http://periodicos.sbu.unicamp.br/ojs/index.php/parc
https://doi.org/10.20396/parc.v15i00.8674763

EVALUATION OF AN INTERNAL WALL SYSTEM ADAPTED TO DFD

AVALIAÇÃO DE UM SISTEMA DE VEDAÇÕES VERTICAIS INTERNAS ADAPTADO AO DFD

Jordana de Oliveira[1]

Marco Aurélio Stumpf González[2]

Andrea Parisi Kern[3]

1 Universidade Feevale, Novo Hamburgo, RS, Brasil, eng.jordanaoliveira@gmail.com
2 Universidade do Vale do Rio dos Sinos, São Leopoldo, RS, Brasil, mgonzalez@unisinos.br
3 Universidade do Vale do Rio dos Sinos, São Leopoldo, RS, Brasil, apkern@unisinos.br

Abstract

Considering the shortage of products and the acceleration of the impacts of climate change, the linear production context of the construction sector has become a matter of concern, making the circular economy a strategy to make it more sustainable. Among the tools proposed by the circular economy is the design for disassembly (DfD), which aims to design buildings that allow the removal of components for later use, expanding the life cycle of products and the adaptability of the space. Therefore, this research aims to evaluate a constructive alternative that allows the application of DfD in vertical multi-family residential buildings, reducing the generation of demolition waste and carbon emission incorporated into the production of the material. Based on a literature review, the methods and materials used to apply DfD were verified, and a system of internal walls was proposed that met the project criteria for disassembly and, consequently, the circular economy. The proposed system, comprising wooden structure panels and drywall, met the criteria of ease of access, independence, simplicity and standardization, connections, and disassembly safety, as well as being assessed to have the potential for reuse based on the evaluation using the proposed indicator. Furthermore, as evaluated in the hypothetical case study, it reduced the mass of the building's walls by 26%, compared to a concrete block masonry system, in addition to a 19% reduction in CO_2 emissions.

Keywords: construction, circular economy, design for disassembly, DFD, internal walls.

Resumo

Com a escassez de produtos e a aceleração dos impactos das mudanças climáticas, o contexto linear de produção do setor da construção civil se tornou uma preocupação, fazendo da economia circular uma estratégia para torná-lo mais sustentável. Entre as ferramentas propostas pela economia circular está o projeto para desmontagem (do inglês, Design for Disassembly – DfD), que visa o projeto de edificações que permitem a remoção de componentes para posterior utilização, ampliando o ciclo de vida dos produtos e a adaptabilidade do espaço. Diante disso, o objetivo da pesquisa é avaliar uma alternativa construtiva que possibilite a aplicação do DfD em edificações verticais residenciais multifamiliares, reduzindo a geração de resíduos de demolição, e a emissão de carbono incorporado à produção dos materiais. A partir de uma revisão de literatura, foram verificados quais os métodos e materiais utilizados para aplicação do DfD, sendo proposto um sistema de vedações verticais internas que atendesse aos critérios do projeto para desmontagem e, por consequência, da economia circular. O sistema proposto, composto por painéis de estrutura de madeira e revestimento de placas de gesso acartonado, atendeu aos critérios de facilidade de acesso, independência, simplicidade e padronização, conexões, e segurança de desmontagem, bem como, se avalia que tem possibilidade de reutilização direta, a partir da avaliação por meio do indicador proposto. Ainda, reduziu em 26% a massa das vedações do edifício avaliado no estudo de caso hipotético, comparado a um sistema de alvenaria de blocos de concreto, além de uma redução de 19% de emissões de CO_2*.*

Palavras-chave: *construção civil, economia circular, projeto para desmontagem, DFD, vedações verticais internas.*

Contribuição dos autores:
JO: conceituação, curadoria dos dados, análise formal, investigação, metodologia, administração de projeto, validação, visualização, escrita - rascunho original, escrita - revisão e edição. **MASG:** conceituação, investigação, metodologia, administração de projeto, supervisão, escrita - revisão e edição. **APK:** conceituação, investigação, metodologia, escrita - revisão e edição.

Fomento: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior.
Declaração de conflito: nada foi declarado.

Editora Responsável:
Regina Coeli Ruschel

How to cite this article:

OLIVEIRA, Jordana de; GONZÉLEZ, Marco Aurélio Stumpf; KERN, Andrea Parisi. Avaliação de um sistema de vedações verticais internas adaptado ao DFD. **PARC Pesq. em Arquit. e Constr.**, Campinas, SP, v. 15, p. e024009, 2024. DOI: https://doi.org/10.20396/parc.v15i00.8674763

Submitted 08.10.2023 – Approved 12.04.2024 – Published 03.07.2024

Introduction

Reconciling environmental, economic, and regulatory demands in construction is currently a requirement, but it is still a major challenge to overcome. Therefore, mechanisms need to be created to curb the excessive consumption of natural resources and reduce the amount of waste generated daily by the sector (Carvajal-Arango *et al*., 2019).

According to Tam, Soomro and Evangelista (2018), Brazil produced 101 million tons of construction and demolition waste (CDW) in 2015, of which 6.14% was recovered. Furthermore, according to the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE, 2022), in 2021, Brazilian municipalities collected around 48 million tons of CDW, which represents 227 kg/inhabitant/year, and an increase of 2.9% compared to the previous year.

The United Nations (UN) points out that 70% of the world's inhabitants will live in urban centers by 2050, with more and more construction needed to meet this demand (DELOITTE Brasil, 2019). When dealing with social aspects, there is a need for constructions that are more adaptive to users' needs (Longo, 2020), and the main consumption trends in this segment are aimed at flexibility, security, and longevity of the population (DELOITTE Brasil, 2019).

However, addressing these sociodemographic changes by using traditional construction techniques implies a significant generation of solid urban waste by civil construction, which arises from building demolitions and neglects the potential reuse of components (Galante, 2021). Thus, reuse, adaptation, recycling, and disposal are the methods to be prioritized when it comes to construction and demolition waste to promote the circularity of products (Longo, 2020). Reuse minimizes the extraction of a new resource, saving new product processing and saving up to 60% of the energy incorporated in construction elements. On the contrary, recycling results in more energy incorporated into the system, which is undesirable (GÁLVEZ-MARTOS; STYLES; SCHOENBERGER; ZESCHMAR-LAHL, 2018).

Given this, among the initiatives that can be used to minimize these impacts is design for disassembly (DfD). DfD aims to consider construction in a way that facilitates its disassembly and reuse of components, with the least possible waste generation (Longo, 2020). It can enhance a building's design life and service life by adopting design techniques. On the other hand, its use becomes viable when alternatives are studied in the initial design phase, and it is strongly dependent on the return on investment time and the risks associated with the process (ISO, 2020).

Jensen and Sommer (2016) listed five principles for applying this methodology. The first three are choosing high-quality, non-toxic materials that ensure reuse, designing the building with its entire life cycle in mind, designing in independent layers and thinking about project flexibility, designing simple and standardized solutions/details that fit into different contexts, and considering modular and prefabricated elements. Additionally, connections must allow for repeated assembly and disassembly, and a deconstruction plan must be developed.

When dealing with internal and external walls, which is the focus of this work, Akanbi is among the main proposed systems (Akanbi *et al.,* 2019). According to the authors, the best design solution was steel curtain partitions with bolted connections, with a possibility of up to 93% recovery. Arrigoni, Zucchinelle, Collatina and Dotelli (2018) used drywall systems for a temporary pavilion consisting of galvanized steel beams covered with plasterboard, fiber cement, or polycarbonate according to the function they were supposed to fulfill.

Minunno, O'Grady, Morrison and Gruner (2020) designed and built a building with a completely detachable interior cladding system, with access points to facilities and insulation, without generating waste for maintenance. In the system, the positioning of threaded parts was used, allowing minor adjustments to the height of the panel mount and ensuring greater flexibility for the part. As constituent materials, reforestation wood was used for the panel structure, and MDF sheets were used for the covering.

According to these studies, a series of possibilities can be applied to facilitate dismantling internal vertical seals in buildings. However, most of them are aimed at commercial and small buildings. Therefore, it is worth asking: how can design for disassembly be applied to residential building projects, to promote reuse of their internal components and greater design flexibility, compared to a traditional Brazilian construction system?

