive supply chain, labor-intensive operations, and broad range of activities, the sector drives capital flows and generates significant employment. Given its scale and capacity to stimulate related services, industries, and jobs, civil construction is considered a strategic component of national economies and public policy agendas (Campos; Guilhoto, 2017). Therefore, it is mandatory to consider the entire production process, from decisions on the use of material resources, labor, energy, tools, and capital, to the understanding of the way choices made in one area may significantly influence others.

The discussion presented here explicitly addresses the technological dimension of construction. Since the Industrial Revolution, technology has been understood as the theoretical organization of technical knowledge (Lopes, 2006). Construction technology refers to the systematized body of theoretical and practical knowledge that enables the production of buildings and their components, including gestures, timing, and physical forces. It encompasses aspects related to materials, labor, means of production, and the foundational knowledge involved (Tavares, 2024), all of which are structured into processes, procedures, and methods that determine how and why certain materials, techniques, or tools are used. Among

other factors, it identifies those who hold the productive intelligence, the time, and the conditions (Gama, 1987).

Technology is a social construct, i.e., it is neither neutral, nor immutable, but somewhat shaped by the interests of the dominant class within a specific historical and spatial context (Harvey, 2016; Feenberg, 2002). No technology is proposed independently of the prevailing mode of production. Preference is currently given to natural resources that are accessible, abundant, and inexpensive, processed in centralized production units, and transformed into construction materials and components through energy-intensive means that generate substantial waste and pollution. Such products are distributed over long distances via integrated transport networks heavily reliant on fossil fuels. The overarching goal of the entire process is to increase production while simultaneously reducing time and costs and ensuring economic viability and profitability.

One of the core mechanisms of capitalist accumulation operates according to the following logic: the more and the faster the production, the greater the number of items available for sale at a lower cost. Expanding production is, therefore, essential for enhancing investments in the means of production (e.g., physical space, machinery, and labor), maintaining a company's competitiveness in increasingly saturated markets, and, above all, ensuring profit generation (Marx, 2013). Such operational logic is also presented as a (false) justification for making goods more accessible to a broader population. However, it ultimately promotes the homogenization of construction alternatives in culturally and geographically distinct territories, disregarding local potential, knowledge, and traditions (Magnaghi, 2011).

Increasing production inevitably entails greater exploitation of natural resources, heightened generation of pollutants and waste (even when subject to rationalization), and encouragement of consumption. In most cases, the relevance or actual usefulness of what is produced is not questioned; the central aim is to maintain high manufacturing output to sustaining continuous consumption and keeping the economy active. Technologies are, in general, conceived and implemented within that same paradigm (Harvey, 2016).

Latouche (2009) highlighted compensatory technology, which anticipates repairing potential damage from its use - not to mention the need to create corrective technologies that fix an undesired effect of a previous technology (Huesemann; Huesemann, 2011). In both cases, a business opportunity is generated with little reflection on the problem's causes and the solution's

effects. In general, problems are regarded as a necessary evil or a risk to be faced towards the collective good, when it is known that damages usually concentrate in some territories and among specific populations (Saramago; Lopes, 2024; Chomsky; Pollin, 2020).

Such productivist and consumerist logic can be exemplified in the construction industry context as follows. Urban boundaries are expanded to addressing the identified housing deficit through the construction of new residential units and supporting urban infrastructure, including roads, public lighting, drainage networks, sanitation and water supply systems, public transport lines, schools, daycare centers, health clinics, and public green spaces. New construction technologies, often industrialized, rationalized, or even sustainable, are employed in those developments. They are designed to ensure speed and cost-effectiveness while meeting the minimum performance criteria established by ABNT NBR 15.575 standard (2021).

Despite the absolute need for new housing, 27% of the housing deficit in Brazil correspond to substandard dwellings (FJP, 2023), which require specific and tailored responses for promoting improvement. The industrial productivist logic rarely meets those responses. Furthermore, it is observed that several municipalities choose to build new units even when the number of vacant and/or abandoned properties exceeds the demand for new buildings, or when the excessive burden of rent per household prevails. Although such a practice generates new business opportunities and stimulates local economy, it fails to address more complex issues (e.g., the social function of land). 52.12% of the national housing deficit is related to excessive rent burdens (FJP, 2023), which refer to constructed assets and environmental and social resources invested. Access to housing might be solved through alternative means; however, the favored solution is the one that promotes capital accumulation.

The large-scale production of units homogenizes spatial and construction solutions, disregarding family size and cultural and climatic contexts. On the other hand, the model is accompanied by issues such as land concentration, socio-spatial segregation, and gentrification and requires exploitation of additional environmental resources, even when what is already built and consolidated could be optimized. Operating within that context involves complex challenges, such as private land ownership. However, on the other hand, we are haunted by climate change and its various disasters stemming from how we interact with the world.

In that regard, framing the discussion on sustainability around the development of new technologies, when technologies aim to improve, enhance, and maximize the efficiency of production processes and, ultimately sustain the continuous production growth, is insufficient and even contradictory, given the challenges posed. It is essential to rethink technology and advance in addressing the fundamental issues that underpin it.

Based on the foregoing, this paper proposes and discusses principles that can contribute to both formulation and development of alternative construction technologies capable of reducing greenhouse gas emissions within the sector. The principles consider the construction industry context beyond a mere building object and define and characterize “Low-Carbon Building Technology” (LCBT).

3. METHODOLOGY

This research is based on the hypothesis that the organization of architectural production is the primary factor that contributes to its unsustainability. Therefore, it is essential to rethink the technology developed for building construction.

The conceptualization and characterization of Low-Carbon Building Technology comprise Phase 1 of the research project entitled “Low Carbon Building Technologies - LCBT: Timber and New Paradigms for Architecture and Construction”, developed by the Housing and Sustainability Research Group (Habis) at the University of São Paulo. The principles were established through logical argumentation, a methodology that supports a coherent framework delineating the proposed theoretical construct.

The research design was structured into three phases, namely, 1) state-of-the-art review or strategic conceptual mapping, 2) analysis and synthesis of the mapping results, and 3) definition of the principles and formulation of the argument.

Phase 1 focused on three key concepts, namely, a) Technology, b) Sustainability, and c) Low Carbon. Understanding what technology and construction technology are, their assumptions and implications, and the processes through which they are developed and disseminated was essential to underpin the research aimed at developing a concept of technology. In turn, “low carbon” and “sustainable” were considered qualifying concepts for the technology to be proposed and conceptualized. Therefore, discussions on those topics, including their outcomes, contradictions, limitations, and potentialities were mapped and analyzed. The result of the literature review mapped the main talks on low carbon and sustainability, drawing from general literature (other fields of knowledge) and specific literature (architecture and civil construction). The approach is justified, since the specific literature shares broader discussions and its actions are often conditioned by them (e.g., how the Rio 92 conference fostered initiatives within the construction sector through agreements and policies).

In Phase 2, building on the strategic mapping previously developed, the following objectives were a) to understand the actions and processes that contribute to GHG emissions in architecture and civil construction, as well as other negative impacts related to their contradictions and shortcomings, and b) to identify the actions and processes necessary for an effective reduction of those emissions and to mitigate other associated negative impacts, addressing their potentialities and possibilities. The results of are summarized in Table 1, whose organization was based on three guiding questions, namely, a) How do greenhouse gas (GHG) emissions occur during building construction? b) What are the other associated negative impacts?, and c) What actions and processes are necessary to effectively reduce GHG emissions and other impacts and foster more accessible, scalable, and equitable human development? In response to them, the following thirteen situations were identified and mapped.