Based on this problem, the article, developed from the author's Master's thesis, aims to develop and technically evaluate a constructive alternative that makes it possible to apply the design DfD in internal walls to optimize the reuse of components and reduce embodied carbon emissions into the system. For the sake of analysis, a comparative case study was carried out between a traditional masonry system with non-structural concrete blocks and the solution adapted to the DfD, consisting of panels with a wooden structure and drywall covering.

The study is limited to applying the systems to vertical multi-family residential buildings built in the southern region of Brazil. The choice of this project model is mainly due to the representation of this category in the national real estate sector. Data shows that, for the southern region, 92% of properties purchased between February 2020 and 2021 are for residential use. Among consumers in the region, 27% express a preference for purchasing apartments. (ABRAINC, 2022). Therefore, the average data from these acquisitions served to delimit the characteristics of the study building based on the largest proportion of the region's real estate market.

Referring to the design systems that are the focus of the work, when considering the possibilities of removing and reusing components of vertical buildings, it appears that the greatest study potential for DfD lies in the seals, their interface with doors and windows, and floor and ceiling coverings. According to Longo (2020), as the building is made up of layers (structure, fence and partitions, for example), disassembly generally follows the opposite sequence of construction. This makes removing internal partitions easier, in addition to being lighter and having more suitable dimensions for transportation.

As a research hypothesis, it was considered that adopting these techniques could promote environmental benefits for the project. Examples include the possibility of reusing components to promote a more circular construction and the reduction of carbon emissions due to the choice of materials with lower environmental impact due to their production. To prove these hypotheses, the results were evaluated based on indicators of compliance with disassembly criteria, circularity, and carbon emissions.

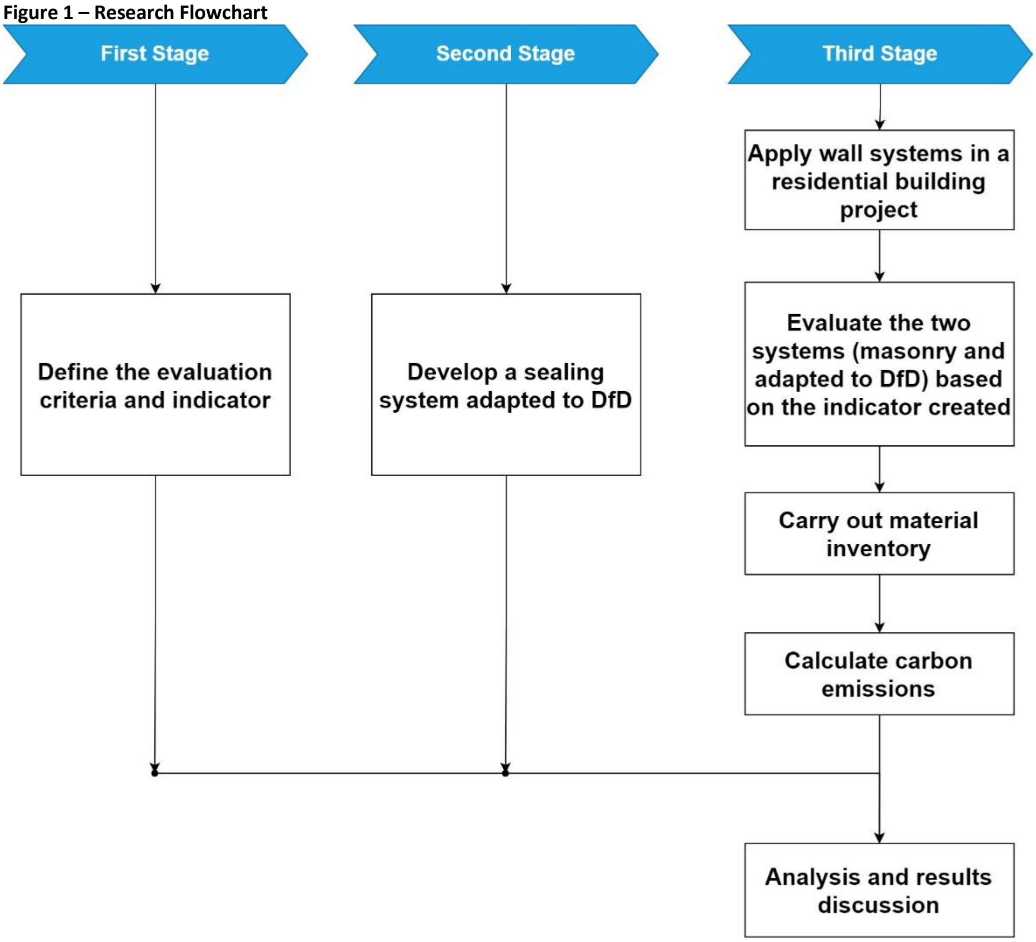
The first of them, developed by the authors, evaluates the degree of disassembly of solutions, considering compliance with DfD principles (ease of access, independence, simplicity and standardization, connections, and disassembly safety) and the possibilities of reusing components through circular economy strategies. Secondly, the impacts of carbon emissions embodied in construction materials were calculated.

The methodology applied in the article, as well as the discussions and results, are presented in the next chapters.

Methods

This chapter presents the proposed methodology for the research. To achieve the objective of technically evaluating a construction solution that enables the application of the project for dismantling internal walls, an evaluation indicator was developed considering five project principles for disassembly listed in the literature and ten waste disposal strategies proposed for the circular economy. Subsequently, the internal wall system adapted to the DfD was developed. Finally, based on a hypothetical case study, the solutions were evaluated using the proposed indicators. Therefore, Figure 1 presents the general flowchart of the activities carried out.

Figure 1 – Research Flowchart



Source: the authors.

Based on Figure 1, the next topics address each of the research stages.

DfD and circularity assessment indicator

The first stage of the methodology was to define the criteria for evaluating the wall systems. To evaluate the degree of disassembly of the elements, the DfD principles were used as criteria. The main references used for these requirements were ISO 20887 (ISO, 2020) and Jensen and Sommer (2016). Five criteria were selected, and for each, it was evaluated whether or not the project option met the specifications presented. The criteria evaluated in the research are described in Chart 1.

Chart 1 – Criteria for Assessing the Building Components Disassembly Degree

Criterion	Assessment Description	Reference
Ease of access to components and services	Material, component or connector of an assembly, especially with the shortest expected life cycle, should be easily accessible, with minimal damage and impacts on it and adjacent assemblies. Visible or exposed connections and installations must be prioritized, with sufficient space on all sides to carry out disassembly.	ISO (2020)
Independence	Design in independent layers, which allows plant flexibility, through the replacement, removal or updating of components, without damaging adjacent elements.	Jensen; Sommer (2016); ISO (2020)
Simplicity and standardization	Design simple and standardized solutions/details that fit into different contexts, thinking about modular and prefabricated elements. Avoid unnecessary treatments and finishes.	Jensen; Sommer (2016); ISO (2020)
Connections	Connections must allow repeated assembly and disassembly cycles without damaging components.	Jensen; Sommer (2016)
Disassembly safety	Preparation of a dismantling plan, which considers the previous criteria to increase safety. The more accessible, standardized and with fewer components, the easier and safer disassembly will be.	Jensen; Sommer (2016); ISO (2020)

Source: the authors.

To evaluate the circularity of the process, possible strategies were verified for each of the elements that comprise the internal walls and their interdependencies (openings, floor and lining), based on the 9R's proposed by Potting, Hekkert, Worrell and Hanemaaijer (2017). The description of each of the processes is available in Chart 2.

Chart 2 – Circular Economy Strategies (9R's)

Strategy	Description
R0 – Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
R1 – Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
R2 – Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
R3 – Re-use	Re-use by another consumer of a discarded product, which is still in good condition and fulfils its original function
R4 – Repair	Repair and maintenance of defective product so it can be used with its original function
R5 – Refurbish	Restore an old product and bring it up to date
R6 – Remanufacture	Use parts of discarded product in a new product with the same function
R7 – Repurpose	Use discarded product or its parts in a new product with a different function
R8 – Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality of materials
R9 – Recover	Incineration of materials with energy recovery

Source: the authors.