Sources of GHG emissions	Additional adverse impacts	Potential Solutions	Authors
1) By considering nature as an inexhaustible source of resources (both material and energetic), or merely as a manageable source of such resources;	Waste, improper use, depletion of essential resources; land use exploitation and change; destruction of biomes and biodiversity;	Productive rationality; durability; circularity; passive architecture; prioritize renewable-source materials; apply Life Cycle Assessment (LCA); apply the 8Rs; reduce consumption;	Meadows (1972); Daly (2012); Ward, Dubbos (1973); Acselrad (1993); Layrargues (1997); CMMAD (1991); Bonaiuti (2016); Kibert (1994);

Sources of GHG emissions	Additional adverse impacts	Potential Solutions	Authors
2) Considering nature as external to human beings , and that humanity controls all variables of its existence through technological development;	Destruction of biodiversity; species extinction; air/water/soil pollution; occupation of areas that could be preserved; alteration of the landscape; need for corrective technologies;	Durability; circularity; LCA; rethinking the way buildings and cities are implemented; prioritizing the use of renewable materials; 8Rs; humans and nature as rights holders;	Georgescu-Roegan (2012); Gudynas (2011); Bonneuil, Fressoz (2024); Rockström et al. (2009);
3) Considering the negative impacts (social, environmental, economic, cultural) as externalities of the production process;	Air/water/soil pollution; poisoning; social inequality; destruction of people/cultures and biomes; alteration of land use;	Incorporate the costs of impacts into products to encourage the search for new solutions; implement eco-taxes; highlight impacts through LCA; pursue systemic and transdisciplinary understanding of decisions;	Georgescu-Roegan (2012); Daly (2012); Furtado (2012);
4) By prioritizing decisions , at all stages of civil construction, following the logic of productive rationality, productivity, and aiming for economic viability;	Increasing exploitation of resources and associated pollution; worsening labor conditions; concentration of profits and wealth; growing inequality; obsolescence; creation of needs; unnecessary production of goods;	Add other variables to the decision-making process beyond productivity; include additional variables in cost composition; change the arrangement of people involved in decision-making; apply LCA; educate society for value change; generate quality employment;	Latouche (2009, 2010); Acosta (2016); Silva, Silva, Agopyan (2003); Duplessis (2002); Rios, Chong, Grau (2015); Viola, Basso (2016);
5) By turning everything into disposable products , not subject to reuse or maintenance, aiming at the continuity of production and consumption;	Need for exploration of new resources and continuous extraction of raw materials; depletion of essential resources; use of land for waste disposal; generation of pollutants; destruction of biomes; land-use change; creation of large landfills;	Durability; circularity; LCA application; professional training for renovation, maintenance, and dismantling of buildings; construction management; 4Rs (Reduce, Reuse, Recycle, Recover); productive rationality; rationalized design; circular production; implemented and enforced public policies for final waste disposal, reuse, and recycling; use of simple (non-composite), minimally processed materials;	CMMAD (1991); Kibert (1994); Kallis, Demaria, D'Alisa (2016); Latouche (2009, 2010); Daly (2012); Sachs (1986); UNFCCC (1997); Duplessis (2002); Rios, Chong, Grau (2015); Kibert, Chini, Languell (2001);
6) By wasting materials and generating waste at all stages of a building's life cycle;			
7) By universalizing solutions aimed at cost reduction – design, materials, work arrangement, methods of execution;	Disregards local specificities and potentialities as well as human creative capacity; increases GHG emissions during transportation and distribution stages;	Decentralize, diversify, consider local characteristics and potentialities; promote the economy by using local resources (materials and labor);	W. Sachs (1996); I. Sachs (1986); Santos (2003); Latouche (2009, 2010); Acosta (2016); Duplessis (2002); Magnaghi (2011);

Sources of GHG emissions	Additional adverse impacts	Potential Solutions	Authors
8) By valuing mass production to reduce costs, disregarding the diversity of needs and solutions;	Disregards social diversity; creates monotonous spaces; contributes to social and spatial segregation; reduces labor cost by simplifying it, stripping it of meaning;	Diversify housing typologies considering different family arrangements; develop techniques suitable for renovation and maintenance, training professionals, and generating dignified employment and income opportunities; take local characteristics into account;	Duplessis (2002); Rios, Chong, Grau (2015); Gonçalves, Duarte (2006); Schneider, Till (2005); Esteves (2013); Giesekam, Barrett, Taylor (2016);
9) Concentrate income, decision-making power, knowledge, and means of production, disregarding social, cultural, and territorial diversity;	Capital accumulation and concentration; increase in social and political-economic inequality; increased production to sustain the business; devaluation of the multiplicity of solutions;	Social participation; collaboration; mutual aid; knowledge sharing; decentralizing means of production; distributing income through dignified and skilled work; prioritizing transdisciplinarity;	Daly (2012); Acosta (2016); Latouche (2009); Dawood et al. (2013); Schumacher (1981); Magnaghi (2011);
10) Increasing consumption of energy (both operational and embodied), driven by continuously growing demand and centered on fossil fuel sources;	Need for increased energy generation; pollution and destruction of biomes; geopolitical conflicts; recurrent use of public subsidies;	Passive design; use of renewable energy; building energy efficiency; substitution of energy-intensive materials and components; prioritizing local solutions and materials; using efficient machinery and minimally processed materials; harnessing the power of photosynthesis; conserving energy;	Silva (2000); I. Sachs (2002, 2007); UNFCCC (1997); Duplessis (2002); Luo et al. (2019); Patil, Kumthekar (2016); Pomponi, Moncaster (2016); Luo et al. (2019); Shove (2018);
11) Prioritizing cost over the quality , performance, and long-term usefulness of the building;	Low durability of the building and its components; generation of waste; need for new resource extraction to replace damaged parts;	Ensure passive environmental comfort, accessible renovation and maintenance, quality and performance of used components; rethink building design and technologies considering the possibility of rehabilitation, renovation, expansion, and disassembly;	I. Sachs (1986); Duplessis (2002); John et al. (2002); Finch (2009); Devecchi (2010);
12) High CO ₂ -emitting materials used in a disposable manner, as well as toxic or somewhat toxic materials that cannot be reincorporated into nature;	Pollution and destruction of biomes; increased need for landfills; generation of waste; expansion of landfills and disposal areas; low awareness in the sector;	Establish policies that restrict the use of high-impact materials, increasing their reuse and recycling; choose materials that act as carbon sinks, tend toward neutrality, or are biodegradable; prioritize local materials; implement ecotaxes, public policies, legislation, and regulations; propose credit lines and research funding, as well as education and training programs for new practices; opt for materials and systems that are reusable;	I. Sachs (1986, 2002); Daly (2012); Takano (2015); Duplessis (2002); Rios, Chong, Grau (2015); Kibert, Languell (2001); Huang et al. (2018); Luo et al. (2019); Peñaloza, Erlandsson, Falk (2016); Pittau et al. (2019); Howe (2015); Shi, Yu, Zuo (2015);
13) By depriving the various agents in the sector of understanding the impact of their actions and choices based on profit and "progress".	Permanent environmental impacts; implementation of partial or self-interested solutions; lack of awareness of new practices.	Educate (universal and professional education); provide access to tools; create collective decision-making spaces; strengthen regulatory institutions.	Sachs (1986); Wang et al. (2016); Duplessis (2002); Shi, Yu, Zuo (2015); Giesekam, Barrett, Taylor, (2016); Ferro (2018); Magnaghi (2011);

Table 1: Literature mapping in response to the guiding questions.