To quantify these results, compliance with each of the five DfD criteria was scored (Chart 1, here called Group 1), each worth 10 (ten) points, totaling 50 (fifty) points. Regarding circularity (Chart 2, called Group 2), it should be prioritized from R0 to R9, as defined by Potting, Hekkert, Worrell and Hanemaaijer (2017), where energy recovery is the last option to be considered. Thus, compliance scores were established for each of these alternatives so that each group of indicators has a maximum score of 50 points, totaling 100 possible points. Therefore, R0 considers 9.5 points, with each of the others having one point less, until reaching R9, which is equivalent to 0.5 points. Chart 3 describes the composition of the indicator.

Chart 3 – Indicator for evaluating design options disassembly and circularity.

Group	Criteria	Score	Assessment (Does it meet it?)
Group 1: DfD Principles	Ease of access to components and services	10	Yes (10)/ No (0)
	Independence	10	Yes (10)/ No (0)
	Simplicity and Standardization	10	Yes (10)/ No (0)
	Connections	10	Yes (10)/ No (0)
	Disassembly safety	10	Yes (10)/ No (0)
Group 2: Circularity Assessment	R0 – Refuse	9.5	Yes (9, 5)/ No (0)
	R1 – Rethink	8.5	Yes (8, 5)/ No (0)
	R2 – Reduce	7.5	Yes (7, 5)/ No (0)
	R3 – Re-use	6.5	Yes (6, 5)/ No (0)
	R4 – Repair	5.5	Yes (5, 5)/ No (0)
	R5 – Refurbish	4.5	Yes (4, 5)/ No (0)
	R6 – Remanufacture	3.5	Yes (3, 5)/ No (0)
	R7 – Repurpose	2.5	Yes (2, 5)/ No (0)
	R8 – Recycle	1.5	Yes (1, 5)/ No (0)
	R9 – Recover	0.5	Yes (0, 5)/ No (0)
Indicator		(∑ G1 score) +(∑ G2 score)	

Source: the authors.

Development of the internal wall system adapted to DfD

The development of the internal wall model adapted to the DfD took into account literature research on the alternatives proposed in the literature for this layer of the project. The main references are presented in Chart 4.

Chart 4 – Summary of alternatives for detachable internal vertical seals

Construction system	Type of Building	Country	Reference
Drywall , with steel beams covered with plasterboard and fiber cement, thermal insulation with rock wool	Temporary Pavilion	Italy	Arrigoni, Zucchinelle, Collatina and Dotelli (2018)
Concrete walls with bolted connections	Not specified	Denmark	Jensen; Sommer (2016).
Partitions with plywood cladding, with aluminum frames	Commercial (offices)	Australia	Minunno, O'Grady, Morrison and Gruner (2020); O'Grady, Minunno, Chong and Morrison (2021)
Steel and wood structure, with wood and polycarbonate cladding	Not specified	Netherlands	Durmisevic (2019)
Removable metal profile and plywood panel	Offices or residential properties	Netherlands	Juunno (2022)
Prefabricated wooden panels	Not specified	Brazil	Ghellere (2020)
Modular wooden panel with MDF sheet cladding	Not specified	Brazil	Rezende (2016)
Multi-panel shear wall with shear key connectors and connector details	Not specified	Italy	Polastri, Casagrande (2022)
PVC panels	Popular residential housing	Brazil	Barbosa (2015)

Source: the authors.

Based on the references, pine wood was chosen for the panel structure. The choice for this material is initially due to the lower amount of carbon incorporated into its production. Furthermore, it was considered easier to propose different modulations for wood, as it is manufactured in small and medium-sized companies, compared to companies producing metal profiles.

Modulation concepts were applied to optimize the coating plates available on the market, generating the lowest number of cuts and waste. Therefore, to identify the dimensions of the covering plates that could be used, a search was carried out on the models available for sale on the Internet. Based on the research, it was decided to use plasterboard sheets to cover the internal walls, considering the lower value compared to MDF, the variety of options and suppliers, and the available measurements, which facilitate modulation with reduced material waste.

In the proposal, two ceiling height options, 2.50m, and 2.80m, were considered so that the system can be used in low—and medium-standard constructions. The development process and assembly and disassembly solutions are presented in the chapter on results and discussions.

Hypothetical case study

The third stage consisted of preparing the project that was the subject of the case study. The architectural system was analyzed in the project. Structural projects, foundations, electrical and hydraulic installations, or other complementary projects were not evaluated. The focus of the research was internal walls and their interface with doors, floor coverings and ceilings.

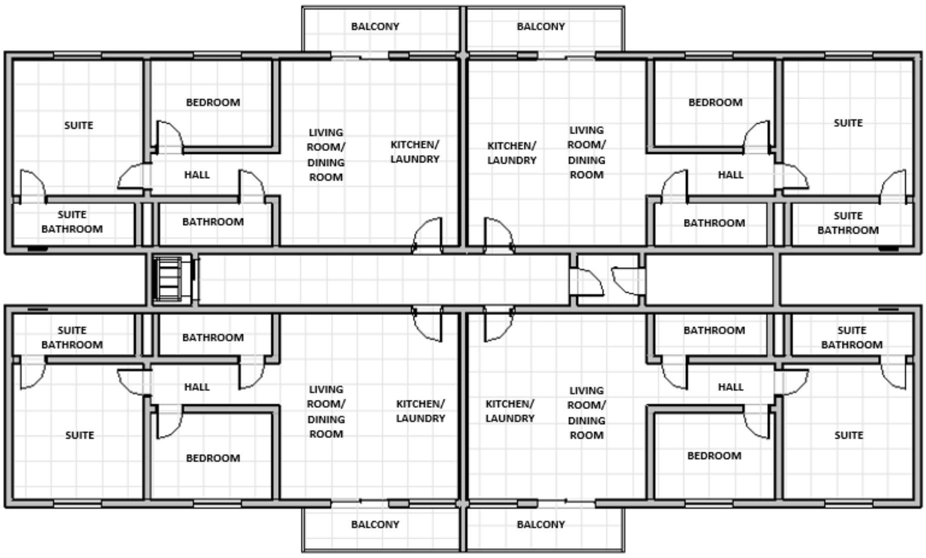
A vertical, multi-family residential building characterizes the hypothetical project developed by the authors. This building model was chosen because it is representative of the construction sector in the region where the work was developed and presents dismantling alternatives that can be applied to the local context.

The building consists of 10 floors: eight floors of standard apartments (identical), the first floor of the garage, entrance hall, and party room, and the top floor for equipment and water tank, with a total area of 4264m². The apartments have two bedrooms, one of which is a suite, a social bathroom, an integrated living room, and a kitchen. The beam-column structural system was adopted to compare two non-structural wall systems, one adapted to DfD and the other using non-structural concrete block walls.

The characteristics of the building considered previous research, in which data from the Brazilian Association of Real Estate Developers (ABRAINC, 2021; 2022) were analyzed on the profile of properties acquired in the metropolitan region of Porto Alegre in 2021 (area of 66m² and price per square meter of the private built area of R$4,712). Considering these characteristics, a survey was carried out among new properties for sale in the region, in which the standard floor plan of the apartments was identified.

Based on these premises, a project for a medium-standard building characteristic of the Porto Alegre – RS metropolitan region was created. Furthermore, in order to facilitate the extraction of quantitative data and interface with other software, Autodesk Revit 2022, educational version, was used for modeling. Figure 2 shows the floor plan of the

Figure 2. Floor plan of the typical floor



Source: the authors.

Considering the category chosen for evaluation, it was decided to use the 2.80m ceiling height alternative for the internal vertical fences planned for disassembly in the hypothetical case study. The external walls were maintained with concrete block masonry, as hydro-sanitary installations can be built into them, maintaining the structural stability of the building as no solutions were proposed for this discipline. In the two bathrooms provided for each apartment, it was proposed to close them with internal walls adapted to the DfD, using plasterboard sheets specific for wet areas in these places. The placement of a shared shaft between the two bathrooms to pass the hydro-sanitary installations can be observed.