Source: Elaborated by the authors. Adapted from Tavares (2024).

In the third phase of the research, the information was categorized into themes that ensured coherence across the dataset while avoiding repetition or content overlap. Three grouping proposals were developed, resulting in the diagram shown in Figure 1.

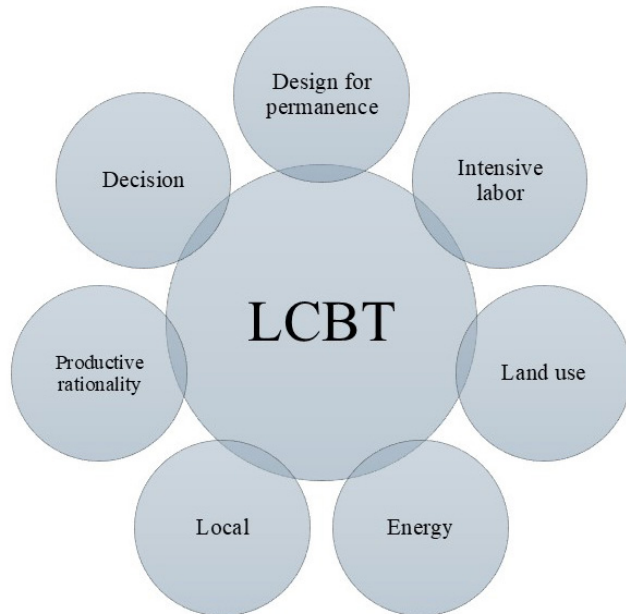


Figure 1: Diagram of the seven categories of analysis.

Source: Elaborated by the authors. Adapted from Tavares (2024).

Each category was presented, described, and justified; its objectives and the prescriptive aspects applicable for the development of an LCBT (Low-Carbon Building Technology) were outlined. A new literature review explored issues not addressed in the previous phases.

Finally, a new synthesis effort was undertaken towards the definition of the principles by posing the following question: “If the development of an LCBT (Low-Carbon Building Technology) involves issues raised by the analytical categories, what specific features of each category determine the different principles of an LCBT?” The outcome of the process is summarized in Table 02.

The broader research also sought to establish relationships among the various principles and understand their mutual influences. It mapped the agents and actions required to make the proposal viable and speculated on processes that could enable new approaches to inhabiting the world. This article focuses on the discussion of the seven principles that define and characterize LCBT.

Concept	Analysis category	Principles
Low-Carbon Building Technology (LCBT)	Design for permanence ->	Permanent building
	Intensive labor ->	Non-alienated labor
	Land use ->	Man-nature integration
	Energy ->	Less energy
	Local ->	Self-determination
	Productive rationality ->	Productive rationality
	Decisions ->	Popular empowerment

Table 2: LCBT Categories and Principles.

Source: Elaborated by the authors. Adapted from Tavares (2024).

4. RESULTS AND DISCUSSION – PRINCIPLES FOR A LOW-CARBON BUILDING TECHNOLOGY

Low-Carbon Building Technologies result from a set of seven independent yet complementary principles aimed at supporting the creation, refinement, and dissemination of construction technologies that minimize GHG emissions from the production of the built environment, but are not limited to that. The proposal also fosters meaningful improvements in people’s quality of life by enabling dignified means of material and social reproduction and recognizing civil construction involves much more than building structures. The principles point to a new way of organizing production, redefining its purpose and the way it is conducted, encompassing labor, materials, tools, territory, and people. The seven principles are presented in what follows.

Principle 01: Permanent building

The principle advocates for preserving and optimizing all natural resources extracted (e.g., raw materials, water, and energy) by valuing the environmental, social, and financial efforts invested in the construction of buildings and their components. It aims to avoid further extraction and reduce waste generation, greenhouse gases, and various pollutants related to the construction process. It does not prohibit replacing building parts, but prioritizes maintenance of the primary structure’s functionality and preservation of the existing urban infrastructure. Additionally, it emphasizes the reuse of previously

employed components, encouraging actions that promote reuse and recycling towards the same goal.

Permanent building assumes:

- Application of principles of flexible and adaptable design that promote easy renovation and maintenance, enabling buildings to accommodate different uses or needs over time;
- Assurance of construction, spatial, and environmental quality for avoiding demolitions and need for new buildings;
- Use of materials that can be employed in multiple technical cycles, prioritizing those that are non-toxic, minimally processed, simple (rather than composite), and of standardized or modular dimensions;
- Design for assembly, disassembly, and deconstruction, incorporating simplified and accessible mechanical connections between components, with weights compatible with human lifting capacity;
- Training and qualification of labor at all levels of action, with a focus on demolition, disassembly, renovation, and maintenance of buildings;
- Promotion and strengthening of a market niche for previously used materials such as those from demolitions or disassemblies, through laws, financing programs, and credit lines.

As previously discussed, the proposal for permanent buildings incorporates concepts of circularity and design for assembly, disassembly, and deconstruction. Regarding durability, it aims to go beyond conventional logic based solely on the relationship between initial cost and warranty period, a rationale often used to justify solutions that intensify negative environmental impacts by disregarding factors such as material origin, reuse and recycling potential, and methods of processing and final disposal.

According to John et al. (2002), durability is not an inherent property of the material, but rather, the result of a set of decisions and actions spanning the design and construction phases, as well as environmental conditions, usage, and exposure of the building along with maintenance, which must also be planned during design. In this context, the use of natural, minimally processed, or even biodegradable materials may be a viable option if replacements and maintenance are anticipated over time without compromising the overall safety and stability of the structure.

Principle 02: Non-alienated labor

This discussion aims to promote forms of labor in which productive intelligence belongs to the worker, ensuring autonomy in the production process and fostering knowledge expansion, rather than concentration. Daly (2012) argued that shared knowledge has a multiplying capacity and should not be treated as a scarce resource. However, since knowledge confers power, withholding it becomes a form of control, especially by keeping workers - particularly those on construction sites - in a state of alienation. This explains the strong emphasis on labor division and specialization, task simplification, and structuring of production in ways that reduce the worker to a mere executor of external orders, operating at a pace not determined by themselves. The issue, therefore, is not merely a lack of qualified labor, as often claimed in the construction sector, but rather, a deliberate devaluation and underpayment of site work, which makes it unattractive and actively discourages the professional development of workers, thus limiting their bargaining power (Ferro, 2018). A worker with more knowledge and know-how will naturally seek better working conditions, just like anyone in any sector of the economy.

Alienated, subdivided, and simplified labor is one of the key mechanisms of the current mode of production, employed to reduce the cost of labor, hence, the price of products (Marx, 2013). It results from the organization of productive arrangements that centralize manufacturing in large hubs and rely on complex supply and distribution networks, which are feasible only for large-scale production. Such a scale is necessary to amortize the high fixed capital costs and lower production costs per unit. The model concentrates power, capital, and profit while disregarding alternative construction methods or local business models rooted in practices and opportunities specific to each region. Consequently, traditional and local knowledge is gradually diluted.

Considering this discussion and aiming to overcome it in certain aspects, the concept of non-alienated labor proposes:

- Development of non-alienating production processes and construction components, elements, or systems in which the worker fully understands the tasks performed, has mastery of the tools used, and are free to propose solutions. The goal is not to simplify processes for accommodating low skill levels, but to promote worker training so that they can competently perform their functions;

- Promotion of worker training through comprehensive learning that encompasses both theoretical and practical knowledge and is not limited solely to the specifics of their trade, ensuring autonomy and room for creativity;
- Valuing of labor and workers by establishing laws and regulations that recognize the importance of various professions and ensure safety and rights of workers
- Promotion of methods of organizing work and workers based on small businesses or cooperatives geographically dispersed and aligned with local demands and opportunities. Decentralized, smaller-scale operations are advocated.

In this context, the aim is to overcome the logic of concentration easily observed in physical objects such as industrial conglomerates, by addressing something immaterial and less visible: knowledge. The concentration of knowledge impacts social organization and everyday life practices, influencing professions, determining the value of labor, and leading to disappearance of trades, resulting in devaluation or undervaluation of workers, who become increasingly “disposable.” The process also affects territorial organization and the overall quality of life of the population.

Principle 03: Man-nature integration

The way natural resources are exploited is impactful, predatory, and reckless, especially considering people’s dependence on them for survival. Historically, nature has been regarded as an infinite source of resources, resilient to interference, and as a suitable space for the disposal of various types of waste. However, land use - whether through occupation or alteration of its functions for resource extraction - has directly affected the planet’s natural cycles, causing impacts that cannot be reversed by isolated, partial technological solutions.

Towards changing such a way of operating, humans must recognize they are part of nature and their survival and interaction activities must be aligned with natural cycles. In this context, the following actions are proposed within the field of civil construction: 1) avoidance of use of highly polluting materials and energy - and carbon-intensive processes, 2) increases in the use of resources from renewable sources, and 3) promotion of circularity in the production and use of construction materials (UNEP, 2023). Since all of them impact land use and land-use change, the proposal of LCBT requires:

- Promotion of the use of materials and resources in ways that reduce pressure on land, by specifying those that can be reused or recycled, thereby avoiding premature disposal and need for new resource extraction;
- Promotion of the use of materials and resources from renewable and biodegradable sources, supporting the preservation of non-renewable and/or scarce resources, while always prioritizing low-carbon production and construction processes;
- Respect to the characteristics of the local environment during siting of buildings for avoiding drastic changes to the terrain and disruption of the local ecosystem;
- Prioritization of selection of local materials and resources, preserving traditional cultures and ways of building, even if revised and adapted to contemporary needs;
- Promotion of actions throughout the construction industry's supply chain that generate positive environmental impacts and contribute to both maintenance and enhancement of ecosystem services

Respecting natural cycles and avoiding environmental degradation would result from a new attitude towards the world.

Principle 04: Less energy

As addressed elsewhere, energy production and use are central themes in discussions on sustainability and low-carbon strategies. Reducing and avoiding energy consumption are a main priority in the construction and use of buildings, even surpassing the importance of improving energy efficiency and switching energy sources, which are also essential. In this regard, LCBT should consider:

- Avoiding energy use by eliminating the need for its production and consumption through a) reductions in the amount of materials used in a building by eliminating unnecessary steps, streamlining construction processes, and minimizing waste, b) choice of less processed or less energy-intensive materials, c) specification of locally sourced materials for reducing transportation demands, d) assurance of proper environmental performance of buildings by avoiding mechanical equipment and prioritizing passive comfort strategies;

- Rationalization of energy use by prioritizing high energy-efficiency systems, tools, and machinery at all stages of production (from material manufacturing to construction) and during the building's use and occupancy;
- Choice of renewable energy sources for both production and use of buildings.

Principle 05: Self-determination

The capitalist production system is characterized by the standardization and uniformity of products, processes, relationships, and people, universalizing lifestyles. It is a monoculture that affects what is produced, the way it is produced, the materials used, and the way people live (W. Sachs, 1996). Such uniformity stems from the productive efficiency required for viability, based on repetition and mass production principles. On the other hand, towards social acceptance of that production, efforts and resources are invested in advertising and marketing for persuading people from different regions to desire the common overcoming local beliefs and traditions. Furthermore, reducing production and distribution costs creates unfair competition with local producers.

According to Magnaghi (2011), that mode of production directly impacts territorial organization, since territories are used merely as technical support for specialized productive activities, thus interfering with people's understanding of the context in which they live and diminishing local possibilities in favor of the demands of an increasingly globalized market. In the author's words:

The local territory is no longer known, interpreted, or experienced by its inhabitants as the source of elements necessary for the reproduction of biological life (water, springs, rivers, air, soil, food, fire, and energy) or social life (neighborhood, community, symbolic relations, etc.). The dissolution of places and their transformation into amorphous dust within the broader framework of a process of deterritorialization of life definitively produces a total loss of sovereignty of individuals and local communities over the material, social, cultural, and symbolic forms of their existence (Magnaghi, 2011, p. 282, our translation).

The idea of self-determination is a counterpoint to that trend, since it proposes the construction of a political and economic alternative based on territory (Acosta,

2016). It involves decentralizing decision-making control, creating opportunities from within the territory outward, and valuing local resources and needs. Participation, autonomy, solidarity networks, decentralization of productive units, knowledge, and power, as well as diversity of solutions are key concepts in this discussion

Aligned with those objectives, LCBT proposes:

- Recognizing and utilizing local conditions and resources such as climate, construction techniques, cultures, unique characteristics, materials, energy sources, and knowledge towards promoting varied solutions tailored to each context, fostering greater harmony with the territory;
- Recognizing the value of people and encouraging collective agreements to boosting social cohesion, empowerment, and community autonomy. Therefore, it requires promotion of active participation and establishment of collective spaces for decision-making and knowledge exchange, thus fostering the development of a community based on dialogue and diversity;
- Encouraging local development through technologies adapted to a reduced production scale using simple and accessible tools and machinery. The goal is to generate jobs and income in the region, foster creativity and autonomy among the professionals involved in the production process, and facilitate training and knowledge exchange among participants in the production cycle.

Principle 06: Productive rationality

In the face of an environmental collapse and the intrinsic need to extract, exploit, and use resources for construction production, such activities must be performed rationally, avoiding waste or loss. The optimization of the use of a resource avoids its exploitation at the source, thus minimizing inherent impacts. The so-called externalities of the production process must be rethought as integral elements of the production chain, internalizing their impacts. In this sense, LCBT should consider:

- Ensuring the optimization of resource use in the construction of a building and its components, eliminating waste, residue generation, and material loss, as well as energy, human effort, water, and production time;
- Reducing resource consumption by eliminating unnecessary construction steps, especially

those used to hide construction process flaws or interface errors, properly sizing materials by applying the minimum of them required to ensure adequate safety and comfort for users, and minimizing distances between materials and the construction site;

- Promoting circularity principles in production through waste management and utilization, material reuse, and design for disassembly for maximizing the lifecycle of a resource extracted from nature.