For both project proposals, the same plant typology was considered (Figure 1). Once the base project was completed, with the internal walls adapted to DfD (Project 1), the system was replaced by masonry fences (Project 2). For Project 2, traditional construction methods were considered, including internal and external masonry walls with concrete blocks. The model of masonry walls, windows, doors, and floors was extracted from the National BIM Library, maintained by ABDI, to seek standardization in construction elements. After preparing the project, the quantity of materials was extracted using the Revit table tool.

The first evaluation was qualitative, analyzing both walls' systems in terms of the indicators in Chart 3. The authors carried out the analysis, considering the description of what should be considered in each of the criteria.

Then, to calculate the carbon incorporated into the project, the amount of CO_2 emission from the materials making up the internal walls was used, multiplied by the amount of material estimated for the project. The CO_2 emission indicators from Costa (2012) were used, which consider emissions from the extraction, processing, and transportation stages, of raw materials and finished products, evaluating the Brazilian energy matrix, and average data from the national production process.

Pine wood was selected for the structure of the fence panels due to the availability of the material in the southern region of the country. Costa (2012) proposed a methodology already considering losses during the production of the material; therefore, because the panel structure adapted to the DfD is prefabricated, only this loss was considered. Based on calculations of the energy required to extract trees and associated CO_2 emissions, in addition to the energy consumed in production, the emission factor considered was 0.321 tCO_2/m^3, according to Costa (2012).

In the case of mortar, the emission factor was the sum of the emissions generated by extraction, processing, and transportation of raw materials, added to the energy consumption of the equipment used to mix the mortar on site. The mass mix considered was 0.246/0.142/1.226 (cement/hydrated lime/dry natural sand), with a water/cement ratio of 1.58 and a density of 2.001 (t/m^3). Therefore, the factor used was 0.197 tCO_2 /t mortar (Costa, 2012).

The other two materials evaluated are concrete blocks and plasterboard sheets, and the data are presented in Chart 5.

Chart 5 – CO2 emission factors according to researched literature

Identification	Unit	Value	Reference
Mortar	tCO_2/t product	0.197	Costa (2012)
Concrete (block)	tCO_2/t product	0.184	Costa (2012)
Plaster (plates)	tCO_2/m^3 product	0.766	Costa (2012)
IMPM wood, for Pine	tCO_2/m^3 product	0.321	Costa (2012)

Source: the authors.

To calculate the carbon incorporated into the materials that make up the fences in Project 1, wood, plaster, mortar, and concrete blocks (which comprise the external fences) were used. Based on the volume data extracted from Revit, the total mass was calculated, considering the density of each element. Finally, the embodied carbon was calculated based on the parameters available in Chart 5.

To compare with a traditional construction model, project 2 replaced all lightweight fences with concrete block masonry walls. Then, the mass of the material equivalent to the concrete and mortar of the external and internal walls was considered, and carbon emissions were calculated again for this configuration.

Eberhardt, Birgisdóttir and Birkved (2019) proposed that only virgin materials were used for construction. Furthermore, according to the methods proposed by Minunno, O'Grady, Morrison and Gruner (2020) and Arrigoni, Zucchinelle, Collatina and Dotelli (2018), when using techniques that involve the disassembly of the building, the carbon equivalent can be offset by the elements that will be used in the next life cycle. This was the premise used for cases in which it was classified that a new cycle of use would be possible after the building's end of life, as in the project adapted to DfD.

In conclusion, the results were analyzed using indicators of compliance with DfD and circularity criteria, in addition to CO2 emission estimates in each of the project options.

Results and discussions

The next topics present the article's results and discussions. The process of developing the internal wall system adapted to disassembly was described initially, and subsequently, the systems applied in the hypothetical case study were evaluated using the proposed indicators.

Disassembly-oriented internal wall system

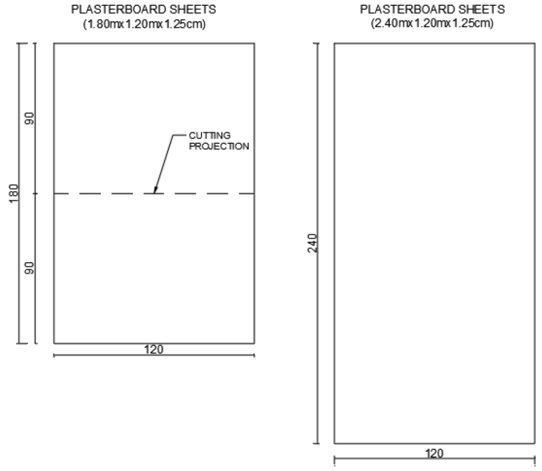
To define the modulation of the profiles, we started with the measurements of the plasterboard sheets that would be used. Plasterboard is the most industrialized product in the system, and due to the difficulty in recycling it, it is necessary to generate the smallest volume of waste possible. As a result, it was decided to use plasterboard sheets measuring a) 1.80x1.20mx1.25cm (for a ceiling height of up to 2.80m) and b) 2.40x1.20mx1.25cm (for a ceiling height of up to 2.50m).

When selecting these models, we considered using plate "a" positioned so that the width is 1.20m and the height is 1.80m. To make up the height of 2.70m, it is proposed to place an entire plate plus half a plate with a height of 0.90m. For a height of 2.40m, plate "b" is placed in one piece.

It is worth noting that, to achieve ceiling heights of 2.80m and 2.50m, it is proposed to install a skirting board and ceiling wheel. These will also hide the module's connections with the slab and floor, as will be detailed later. The plan for using the sheets is shown in Figure 3 and the arrangement of the covering boards on the wall is shown in Figure 4.

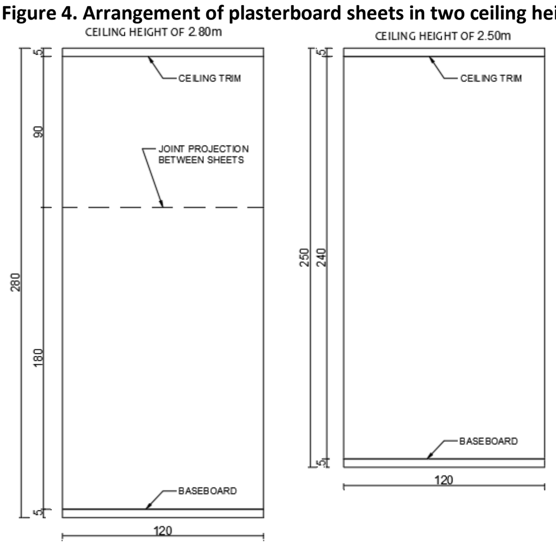
Based on the definition of the seal coating, the modulation of the wooden structure was created. Thus, they should fit within a horizontal measurement of 1.20m, and a vertical measurement of 2.70m or 2.40m. For a ceiling height of 2.70m, three modules measuring 0.90m x 0.40m each were considered. For the measurement of 2.40m, the modules are 0.80m x 0.40m. Observing Greven and Baldauf's (2007) guidelines, this modulation meets the use of the decimeter as a modular coordination system, adopted internationally, in addition to considering a reasonable distance to avoid unnecessary consumption of material. Figure 5 shows the modules for the two heights evaluated.

Figure 3. Plan for using plasterboard sheets, with cutting projection



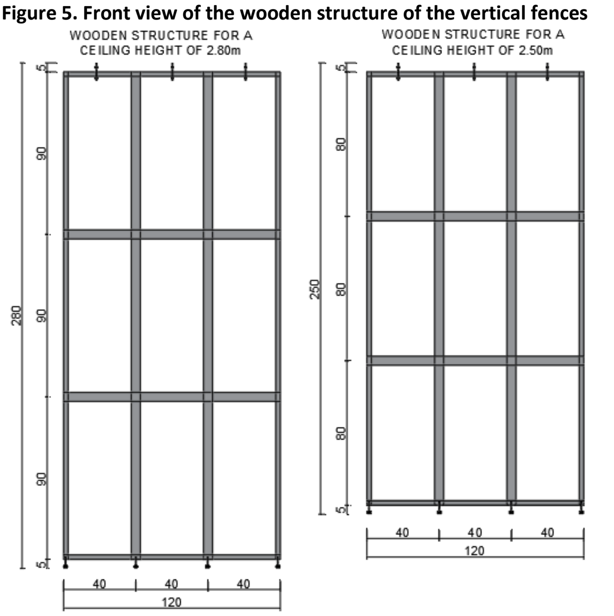
Source: the authors.