Principle 07: Popular empowerment

The discussion on “popular empowerment” proposes decentralizing decision-making power by promoting the participation of agents besides those who hold capital and means of production towards establishing goals that surpass the logic of productivity, multiply solutions, and prioritize human life on a planet with finite resources. From such a perspective, LCBT should:

- Promote the active participation of diverse agents, representatives, and collectives in the design phases of construction technologies towards a collaborative, eclectic, and multidisciplinary approach without hierarchies. The goal is to create solutions that appropriately address the group’s needs and represent their realities;
- Foster collective arrangements that strengthen the autonomy and self-esteem of groups;
- Adopt a grounded and conscious approach to each choice’s environmental, social, cultural, political, and economic impacts, use analytical tools such as Life Cycle Assessment (LCA), Ecological or Water Footprint, and develop other tools to assess quantitative effects;
- Be revolutionary, since those choices must be grounded in new social relations, hence, in transformations of production relations.

4.1. Discussion

This research is based on the hypothesis that the way architectural production is organized makes it a more unsustainable activity. It argues practical solutions cannot be proposed without breaking away from the paradigm of the current mode of production, in which:

- Nature is understood as an inexhaustible source of resources and as something external to human beings;

- Negative environmental impacts are considered externalities of the production process, a price to be paid for progress;
- Wastefulness and disposability prevail;
- Decisions remain concentrated within certain groups, similarly to knowledge, income, and means of production;
- Economic viability is the determining factor in decision-making;
- Dependence on energy is increasing;
- All social, territorial, climatic, and environmental diversity is disregarded;
- There is no robust, socially shared understanding of the impacts of human actions.

Greenhouse gas (GHG) emissions and other environmental and social impacts result from decisions that perpetuate those productive assumptions, although production rationality focused on resource efficiency is a present concern.

According to Arthur (2009), the conception of a technology begins with the formalization of a technical problem to be solved along with its justification, followed by the definition of possible solutions that consider the phenomena to be overcome. Both formulation of the problem and its solution are choices aligned with the interests of specific human groups. Although they have been based on paradigms over the past three centuries, they are now known to directly contribute to climate change.

With a basis on a literature review and logical argumentation, this study defined and characterized seven inseparable principles that, together, assist in the formulation of a low-carbon construction technology when considering:

- The produced asset, its design, and the production of its components and systems, aiming at its maximum permanence;
- The labor involved, the tools, and the knowledge about the production process, encouraging autonomy and multiplication of ways of doing things;
- The human relationship with nature, respecting its natural cycles, promoting actions that impact the environment positively, and collaborating with ecosystem services;
- The reduction of energy demand by first avoiding its consumption and then by promoting optimized forms of use based on renewable sources;
- The social, environmental, cultural, and economic characteristics of different territories, multiplying

and diversifying solutions, decentralizing, dispersing, and reducing the scale and complexity of productive units;

- The mode of production, valuing the maximum and best use of resources;
- The way of deciding and evaluating the impacts of different needs and solutions beyond what is economically viable.

Which material should be selected among the wide range of available materials? Such a choice must consider aspects that enhance discussions on Low-Carbon Building Technology (LCBT), placing the material at the center of the diagram, as shown in Figure 2. The same approach should be applied to the other components of technology.

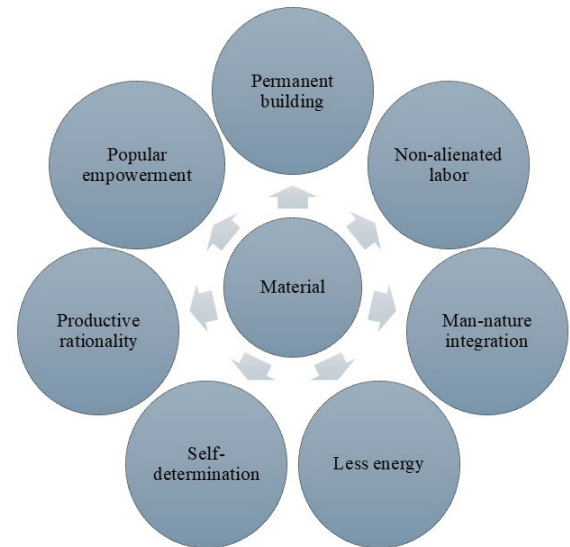


Figure 2: Principles to be considered for the selection of construction material.

Source: Elaborated by the authors.

Diagram 1 summarizes the process for the development of a technology based on Arthur (2009) and the constituent parts of construction technology, according to the theory developed by Gama (1986). The objectives of technology and the values that will guide the solution are defined in the process. This research advocates the seven principles serve as a reference for describing the solution, which will determine all aspects related to materials, labor, means, and forms of production organization.

The application of the principles that define Low-Carbon Building Technology (LCBT) establishes neither a fixed roadmap to be followed, nor a set of elements to be further added to an existing process. Instead, it is a way of conceiving and designing procedures and methods focused on construction. Another key aspect is LCBT is not a rigid or a static concept in time and space and does not aim to produce standardized or replicable solutions - on the contrary, different social, environmental, economic, and cultural contexts will define unique problems and responses.

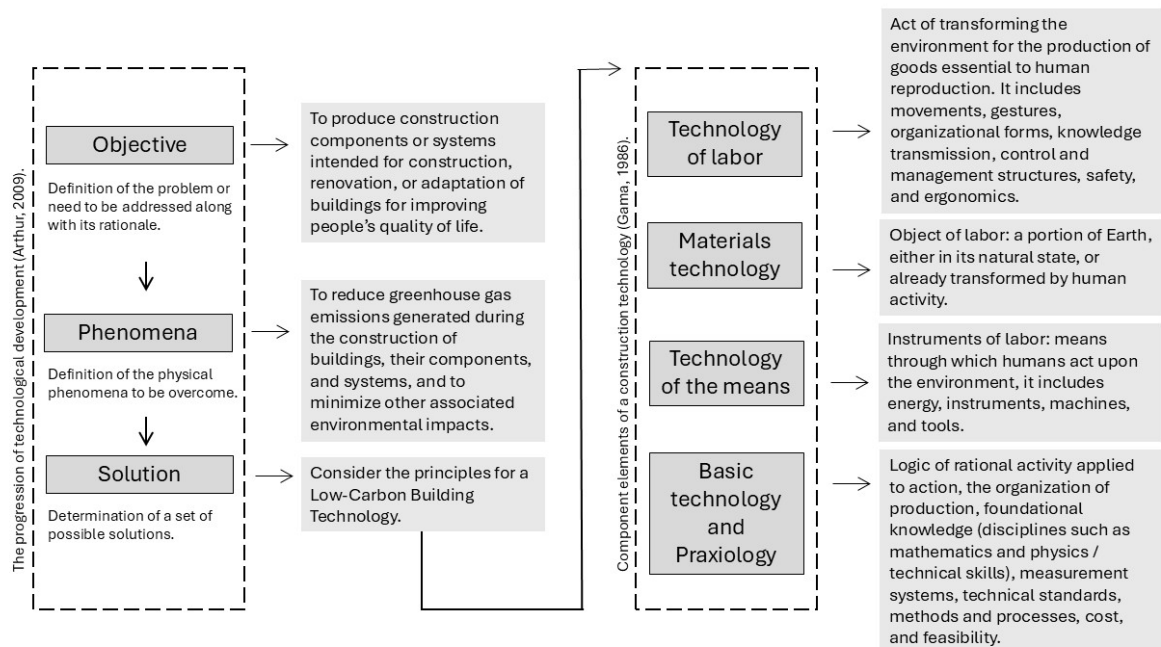


Diagram 1: Relationship between LCBT principles in defining a construction technology.