Figure 4. Arrangement of plasterboard sheets in two ceiling height alternatives



Source: the authors.

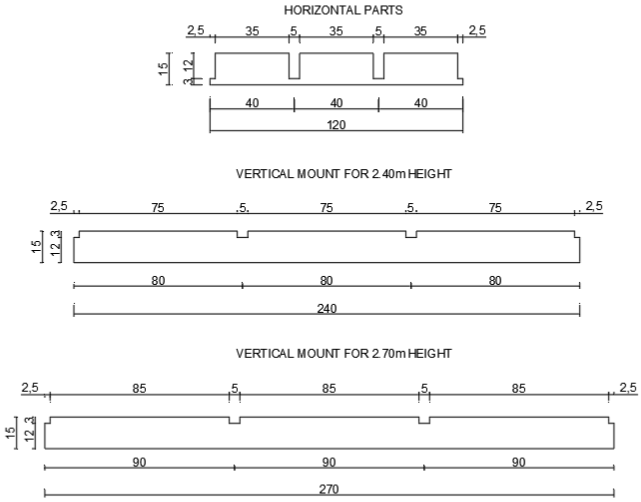
Figure 5. Front view of the wooden structure of the vertical fences



Source: the authors.

As seen in Figure 5, the measurement of the modules is considered from axis to axis of the upright. Each internal upright measures 5cm x 15cm. However, for the external uprights, the thickness is 2.5cm so that modulation can be maintained. It should be noted that two 2.5 cm pieces will be joined when joining two wall modules, making up the 5 cm of the remaining uprights. The fit between the amounts was based on the system proposed by Durmisevic (2019). Furthermore, the fit reduces the need for screws to join the pieces together. The details are shown in Figure 6.

Figure 6. Detailing of wooden uprights



Source: the authors.

Threaded rods are proposed to achieve a ceiling height of 2.80m or 2.50m, which can adjust the wall measurement to the desired height. The system is inspired by the solution proposed by Rezende (2016), which is to obtain greater flexibility in the ceiling height. At the bottom, a leveling foot must be placed, eliminating the need to drill holes in the floor, facilitating disassembly, and reducing the need for maintenance after removing the wall. At the top, the proposal is for a concrete anchor to be fixed to the slab so that minor height adjustments can also be guaranteed during assembly.

To join two modules, the proposal is to use an intermediate module, which will allow access to the main modules, in which only a small percentage of the plaster is damaged in the event of disassembly. Vertical uprights 2.5cm thick are used, spaced 12.5cm apart, totaling 17.5cm wide. The spacing is proposed so that the tool can be used to thread the connections between the modules ensuring the electrical installations pass through there, but mainly, as this is the exact measurement of the total width of the wall, making it feasible to join the modules in corners. Or in a "T", as seen in Figure 7.

Based on these definitions, it is proposed that the modules be prefabricated and taken to the site already assembled to complete the finishing work. The proposed assembly sequence is as follows:

a) Fit the uprights, forming the structure;

b) Screw the vertical uprights at the ends;

c) Drill and connect the upper rod and leveling foot;

d) Fix the first layer of plaster covering with screws;

e) Place filling, if necessary;

f) Close the wall with the second sheet of plasterboard;

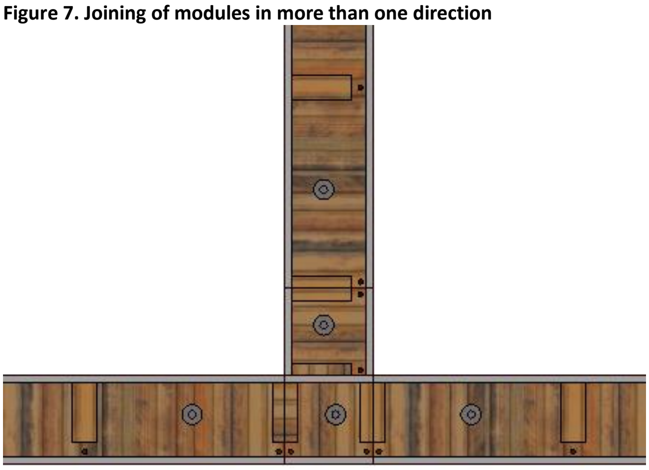
g) On site, fix the first auxiliary module to the edge wall and the slab, adjusting the height using the leveling foot on the base;

h) Position the other modules by fitting them into the auxiliary panels, slab and adjusting the height by foot;

i) Finally, attach the skirting board and lining wheel, for finishing.

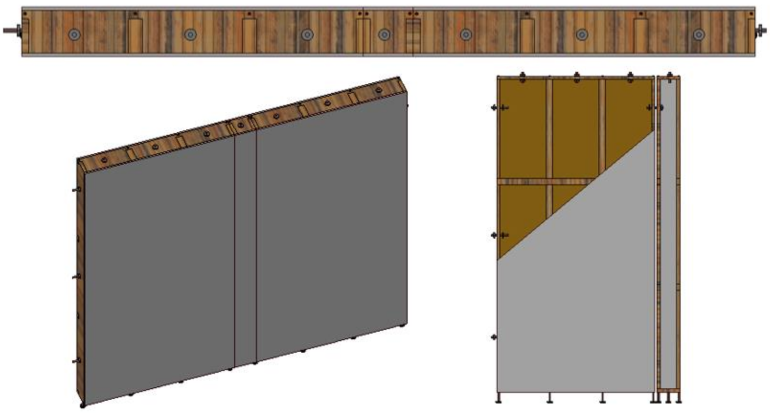
Based on this, Figure 8 shows the view of the joining of two main modules, with an intermediate module.

Figure 7. Joining of modules in more than one direction



Source: the authors.

Figure 8. View of the pre-assembled modules

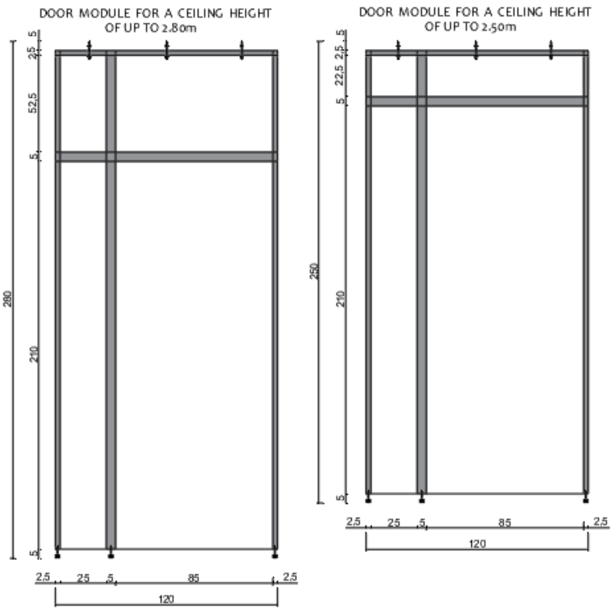


Source: the authors.

From the assembly sequence, the wall can be removed without leaving permanent marks on the floor since the wall and the slab can be easily repaired by covering the holes and reapplying the paint, while the floor presents greater difficulties to repair when damaged. In the case of maintenance, intervention must be carried out using auxiliary modules, reducing the volume of waste generated.

To insert the doors, a standardized measurement of 80cm wide by 2.10m high was considered. Greven and Baldauf (2007) propose that the modular span of the frame should be 5cm larger than the size of the frame; therefore, the required span would be 85cm x 2.15m. To cover the gap, considering the modules 1.20m by 2.70m and 1.20m by 2.40m, one row of vertical uprights and two of the horizontal pieces must be removed, as shown in Figure 9.

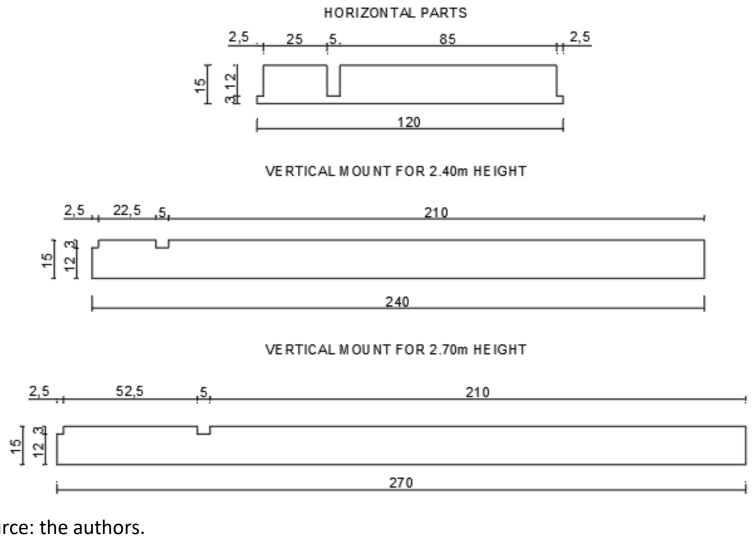
Figure 9. Details of the door modules



Source: the authors.

Figure 9 shows that the gap of 2.15m for the door's height is reached by 2.10m plus 5cm of the leveling rods; otherwise, it would not be possible to fix the door to the horizontal beam. Figure 10 shows the details of the door module parts.

Figure 10. Details of the uprights for fitting the door



Source: the authors.

Once the wooden structure of the door module was defined, it was proposed that plasterboard sheets should be used for cladding. As for complementary installations, considering the integrity of the wood and the greater flexibility in removing walls, it is expected that the hydrosanitary installations will be concentrated on the edge walls and partitions between apartments, which can be made of concrete or ceramic bricks. Electrical installations and outputs for switches must be concentrated in the connection modules between the walls.

Regarding the filling material of the main modules, the objective of the work was not to evaluate the acoustic and thermal performance of the system or its fire resistance properties. Due to the importance of these requirements, the composition of the filling could be a subject for future research.

For the disassembly sequence, the following process was suggested:

a) Remove skirting board and lining wheel;

b) Cut the plasterboard joints, once they are mapped;

c) Remove intermediate modules to access the main modules;

d) Unscrew the intermediate modules from the main module;

e) Unscrew the main module from the slab and remove the entire piece.

Having completed the development of the internal sealing system adapted to DfD, the following section presents the results of the evaluation of the walls applied to the hypothetical case study.

DfD principles and circularity of design options

Considering construction characteristics of internal vertical masonry walls, comprising concrete blocks and mortar covering, built in situ, Chart 6 presents the disassembly and circularity evaluation indicator of this alternative, based on the authors' analysis.

Chart 6 – Indicator for evaluating disassembly and circularity of masonry walls

Group	Criteria	Score	Assessment (Does it meet it?)	Score obtained
Group 1: DfD Principles	Ease of access to components and services	10	No	0
	Independence	10	No	0
	Simplicity and Standardization	10	No	0
	Connections	10	No	0
	Disassembly safety	10	No	0
Group 2: Circularity Assessment	R0 – Refuse	9.5	No	0
	R1 – Rethink	8.5	No	0
	R2 – Reduce	7.5	No	0
	R3 – Re-use	6.5	No	0
	R4 – Repair	5.5	Yes	5.5
	R5 – Refurbish	4.5	Yes	4.5
	R6 – Remanufacture	3.5	No	0
	R7 – Repurpose	2.5	No	0
	R8 – Recycle	1.5	Yes	1.5
	R9 – Recover	0.5	Yes	0.5
Indicator		∑		12

Source: the authors.

It was assessed that the traditional masonry wall construction system does not meet any of the DfD principles; this is because the system has chemical bonds that can be demolished and used for recycling, without the possibility of direct reuse. Concerning other criteria, the equipment required for demolition does not favor dismantling safety, and on-site construction makes it difficult to standardize the elements. Furthermore, there is no independence between the systems since electrical and hydraulic installations in the wall can only be accessed by partially demolishing the elements, generating waste, and purchasing new materials for repairs.

Regarding the circularity assessment, the options that would meet the principles are repair or renovation in case of damage to the wall and recycling as the final destination. Despite the evaluation, solutions can be proposed for this system based on the prefabrication of concrete brick walls, for example, as industrialization can support the standardization of components and provide easier access points to the facilities. Furthermore, examples such as the threaded connections proposed by Jensen and

Sommer (2016) can be an alternative to facilitate the disassembly of components and subsequent reuse.

Regarding the fencing system with a wooden structure and plasterboard covering developed in the research, Chart 7 presents the authors' assessment.

Chart 7. Indicator for evaluating disassembly and circularity of wood and plaster walls

Group	Criteria	Score	Assessment (Does it meet it?)	Score obtained
Group 1: DfD Principles	Ease of access to components and services	10	Yes	10
	Independence	10	Yes	10
	Simplicity and Standardization	10	Yes	10
	Connections	10	Yes	10
	Disassembly safety	10	Yes	10
Group 2: Circularity Assessment	R0 – Refuse	9.5	No	0
	R1 – Rethink	8.5	Yes	8.5
	R2 – Reduce	7.5	Yes	7.5
	R3 – Re-use	6.5	Yes	6.5
	R4 – Repair	5.5	Yes	5.5
	R5 – Refurbish	4.5	Yes	4.5
	R6 – Remanufacture	3.5	No	0
	R7 – Repurpose	2.5	Yes	2.5
	R8 – Recycle	1.5	Yes	1.5
	R9 – Recover	0.5	Yes	0.5
Indicator		∑		87

Source: the authors.

Considering the DfD principles, it was considered that the proposed system meets the five requirements since access to electrical installations is facilitated, located in intermediate modules, which, if damaged, can be replaced, causing a low impact. The system is independent of the structure and can be placed on the finished floor, screwed to the slab and edge walls. Connections are mechanical and reversible, using screws. Furthermore, it is estimated that removing the entire module increases safety by reducing the number of tools needed for disassembly and demolition waste. However, the feasibility of transporting the modules by elevator or stairs or installing equipment for removal from the outside of the building should be evaluated.

Regarding the evaluation of circularity, the reduction criterion is considered met, comparing the system's mass in relation to a masonry wall with concrete blocks. Reuse is also possible, depending on the assembly and disassembly sequences presented, in addition to repair, reuse, and renovation actions.

It should be noted that for the reuse of modules, the project must be accessible to the owner, as the modulation must be known at the time of disassembly. Otherwise, parts could be damaged due to a lack of knowledge of the project. Finally, if none of the alternatives are more viable, considering the life cycle of the material, wood recycling or energy recovery is possible as a last alternative.

The system achieved 87 points out of a possible 100, higher than the 12 points evaluated for the masonry wall. Once this analysis has been carried out, the following section presents the assessment of the carbon embodied in the two project options.

Assessment of carbon emissions

In the last stage, carbon emissions were calculated due to the production processes of mortar, concrete blocks, wood, and plaster, considering the mass of each material in the two design options. Table 1 presents the results obtained.

Table 1. Results of CO2 emissions due to the production of construction materials for the vertical fences of the two projects

Project	Material	Total Volume in the Project (m³)	Total Mass in the Project (t)	CO2 emissions (tCO2)	Total per project (tCO2)
1 (DfD)	Pine Wood	48.8	23.4	15.7	460.0
	Plasterboard	41.6	27.7	31.9	
	Mortar	245.9	492.0	97.0	
	Concrete blocks	779.6	1,715.0	315.6	
2 (Traditional)	Mortar	338.2	676.8	133.4	567.7
	Concrete blocks	1,072.9	2,360.3	434.3	

Source: the authors.

According to the results in Table 1, the total mass of the design adapted to DfD is 26% smaller than the traditional design, as all external walls remained in masonry. As a result, the total carbon incorporated into the construction materials of the vertical walls from the DfD-oriented design was 460 tCO_2, 19% lower compared to the total of 567.7 tCO_2 from the traditional design with all masonry walls. Thus, already in the construction phase, a reduction in carbon emissions is observed due to the production of construction materials, proving that R1 (Rethink) and R2 (Reduce) were circularity criteria met by the project.