Source: Elaborated by the authors. Adapted from Arthur (2009) and Gama (1986).

5. CONCLUSIONS

The objective of this article was to propose and discuss the seven principles that characterize Low-Carbon Building Technology, namely, permanent building, unalienated labor, human-nature integration, less energy, self-determination, productive rationality, and popular empowerment, which aim to restructure the way construction technology is decided and defined in building practices.

The development of construction technologies according to those principles is expected to reduce the sector's negative impacts, particularly greenhouse gas (GHG) emissions. Moreover, they will expand their positive impacts by promoting social and territorial development decoupled from the global logic of productivity, increasing social access to the goods necessary for the material reproduction of life through actions that value labor, respect natural cycles, share knowledge, and multiply solutions.

The proposed challenge is huge and does not fall solely on architecture and engineering professionals. It is a socially driven project that demands cultural change and can be fostered through public policy and education. Furthermore, it must involve all actors in the construction sector, including manufacturers of machinery, tools, and materials, design firms, researchers, educational institutions, certification bodies, public authorities, investors, cooperatives and construction companies, financial agents, professional associations, and technology incubators.

The continuation of this research will involve analyses and development of construction technologies based on the proposed conceptual framework towards the understanding of their strengths and weaknesses in practice. Experiences that align with the defined concept must be mapped through examinations of their contexts, conditions, and limitations as an initial test of feasibility and Life Cycle Assessments (LCA) of the selected case studies must be conducted towards the comprehension of their quantitative impact and reflections on characteristics not addressed by the theory. Such investigations will enable revising or adjusting the TCBC framework for making it more coherent and feasible.

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PARAMETRIC DESIGN FOR RESILIENT DESIGN IN LATIN AMERICA

DESIGN PARAMÉTRICO PARA DESIGN RESILIENTE NA AMÉRICA LATINA

DISEÑO PARAMÉTRICO PARA EL DISEÑO RESILIENTE EN LATINOAMÉRICA

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ABSTRACT

In recent years, with the continuous increase in the effects of climate change on people's health, the concept of resilient design has gained traction. However, one of the regions most affected by this phenomenon is Latin America, as it experiences high levels of thermal variability, which negatively impacts the comfort of its inhabitants and increases the energy demand of buildings. In this context, understanding that the use of digital technologies, parametric measures, and optimisation tools allows for designs that respond to various climatic requirements, the aim of this article is to identify the potential of parametric design for resilience in Latin American cities. To achieve this, a systematic review was conducted according to the PRISMA method. As a result, it was found that there are two main approaches to applying resilience through parametric design and a range of specialised software that can be adapted to the objectives set by each author. Finally, it was concluded that, although urban morphology influences the resilience of a place, the building envelope is an essential factor when discussing resilient design, and parametric characteristics make a significant contribution to this in terms of energy efficiency.

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KEYWORDS

Parametric design; Resilient design; Energy efficiency; Latin America; Thermal variability..

RESUMO

Nos últimos anos, com o aumento contínuo dos efeitos das mudanças climáticas sobre a saúde das populações, o conceito de design resiliente tem ganhado destaque. No entanto, uma das regiões mais afetadas por esse fenômeno é a América Latina, que enfrenta altos níveis de variabilidade térmica, impactando negativamente o conforto dos habitantes e aumentando a demanda energética dos edifícios. Nesse contexto, compreende-se que o uso de tecnologias digitais, ferramentas paramétricas e métodos de otimização possibilita projetos que respondem a diversas exigências climáticas. Assim, o objetivo deste artigo é identificar o potencial do design paramétrico para a resiliência nas cidades latino-americanas. Para isso, foi realizada uma revisão sistemática conforme o método PRISMA. Como resultado, identificaram-se duas principais abordagens para a aplicação da resiliência por meio do design paramétrico, bem como uma variedade de softwares especializados que podem ser adaptados aos objetivos definidos por cada autor. Conclui-se, por fim, que, embora a morfologia urbana influencie a resiliência de um local, o envoltório dos edifícios é um fator essencial na discussão sobre design resiliente, sendo que as características paramétricas contribuem significativamente nesse aspecto, especialmente em termos de eficiência energética.

PALAVRAS-CHAVE

Design paramétrico; Design resiliente; Eficiência energética; América Latina; Variabilidade térmica.

RESUMEN

Durante los últimos años, con el continuo aumento de los efectos del cambio climático en la salud de las personas, la idea de diseño resiliente ha incrementado. Sin embargo, una de las regiones más afectadas por este fenómeno, es América



Latina, pues presenta altos niveles de variabilidad térmica, perjudicando el confort en sus habitantes e incrementando la demanda energética de los edificios. En este sentido, entendiendo que el uso de tecnologías digitales, medidas paramétricas y herramientas de optimización, permiten diseñar para responder a los diversos requisitos del clima, el objetivo de este artículo es identificar el potencial del diseño paramétrico para la resiliencia en las ciudades latinoamericanas. Para esto, se realizó una revisión sistemática de acuerdo al método PRISMA. Como resultado, se encontró que existen dos enfoques principales del diseño paramétrico para aplicar la resiliencia y una serie de software especializados que se pueden adaptar a los objetivos planteados por cada autor. Finalmente, se concluyó que, aunque la morfología urbana influye en la resiliencia de un lugar, la envolvente es un factor indispensable a la hora de hablar de diseño resiliente y, las características paramétricas un aporte importante para ello en términos de eficiencia energética.

PALABRAS CLAVE

Diseño paramétrico; Diseño resiliente; Eficiencia energética; América Latina; Variabilidad térmica.

1. INTRODUCTION

In recent years, the global climate has been changing at a faster rate than before, bringing with it effects such as an increase in the planet's average temperature and a higher frequency of extreme temperatures. Additionally, the environmental conditions for thermal comfort are critical for most Latin American countries, as they are among the most affected by climate change (Calvo et al., 2021). From this perspective, to protect human health and reduce energy demand in buildings, it is necessary to anticipate future discomfort conditions (Hernández Moreno et al., 2021).

One measure is to opt for resilient design, which seeks the adaptation of projects to be more resistant to the consequences of climate change (García, 2019; Rajkovich & Holmes, 2021), without compromising indoor air quality and health. In this regard, Januszkiewicz (2019) states that with the use of digital technologies, parametric and multicriteria approaches, and optimisation tools, buildings can be designed to meet diverse climate requirements.

Thus, considering that the world is experiencing the so-called digital age, in design and architecture, digital technologies range from Computer-Aided Design (CAD) to mass customisation, including Building Information Modelling (BIM) and Parametric Modelling (Willis & Woodward, 2010). CAD was initially perceived as a drawing and representation tool that allows architects and designers to save time when presenting architectural projects.

In the case of technologies such as BIM and Parametric Modelling, there is a growing use as generative instruments rather than mere representational tools. This is because they accommodate more complex design conditions interactively. According to Chen et al. (2019), digital design through parametrics and fabrication technologies such as robotics, integrating software and hardware, enables opportunities for creative experimentation. It also requires clear design objectives so that, according to established parameters, necessary variables can be manipulated, increasing the pace of the creative process.

As such, there are significant advantages to adopting parametric design tools to achieve resilient projects, as they grant the necessary flexibility in design and contribute to speeding up processes such as modularisation (Habibi Rad et al., 2021). Therefore, the aim of this study is to identify the potential of

parametric design for resilience in Latin American social housing. To this end, a systematic review was conducted following the PRISMA method. The methodology is described below, followed by the results and discussion, and finally, the conclusions and references.

2. METHODOLOGY

The methodology of this study is qualitative and exploratory in nature, employing bibliographic research to gather data. For its development, the PRISMA method (Moher et al., 2009) was used as a reference, which consists of a checklist for the selection and review of documents distributed over four phases: 1) identification, 2) screening, 3) eligibility, and 4) inclusion.

In the identification phase, the Scopus database was used to obtain structured data sources, and Google Scholar was also consulted. The review was filtered for open-access publications from the last five years (2018–2022), excluding theses and dissertations. Seven keyword-based reviews were conducted. Two of these yielded no results (see Table 1).

Keywords		1. Screening	
		Database Records Scopus	Records from Other Sources Google Scholar
Review 1	Climate Change Parametric design Social housing	(n = 0)	(n = 4)
Review 2	Climate Change Parametric design	(n = 9)	(n = 13)
Review 3	Resilient Design Parametric design social housing	(n = 0)	(n = 0)
Review 4	Resilient Design Parametric design	(n = 0)	(n = 0)
Review 5	Resilience Parametric design Social housing	(n = 0)	(n = 2)

Keywords		1. Screening	
		Database Records Scopus	Records from Other Sources Google Scholar
Review 6	Resilience Parametric design	(n = 2)	(n =20)
Review 7	Parametric design Social housing	(n = 0)	(n = 4)

Table 1: Identification Stage according to PRISMA.

Source: The authors.

Consequently, the five searches that yielded results greater than zero were pursued, leading to an initial set of 54 articles in total. Through the subsequent phases of screening, eligibility, and inclusion, this number was reduced to 19 documents for full review, as shown in Tables 2 and 3. After the review, the relevant texts were classified and synthesised according to their main approach. Similarly, it is worth noting that the results and discussion sections primarily explored the software and methodologies used by the authors, as well as their objectives and main conclusions.

Keywords		2. Screening	2. Eligibility
		Duplicates Removed	Full-text Articles
Review 1	Climate Change Parametric design Social housing	(n = 4)	(n = 0)
Review 2	Climate Change Parametric design	(n =13)	(n = 9)
Review 3	Resilience Parametric design Social housing	(n = 1)	(n = 1)
Review 4	Resilience Parametric design	(n =16)	(n = 6)
Review 5	Parametric design Social housing	(n = 1)	(n = 3)

Table 2: Screening and Eligibility Stages based on PRISMA.

Source: The authors.

Keywords		3. Inclusion		
		Quantitative Synthesis	Qualitative Synthesis	Mixed Synthesis
Review 1	Climate Change Parametric design Social housing	(n = 0)	(n = 0)	(n = 0)
Review 2	Climate Change Parametric design	(n = 8)	(n = 9)	(n = 0)
Review 3	Resilience Parametric design Social housing	(n = 0)	(n = 1)	(n = 0)
Review 4	Resilience Parametric design	(n =16)	(n = 6)	(n = 0)
Review 5	Parametric design Social housing	(n = 1)	(n = 3)	(n = 0)

Table 3: Inclusion Stage based on PRISMA.

Source: The authors.

3. RESULTS

According to the review carried out, two main approaches were identified in studies on parametric design aimed at addressing the impacts of climate change on human comfort and health. On the one hand, there is the use of

parametric tools in the building envelope, focusing on its adaptation to external climate conditions. On the other hand, the second approach addresses this form of design on a broader scale, through the exploration of alternatives in urban morphology within cities (see Table 4).

Approach	No. of Articles
Parametric Design for:	
1. Resilience in the Envelope for Indoor Comfort	10
2. Resilience through Urban Morphology for Comfort	9

Table 4: Inclusion Stage based on PRISMA.

Source: The authors.

In the same vein, it was observed that most of the reviewed studies are quantitative syntheses (12 articles), although a significant number of qualitative explorations were also found (7 articles). The quantitative articles were characterised by simulations carried out using different software and specialised plugins, depending on the approaches mentioned above (see Figure 1). The most commonly used software for modelling was Rhinoceros, supported by the Grasshopper plugin, which functions as a visual programming language and was mainly used in studies related to the first approach (envelope).

Additionally, the Grasshopper plugin Ladybug was widely employed in both approaches (envelope and urban morphology) to analyse climatic data from locations defined by each author. Following this, the Honeybee plugin stood out, enabling energy simulations using the EnergyPlus and OpenStudio engines, and its use was more focused on the architectural object and its envelope. Similarly, Autodesk CFD software appeared, used to simulate ventilation conditions in articles linked to both the envelope and urban morphology.

Furthermore, three software tools were specifically applied to the second approach: 1) CitySim, for simulating buildings at the urban district scale and estimating their energy demand; 2) Envi-met, for analysing the environmental impact of design on the local context and determining sustainable living conditions in scenarios of constant change; and 3) CityEngine, for simulating large-scale urban environments using GIS¹.

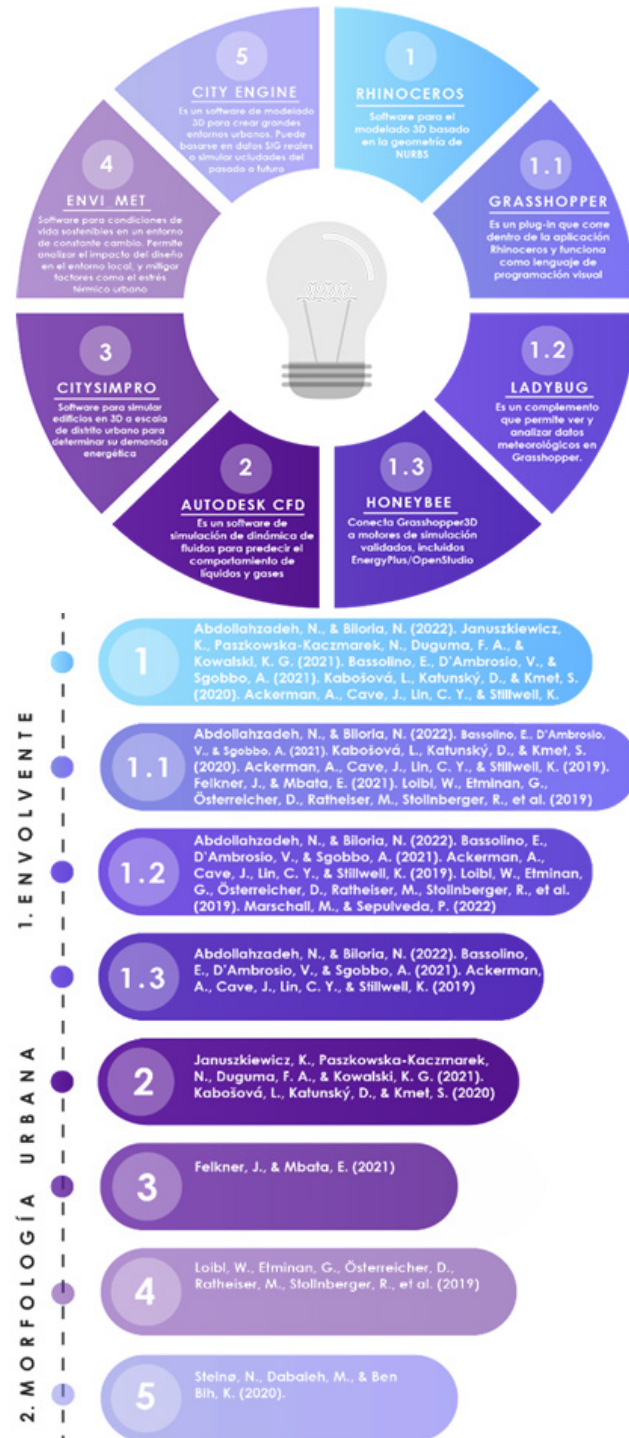


Figure 1: Summary of the most used parametric design software and plugins for resilience.