Compared with the literature data, Minunno, O'Grady, Morrison and Gruner (2020) achieved an 88% mass reduction and a saving of 17 tCO_2 with a project fully adapted to DfD considering the material production stage. Regarding the savings of 107.7 tCO_2 obtained in this project, the difference lies in the size of the construction, which in the case of Minnuno, O'Grady, Morrison and Gruner (2020) was two stories high.

Arrigoni, Zucchinelle, Collatina and Dotelli (2018) obtained a 37% reduction in emissions in a pavilion project fully adapted to the DfD. The 19% reduction in this case study is a positive result since only the internal walls have already achieved a relevant result.

As described in the methodology, when the building is dismantled, the carbon equivalent to the elements that can be used in the next life cycle is deducted from the subsequent use. Based on the qualitative assessment, it is considered that masonry fences built with a conventional methodology cannot be reused in a new life cycle, only used for recycling, and can be crushed and reinserted in the construction. However, for walls adapted to DfD, if the modules are maintained correctly and transported to a new project, they can be reused in many cycles.

The performance standard (ABNT, 2024) defines that, for the higher level, internal walls must last at least 20 years; thus, considering another use cycle, the savings in carbon emissions can reach another 47.5 tCO_2 during this period, calculating the emissions incorporated into the plaster and wood. Thus, considering the same project, the savings in carbon emissions for a second life cycle would reach 27%. Furthermore, considering that, according to the same standard, the structure and external walls must last at least 50 and 40 years, respectively, having greater flexibility in changes to the internal walls can facilitate the extension of the useful life of these other layers.

Despite the positive results, more significant gains will only be observed if the entire building is planned for disassembly. Proposals that could be applied to the design in order to optimize deconstruction are the use of prefabricated steel structures, as proposed by Akanbi *et al.* (2019); dropped ceiling systems, used by Arrigoni, Zucchinelle, Collatina and Dotelli (2018), which allows the installation of electrical and hydraulic pipes in a more accessible way, and can be executed in ordinary plaster, plasterboard, PVC or wood, for example; in addition to raised floors, supporting the floor plates on a structure with a raised gap over the subfloor, according to a proposal by Legonde (2017).

The use of prefabricated concrete, as proposed by Eberhardt, Birgisdóttir and Birkved (2019) for floors, slabs, facades, central walls, pillars, and beams, can also be an alternative if mechanical connections are planned to join these elements. However, as observed in this case study, concrete is responsible for high levels of CO_2 emissions due to its production processes. It is not the most suitable material, considering the criteria of the circular economy.

Conclusions

The objective of this article was to evaluate construction alternatives that enable the application of the design for the disassembly of internal walls, optimizing the reuse of construction components and the carbon embodied in the project. Based on literature research on the topic, design alternatives used for constructing buildings adapted to the DfD were identified. The primary basis was the replacement of chemical bonds by reversible mechanical bonds and replacing concrete with steel and wood.

Based on these solutions, a model was developed of detachable panels with a wooden structure and plasterboard covering, which met the five DfD criteria evaluated in the indicator proposed in the methodology (ease of access, independence, simplicity and standardization, connections, and disassembly safety), in addition to obtaining a score of 87 points, out of a total of a possible 100, considering the circular economy criteria together. Thus, through qualitative analysis, it was proven that it is possible to think of solutions upstream of the process, which make the deconstruction of building elements viable.

From a quantitative point of view, the proposed alternative promoted savings of 107.7 tCO_2, representing a 19% reduction in carbon emissions incorporated into the production process of the building's sealing materials, compared to the traditional system, composed entirely of non-structural concrete brick masonry. Considering the multiple life cycles possible for the panels developed, with direct reuse of the module, and the gains in maintenance and flexibility for users, the savings can be even more significant.

Given the results obtained, it is assessed that the internal wall alternative proposed in the work meets the DfD criteria and the circular economy, in addition to presenting a reduction in the carbon emission incorporated into the project. More life cycles can be applied to the panels. The more lifecycle cycles can be applied to the panels, the greater the carbon savings, especially when compared to conventional masonry systems.

Despite the positive outcomes of the research, it is worth noting that simply changing the internal wall system of a building is not sufficient to promote the circularity of the building's components. Alternatives need to be studied for all design systems, especially the structure responsible for a considerable portion of the building's mass, in addition to the other floor, ceiling, and facade coverings. Given this, this work can serve as an initial study to apply the strategies of the circular economy and the DfD in vertical residential buildings in Brazil, a sector responsible for a large part of the national real estate market but which rarely applies these principles.

Future research could investigate a complete building for dismantling, considering all project disciplines; prepare a prototype of the proposed panels to carry out a performance assessment of the panels, verifying their compliance with thermal, acoustic, and fire resistance criteria; as well as carrying out an economic analysis on the viability of its production. Due to the proposition of a prefabricated system, it was impossible to conduct an economic comparison with a masonry system, given the need for a case study with a company willing to develop the panel prototype, evaluating the raw material costs and labor.

Acknowledgements

This research was supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Financing Code 001.

References

ABNT. ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 15575-1**: Edificações habitacionais -Desempenho. Parte 1: Requisitos gerais. Rio de Janeiro: ABNT, 2024. 107 p.

ABRAINC. ASSOCIAÇÃO BRASILEIRA DE INCORPORADORAS IMOBILIÁRIAS. **Expectativa do mercado imobiliário na região sul do Brasil.** São Paulo: ABRAINC, 2022. Disponível em: https://www.abrainc.org.br/wp-content/uploads/2021/03/Expectativa-do-Mercado-Imobiliario-na-Regiao-Sul-do-Brasil-03_03.pdf. Acesso em: 24 jul. 2023.

ABRAINC. ASSOCIAÇÃO BRASILEIRA DE INCORPORADORAS IMOBILIÁRIAS. **Indicadores de affordability**. São Paulo: ABRAINC, 2021. 23p. Disponível em: https://www.cimentoitambe.com.br/wp-content/uploads/2022/01/pesquisa_Fipe.pdf. Acesso em: 24 jul. 2022.

ABRELPE. ASSOCIAÇÃO BRASILEIRA DE EMPRESAS DE LIMPEZA PÚBLICA E RESÍDUOS ESPECIAIS. **Panorama dos resíduos sólidos no Brasil 2022**. São Paulo: ABRELPE, 2022. Disponível: file:///C:/Users/Windows/Downloads/Panorama_Abrelpe_2022.pdf. Acesso em: 15 fev. 2024.

AKANBI, L.; OYEDELE, L. O.; OMOTESO, K.; BILAL, M.; AKINADE, O. O.; AJAVI, A. O.; DELGADO, J. M. D.; OWOLABI, H. A. Disassembly and deconstruction analysis system (D-DAS) for construction in a circular economy. **Journal of Cleaner Production**, v. 223, p. 386–396, June 2019. DOI: https://doi.org/10.1016/j.jclepro.2019.03.172.

AKINADE, O.; OYEDELE, L. O.; OMOTESO, K.; AJAYI, S. O.; BILAL, M.; OWOLABI, H. A.; ALAKA, H. A..; LOONEY, J. H. BIM-based deconstruction tool: Towards essential functionalities. **International Journal of Sustainable Built Environment**, v. 6, n. 1, p. 260–271, June 2017. DOI: https://doi.org/10.1016/j.ijsbe.2017.01.002.

ARRIGONI, A.; ZUCCHINELLE, M.; COLLATINA, D.; DOTELLI. Life cycle environmental benefits of a forward-thinking design phase for buildings: the case study of a temporary pavilion built for an international exhibition. **Journal of Cleaner Production**, v. 187, p. 974–983, June. 2018. DOI: https://doi.org/10.1016/j.jclepro.2018.03.230.

BARBOSA, T. F. **PVC na construção**: Análise de algumas aplicações. 2015. 137 f. Dissertação (Mestrado em Engenharia Civil – Especcializaçã em Construções) – Faculdade de Engenharia, Universidade do Porto, Porto, 2015. Disponível em: https://hdl.handle.net/10216/80105. Acesso em: 17 nov. 2022.