Source: The authors.

¹Sistemas de Información Geográfica - SIG: consiste en un conjunto de herramientas que relacionan elementos para la organización y análisis de datos sobre una referencia espacial determinada.

Based on the above, it can be stated that the various software tools involved in parametric design can be applied to resilience practices depending on the case, and can be combined according to the objectives set. For instance, Abdollahzadeh and Bioria (2022) used Rhinoceros and the Grasshopper plugin to optimise design factors based on thermal conditions in outdoor spaces and the energy used for cooling and heating indoor spaces, simulating the Australian urban microclimate and the energy efficiency of its buildings using the Ladybug and Honeybee plugins.

Similarly, Bassolino, Ambrosio, and Sgobbo (2021) employed the same tools to define critical aspects of urban spaces in response to heatwave phenomena and subsequently, with the help of GIS, transformed the results into databases, maps, and potential levels of adaptation for climate-oriented projects. Regarding the building envelope, Rossi-Schwarzenbeck and Figliola (2019) used these software tools to develop a methodology for designing energy-efficient buildings with façades capable of dynamically responding to changing climate conditions. In turn, Marschall and Sepulveda (2022) employed Grasshopper and Ladybug to enhance dynamic models in order to detect overheating risks in buildings and propose appropriate mitigation strategies.

On the other hand, some authors (Januszkiewicz et al., 2021; Kabošová et al., 2020; Palusci & Cecere, 2022) used Rhinoceros and CFD to design with consideration for local wind microclimates, evaluating both the disadvantages and opportunities presented by wind effects in urban and architectural projects. In contrast, Felkner and Mbata (2021) applied Grasshopper and CitySim to assess energy performance and overheating in urban renewal scenarios. For this purpose, they also relied on PostgreSQL and PostGIS to analyse large datasets, and on QGIS to spatially link the information.

Lastly, Loibl, Etmann, Österreicher, Ratheiser, and Stollnberger (2019) used Envi-met to analyse the relationship between urban densification and climate under climate change conditions, as well as to examine necessary mitigation and adaptation measures. Additionally, they opted for the use of Grasshopper and Ladybug for local microclimate calculations. To achieve a similar objective, Steinø, Dabaieh, and Ben Bih (2020) used CityEngine in combination with ArcGIS Online as their main parametric urban model.

Finally, it is worth noting that most of the articles involving simulations for specific climates were developed primarily in European countries (8), particularly in Italy

(3), followed by studies carried out in Australia (2), North Africa (1), and lastly, the United States (1), as shown in Figure 2. This highlights the limited interest among authors in conducting studies of this nature in Latin American countries.



Figure 2: Geographic distribution of reviewed quantitative synthesis articles.

Source: The authors.

4. DISCUSSION

In line with the results obtained, it can be stated that the variation of urban design factors that alter the urban configuration or morphology enhances its potential for adaptation to climatic conditions through parametric design (Abdollahzadeh & Bioria, 2022). In this context, the exchange of data between ICT tools based on GIS, as seen in the Italian case studies, may also prove valuable for analysing microclimatic behaviour and the performance of urban spaces (Bassolino et al., 2021).

Similarly, with the use of these multicriteria tools, buildings can be designed to adapt to a wide range of requirements, bearing in mind that the capacity of a building's envelope to support its energy balance is crucial for the future wellbeing of occupants (Januszkiewicz et al., 2021). This means that such optimisation processes generate variations and outcomes that may allow for the formulation of general rules or recommendations for architects (Rossi-Schwarzenbeck & Figliola, 2019).

In addition, digital design processes based on wind data make it possible to estimate the influence of wind conditions during the conceptual design phase (Kabošová et al., 2020). However, in these cases, the properties of envelope materials are not taken into account, which reduces the reliability of such simulations from a resilience perspective; nevertheless, this approach can help identify areas potentially exposed to poor air quality and therefore vulnerable to pollution and heat stress (Palusci & Cecere, 2022).

That said, parametric design facilitates the generation of different scenarios through the variation of parameters.

This enables the rapid creation of generic designs at various scales, such as district and neighbourhood plans, as well as buildings and construction elements (Steinø et al., 2020), with its principal advantage being the flexibility in data input (Felkner & Mbata, 2021). From this perspective, resilient design through parametric modelling can also be enhanced when integrated with BIM tools, enabling a coordinated design dynamic. To this end, it is necessary to progressively incorporate parametric design into practice, using more detailed and realistic data (Tronchin et al., 2018).



Figure 3: Discussion synthesis.
Source: The authors.

5. FINAL CONSIDERATIONS

Parametric design, through specialised software, enables the generation of a large number of design alternatives and simulations within short periods of time. In the fields of urbanism and architecture, particularly from the perspective of resilient design, this represents a significant development potential, as it facilitates the creation of multiple responses for both urban morphology and architectural objects. These responses can address the effects of climate change on comfort and human health according to specific locations. In this regard, the Grasshopper plugin, along with its Ladybug and Honeybee extensions, becomes a highly valuable tool, as it supports simulations under changing climate conditions with projections based on location-specific meteorological data.

Additionally, it is important to highlight that, although there are digital programmes for parametric modelling in large-scale design proposals involving variations in urban morphology, the absence of detail regarding architectural object properties—such as materiality—may increase the level of uncertainty surrounding resilience to climate change in such cases. For this reason, the building envelope is an indispensable factor when discussing resilient design, and parametric characteristics offer a significant contribution to this, particularly in terms of energy efficiency.

However, although it is an emerging topic, studies of this nature have mainly been carried out in European countries, especially those addressing the Italian climate. Similarly, in the Americas, only one related study was identified, conducted in Texas (United States). This points to a great potential for exploration in this region—particularly in Latin America—given its vulnerability to phenomena such as climate change. Nevertheless, this also implies a need for greater training and research in the field among the professionals involved.

To conclude, and in line with the foregoing, parametric modelling requires clear design objectives and prior reflection, as the use of programming languages can otherwise lead to meaningless automation. The use of these new digital technologies alone does not necessarily lead to better architecture, but it does represent an important aid. Therefore, it is necessary to promote their use critically and consciously in design processes, in order to support the creation of resilient and sustainable projects over time.

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GTC: conceptualization, formal analysis, funding acquisition, investigation, methodology, project management, supervision, validation, visualization, writing - original draft and writing - review & editing.

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