CARVAJAL-ARANGO, D.; BAHAMÓN-JARAMILLO, S.; ARISTIZÁBAL-MONSALVE, P.; VÁSQUEZ-HERNÁNDEZ, A.; BOTERO, L. F. B. Relationships between lean and sustainable construction: Positive impacts of lean practices on sustainability during construction phase. **Journal of Cleaner Production**, v. 234, p. 1322–1337, Oct. 2019. DOI: https://doi.org/10.1016/j.jclepro.2019.05.216.

COSTA, B. L. C. **Quantificação das emissões de CO2 geradas na produção de materiais utilizados na construção civil no Brasil.** 2012. 208 f. Dissertação (Mestrado em Engenharia Civil) - Programa de Pós-Graduação em Engenharia Civil, COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2012. Disponível em: http://www.coc.ufrj.br/en/master-dissertations/308-2012/ 3131-bruno-luis-de-carvalho-da-costa. Acesso em: 27 jan. 2022.

DELOITTE Brasil. **Comportamento do consumidor de imóveis em 2040:** onde e como habitaremos? São Paulo: Deloitte Brasil, 2019. 60p. Disponível em: https://www2.deloitte.com/br/pt/pages/real-estate/articles/comportamento-consumidor-imoveis-2040.html. Acesso em: 10 mar. 2022.

DURMISEVIC, E. **Circular economy in construction**: design strategies for reversible buildings. Netherlands: BAMB; European Commission, 2019. 94 p. Disponível em: https://www.bamb2020.eu/wp-content/uploads/2019/05/Reversible-Building-Design-Strateges.pdf. Acesso em: 16 nov. 2022.

EBERHARDT, L. C. M.; BIRGISDÓTTIR, H.; BIRKVED, M. Life cycle assessment of a Danish office building designed for disassembly. **Building Research and Information**, v. 47, n. 6, p. 666–680, Sept. 2019. DOI: https://doi.org/10.1080/09613218.2018.1517458.

GALANTE, Raquel. **Economia Circular no Setor da Construção**. Webinar. 2021. Disponível em: https://espacodearquitetura.com/formacoes/webinar-economia-circular-no-setor-da-construcao/. Acesso em: 08 jan. 2022.

GÁLVEZ-MARTOS, J-L.; STYLES, D.; SCHOENBERGER, H.; ZESCHMAR-LAHL, B. Construction and demolition waste best management practice in Europe. **Resources, Conservation and Recycling**, v. 136, p. 166–178, Sept. 2018. DOI: https://doi.org/10.1016/j.resconrec.2018.04.016.

GHELLERE, F. B. **Painel de vedação vertical pré-fabricado em madeira**. 2020. 172 f. Dissertação (Mestrado em Arquitetura e Urbanismo) - Programa de Pós-Graduação em Arquitetura e Urbanismo, Instituto de Arquitetura e Urbanismo, Universidade de São Paulo, São Carlos, 2020. DOI: https://doi.org/10.11606/D.102.2020.tde-04022021-155602.

GREVEN, H. A.; BALDAUF, A. S. F. **Introdução à coordenação modular da construção no Brasil**: Uma abordagem atualizada. Porto Alegre: ANTAC, 2007. 7 2p. (Coleção Habitare, 9). Disponível em: http://www.habitare.org.br/pdf/publicacoes/arquivos/colecao10/livro_completo.pdf. Acesso em: 17 nov. 2022.

ISO. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION**. ISO 20887:2020(en)**: Sustainability in buildings and civil engineering works - Design for disassembly and adaptability - Principles, requirements and guidance. Geneva: ISO, 2020. Disponível em: https://www.iso.org/obp/ui#iso:std:iso:20887:ed-1:v1:en. Acesso em: 14 feb. 2022.

JENSEN, K. G.; SOMMER, J. **Building a Circular Future**. 3rd ed. Copenhagen: GNX, 2016. 309 p. Disponível em: https://gxn.3xn.com/wp-content/uploads/sites/4/2018/09/Building-a-Circular-Future_3rd-Edition_Compressed_V2-1.pdf. Acesso em: 14 feb. 2022.

JUUNOO. **Technische documentation**. Zwevegem: Juunoo, 2022. 123 p. Disponível em: https://www.juunoo.com/wp-content/uploads/2021/05/JUUNOO-technische-documentatie.pdf. Acesso em: 24 jul. 2022.

LEGONDE, C. K. **Flexibilidade em edificações residenciais**: diretrizes de projeto e análise da aplicação no mercado imobiliário brasileiro. 2017. 211 f. Dissertação (Mestrado em Arquitetura e Urbanismo) - Programa de Pós-Graduação em Arquitetura e Urbanismo, Universidade do Vale do Rio dos Sinos, São Leopoldo, 2017. Disponível em: http://www.repositorio.jesuita.org.br/handle/UNISINOS/6657. Acesso em: 24 jul. 2022.

LONGO, L. F. M. **Projeto para Desmontagem e BIM**: ferramentas projetuais para aperfeiçoar a reutilização dos materiais. 2020. 252 f. Tese (Doutorado em Arquitetura e Urbanismo) – Universidade de São Paulo, Instituto de Arquitetura e Urbanismo - São Carlos, São Carlos, 2020. DOI: https://doi.org/10.11606/T.102.2020.tde-23112020-223721.

MINUNNO, R.; O'GRADY, T.; MORRISON, G. M.; GRUNER, R. L. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. **Resources, Conservation and Recycling**, v. 160, p. 1-14, Sept. 2020. DOI: https://doi.org/10.1016/j.resconrec.2020.104855.

O'GRADY, T.; MINUNNO, R.; CHONG, H-Y; MORRISON, G. M. Design for disassembly, deconstruction and resilience: A circular economy index for the, built environment. **Resources, Conservation and Recycling,** v. 175, p. 1-13, Dec. 2021. DOI: https://doi.org/10.1016/j.resconrec.2021.105847.

POLASTRI, A.; CASAGRANDE, D. Mechanical behavior of multi-panel cross laminated timber shear-walls with stiff connectors. **Construction and Building Materials**, v. 332, p. 1-13, May 2022. DOI: https://doi.org/10.1016/j.conbuildmat.2022.127275.

POTTING, J.; HEKKERT, M.; WORRELL, E.; HANEMAAIJER, A. **Circular economy**: Measuring innovation in the product chain. Policy Report. The Hague: PBL Netherlands Environmental Assessment Agency, 2017. Disponível em: https://www.pbl.nl/uploads/default/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf. Acesso em: 23 mar. 2022.

REZENDE, S. R. **Painéis de madeira para vedações internas com foco na região Uberlândia**. 2016. 150 f. Dissertação (Mestre em Engenharia Civil) – Faculdade de Engenharia Civil, Universidade Federal de Uberlândia, Uberlândia, 2016. DOI: http://doi.org/10.14393/ufu.di.2016.233.

TAM, V. W. Y.; SOOMRO, M.; EVANGELISTA, A. C. J. A review of recycled aggregate in concrete applications (2000–2017). **Construction and Building Materials**, v. 172, p. 272–292, May 2018. DOI: https://doi.org/10.1016/j.conbuildmat.2018.03.240.

---

1 **Jordana de Oliveira**
Civil engineer. Master in Civil Engineering at the Universidade do Vale do Rio dos Sinos. PhD student in Environmental Quality at the Universidade Feevale. Postal address: ERS-239, 2755, Novo Hamburgo, RS – Brazil. Zip code: 93525-075.

2 **Marco Aurelio Stumpf Gonzalez**
Civil engineer. PhD in Civil Engineering (Construction) form the Universidade Federal do Rio Grande do Sul. Professor of the Universidade do Vale do Rio dos Sinos. Postal address: Av. Unisinos, 950, São Leopoldo, RS – Brazil. Zip code: 93022-000.

3 **Andrea Parisi Kern**
Civil engineer. PhD in Civil Engineering (Structures) from the Universidade Federal do Rio Grande do Sul. Professor of the Universidade do Vale do Rio dos Sinos. Postal address: Av. Unisinos, 950, São Leopoldo, RS – Brazil. Zip code: 93022-000.